**SAARLAND UNIVERSITY (GERMANY)**

**Institute of Sport and Preventive Medicine**

**UNIVERSITY OF TECHNOLOGY SYDNEY (AUSTRALIA)**

**Faculty of Health**

# SLEEP-RELATED ISSUES FACING PROFESSIONAL FOOTBALL PLAYERS

By

Hugh H.K. Fullagar

This thesis is presented for the award of a Doctor of Philosophy (Sports Medicine) from the
Philosophical and Medical Faculty, Saarland University, Saarbrücken, Germany in
conjunction with the Faculty of Health, University of Technology Sydney, Australia

## CERTIFICATE OF AUTHORSHIP/ORIGINALITY

I, Hugh Head Kelsham Fullagar, declare that this thesis, is submitted in partial fulfilment of the requirements for the award of Doctor of Philosophy in the Institute of Sport and Preventive Medicine, Saarland University (Germany) and at the University of Technology Sydney (Australia) conducted jointly under the Memorandum of understanding between both institutions as part of an international joint PhD program. This thesis is wholly my own work as the sole author unless otherwise referenced or acknowledged. I have observed proper academic practice in the production of this thesis, and recognise and am thankful for the assistance in the production of this research and the preparation of this thesis from Saarland University supervisor Professor Tim Meyer and the Doctoral Graduate Research Program within Saarland University, in conjunction with University of Technology Sydney supervisor Associate Professor Rob Duffield and the respective Graduate Research School and Faculty of Health at the University of Technology Sydney. As such, I also certify to the best of my knowledge and belief that this thesis does not:

i. incorporate any material previously submitted for a degree or diploma in any institution of higher education without acknowledgement;

ii. contain any material previously published or written by another person; where due reference is made in the text; or

iii. contain any defamatory material

I also acknowledge that this research was supported by an Australian Government Research Training Program Scholarship.

I also grant permission for the library at Saarland University and University of Technology Sydney to produce duplicate copies of my thesis as required.

Hugh Head Kelsham Fullagar

30 June 2017

# TABLE OF CONTENTS

6.1 REVIEW: SLEEP AND ATHLETIC PERFORMANCE: THE EFFECT OF SLEEP LOSS ON EXERCISE PERFORMANCE, AND PHYSIOLOGICAL AND COGNITIVE RESPONSES TO EXERCISE
6.2 REVIEW: SLEEP AND RECOVERY IN TEAM SPORT: CURRENT SLEEP-RELATED ISSUES FACING PROFESSIONAL TEAM SPORT ATHLETES
6.3 IMPAIRED SLEEP AND RECOVERY FOLLOWING NIGHT MATCHES IN ELITE FOOTBALLERS
6.4 SLEEP, TRAVEL AND RECOVERY REPSONSES OF NATIONAL FOOTBALLERS DURING AND FOLLOWING LONG-HAUL INTERNATIONAL AIR TRAVEL
6.5 THE EFFECT OF AN ACUTE SLEEP HYGIENE STRATEGY FOLLOWING A LATE-NIGHT SOCCER MATCH ON RECOVERY OF PLAYERS

# ACKNOWLEDGEMENT

Firstly, I would like to thank my primary supervisor Prof. Tim Meyer. I am deeply appreciative of your wisdom, guidance, honesty and tolerance but most all for your unselfishness throughout the PhD process. Thank you for your understanding of my personal situations throughout this vastly international PhD and for your endless support. Through your excellent supervision and outstanding support, I now believe I have honed many skills, knowledge and most importantly, a passion for research and work within high performance sport. Special thanks must also go to Associate Prof. Rob Duffield and Prof. Aaron Coutts. Almost anytime on call you would be willing to put away not just knowledge and time for the project but also to simply offer advice for life in general. It is these lessons that make the time spent with you (albeit brief) even more valuable. You have been absolutely critical to both my professional and personal development and I look forward to the good times ahead.

Secondly, I would like to acknowledge everyone in the office for their assistance, friendship and generosity. To Ross Julian, Bob McCunn, Emiel Schulze, Jan Schimpchen, Sascha Schwindling, Daniel Hammes and all the practicants, doctors, visitors and staff thank you all for providing the endless amounts of help, madness, insanity, laughter and overall: fun. A special mention must also go to Sabrina Skorski for the hours put in to assist with all my studies, without you this would not have happened nearly as smoothly as it did. Your assistance, guidance and friendship will not be forgotten. Thirdly, I would like to thank my friends both in Germany and back home. Thank you all for the happiness you provide, for the lack of judgement you offer and for putting a smile on my face. I would also like to pay tribute to Marvin Löscher, whose ability to put things in perspective and cheer me up got me through so many happy, crazy and sad times will always be remembered. Thank you as well to all the players, professional staff and coaches who helped me across Europe.

Penultimate thanks are reserved for a special woman who knows who she is. I cannot thank you for enough for the love we shared, the amazing times we experienced and your unnerving support in allowing me to chase my dreams. Thanks for being you; this simply would not have been possible without you.

Finally, I would like to thank Mum, Dad and Hannah for their endless encouragement, support and love. I am truly grateful for your patience and for putting up with me all these years.

# STANDARD ABBREVIATIONS

| | |
|---|---|
| $^{O}$ | Degrees |
| $^{O}C$ | Degrees Celsius |
| ANOVA | Analysis of variance |
| CV | Coefficient of variation |
| d | Day |
| g | Gram |
| HR | Heart rate |
| ICC | Inter-class coefficient |
| Kg | Kilogram |
| km | Kilometre |
| m | Metre |
| mM | Milli-molar |
| min | Minute |
| n | Number of (participant sample size) |
| r | Correlation statistic |
| RPE | Rating of perceived exertion |
| s | Second |
| SEM | Standard error of measurement |
| SD | Standard deviation |
| $VO_{2max}$ | Maximal oxygen consumption |
| W | Watt |
| y | Year |

# TABLES

# FIGURES

# LIST OF PUBLICATIONS RELEVANT TO THE THESIS

## Literature Review

1. **Fullagar, H.H.K.,** Skorski, S, Duffield, R, Hammes, D, Coutts, A, Meyer, T. (2015). Sleep and athletic performance: The effects of sleep loss on exercise performance, and physiological and cognitive responses to exercise. *Sports Medicine.* 45(2):161-186. DOI: 10.1007/s40279-014-0260-0

2. **Fullagar, H.H.K.,** Duffield, R, Skorski, S, Coutts, A, Julian, R, Meyer, T. (2015). Sleep and recovery in team sport: current sleep-related issues facing professional team-sport athletes. *International Journal of Sports Physiology and Performance.* 10(8):950-7. DOI: 10.1123/ijspp.2014-0565

## Studies - Original Investigations

3. **Fullagar, H.H.K**., Skorski, S, Duffield, R, Julian, R, Bartlett, J, Meyer, T. (2016). Impaired sleep and recovery following night matches in elite football players. *Journal of Sports Sciences: Science and Medicine in Football*. 34(14):1333-9. DOI: 10.1080/02640414.2015.1135249

4. **Fullagar, H.H.K,** Duffield, R, Skorski, S, White, D, Bloomfield, J, Kolling, S, Meyer, T. (2016). Sleep, travel and recovery responses of national footballers during and following long-haul international air travel. *International Journal of Sports Physiology and Performance.* 11(1):86-95. DOI: 10.1123/ijspp.2015-0012

5. **Fullagar, H.H.K,** Skorski, S, Duffield, R, Meyer, T. (2016). The effect of an acute sleep hygiene strategy following a late-night soccer match on player recovery. *Chronobiology International.* 33(5):490-505. DOI: 10.3109/07420528.2016.1149190

# ABSTRACT

**Introduction:** The ability of football players to tolerate and recover from the physiological and psychological stressors of training and match play is critical to ongoing performance success. The ability to recover from these stressors is affected by numerous factors; including, experience, fitness, motivation and the natural fluctuation of physiological and behavioural processes – particularly the sleep-wake cycle. Indeed, sleep loss incurred prior to competition may reduce subsequent performance; whilst a reduction in sleep quantity or quality following competition may impede the recovery timeline. As such, sleep for athletes' has been recognised anecdotally amongst coaches and players as critical to performance and recovery. However, normative sleep behaviour in football players remains unknown. Moreover, there is limited evidence to show that when sleep is disturbed, performance and recovery suffer within the elite football environment. Consequently, the potential positive impact of improving sleep parameters on the recovery and performance timeline therefore remains to be substantiated. Thus, the aim of this thesis was three-fold: i) to determine the sleeping patterns of football players and to assess whether and when disrupted sleep indices occurred and ensuing effect on perceptual recovery status; ii) to assess the sleep, travel and recovery responses of footballers during and following long-haul international air travel and ensuing matchplay; and iii) to investigate the effect of an acute sleep hygiene strategy on physical, physiological and psychological recovery of players following a late-night match.

**Methods:** i) To determine the sleeping patterns in elite football, a group of sixteen elite football players completed a subjective online questionnaire twice a day (morning and night) for 21 days during the regular season. Subjective recall of sleep variables (duration, time of wake and sleep, wake episode duration), a range of perceptual variables related to recovery, mood and performance, internal training loads and non-exercise stressors were collected. ii) To assess the sleep, travel and recovery responses of footballers during and following long-haul international air travel and match-play, fifteen national football players undertook 18 h of predominately westward international air travel from the United Kingdom to South America (-4 h time-zone shift) for a 10-day tour (including two night matches). Objective sleep parameters, external and internal training loads, subjective player match performance, technical match data and perceptual jet-lag and recovery measures were collected. iii) The final investigation determined the effect of an acute sleep hygiene strategy (SHS) on physical, physiological and psychological recovery of players following a late-night match. Two highly-trained amateur teams (20 players) played two late-night friendly matches (20:45 start) against each other seven days apart. Players completed a sleep hygiene strategy after the match or undertook normal post-game routines in a randomised cross-over design. Objective sleep parameters, countermovement jump (CMJ), YoYo Intermittent Recovery test (YYIRT), venous blood and perceived recovery and stress markers were collected prior to and during the ensuing 48 h post-match.

**Results:** In summary of the above studies; i) Elite club players appear to sleep within healthy adequate ranges following training days and match days. However, players report significantly reduced sleep duration and perceptual recovery following night matches compared to day matches and training. The reasons for this poor sleep were varied and very individualistic in nature. ii) Similarly, objective measurements of sleep show sleep duration is truncated during long-haul international travel with a 4 h time-zone delay in national level players. Furthermore, sleep duration is reduced following night matches, though limited effects on perceptual recovery were evident in this professional cohort. iii) To combat such a reduction in sleep duration in night matches, a SHS was shown to be able to improve sleep quantity following a late-night football match in highly trained amateur players. Despite such increased sleep duration, no improvement in physical performance, perceived stress and recovery or blood-borne markers of muscle damage and inflammation were evident.

**Discussion/conclusion:** The first study in this dissertation provided evidence that sleep duration and quality is hindered following night matches in elite footballers, though sleep responses were deemed within normal population-based ranges following training and day-based match days. In addition, perceptual recovery is significantly worse following these night matches compared to day matches and training. The second study showed that long-haul international travel results in lower sleep quantities than healthy averages for adults. Further, there were limited changes in perceptual recovery markers due to reduced sleep; possibly due to increases in sleep duration on the days upon arrival. However, the effect of the reduction in sleep quantity on physiological and perceptual recovery (especially during/over the course of a season) remains unclear. In the final study of this thesis, results suggested football players might consider sleep hygiene strategies where possible following a late-night match to promote restorative sleep. There appeared to be no additional benefit for the acute recovery of exercise performance markers, perceptual stress, or blood-borne markers of muscle damage and inflammation. Accordingly, more research is required to

assess whether a larger sleep differential (e.g. longer duration/higher quality sleep) is required to affect the physical and physiological markers measured here. In addition, the effect of (chronic) SHS on recovery in real-world elite environments requires further research.

# 1. INTRODUCTION

## 1.1 Conceptual introduction to performance, fatigue and recovery in football

Football performance requires the optimisation of a myriad of intertwined factors including, physical, tactical, technical and socio-psychological abilities [1-3]. Of these factors influencing football performance, a critical aspect involves physical performance, and as shown in Figure 1.1, conceptually comprises endurance capacity, high intensity exercise, maximal sprint and peak muscular force performance [1, 4]. Whilst each capacity may be important within its own right, these abilities can also impact on one another. For instance, performance of respective physical capacities can be influenced by the maximal functioning of that capacity (i.e. training or injury) and the specific match demands requiring that capacity (i.e. playing position, tactical role, quality of the opponent [5]). In addition, these performance-related capacities can be affected by external (i.e. time of season, type of playing surface and environmental factors) and internal (i.e. sex and age) factors [1, 2].

As an example of the demands on football players, training and match loads require professional players to endure varied physiological, psychological and neuromuscular stressors [2-4, 6]. Both training and matches require high loading stressors during different speeds of movement running (i.e. walking, jogging, sprinting) along with rapid changes in direction and accelerations in combination with jumps and tackles. For instance, on average professional players cover a total of 9-13 km per match [5], inclusive of around 700 changes of direction [7]. Additionally, players are required to perform numerous technical actions such as dribbling, shooting and passing [8], whilst also endure numerous psychological demands inducing various degrees of mental fatigue [9]. For example, players can be subjected to various levels of mental demands during matches due to level of opposition, importance of the match and changes in tactics [10]. Alternatively, they may face personal challenges caused by extraneous sources (i.e. media, fan pressure) that can affect the perception of these loads, if not the ability to perform them.

Whilst coping with some or all of these demands, a decline in (physical, technical or perceptual) performance (i.e. fatigue) can occur throughout the duration of training or matches [9, 11]. A number of different operational definitions of fatigue exist. For instance, Pyne and Martin [12] define fatigue as ‘an inability to complete a task that was once achievable within a recent time frame’. However, fatigue is a complex and multifaceted

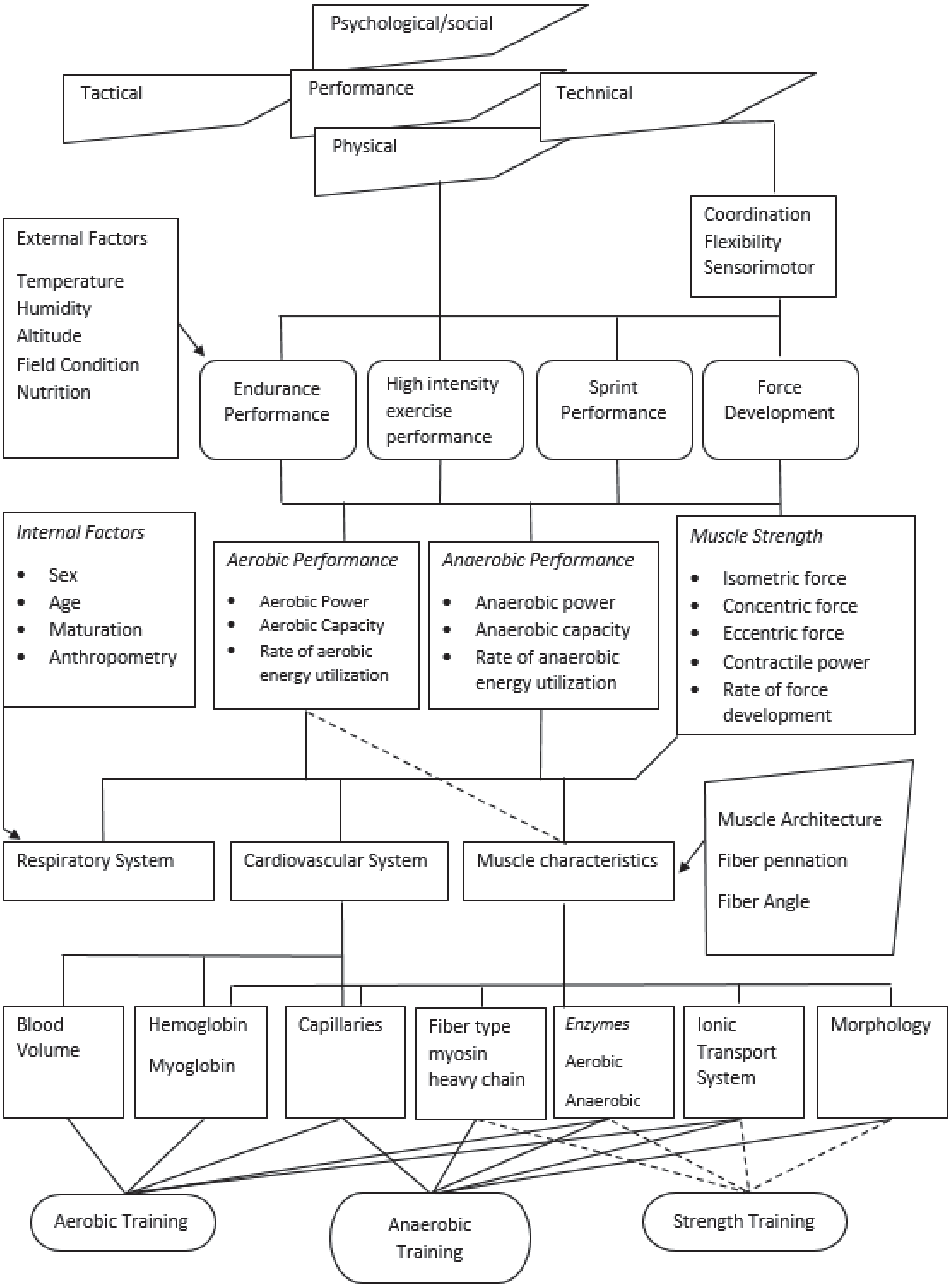


**Figure 1.1:** A model of football performance (adapted from a holistic model of sports performance by Bangsbo et al. [1])

phenomenon, and can originate from a variety of possible mechanisms; thus operational definitions are predominately based upon the experiment used or the conditions under which they occur [13]. Regardless, the best football nations [14] and professional clubs [15] rate “fatigue” as the second most important factor contributing to injury risk (after a previous injury), suggesting the relevance of monitoring and understanding fatigue within the confines of elite football. For instance, it is well established that the amount of high-intensity running is reduced toward the end of a football match [11, 16, 17], whilst others have demonstrated that maximal sprint and intermittent-exercise performance after a match are both reduced [18]. This fatigue in a classical neuromuscular sense is defined as an exercise-induced reduction in force generating capacity of the muscle [19, 20]. In addition to within–match evidence, suppressed performance of physical capacities following a match further reinforces this concept. For example, Rampinini and colleagues [21] found that after a 90-min game, there was a reduction in maximal voluntary contraction and sprint performance (-11%, $P < 0.001$ and -3%, $P < 0.001$, respectively) compared with pre-match baseline in 20 professional players. Furthermore, 48 h had passed post-match before these values were returned to baseline. Whilst this decline in performance is a necessary and expected part of football, it requires sufficient reversal to allow optimal player performance in ensuing training or matches.

To restore performance for the next ensuing bout, whether that is a training session or an additional match, there is a clear need to hasten the recovery of performance. As such, there is a vital requirement for players to balance the numerous physiological, psychological and neuromuscular stressors during training and competition stressors with adequate recovery to maximise performance and ensure effective adaptation [22]. Recovery is a multidisciplinary process, classically defined by Kellmann and Kallus as “an inter-individual and intra-individual multi-level (e.g. psychological, physiological, social) process in time for the re-establishment of performance abilities” [23]. With the objective of improving and peaking for a specific event (e.g. match), football coaches, performance staff and researchers focus on developing the quantity, quality and composition of training and degree of recovery necessary to maximise performance [24]. As observed in Figure 1.2, a theoretical model of training load-recovery sequence depicts that if appropriate recovery is allowed following fatiguing stimuli (i.e. football demands) then a supercompensation effect (adaptive response) will occur, resulting in an improvement in the subsequent performance [24].

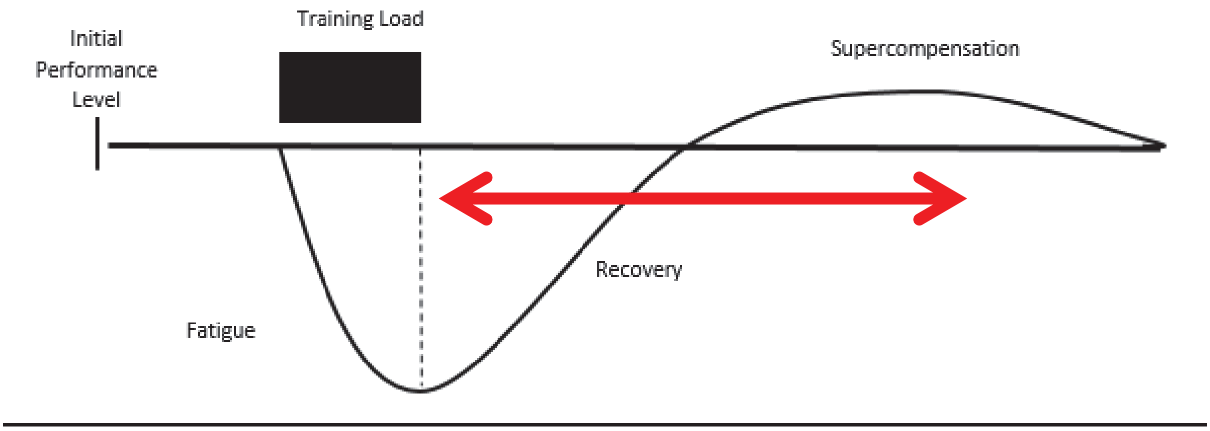


**Figure 1.2:** Adapted theoretical model of the relationship between the fatigue induced by training and/or match load, the recovery from such a performance and the subsequent effect of the next performance (reproduced from Kellmann [24]). The red arrow indicates the 'recovery time course' from the end of one performance to the beginning of another.

However, from the end-point of a typical football performance, it can take more than 72 h to restore pre-match values of physical and mental performance [8]. As such, the time from the end of the game to ~ 72-96 h post-match is often referred to as the 'recovery time course' (Figure 1.2). Since professional players are often required to play three games in seven days, this may be insufficient to restore performance to desired match standards in professional players. Thus, understanding the time course of various physical and mental indices and the influence of a multitude of factors within this recovery time course is viewed as critical for player preparation and subsequent performance.

Despite the myriad of factors affecting recovery, a key one often highlighted by practitioners is the influence of sleep. Since a variety of crucial cognitive, metabolic and immune processes occur during sleep, it is generally considered that a relationship exists between the quantity and quality of sleep and the capacity of athletes to perform and recover. However, regardless of this assumption, the role of sleep is perhaps the least understood factor within the 72-96 h recovery period. This is surprising since sleep will generally occupy a large proportion of this time due to biological requirements [25], and athletes often rate sleep as one of the most important factors hindering recovery [26]. Indeed, since the ability to tolerate these training and match stressors are affected by numerous factors; including, experience, fitness, motivation and the sleep-wake cycle; it would appear understanding the interaction of sleep and recovery is critical. However, there remains little research on the understanding of the role of sleep in the recovery of performance in athletes [27]. This is likely in part due to the complexity of sleep function, different athletic environments and the variability in the individual requirement for sleep [28, 29].

As such, the evaluation of the interaction between sleep and recovery in football remains largely unanswered within the scientific literature. Given this lack of evidence, the interaction between sleep and recovery in football will become a primary focus of this thesis. However, prior to investigating this pertinent issue, this dissertation will endeavour to lay a foundational understanding regarding the fatigue induced from football-related activity and the numerous factors that need to be considered within the recovery process. This understanding is critical, as to appreciate the recovery process, an understanding of what is causing the need for recovery is pertinent – which in turn will assist explain the sleep-recovery relationship.

## 1.2 Fatigue induced from football load

When training or playing in matches, professional players endure numerous physiological, psychological and neuromuscular stressors [2-4, 6]. In response to these demands professional players show exacerbated physiological and psychological states, along with reductions in performance domains. This acute reduction in performance is referred to as transient or acute fatigue (Figure 1.3). When players suffer acute fatigue towards the end of the game it is postulated this is due to either a depletion in muscular glycogen stores, disturbances to skeletal muscle structure (which can be associated with a reduction in contractile function) and a concomitant rise in markers of contractile damage (such as creatine kinase; CK) [3, 8, 19, 30, 31]. It is also hypothesised from a muscular contractile perspective that transient fatigue is caused by either disturbances in muscle sodium, potassium and chloride homeostasis (causing depolarisation of the resting membrane potential) or the intramuscular accumulation of hydrogen ions [3, 6, 16]; although numerous other factors no doubt play a role. Indeed, fatigue related to either training or match load may be summarized as primarily determined by a combination of central and peripheral factors [8]. Fatigue can also remain present beyond the end of the match, as is termed residual or chronic fatigue (Figure 1.3). Chronic fatigue is often characterised by an ongoing suppression in performance or alterations of the markers mentioned above over the 72-96 h period following match play. Collectively, these acute and chronic alterations to physiological, perceptual and performance characteristics observed arise from a combination of mechanisms, which will be briefly discussed in the proceeding sections.

### 1.2.1 Football load

From a physical perspective, football involves many demanding activities including different levels of running (i.e. walking, jogging, sprinting) along with rapid changes in direction and running speed [2, 4]. These demands can be derived from time motion analysis (TMA) or global positioning system (GPS) devices [5]. For instance, on average professional players cover a total of 9-13 km per match [5]. Typically the majority of this activity is performed at walking pace (speed zone 0.1-7 km/h) and lower intensities (7-14 km/h) [5]. To a lesser extent, match activity is also made up of high-intensity running (21–24 km/h) and sprinting (>24 km/h). As evidence, extensive analyses of Spanish La Liga and English FA Premier League players revealed that high-intensity running and sprinting accounted for 3.9% and 5.3% of the total distance covered respectively [32]. In addition to performing various bouts

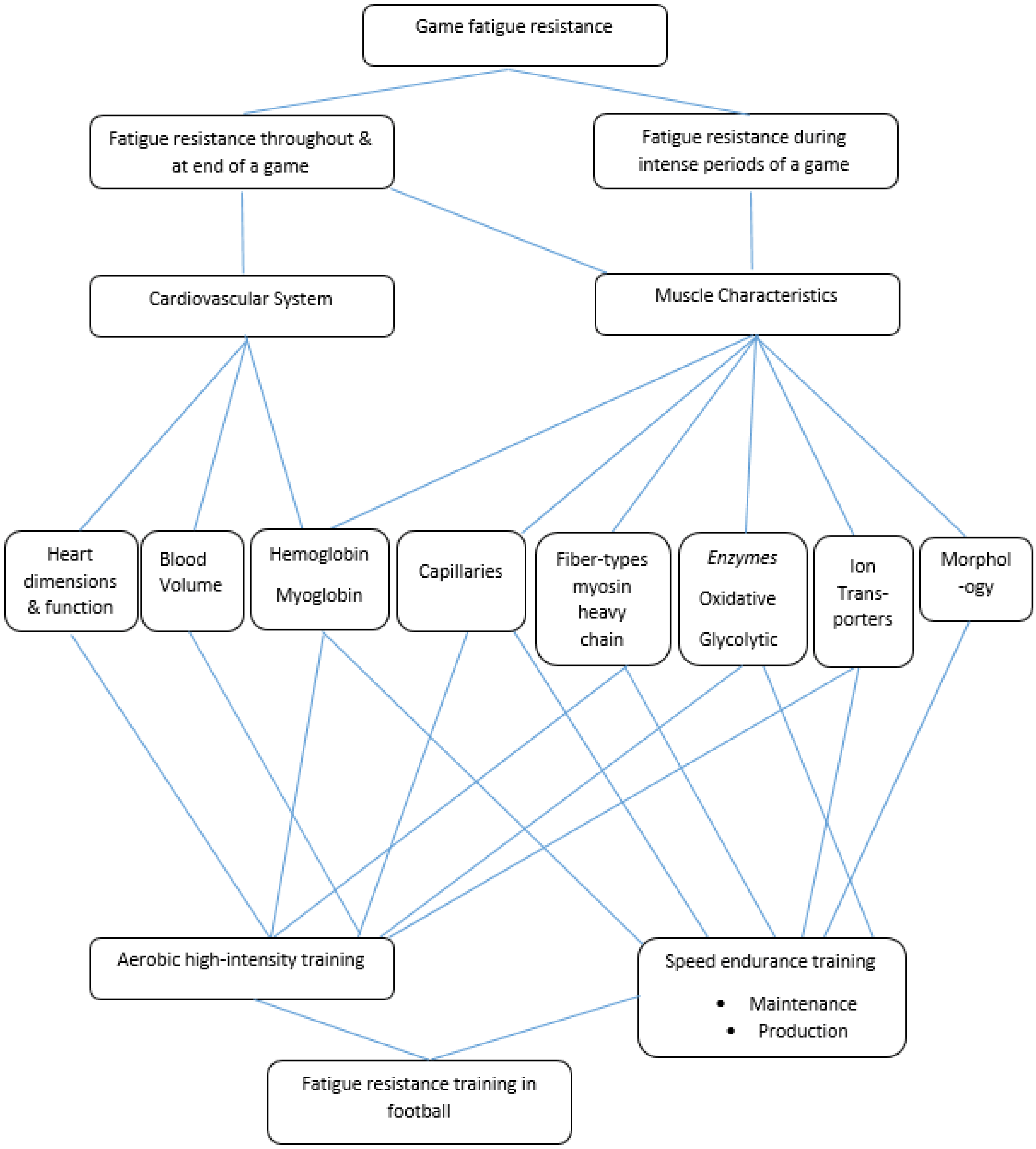


**Figure 1.3:** A theoretical model of the relationship between match-induced fatigue and training characteristics (reproduced from Mohr and Iaia [30]).

of intermittent running activity, professional players also encounter other physical demands such as tackles, jumps, accelerations, decelerations, headers and directional turns. For instance, it has been reported that English Premier League players complete on average around 700 changes of direction per match, with ~ 600 of these being in an arc of 0° to 90° to the left or right, and are involved in the equivalent of ~ 110 on the ball movement activitiesper match [7]. Of further note, players can be subjected to various levels of mental demands during matches due to level of opposition, importance of the match and changes in tactics [10]. In a laboratory based-study, Greig and colleagues [33] investigated the performance on a vigilance task (continual attention and sporadic target response within a letter grid) of ten semi-professional soccer players when completing a 90-minute laboratory-based treadmill protocol replicating the activity profile of soccer match-play. The authors found that performance was reduced during the latter stages of the second half, highlighting the psychological demands of soccer-related physical activity. Interestingly, this mental fatigue can also result in impacts on soccer-specific decision making [10] and physical and technical performance [34]. Taken collectively, professional players endure numerous physiological, psychological and neuromuscular loads during training and matches.

### 1.2.2 Fatigue in physical performance

This array of demands during matches generally results in players experiencing fatigue, shown by reductions in-game sprints from half time to the end of matches [11, 35], alongside further reductions in match running performance following intense match periods [16, 36, 37]. For instance, Bradley [37] showed that high intensity running following the most intense 5-min period during was significantly reduced, especially in attackers and central defenders (both $P < 0.01$) over 28 English FA Premier League games using a TMA system. Research also supports that the number of accelerations and decelerations performed are reduced in the final stage of matches compared to the opening stages, especially the final 15 min [38, 39], and at the end of a congested fixture period (five matches in 72 h [40]). This fatigue in movement patterns not only exists within the match but also remains after the match. For instance, there are several examples of reductions in single sprint, repeated sprint and shuttle run performance up to 72 h post-match or soccer specific exercise (Table 1.1). Rampinini and colleagues found an immediate significant reduction in the mean sprint performance (-3%) of 20 professional players following a 90 min match, with this reduction taking 48 h to return to baseline values [21]. A collection of recent evidence shows these reductions in intermittent running performance range from decrements of -2 to -9%, with the recovery of these

**Table 1.1:** Recovery time course for single sprint and repeated-sprint ability following soccer-specific exercise (reproduced from Nedellec et al. [8]).

| Study | Subjects | Soccer-Specific Exercises | Performance Task | Time (hours after soccer-specific exercise) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 0 | 5 | 21 | 24 | 27 | 45 | 48 | 51 | 69 | 72 |
| **Sprint** | | | | | | | | | | | | | |
| Andersson et al. | 9 elite F | Soccer match | 20 min | ↑-3.0 | NS | NS | | NS | NS | | | NS | |
| Ascensão et al. | 16 trained M | Soccer match | 20 min | ↑-7.0 | | | ↑-6.0 | | | ↑-5.0 | | | ↑-5.0 |
| Fatouros et al. | | | 20 min | | | | ↑-8.0 | | | ↑-5.0 | | | ↑-3.0 |
| Ispirlidis et al. | 14 elite M | Soccer match (68 min) | 20 min | | | | ↑2.0 | | | ↑2.5 | | | ↑1.6 |
| Magalhães et al. | 16 trained M | Soccer match | 20 min | ↑-9.0 | | | ↑-7.0 | | | ↑-6.0 | | | ↑-5.0 |
| Rampinini et al. | 20 elite M | Soccer match | 40 min | ↑-3.0 | | | ↑-1.0 | | | NS | | | |
| Ingram et al. | 11 trained M | Simulated team sport exercise | 20 min | | | | | | | ↑1.7 | | | |
| Magalhães et al. | 16 trained M | LIST | 20 min | ↑-5.0 | | | ↑-1.0 | | | ↑-1.0 | | | ↑-1.0 |
| **RSA** | | | | | | | | | | | | | |
| Krustup et al. | 11 trained M | Soccer match | 5 x 30 min | ↑2.8 | | | | | | | | | |
| Krustup et al. | 14 elite F | Soccer match | 3 x 30 min | ↑4 | | | | | | | | | |
| Mohr et al. | 16 trained M | Soccer match | 3 x 30 min | ↑2 | | | | | | | | | |
| Bailey et al. | 10 trained M | LIST | 11 x 15 min | | | | | | | NS | | | |
| Ingram et al. | 11 trained M | Simulated team sport exercise | 10 x 20 min | | | | | | | NS | | | |

a Blank cells indicate no data reported.

b Data presented are means (%).

**F** = female; **LIST** = Loughborough Intermittent Shuttle Test; **M** = male; **NS** = non-significant; **RSA** = repeated-sprint ability; ↑ indicates increase.

parameters to performance baseline ranging from 5 to 96 h post-match (Table 1.1; [8]).

As evidence of the above, reductions in lower-body peak power during countermovement jump (CMJ) performance following match-play are commonly reported ([8, 31, 41]; Table 1.2). For instance, Nedelec et al. [41] examined the relationship between the frequency of playing actions performed during 4 competitive matches and the recovery kinetics after the match of 10 professional players. The authors reported significant neuromuscular fatigue for up to 72 h post-match, with significant correlations between the number of short sprints (<5 m) performed and the increase in muscle soreness at 48 and 72 h after match play. In addition, Russell et al. [42] examined a variety of GPS variables and the change from baseline in peak power output during the CMJ in fifteen English Premier League reserve team players at 24 h and 48 h post-match (1-4 matches). High-intensity distance covered, high-speed running distance and the number of sprints per min within the match were all significantly related to the change in peak power output at 24 h post-match. Given the importance of lower-body peak power for typical football specific physical performance, the post-match recovery of peak power can be an important determinant of ensuing training quality or match success in football [43].

Fatigue from a match can also result in reductions force production. For instance, concentric and eccentric maximal voluntary contraction (MVC) of the knee flexors can be reduced for up to 72 h post-match [44-46]. Ascensao et al. [44] found reductions in concentric knee flexion strength immediately following match play (~-15% compared to baseline) and up to 72 h later ( ~-8%). In addition, Magalhaes and colleagues [45] found similar reductions (~-12%) following match play and 72 h post match (~-8%). Knee flexors appear more susceptible to extensive periods of fatigue than knee extensors [8], with some authors reporting sufficient recovery of this muscle group 24 h post match [47]. The difference in findings between knee flexors and extensors is most likely due to the fact that flexors are the weaker of the two muscle groups and work eccentrically during high power efforts – suggesting being more prone to injury [41]. This seems a reasonable hypothesis given the knee flexors (i.e. hamstrings) are one of the most common injuries in professional football [48], and particularly towards the end of both halves [49]. Clearly, playing football leads to various decrements in force production that progressively return to initial values during the recovery process [8]. As such, the measurement of torque during maximal voluntary contraction is now considered an appropriate measure of quantifying muscular recovery with

**Table 1.2:** Recovery time course for jump performance following soccer-specific exercise (reproduced from Nedellec et al. [8]).

| Study | Subjects | Soccer-Specific Exercises | Performance Task | Time (hours after soccer-specific exercise) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 0 | 5 | 21 | 24 | 27 | 45 | 48 | 51 | 69 | 72 |
| Andersson et al. | 9 elite F | Soccer match | CMJ | ↓4.4 | ↓-2.0 | ↓-4.0 | | ↓-2.0 | ↓-2.0 | | ↓-2.0 | ↓-3.0 | |
| Fatouros et al. | 20 trained M | Soccer match | CMJ | | | | ↓10.0 | | | NS | | | NS |
| Ispirlidis et al. | 14 elite M | Soccer match (68 min) | CMJ | | | | ↓9.3 | | | NS | | | NS |
| Krustup et al. | 15 elite F | Soccer match | CMJ | NS | | | | | | | | | |
| Magalhães et al. | 16 trained M | Soccer match | CMJ | ↓-12.0 | | | ↓-8.0 | | | ↓-8.0 | | | ↓-8.0 |
| Thorlund et al. | 9 trained M | Soccer match | CMJ | NS | | | | | | | | | |
| Bailey et al. | 10 trained M | LIST | SJ | | | | ↓-2.8 | | | ↓-5.6 | | | |
| Magalhães et al. | 16 trained M | LIST | CMJ | ↓-12.0 | | | ↓-10.0 | | | ↓-9.0 | | | ↓-10.0 |
| Oliver et al. | 10 trained M | NMT | CMJ | ↓-10.4 | | | | | | | | | |
| | | | SJ | ↓4.9 | | | | | | | | | |
| Robineau et al. | 8 trained M | Soccer match modeling | CMJ | NS | | | | | | | | | |
| Robineau et al. | 8 trained M | Soccer match modeling | SJ | ↓8.0 | | | | | | | | | |

a Blank cells indicate no data reported.

b Data presented are means (%).

**CMJ** = countermovement jump; **F** = female; **LIST** = Loughborough Intermittent Shuttle Test; **M** = male; **NMT** = non-motorized treadmill; **NS** = non-significant; **SJ** = squat jump; ↓ indicates decrease.

relation to football [50].

### 1.2.3 Muscle damage

As mentioned, football players will endure various lower and upper body demands such as changes in direction, passes, shots on goal, tackles, jumps or contact with opposing players [2]. The high power and eccentric nature of contractions responsible for these movements most likely explain the subsequent occurrence of exercise-induced muscle damage and inflammation [42]. For instance, following match play an acute-phase inflammatory response occurs (Figure 1.4). Cellular disturbance caused by prolonged or intense muscular activity can cause CK to leak from the cell into blood serum and increasing serum CK activity [51]. Due to the inter-relationship with muscle damage and concomitant rise following exercise, CK is currently used to infer the extent of muscle fibre damage, and thus has a likely influence on fatigue and recovery [51-54]. The time course of CK release and return to baseline is extended, with elevated responses lasting up to 120 h post-match [8], further contextualising the prolonged post-match recovery time required by professional players.

An example of the above concept is provided by the significant relationships between the change in CK from 24 h pre- to 24 h post-match with the amounts of high intensity distance covered ($r = 0.386$, $P = 0.029$), high speed running distance ($r = 0.363$, $P = 0.041$) and the number of sprints per min ($r = 0.410$, $P = 0.020$) performed in reserve English Premier League matches [42]. Despite such associations, the time course of CK release (e.g. 48-120 h [8, 31]), combined with between-player and between-match variability of CK responses to football match-play [55] hinders the interpretation of CK as an explicit marker of post-match recovery status [42]. Moreover, players who participate in regular training have consistently high CK values making it difficult to establish comparative baseline values [8]. Nonetheless, if sensitive and accurate baseline values can be established, then the magnitude of the increase of CK supports its use to infer the likelihood of muscular damage, and thus potential for ensuing fatigue.

When the working musculature sustains damage to the contractile proteins, a local inflammatory response is initiated, involving the release of a suite of cytokines [8]. Specifically, this consists of an immediate post-game peak in leukocytes, the cytokines interleukin (IL) six and 1β (IL-6, IL-1β), and cortisol. In turn, IL-6 promotes an infiltration

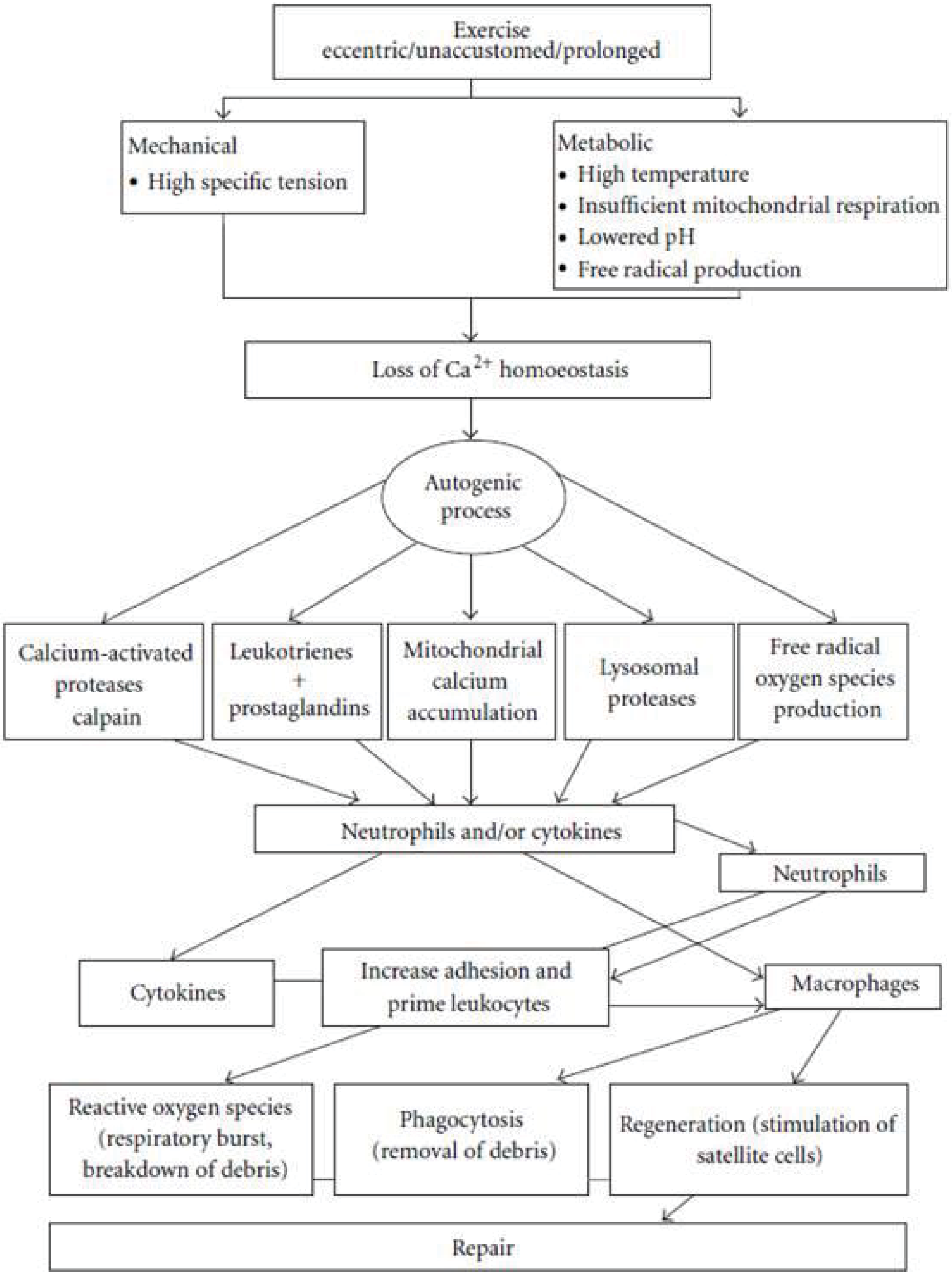


**Figure 1.4**: Model representing the muscle damage and repair cycle (reproduced from Kendall and Eston [56])

C-reactive protein (CRP) over the ensuing 24h, alongside increases in thioburbituric acid-reactive substances (TBARS) lactate dehydrogenase (LDH) and uric acid (UA), all representative of leakage due to damaged fibres [57]. A typical football match will also result in increases in reactive oxygen species, caused by either mitochondrial functioning as part of the oxidative cellular processes, ischaemia-reperfusion events in skeletal muscle or inflammatory response to exercise-induced muscle injury [44]. It should be noted that these biochemical parameters may not always be appropriate for indicating fatigue status; rather, they should be restricted to interpret skeletal muscle fibre disturbance. For instance, Meister et al. [58] investigated differences in blood count, CK, urea, UA, CRP and ferritin between high intensity match exposure (>270 min during 3 weeks before testing) and low intensity match exposure (<270 min) in 88 players of the first and second German leagues. The authors reported no differences between exposure periods for any of these parameters ($P = 0.36$), limiting their inference as explicit markers of fatigue due to muscular disturbances in elite footballers. These results are possibly due to the typical group-based analysis of fatigue-induced changes which will inevitably show high variability [59] and/or that that muscle contraction is not affected by cell content level [19]. There, whilst biochemical parameters can assist in determining disturbance in the working musculature it should be acknowledged that without any performance markers they may not always be appropriate for indicating ensuing fatigue.

In summary, muscle fibre damage and subsequent increased exercise-induced muscle damage markers are likely induced by the various lower and upper body demands faced by the typical football player, such as changes in direction, ball kicks, shots on goal, tackles, jumps or contact with opposing players [2]. In collaboration, increased inflammation and up-regulation of oxidative stress markers appear in ensuing timelines, thus creating an elevated state of damage and inflammation. Collectively, these changes in damage and inflammatory states may partially explain the reduction in inability to reproduce peak power, force or match relevant performances within this 72 h post-match period.

### 1.2.4 Energy demands and glycogen depletion

The volume of work (i.e. 9-13km distance) and magnitude of intense actions performed during a football match (i.e. 150-200 actions) [11] suggest that the working musculature of footballers requires high aerobic and anaerobic energy demands. From an anaerobic perspective, glycolysis results in the catabolism of glucose to pyruvate, and production of lactate when the presence of oxygen is limited. In footballers, mean blood lactate concentrations during matches have been observed ranging from 2–12 $mM \cdot L^{-1}$ [16], dependent on sampling time. Despite high variability in lactate values, the elevation in accumulated lactate response is likely resultant from the extensive high-intensity activities performed in a match [11, 60]. Although limited in linking lactate concentration with fatigue (given exercise performance can be maintained even with increasing muscle lactate), the finding of high blood lactate and moderate muscle lactate concentrations during matchplay highlights the regularity of high rates of anaerobic glycolysis [60]. In addition to the role of glycolysis during a football match, the reduction in muscle glycogen stores appear to be important substrates for football players. For example, Saltin indicates that matches typically (56), though not always, result in a substantial depletion of glycogen stores [16, 61]. This depletion in a significant number of muscle fibres would represent one of the most plausible physiological reasons as to why fatigue becomes more evident towards the end of a match [16]. For example, Krustrup et al. [16] found that 73% of muscle fibres were considered full of glycogen prior to three matches played by semi-professional Danish players, compared to ~ 20% after the match ($P < 0.05$). Replacing glycogen stores in the 24-48 h period following match play would thus appear a necessary part of the recovery process. Consequently, the optimal intake of carbohydrate is recommended as the most important nutritional requirement for footballers [3]. Taken collectively, players endure many aerobic and anaerobic energy demands during matches with perhaps the most significant factor to consider being the reduction in, and requirement to replenish, muscle glycogen stores.

### 1.2.5 Thermoregulation and dehydration

Limited information exists on the influence of thermoregulatory responses related to fatigue during football matches [18, 62], though core temperatures of 39-40°C have been suggested to occur during matches and training [63]. For instance, Duffield and colleagues examined the relationship between intensity of training "higher-intensity" (140 min), "lower-intensity" (120 min) and "game-simulation" (100 min) and changes in hydration status, core temperature, sweat rate and composition and fluid balance in thirteen professional football players training in the heat (3 training sessions; 26.9 ± 0.1 °C and 65.0 ± 7.0% relative humidity). The authors found that the biggest predictor of the rate of rise in core temperature was mean speed of the session ($r = 0.85$). Furthermore, there is evidence to suggest excessively elevated core temperature results in a reduction in physical performance. For instance, when the environmental temperature is increased from 20°C to 30°C the total distance covered during a game is reduced [4]. Mohr et al. [64] reported that when environmental temperatures increases from ~21°C to ~43°C total distance and high intensity running distance covered is reduced by 7% and 26% respectively. Interestingly, increases in core temperature in the 43°C conditions were correlated to total game distance in the heat ($r = 0.85$; $P < 0.05$); however this relationship was not apparent for high intensity distance covered [64]. Together, this would suggest that the extent of core temperature increase, and resultant fluid replacement, are critical factors which can influence the recovery process, necessitating important considerations for experimental research design.

In addition, some report that both match and simulated-match exercise in hot conditions results losses of ∼5% of body mass [65] compared to 1.5–2% in thermoneutral conditions [18, 62]. Edwards et al. [66] assessed whether moderate water loss (1.5–2% of body mass) represented a significant impairment to football match-play and football-specific activities by comparing the effect of three different conditions: 1) fluid intake, 2) no fluid and 3) mouth rinse in a individually randomised order. Core temperature increased in the no fluid condition compared with the fluid condition (39.28°C (0.35°C) and 38.8°C (0.47°C), respectively; $P < 0.05$), whilst the post-match performance of a sport-specific fitness test was significantly reduced with no fluid. However, whilst the authors showed moderate dehydration can be detrimental to football performance, interestingly the post-test evaluation of rating of perceived exertion and thirst was greatest (i.e. most challenging) in the no fluid condition. Therefore, whether this reduction in performance is attributable to water lost or the negative psychological associations derived from a greater perception of effort in the no fluid condition, remains unclear [66]. In summary, thermoregulatory and hydration effects on physiological and psychological performance need to be considered when investigating the recovery time course in football, including accounting for changes in sweat rate and electrolyte losses in response to football-related activity which suggest that rehydration practices should be adopted post-exercise [67].

### 1.2.6 Mental fatigue

Players can experience a vast array of psychological demands specific to football, such as motivation, anxiety, arousal, emotion, competitiveness, concentration, confidence and communication [68]. Furthermore, various cognitive abilities such as reaction time, decision making and spatial awareness are required to execute football-specific skills [8]. Indeed, psychological demands of sport are an often less examined, but by no means less important, aspect to understanding the fatigue response relevant to football performance [69, 70]. Indeed, there are recent examples of mental fatigue impairing physical performance [9], soccer-specific physical and technical performance [34] and even soccer-specific decision-making skill in footballers [10]. Furthermore, many authors hypothesise that subconscious pacing may take place when players are in a fatigued state (whether within a game or as a result of many games in a congested period) [71, 72].

### 1.2.7 Subjective stress

Perhaps the most important aspect of football psychology is how the player perceives the effort or load he or she is exerting during training or matches [10, 34, 73]. Indeed, the ability of scientists and coaches to accurately monitor training load is an important aspect of understanding the fatigue induced by training/matches leading to effective injury and recovery management. One aspect of quantifying this perception of training load is through collecting the player's rating of perceived exertion (RPE; [74]) and multiplying it by the duration of the physical session (i.e. internal arbitrary training load = RPE x duration of session (min)) [75]. The use of RPE is now widespread in football due to its practicality, cheapness to operate, correlation with various HR-based training load ($r = 0.50$ to $r = 0.85$, $P < 0.01$ [76]) and relationship with injury occurrence [77]. For instance, using RPE compared to the assessment of other psychological demands is suggested as advantageous to represent the athlete's own perception of training stress, which can include both *physical* (oxygen uptake, HR, ventilation, beta endorphin, circulating glucose concentration, and glycogen depletion) and *psychologica*l stress (motivation, anxiety) [76]. Overall, the use of RPE provides a valuable assessment of the perceived exertion involved in playing football, and as such may help one understand the fatiguing stimuli present in, and recovery from, training and matches.

Outside markers to quantify the perception of effort during exercise or specific cognitive markers which assess psychological function *per se*, various subjective (self-reported) markers are used to assess players' perceived wellbeing. Indeed, many authors and practitioners theorise that perceptual responses may reveal early-warning signs of developing chronic fatigue more readily than the various physiological or biochemical markers of fatigue [78]. For exmple, these perceptual scales include the Recovery-Stress Questionnaire for Athletes (REST-Q-Sport; [23]), Daily Analysis of Life Demands For Athletes (DALDA; [79]), Profile of Mood States (POMS; [80]), feelings of soreness (delayed onset muscle soreness (DOMS)), total quality recovery scale (TQR; [78]) and other more simple, singular Likert scales for psychological mood, wellbeing and stress [81]. For instance, Filaire and colleagues measured mood, as measured by the POMS, and performance four times during a season in seventeen professional male football players [82]. Iceberg profiles of POMS were observed during the first three quarters of the season, which coincided with successful performance. Subsequent decreased performance between the 3rd and 4th quarters of the season coincided with a decrease in vigor and an increase in tension and depression within the POMS [82]. Taken collectively, a range of subjective tools have shown reductions in mood, wellbeing and increases in fatigue, stress and muscle soreness immediately following match, with some aspects taking 48-72 h to return to normal values [31].

In summary, match- and training-induced fatigue is a multifaceted phenomenon which could occur due to factors related to glycogen depletion, dehydration, muscle damage and mental fatigue [8]. For a wide variety of reasons (e.g. high inter- and intra-reliability, internal and external validity issues, difficulty in obtaining participants for experiments, difficulty in comparing matches) there is currently no deterministic marker for states of fatigue or recovery. [53, 81]. Thus, it the current consensus is that a combination of markers related to fatigue are best suited to then monitor the recovery status of a player [12, 13, 83]. Accordingly, the return to (or near) baseline of these parameters (i.e. the state of recovery) is highly variable and dependant on several confounding factors including physiological and psychological load, fixture of matches, previous history of injury and the mode of recovery used [31]. As such, it is critical to understand the fatigue status of players from a variety of perspectives (i.e. physical, physiological, perceptual, neuromuscular), to then interpret the recovery state for professional level footballers.

### 1.3 The importance of sleep in the recovery time course

The post-match recovery timeline is a multi-day and multi-dimensional process, with large portions of this recovery time frame occurring during periods of sleep. A daily occurrence, sleep contributes heavily to cognitive development (learning, memory, and synaptic plasticity - as discussed in detail later), and is proposed as a crucial part of the stress-recovery balance [22]. Sleep also has several molecular purposes, with the release of growth hormone present when humans sleep, stimulating protein synthesis important for regeneration and muscle growth [84]. This process can potentially accelerate the rate of healing to repair peripheral muscular damage as well as support other training-induced anabolic processes [85-87]. For example, it has been confirmed sleep is critical to metabolic homeostasis [88]. Since a variety of crucial metabolic and immune processes occur during sleep, it appears a conceptual relationship exists between the quantity and quality of sleep and the capacity of athletes to perform and recover [89]. Furthermore, since the perception of recovery and other psychological dimensions are just as important aspects of the holistic recovery status of an athlete [24], the cognitive restorative bases of sleep are also likely to be important to aid this process. However, due to the complexity of sleep function, different athletic environments and the variability in the individual requirement for sleep [28, 29], the interaction between sleep and recovery in football remains largely unknown. Thus, to further explore this area it is pertinent to evaluate the theory and function of sleep, the different methods used to measure sleep, and the relationship between sleep and athletic performance and recovery outcomes with relevance to football.

# 2. SLEEP, PERFORMANCE AND RECOVERY

## 2.1 A conceptual introduction to the theory and measurement of sleep

Reoccurring at habitual intervals throughout a 24 h period in humans, sleep is a homeostatically controlled behavioural state of reduced movement and sensory responsiveness [90, 91]. Recognised in the early medical accounts of Aristotle and Galen [92, 93], the process of sleep has widely been regarded as critical to both cognitive and physiological function [89, 91, 94-97]. Recent studies have shown sleep to regulate key molecular mechanisms (i.e. transcriptional regulatory proteins [90, 98, 99]), and have demonstrated that sleep has an integral role in metabolic homeostasis [88]. The duration and quality of sleep is manipulated by numerous environmental factors, among them light [100], time zone zeitgeists [101] and nutrition [26], though sleep architecture is also influenced by genetic predisposition [102, 103]. Notwithstanding the complexity surrounding the need, rationale and outcome of sleep, it seemingly must serve an important purpose for living organisms because it has survived so many years of evolution [102].

A recent review by Frank [104] identified several theories of the function of sleep, including: 1) the restorative effects on the immune and the endocrine systems, 2) a neuro-metabolic theory suggesting that sleep assists in the recovery of the nervous and metabolic cost imposed by the waking state, and 3) cognitive development, supposing that sleep has a vital role in learning, memory, and synaptic plasticity. A critical review of the literature by Frank and Bennington [104] concluded that sleep is a process which serves the brain rather than the body, with the neural processes instrumental in cognitive activity being the most disrupted by altered sleep. In part, these conclusions lead the authors to suggest that the evidence underpinning theories 1 and 2 above are either weak or equivocal, and based primarily on specific stages of sleep [104]. Such a conclusion is supported by Stickgold and Walker, whose reviews provide consistent and strong support for the existence of sleep-dependent memory consolidation and cognitive based development [105, 106]. These works summarize several studies reporting associations between slowed improvement in procedural memory tasks with various measures of reduced and interrupted sleep [105]. In spite of this perceived importance, the consensus regarding the rationale as to why humans sleep remains equivocal, if not robustly debated [91, 104]. Notwithstanding, an interaction between these theories is likely to contribute to the construct of several stages during sleep [104]. Although sleep is often referred to in a global context, the process of sleep comprises several ‘stages’ (Figure 2.1). These respective stages not only differ in depth, but also in the frequency and intensity

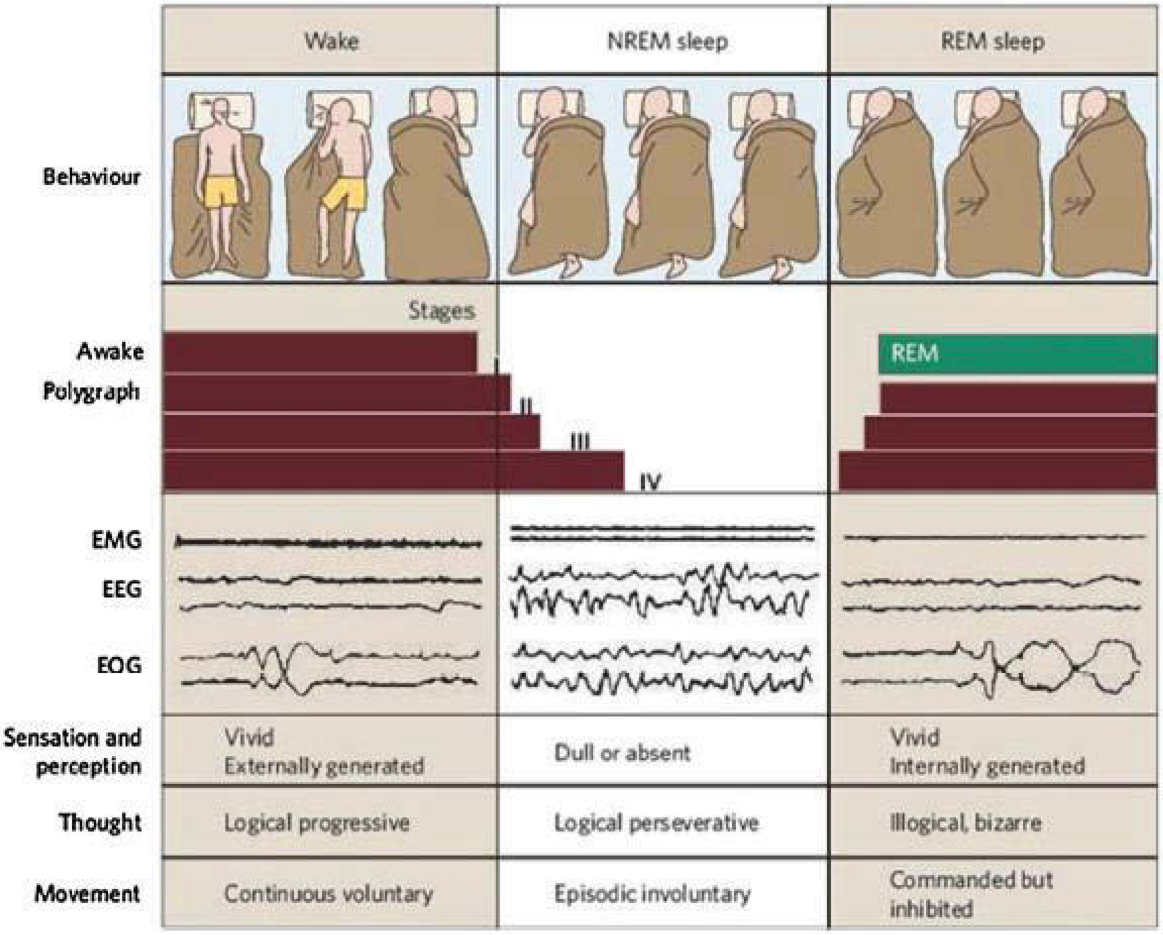


**Figure 2.1**: The behavioural states of humans and phase changes throughout the sleep wake cycle, including states of waking, non-rapid-eyemovement sleep and rapid-eye-movement sleep. The first row depicts a visual representation of movements throughout the sleep night. The second row illustrates REM sleep and the four stages of NREM sleep. The third row includes sample polysomnography tracings (each 20 s) of an electromyogram, an electroencephalogram, and an electrooculogram to help determine the presence or absence of each stage. Rows four, five, and six portray a range of subjective and objective state variables. Reproduced from Hobson [107]. Abbreviations: EEG electroencephalogram, EMG electromyogram, EOG electrooculogram, NREM non-rapid-eye-movement, REM rapid-eyemovement

of dreaming, eye movements, muscle tone, regional brain activation and communication between memory systems [105]. A typical night's sleep is composed of approximately 90 min cycles divided into periods of rapid-eye-movement sleep (REM; associated with dreams), and non-REM sleep (NREM) [108]. NREM sleep is further divided into three (formerly four) different stages (Figure 2.1). All stages are classified according to parameters such as electrical brain activity, blood pressure, and eye movement (Table 2.1 [109, 110]). NREM sleep is defined as the three (formerly four) stages of sleep which possess distinct electroencephalographic responses (Table 2.1), alongside other characteristics mainly comprising the beginning of sleep with slow eye movement ('relaxed wakefulness'), no eye movement ('easily awakened') and slow wave sleep ('deep sleep'). The determination of these stages is performed by the 'gold standard' of sleep quantity and quality monitoring, known as polysomnography (PSG). PSG involves the measurement of various parameters such as electroencephalogram (EEG), electrooculogram (EOG) and electromyography of the submentalis (EMG) to determine and classify these respective sleep stages ([92]; Table 2.1). For instance, SI NREM is defined by the attenuation of alpha rhythm greater than 50% of the epoch which can be replaced by a mixed frequency low amplitude rhythm ([92]; Table 2.1). Specifically, the role for NREM sleep is proposed to assist with energy conservation and nervous system recuperation. As an example of this proposition, it has been shown that growth hormone (GH), which is fundamental to tissue regeneration and growth, is released [84] and oxygen consumption is lowered [111] during phases of NREM sleep. Moreover, NREM sleep seems to be a stimulus for anabolic hormones that increase the synthesis of protein and mobilise free fatty acids to provide energy, thereby preventing amino acid catabolism [112]. Such processes would seem particularly pertinent for athletic populations requiring accelerated rates of healing to repair peripheral muscular damage [87].

Comparatively, REM sleep is the 'fourth' stage of the sleep cycle which occurs following the three stages on NREM sleep, usually occurring at least 90 min after falling asleep. REM sleep is characterised by low amplitude, mixed frequency EEG responses, rapid eye movement EOG measurements and low muscle tone EMG ([92]; Table 2.1). Theories of REM sleep have suggested a role for this state in periodic brain activation, localized recuperative processes and emotional regulation [113]. Especially in the early stages of mammalian life, REM sleep is assumed to be critical in establishing brain connections [113], since neuronal activity is similar to waking in REM sleep [114]. Hence, sleep can be rather

**Table 2.1:** The different stages of sleep and their related polysomnographic findings.

| Stage | EEG Findings | Eye Movements (EOG) | EMGsub |
|---|---|---|---|
| W | **>50% of an epoch has alpha rhythm over occipital region**<br>**Attenuation of alpha rhythm for** | *Typically, no eye movements seen* | **Normal to high muscle tone** |
| N1 | **>50% of the epoch replaced with mixed frequency low-amplitude rhythm or a slowing of PDR from waking of ≥ 1Hz if no alpha rhythm was noted;**<br>*Vertex sharp waves;*<br>N1 stage continues until beginning of N2 stage or arousal | *Slow, rolling eye movements typically* | *Variable, typically less than wake* |
| N2 | **K complexes and/or sleep spindles occurring in the first half of an epoc;**<br>*Low-amplitude, mixed frequency EEG;* N2 stage persists until transition to N3 stage, R stage, or an arousal | *Typically, no eye movements, but slow eye movements may persist* | *Variable amplitude, typically lower than W and higher than R* |
| N3 | **Slow-wave activity (0.5-2 Hz, > 75μV) for > 20% of an epoch;**<br>*Sleep spindles may persist;*<br>N3 persists until transition to N2, R, or an arousal | *Typically, no eye movements seen* | *Variable amplitude, typically lower than N2 and can be as low as R* |
| R | **Low-amplitude, mixed frequency EEG;**<br>*Saw-tooth waves;*<br>R persists until transition to N1, transition to N2, between K complexes without eye movements, or an arousal | **REMs** | **Low muscle tone** |

Abbreviations: W: wakefulness; N1: NREM stage 1 sleep; N2: NREM stage 2 sleep; N3: NREM stage 3 sleep; R: REM sleep stage. Bolded items are requirements for staging. Italicized items are non-required, associated findings that may be present in that sleep stage. (reproduced from Vaughn and Giallanza [92], which was originally adapted from AASM Manual for the Scoring of Sleep and Associated Events [115].

†Previously known as NREM stage 3 and NREM stage 4 sleep.

defined as an actively regulated process than a passive result of diminished waking, and can be viewed as a reorganisation of neuronal activity [114].

The importance of sleep has also been discussed in regards to memory consolidation, especially to motor learning. REM, NREM stage 2 and slow-wave (SWS) sleep have all been implicated in sleep dependent memory procession [105]. For example, several studies showed improvements in motor task tests after a night of sleep, whereas this was not the case in subjects having an equivalent period of being awake [105, 106, 116, 117]. Since sleep loss reduces the overnight improvement in motor learning, it seems that motor task learning may be associated with the amount and duration of specific sleep stages, rather than just one specific aspect of sleep [105]. Ongoing motor learning and cognitive adaptation are crucial requirements for motor performance [118]. This combined with the numerous neurocognitive components of many sports [119], supports that ascertaining an optimal mental state for a range of distinct memory consolidation processes are pertinent for human physical and cognitive performance (this is further addressed from an athletic perspective in section 2.3 [118]). Taken collectively, sleep likely contributes to several vital human functions including restorative effects on the immune and the endocrine systems, assisting in the recovery of the nervous and metabolic cost imposed by the waking state, and playing a critical the role in learning, memory, and synaptic plasticity. With such a critical role in human function there appears a requirement to measure sleep at some stage, especially for athletes. For instance, if sleep is restorative and given the high and intense training loads of present day sport, then sleep factors may be even more pertinent for professional athletes. However, the monitoring of sleep does create logistical issues that affect validity and interpretation challenges.

## 2.2 Method of sleep data collection

As suggested earlier, PSG remains the gold standard of sleep measurement. From a physiological perspective, the most sensitive indication of timing of sleep and onset of the various phases of sleep (through the measurement of a series of physiological responses) is PSG. Given its ability to measure brain activity, muscle tone and eye movements, PSG is considered the most accurate method to quantify sleep; thus its extensive use in clinical settings. This method measures many sleep indices including total sleep time, sleep-onset latency, wake after sleep onset, sleep efficiency, sleep fragmentation index, number of awakenings, time in each sleep stage, and sleep stage percentages [26, 27]. Other physiological parameters can also be measured during PSG including esophageal acid levels, core body temperature, penile tumescence, sweat levels and hormonal levels [92]. Despite the greater accuracy, PSG is expensive, potentially invasive for participants and labour and technically intensive [27], possibly limiting its use in field-based environments and studies involving elite sporting populations such as footballers. For instance, it is unlikely that many clubs would invest copious amounts of money in a piece of equipment that requires specific expertise to operate and players may not like wearing on a continual basis. Moreover, since professional clubs are continually changing sleep environments (i.e. home to hotel to game to flight to new hotel), the use of PSG (which generally requires the use of an 'in-house' laboratory) is unlikely to be logistically feasible. Whilst portable PSG units have begun to show recent promise to alleviate this issue, the validity, accuracy and research pertaining these instruments remains limited at present [120]. In addition, participant issues with these devices (i.e. poor compliance linked to comfort of wearing the device) limit their use in elite sporting environments at present. Consequently, accurately measuring sleep in field based environments is difficult, though remains important to quantify sleep quantity and quality in ecologically valid field settings. With these difficulties in mind, other methods of collecting sleep data exist to aid obtaining sleep information in real-world settings.

Actigraphy is another popular method of objectively estimating sleep parameters. These devices are usually worn either on either wrist of the upper-extremities to continuously monitor body movement and activity (usually on the wrist), and thus estimate sleep based on algorithms primarily related to acceleration and movement [27]. Advantages of actigraphy compared to PSG are the size, transportability and ease of wear, making it more suitable for football-specific environments, especially those which are continually changing due to travel and other commitments. Furthermore, actigraphy is a popular method of measuring sleep due to its relatively un-invasive nature and comfort level compared to PSG. Although admittedly less accurate than PSG, actigraphs are still able to give reliable and valid sleep measures including total sleep time, sleep efficiency, wake episodes and wake episode duration [27], although there are reports of weakened correlations with PSG for sleep onset latency [121] and intermittent awakenings [122]. Signal et al. [123] compared PSG and actigraphy measurements of the in-flight and layover sleep of 21 flight crew. The authors reported that actigraphic and subjective estimates of sleep duration correlated highly with PSG (range r = 0.84-0.95) with the mean differences relatively small between instruments (-36 and -20 min). However, actigraphic estimates of sleep latency and efficiency showed moderate to poor correlation (r= 0.04-0.53) with PSG [123]. In comparison, others have found no significant differences for sleep efficiency between PSG and actigraphy [124]. For example, Kushida and colleagues compared the night responses of 100 sleep disorder patients between epoch-by-epoch comparison of PSG, actigraphic and subjective sleep parameter data. The authors found no difference between PSG and actigraphy for total sleep time, sleep efficiency and number of awakenings [124]. Overall, whilst actigraphy appears to accurately measure sleep duration it remains unclear whether measures of sleep latency, awakening and efficiency are as accurate. Thus, the potential error and threshold for difference should be considered when estimating those other sleep variables from actigraphy [123]. From a practical perspective, in football-specific environments the variables acitgraphy can accurately measure are generally of primary interest in (i.e. sleep duration opposed to the amount of sleep spindles in stage N2; Table 2.1). If a player has a suspected sleep health issue then they may be referred to a sleep medical specialist through which PSG could of course be necessarily employed.

Despite the ease of actigraphy, there are still costs and player comfort issues to consider. For instance, players are still required to wear a “foreign” object on their person at all times, and in many professional leagues around the world there are player agreements in place which restrict monitoring players outside club hours. Thus, normative sleep for players when not attending club practices and games is unknown. Notwithstanding, actigraphy devices only maintain the ability to estimate sleep when sleep diaries are used. Accordingly, the simplest method to monitor sleep involves subjective sleep diaries can also be used to monitor sleep quality and quantity. The reliability and validity of these measures depends on the questionnaire used. Indeed, previous work has shown subjective measurements can be imprecise [125] and can be influenced by mood, memory bias and personality characteristics [126]. However, it has also been shown that respondents are capable of estimating total sleep duration with significant accuracy [127]. Furthermore, the sleep indices within a newly developed subjective sleep questionnaire (RegMan for Sport) have been validated against objective measures of actigraphy, with time in bed (ICC = 0.93 to 0.95) and total sleep time (ICC = 0.90 to 0.92) revealing strong agreement [128]. Thus, if using objective measurements of sleep are not possible, the use of subjective measures can provide an accurate indication of some sleep parameters for athletes. From a practical perspective, subjective measurements of sleep are preferred within elite sport environments as they are less invasive than actigraphy or PSG. For instance, some players feel uncomfortable wearing the watches whilst they sleep and anecdotal reports suggest players are more anxious when they are wearing a device which is measuring their sleep. Further, the intrusion into private life by such monitoring devices is becoming an issue with many player associations. Some medical practitioners additionally question the need for technology to report sleep parameters, when they see little reason for players to 'lie' about their sleep. This is obviously dependant on player-coach-medical team dynamic and relationship. These subjective methods can also be used to confirm actigraphic results [27]. Importantly, both actigraphy and subjective reports have been shown to not significantly differ between PSG data for total sleep time and sleep efficiency [124]. Taken collectively, this suggests that if PSG is not readily available or preferred for use and players are comfortable with other modes of data collection, actigraphy and subjective questionnaires offer the next reliable step with which to assess sleep data for athletes.

Finally, outside the three main methods of quantifying sleep, the identification of athletes' 'morning' or 'evening' types (circadian phenotype) may be an important consideration for when quantifying sleep, especially for athletes. Such classification can be evaluated using the Morning-Evening Questionnaire (MEQ) [129] to determine if sleep chronotype influenced various sleep variables. This questionnaire uses 19 questions regarding sleep behaviour, with a cumulative score used to categorise individuals as 'morning' types (scores 59-86), 'evening' types (14-41) and neither types ('intermediate'; 42-58) [129, 130]. The inclusion of the questionnaire in experiments may be an important consideration, especially given the known variability in the intra-individual requirement for sleep [26, 28, 108]. For instance, whilst circadian rhythms have been shown to regulate key physiological processes involved in athletic performance (with personal best performances occurring generally in the evenings), there is recent evidence that time since awakening, along with the athlete's circadian phenotype (i.e. a preference for going to sleep early/later or arising early/later), are required for consideration when observing optimal athletic performance [131]. Indeed, understanding the interaction between sleep and athletic performance outcomes is one that warrants further examination. Taken collectively, the most sensitive indication of timing of sleep and onset of the various phases of sleep is PSG; thus its extensive use in clinical settings. However, this equipment is limited in field-based practical setting (such as footballers) due to cost, being potentially invasive for participants and labour and technically intensive [27]. Comparatively, actigraphy and subjective sleep diaries are preferred by professional athletes to measure sleep; however the accuracy of in measuring sleep is mixed. Thus, potential error and limitations in accuracy should be considered when interpreting results from these measures in athletes. Having discussed the methods to measure sleep, to further understand the context of sleep loss within athletic performance domains, it is now pertinent to discuss the effects of sleep loss of exercise and physiological and cognitive responses to exercise.

## 2.3 The effects of sleep loss on athletic performance

Associated publication:

**Fullagar, H.H.K.,** Skorski, S, Duffield, R, Hammes, D, Coutts, A, Meyer, T. (2015). Sleep and athletic performance: The effects of sleep loss on exercise performance, and physiological and cognitive responses to exercise. *Sports Medicine.* 45(2):161-186. DOI: 10.1007/s40279-014-0260-0 (Appendices 6.1).

The ability of humans to cope with physiological and psychological stressors is critical to athletic performance outcomes [132], and is affected by numerous factors including experience, fitness, motivation and the natural fluctuation of physiological and behavioural processes across any given 24 h period (i.e. sleep-wake cycle, body temperature, hormone regulation [133]). These *circadian rhythms* are primarily controlled by the suprachiasmatic nucleus (SN) within the hypothalamus [91]. However, the SN is unable to always maintain control over these patterns, as humans are highly sensitive to alterations to their natural environment [68, 91], most notably through the light-dark cycle [134]. When athletes encounter disruptions to their environments (e.g. through travel or training/playing at night), endogenous circadian rhythms and normal sleep-wake cycles can become desynchronised [29, 91]. Such perturbations in sleeping patterns can cause an increase in homeostatic pressure and affect emotional regulation, core temperature and circulating levels of melatonin, causing a delay in sleep onset [135]. Following these periods there is potential for sleep loss to result in neurocognitive and physiological changes and performance to be compromised [25, 26, 89, 136]. Thus, since sleep disruption prior to important events are commonly found in elite athletes [137-139], there are numerous instances where the subsequent performance could be compromised [137, 140, 141].

### 2.3.1 Sleep in normal vs. athletic populations

Subjective mean total sleep duration has steadily reduced in healthy adults since the mid-twentieth century from approximately 8–9 h per night in 1959 to 7–8 h in 1980 [142]. In a nationwide survey of the USA in 2013, data indicate adults slept for an average of 6 h:51 min on ‘workdays’ and 7 h:37 min on ‘non-workdays’ [143]. Interestingly, almost one-quarter of adults who have similar sleep durations to current recommendations report ‘fairly–very bad’ sleep quality. However, such objective data is not currently present in the football related literature. As such, it remains unclear for how long and how well elite players sleep. From an *elite athlete* perspective, it is perhaps concerning when comparing with non-athletic populations, as Olympic athletes were reported to experience significantly poorer sleep durations and qualities compared to non-athletic controls [144]. Some limited data also exists from football case studies, for example elite youth players sleep for 6 h: 44 min ± 41 min at home and 7 h : 45 min ± 1:09 h following training [145]. Training in this study appeared to potentially offer benefits for the youth player’s sleep quality, with a training condition resulting in a significantly higher (7 ± 2; $P < 0.01$) rating of sleepiness at bedtime compared to a home condition (6 ± 1) [145]. In addition, sleep duration and quality have been shown to be significantly reduced on the night of away matches compared to the night prior in elite Australian football players, though normative sleep data for elite players is unclear [146].

Despite sleep data in football players being limited, there is evidence of sleep data in other sports. Mah et al. [147] reported mean average sleep durations of 6.7 ± 1.0 h in collegiate basketballers during a competitive season. Similarly, Lastella et al. [141] found a sample of 58 elite Australian team-sport athletes slept for a mean duration of 7.0 ± 1.2 h during a regular training phase. Juliff et al. [139] reported that more than half of a sample of 283 elite individual and team-sport elite athletes (of which 210 were from team sports) indicated they had slept worse (perceptually reduced quantity and quality) than usual in the night(s) prior to an important competition or game in the past year. The same study also reports these team-sport athletes slept for an average of 7 h: 36 min per night and this does not appear to differ between in- or out- of season. With regard to sleep following competition, Eagles et al. [148] found a significant reduction in sleep durations on game nights compared to non-game nights in rugby union players. Whilst caution needs to be taken in comparing across studies (i.e. due to differences in sleep-assessment methodologies), it seems reasonable to assume sleep in team-sport athletes (i.e. football) is dependent on many factors. These could include the type of sport, training and travel demands, age, personal situation, time of season and team culture [141]. In addition to the knowledge of how well and long footballers sleep, general sleep health is also important.

Taken collectively, normative sleep quantity and quality for elite football players are scarce in the current literature. Furthermore, it remains unclear how sleep is affected by numerous extraneous constraints (e.g. travel, late-might matches and congested schedules) experienced by professional players. However, before exploring the relationship between sleep, performance and recovery in football it is critical these observational studies are investigated to build the foundation for our understanding of sleep within a football context. Furthermore, perhaps it is most pertinent given the lack of specific sleep and football performance data to review the literature on sleep and performance from an over-arching athletic perspective.

### 2.3.2 Effects of sleep loss on exercise performance

Much of the previous research has reported that exercise performance is negatively affected following sleep loss; however, conflicting findings mean that the extent, influence, and mechanisms of sleep loss affecting exercise performance remain uncertain. For instance, research indicates some maximal physical efforts and gross motor performances can be maintained [149, 150]. In comparison, the few published studies investigating the effect of sleep loss on performance in athletes report a reduction in sport-specific performance [151-153]. Perhaps most relevant for athletes, sports-specific skill execution [153], submaximal strength [149], and muscular and anaerobic power [154-158] seem to decline following sleep restriction (involving later sleep or earlier wake times disrupting normal sleep–wake cycle). Indeed, athletes are more likely to encounter this type of sleep restriction. For instance, Reilly and Deykin [159] reported no decrements in endurance running performance (time to exhaustion) following partial sleep loss (3 h of sleep per night for 3 nights). Furthermore, the total distance covered in a YoYo intermittent-recovery test level one was not different following SR [160]. In contrast, maximal work rate has been found to decrease (15 W decrease following SR) during incremental cycling to exhaustion (30 min at 75 % $VO_{2max}$ followed by 10 W increase every min [161]). Similarly, mean and peak power during Wingate anaerobic cycle tests have been shown to decrease in students [156], footballers [162], and judo competitors [154] following 4 h of SR for 1 night. Given these findings, whilst it seems that sleep restriction impedes some aspects of athletic (physical) performance, it remains unclear whether sleep is critical to performance for all athletes who experience small one-off sleep restriction periods. From a football perspective, there are no experiments to the authors' knowledge that evaluate the impact of sleep loss on any performance parameter.

Perhaps the only comparable study was a study by Skein et al. [163] whom reported 0 h of sleep compared to ~8 h of normal sleep to be associated with reductions in muscle glycogen, perceptual stress, sprint performance and slowed pacing strategies during intermittent-sprint exercise for male team-sport athletes (all variables related to aspects of football performance [3]). However, the results of this study are difficult to extrapolate to footballers given it is unlikely players will incur such extreme cases of sleep deprivation. Nonetheless, it is important to consider these results as an example of what potentially occurs at the extremes of such circumstances. In contrast, it should be noted that sleep may not always be necessary for optimal performance outcomes. Although again an extreme case, it was found that non-sleepers completed the North-Face Ultra-Trail du Mont-Blanc 2013 race faster than those who slept during the course [164]. To compensate for this, athletes appeared to increase sleep duration in the days prior to the race. Indeed, the effect of sleep on performance appears to very dependent on numerous factors such as the different exercise performance requirements and scheduling factors specific to each sport.

Whilst not sports-specific, there have been reports of the effect of sleep restriction on occupational performance (i.e. military and fire-fighting; [165]). Indeed, there are numerous performance and physiological outcomes which are similar between physically demanding occupations and elite athletes [166]. In a recent study by Vincent et al. [165] thirty-five firefighters were randomly allocated to a control condition (8 h sleep opportunity) or a sleep restricted condition (4 h sleep opportunity) with subsequent performance on a range of physical work tasks (task completion and physical activity) evaluated over three days. Sleep restriction did not negate the ability of firefighters to perform relevant work tasks; however, their physical activity performed during fire-fighting tasks was reduced. Thus, those performing physically demanding tasks following sleep loss may aim to conserve physical exertion during rest periods in order to still complete the tasks. Indeed, this study supports the findings of Skein et al. [163], whom investigated the effects of 30 h of sleep deprivation on consecutive-day intermittent-sprint performance and muscle glycogen content. Following 30 h of sleep deprivation, the distance covered during the initial and final 10 min periods of a 50-min intermittent-sprint exercise protocol (including a 15-m maximal sprint every minute and self-paced exercise bouts of varying intensities) was reduced compared to a control condition [163]. Although speculative, this could be extrapolated to football performance following sleep loss where players may look to conserve energy during periods where the ball is not in their immediate vicinity.

Finally, it is also important to consider the timing of sporting performance. For instance, whilst circadian rhythms have been shown to regulate key physiological processes involved in athletic performance (with personal best performances occurring generally in the evenings), there is recent evidence that time since awakening, along with the athlete's circadian phenotype (i.e. a preference for going to sleep early/later or arising early/later), are required for consideration when observing optimal athletic performance [131]. Therefore, the identification of athletes' 'morning' or 'eveningness' (circadian phenotype) may be an important consideration for future research. This can be evaluated using the Morning-Evening Questionnaire (MEQ) [129] to determine if sleep chronotype influenced various sleep variables. This questionnaire uses 19 questions regarding to sleep behaviour, with a cumulative score used to categorise individuals as 'morning' types (scores 59-86), 'evening' types (14-41) and neither types ('intermediate'; 42-58) [129, 130]. The inclusion of the questionnaire in experiments may be an important consideration, especially given the known variability in the intra-individual requirement for sleep [26, 28, 108] and variability in recovery time course of numerous recovery markers [8].

### 2.3.3 Effects of sleep loss on physiological responses to exercise

The effects of sleep loss on physiological responses to exercise also remain equivocal [152, 167-169]; however, it appears a reduction in sleep quality and quantity can result in an autonomic nervous system imbalance, acutely simulating symptoms of the overtraining syndrome [170]. Additionally, and whilst speculative, increases in pro-inflammatory cytokines following sleep loss could promote immune system dysfunction [171]. Examples of the susceptibility of physiological responses to exercise following sleep restriction (applicable to footballers) are the increase in heart rate, minute ventilation, and plasma lactate concentration during submaximal and maximal exercise after a partially disrupted night's sleep (3 h of sleep loss in the middle of the night) [167]. These responses are attributed to the increased metabolic demand [172], perceived effort [168], and catecholamine concentrations following SR [173]. This could be interpreted as SR acting as an additional stress to the exercise stress itself [174]. In contrast, Martin et al. [169] showed that 2 nights of fragmented sleep (eight 'wake up' calls ranging 30–75 min) had no significant effect on heart rate, oxygen consumption, minute ventilation, and core body temperature during 30 min of heavy treadmill walking. These differences are perhaps attributable to the exercise mode and SR protocol administered. However, knowledge of the effect of sleep loss on physiological responses to exercise in footballers remains limited given the difficulty and challenges of employing an intervention that will likely not elicit a positive response.

Perhaps the most important finding with relevance to football players is the reduction in the full restoration of muscle glycogen stores in team-sport athletes [163]. Without adequate intake, this could hinder the ability of players to perform for sustained periods, as muscle glycogen shortage is known to reduce muscle function and total work capacity [94, 175] and has been shown to be implicated in fatigue mechanisms in football [2, 3, 16, 63]. Indeed, energy imbalances are associated with sleep deprivation, potentially leading to decreased aerobic and anaerobic power production for players [29]. Since disruptions to the sympathetic–parasympathetic balance are also associated with overtraining [176], it is possible the disturbances to the autonomic nervous system following sleep deprivation could support the development of an over-reaching or over-training status [94, 177]. Nonetheless, it appears more extensive periods of sleep loss are required to affect the majority of physiological responses to exercise. More research is required to assess the impact of various experienced amounts of sleep loss on physiological responses to exercise in elite players; although admittedly this present numerous methodological and practicality issues.

### 2.3.4 Effects of sleep loss on cognitive responses to exercise

Numerous studies report that when sleep duration is less than 7 h in healthy adults, cognitive performance is poorer in tests for alertness, reaction time, memory and decision making [25, 178-184]. For example, heightened levels of sleepiness, depression, confusion and poorer overall mood states have also been reported [185-188]. Decrements in cognitive performance have previously been attributed to disruptions to pre-frontal cortex functioning, as cognitive deficiencies which occur outside this area of the brain malfunction in qualitatively different ways [182]. Recently, a more universal effect of sleep disruption on cognition has been proposed [189], due to the sensitivity of cognitive performance to both arousal (not limited to pre-frontal activity) and attention in a sleep disrupted state [179]. The neuroanatomical mechanisms behind this state are intricately complex [190]. For instance, when the quality and quantity of human sleep is reduced, it appears the largest decreases in cerebral metabolism (compared to the awake-rested state) are apparent in the thalamus, cerebellum and prefrontal, posterior parietal, and temporal cortices [190, 191]. The reduced metabolic rates within these regions have been correlated with decreased cognitive performance [192, 193], highlighting their influence on optimal cognitive functioning [190, 194]. Based on these collective findings, some studies suggest sleep benefits derived from models related to neural mechanisms, rather than peripheral tissues [195]. The detrimental effect of sleep loss on most aspects of cognitive function (slower and less accurate cognitive performance) remains unequivocal, with only minor conflicting findings present for the extent of the effects of mild sleep restriction [196]. These findings would predictably suggest negative consequences for athletes requiring high neurocognitive reliance (i.e. tactical requirements in elite football).

Although football-specific evidence is lacking, reductions in alertness, reaction time, memory and decision making accompanied by heightened levels of sleepiness, depression, confusion and poorer overall mood states could negatively affect numerous dimensions of football performance. For instance, with slower reaction time following minor disruptions to both sleep quality [197] and duration [198], it would seem pertinent for players with a high reliance on this cognitive component to ensure optimum sleep conditions prior to competing. This may be particularly challenging for the top football teams in Europe who play more than 70 home and away matches per season, where sleep conditions will change on an almost daily basis. These recommendations might be extrapolated to other aspects of cognitive function, since football also involves critical decision making [199, 200], which is also susceptible following SR [182]. Similar to the effect of sleep loss on physiological responses to exercise, more research is required to assess the impact of sleep loss on cognitive responses to exercise in elite players. This could be undertaken through observational studies where researchers know sleep reduction may occur naturally (i.e. late-night matches); although once more there are numerous methodological and practicality issues within this process.

### 2.3.5 Future research for athletic performance outcomes with relevance to football

Currently, there is insufficient evidence to clarify the importance of sleep for football players and the effects of sleep loss on exercise or football performance, alongside physiological and cognitive responses to exercise. Indeed, more research is required to confirm what dimensions of exercise performance are affected by sleep loss, especially those with a focus on repeated bouts of intermittent exercise and sport-specific performance. Admittedly, very little of the current literature has been conducted in football, or specifically with footballers, making the extrapolation of assumptions regarding sleep and performance to football difficult. Moreover, the majority of studies that assess the effect of sleep loss on athletic performance are those involving a scenario that is very rare in the real world.

Despite limited ecological sleep data for football players, it would seem more pertinent for research to investigate the effect of sleep restriction (minor sleep deprivation) on parameters related to athletic performance. Admittedly, this is extremely difficult to implement in an elite environment due to the possible outcome of negative performance outcomes. For instance, it would be impossible to ask a coach to deprive his players of sleep prior to a match. Instead, this could be done through field-based observational studies where researchers know sleep reduction may occur naturally (i.e. late-night matches). This would improve our understanding of players' typical sleep behavior, how this behavior shifts when faced with compromising situations and potentially how these shifts impact football specific-performance. Interestingly, there is little literature confirming the importance of sleep to physiological and psychological recovery. In particular, evidence of the role and importance of sleep within the professional football environment during various scenarios is lacking. Thus, although sport science personnel and researchers should be aware of the complex effects of sleep loss on athletic performance, such knowledge needs to be supplemented with sufficient understanding of sleep's role in recovery, and possible sleep hygiene strategies to alleviate these issues. Indeed, whilst it is important to acknowledge pre-match sleep can important for the subsequent performance, the contextual circumstances that often dictate post-match sleep can be vastly affected (i.e. travel, playing at night, home or away) and thus recovery may compromised. Accordingly, future examination of the evidence of sleep and the potential role it may play in recovery for footballers is warranted.

## 2.4 Sleep and recovery for elite footballers

Associated publication:

**Fullagar, H.H.K.,** Duffield, R, Skorski, S, Coutts, A, Julian, R, Meyer, T. (2015). Sleep and recovery in team sport: current sleep-related issues facing professional team-sport athletes. *International Journal of Sports Physiology and Performance*. 10(8):950-7. DOI: 10.1123/ijspp.2014-0565 (Appendices 6.2).

It is clear that elite footballers endure numerous physiological, psychological and neuromuscular stressors during training and competition [19]. Consequently, there is a vital requirement for players to balance these stressors with adequate recovery to maximise performance and ensure effective adaptation, whilst also minimising the risk of injury [22]. A crucial part of this balance is the management of a footballer's normal sleep-wake cycle during competition and training [26]. However, as mentioned previously, disruptions to a footballer's natural environment can force a de-synchronisation between their endogenous circadian rhythms and this sleep-wake cycle, resulting in a circadian shift in the normal sleep-wake cycle [29]. Following periods of altered sleep-wake cycle functioning there is also potential for recovery to be compromised [26, 201]. For footballers these scenarios could include periods of short- or long-haul travel [202], congested competition schedule [203], and training or playing at night [154]. Indeed, sleep loss in athletic populations is predominantly situational [139], with many football teams currently facing the challenge of coping with these specific, but commonly recurring disruptions and stressors. For example, the majority of European football tournaments are commonly played at night. Elite sporting environments also usually involve the interaction of more than one disruptive event. Top level European football teams (i.e. Champions League) can play away matches on a Wednesday night before playing once more during daytime hours the following Saturday - leaving less than 72 h for recovery and later post-match bed times [81]. Of further concern, team sport athletes report high incidences of daytime sleepiness, possibly due to a lack of awareness of sleep hygiene strategies [139]. At least anecdotally it appears there are numerous situations where footballers could endure poor sleep following training or match play, though research evidence of each/any situation appears limited.

### 2.4.1 Theoretical components behind sleep and recovery

There are three key factors which determine the recuperative (regenerative) outcome of sleep; the duration (total sleep time), quality (proportion of time asleep) and phase (circadian timing) of sleep [89]. A 'healthy' volume of night sleep has been suggested to be 7-9 h [204]. In addition to duration, sleep quality is also critical for optimal health and restorative functioning [204]. Although a clear definition is not readily available, sleep quality can best be outlined as the personal satisfaction of the sleep experience [204]. Further, the timing of sleep will also influence the effectiveness of the sleep bout. The timing of an individual's preferred bedtime in turn affects their circadian rhythms (i.e. body temperature, hormone regulation), which can impact both sleep duration and quality [89]. From an athletic perspective, disturbances to one or all of these collective aspects of sleep are suggested to affect the post-exercise recovery process [89].

As mentioned earlier, a typical night of sleep is comprised of approximately 90-min cycles divided into periods of REM and NREM sleep. Whilst REM sleep has a role in periodic brain activation, localized recuperative processes and emotional regulation, the role for NREM sleep is proposed to assist with energy conservation and nervous system recuperation [205]. For instance, motor skill improvements are significantly associated with stage 2 NREM sleep (Figure 2.1; Table 2.1), and the power and density of locally expressed sleep spindles [206]. Taken collectively, there is considerable evidence supporting the recuperative nature of sleep in restoring molecular homeostasis, cellular maintenance and synaptic plasticity [89, 105, 205]. From an athletic perspective, this implicates that disturbances to either the timing of sleep phases, or the quality and duration of sleep within these phases, can result in the hindrance of psychological and physical recovery following an exercise bout [89]. This would seem especially pertinent for football players whom are typically exposed to prolonged bouts of intermittent-sprint activity during both high-intensity training and competition. Logically, exposure to such activity will increase the need for recovery and subsequently increase the overall requirement for sleep [141].

### 2.4.2 The effect of sleep loss on recovery of football performance

Although studies in elite football are lacking, there are recent studies which show that sleep loss following team-sport competition affects the time course of recovery for both performance and psychological measures. For instance, as alluded to previously Skein and colleagues [201] investigated the effect of sleep deprivation (0 h sleep) compared with normal sleep (~8 h) on the physiological and perceptual recovery of eleven rugby-league footballers following competitive matches in a randomised cross-over design. Overall, sleep deprivation negatively affected recovery with significant impairments observed in mean and peak countermovement jump height and cognitive reaction time. Although sleep deprivation was excessive, this study highlights the increased physiological load during wakefulness following sleep loss in team sports, and in turn, suppression of cognitive function and lower body power. Similarly, Fowler et al. [146] reported significant reductions in sleep duration and quality, along with an impaired stress-recovery balance, on the night of a match compared to the night prior for away matches in elite Australian footballers. In particular, there is little longitudinal sleep data (either subjective or objective) available in the scientific literature. This is surprising given this would appear the first step in understanding the relationship between sleep and recovery within a football context.

There is further evidence of this relationship in individual athletes. For instance, significant reductions in sleep quantity and efficiency were associated with increased fatigue and impaired exercise capacity in a group of ten functionally-overreached elite synchronized swimmers [207]. Furthermore, McMurray and Brown [208] investigated the cardiovascular and metabolic responses of five participants during submaximal exercise following 24 h of sleep deprivation. They reported increased minute ventilation and oxygen uptake during the recovery period, suggesting negative effects of sleep loss on physiological recovery [208]. Since disturbed sleeping patterns can also harm muscular physiology though the impairment of protein synthesis, Datillo and colleagues [209] have hypothesised sleep is necessary for muscular recovery. The process of muscular recovery is dependent on the regulation of anabolic (testosterone, growth hormone, Insulin-like growth factor 1 (IGF-1)) and catabolic (myostatin, glucorticoids) hormones [209]. Unfortunately, the regulation of these hormones is susceptible to sleep restriction and deprivation [210]. These hormonal fluctuations can lead to an increased stimulation of protein degradation, causing muscle atrophy, worsening satellite cell proliferation and ultimately hindering the muscle's capacity to recover [209]. However, it should be noted that these mechanisms are theoretical only.

### 2.4.3 Sleep loss and association to illness and injury

Previous work indicates there is an influential link between variables of athletic training and immune health [211]. When these variables are not balanced with adequate recovery, exercise performance can be negated, or conversely, excessive training or performing can lead to illness or injury occurrence [211]. Indeed, overtraining is associated with increased incidence of infection arising from both the physiological stress induced by excessive training and the psychological stress associated with a stress-recovery imbalance [171]. One of the considerations Walsh et al. [211] mentions as critical to this balance is adequate sleep, which is theoretically at risk during intensive training weeks or in-competition [171]. Moreover, athletes who train or compete at high-intensities for prolonged periods can be exposed to extraneous pathogens and other stressors to the immune system, such as severe mental stress [212]. For instance, Anglem et al. [213] investigated symptoms of illness and injury in adventure athletes during a two week international race. Such a race typically involves high-intensity-prolonged exercise along with severe sleep deprivation (mean 1.2 h ± 0.3 h per day). These investigators found symptoms of upper respiratory illness (linked to immune dysfunction in athletes) were most common (suffered in 57% of athletes) upon finishing the race whilst musculoskeletal injury was also prevalent (79%). These findings suggest that illness, injury, exercise performance and sleep disturbances are closely interrelated, but the authors importantly highlight the complexity of this relationship [213].

Recently, Hausswirth and colleagues [170] found a higher prevalence of upper respiratory tract infections in functionally over-reached male tri-athletes compared to a normal training group. These authors also reported progressively worsening sleep duration and efficiency, suggesting minor sleep disturbances during the overloading phase. Additionally, illness prevalence and sleep disturbances were at their highest during the final week of overloading implying an associated relationship; however, whether the impaired sleep and illness occurrence are consequences or symptoms of over-reaching remains unknown [170]. The extrapolation of these results to football is tenuous for various reasons, including the characteristics of sports demands, scheduling, training, sample sizes and the intra-individual requirement for sleep. Like much of the literature throughout this dissertation, such direct exploration in football is somewhat limited. Nonetheless, sleep restriction appears to be associated with increases in pro-inflammatory cytokine secretion [214], unfavourable activity and weight status profile [215] and injury occurrence [216] which are of relevance to footballers; although sleep deprivation does not seem to alter immune indices at rest [217].

### 2.4.4 Situations specific to football affecting sleep and recovery

#### 2.4.4.1 Sleep loss following playing or training at night

As often determined by television scheduling, football associations now schedule the completion of matches at night. Indeed, the pure timing of matches (i.e. some matches in the Spanish La Liga commence at 22:00) will force players into later bedtimes. Furthermore, since physical activity promotes arousal, it has long been assumed exercising during the evening hours produces a greater number of sleep disturbances than exercising during daylight [210]. For example, footballers whom compete at night will be required to perform at times when arousal tends to decrease [218] (i.e. the typical kick off time for Champions league in Germany is 20:45, finishing ~22:45), subsequently leading to possibilities for sleep disturbances [219]. A typical strategy to alleviate this is for players to consume caffeine, which has well established effects of improving endurance performance [220, 221]. However, caffeine has the potential to disrupt sleep post-match as it has been shown to reduce subsequent sleep duration when taken up to 6 h prior to bedtime [222] - a finding which many practitioners support anecdotally. However, it should be acknowledged that there is also evidence of no detrimental effect of caffeine on both subsequent sleep variables (i.e. duration, efficiency) and recovery of physical performance (five sets of 6x20 m sprints with 25 or 60 s of recovery) [223].

An additional reason for possible sleep loss following night matches is the interaction between external light and sleep. This is based on the role of the central body clock (oscillator) which is affected by the light-dark cycle, located within the suprachiasmatic nucleus of the hypothalamus [104]. Melatonin, a molecule which is suppressed by light and secreted during darkness, is proposed to be one affecter of the transmission of time information to this central body clock and many different peripheral oscillators throughout the human body [224]. Floodlights used in modern stadia during night matches may therefore suppress melatonin and possibly influence sleep. For instance, bright light can increase alertness and decrease sleepiness [225]. Of further concern is that following matches players homeostatic drive for sleep would typically be high due to the extended periods of wakefulness, thus exposure to further light sources such as smart phones or lights on a various modes of travel can also affect sleep [219]. These extraneous sources of light likely prolong the need for wakefulness and delay the circadian drive for sleep [219]. Indeed, it has been widely reported that technology use and exposure to light prior to bedtime can prolong sleep onset latency, reduce sleep duration and be detrimental to overall sleep quality [226-228]. Footballers also have extensive post-game commitments such as press conferences, recovery practises and social functions, which could lead to even later bedtimes and disrupt sleep duration and quality [31, 81]. As alluded to previously, Juliff et al. [139] found 52.3% of a sample of 283 elite individual (n=73) and team-sport (n=210) athletes reported sleep disturbances following a night training session/match. Moreover, 59.1% of team-sport athletes reported that that did not use a strategy to overcome these sleep disturbances [139]. Notwithstanding these findings, the anecdotal evidence of athletes reporting sleep disturbances following night competition outweighs that documented in the literature; thus, further research in elite football populations is required to confirm this.

Given the lack of data within a specific football context, it becomes advisable to review the evidence of disrupted sleep following night exercise in other populations. Recent data shows that performing maximal aerobic exercise in the evening results in elevated sleep onset latency, awakenings, and REM sleep latency - suggesting poorer overall sleep quality in judo competitors [154]. Furthermore, sleep onset latency was significantly longer (+ 14 min), sleep duration significantly shorter (-14.6 min) and sleep efficiency significantly poorer (-3.1%) following 40 min of high-intensity treadmill running (80% of HR reserve) performed at 21:20 compared with a non-exercise condition in twelve active young men [229]. Whilst several physiological variables are elevated prior to sleep onset following late-night vigorous exercise (suggesting possible effects on cardiac autonomic control and metabolic function [230]), delayed sleep onset can also be caused by mental stimulation or cognitive fatigue [105]. Moreover, given pain is a significant predictor of a poor night's sleep [231], it is likely prolonged late-night, high-intensity exercise (equivalent to match situations) will incur sleep disturbances throughout the night as a result of pain and soreness. This is of particular relevance for heavy contact sports such as American football, ice hockey, and rugby union; though, this is not specific to night matches as players also incur these stressors during day matches. Furthermore, it should be noted that there is opposing evidence on the effect of competing at night on sleep. For instance, Roach et al. [232] reported no effect of two night (19:00-21:00) matches on sleep in elite junior football players. Similarly, Robey et al. [145] found no effect of early evening high-intensity training (16:30-18:30) on the subsequent sleep quality, duration, onset latency, sleep efficiency and bedtime in elite youth football players. Thus, it appears that that sleep following the performance of exercise at night is dependent on many factors such as the timing of the exercise, physical activity of the population sample, ambient temperature and various physiological (e.g. core temperature) and psychological stressors [219].

In light of this, it should be recognised that the mechanisms behind the effect of exercise (and timing) on sleep are complex due to the main confounding variable (amongst others) of the stress induced by the exercise itself. From an applied perspective, future research must first focus on providing objective evidence (e.g. acute and chronic measurements of actigraphy) on whether disturbances following match play at night occur. Researchers might also focus on the effects of disrupted sleep following match play in footballers and attempt to delineate the mechanisms responsible. At present, practitioners should also be aware of the intra-individual variability in sleep requirement and chronotype (those who arise early in the morning vs. those who prefer later bedtimes). Accommodating these differences within an elite football environment is difficult as it may require more individualised approaches. Indeed, this would be even more pertinent for team scheduling training the day after a game. For instance, training in the absence of sufficient sleep following late-night matches may potentiate the negative outcomes. This may create recovery concerns given players will sleep differently after these matches, whilst also possibly placing those whom are training at an unnecessary injury risk.

#### 2.4.4.2 Sleep responses to short and long-haul travel

Cumulative sleep loss occurs as a consequence of travel during busy scheduling periods, which can lead to accumulative fatigue over a season [101]. Travel fatigue is dependent on the distance and frequency of travel, and the length of the season. It should be noted that travel-induced fatigue is separate to jet-lag, with the main difference being jet-lag comprises an effect of time-zone change (Figure 2.2; [101]). Sleep disturbances during or following travel can result in reductions in mood, acute fatigue and difficulty in initiating sleep at the arrival destination [101]. For footballers the method, mode, distance and timing of travel vary greatly and are largely dependent on scheduling, team budget and the coach's preference. Many teams, particularly in America and Australia, endure one-way short haul domestic or international travel up to 6 h prior to or following competition [233]; although this is less likely in European competition. In addition to sleep disturbances, travelling can result in detrimental health, impaired mood, dehydration and loss of motivation all of which can affect recovery [101]. Of further concern, it has been shown that baseball teams whose circadian rhythms are more synchronised to optimal performance times are more likely to be successful, indicating either a negative effect of travel and/or desynchronised body-clock functioning [234]. However, it should be noted that these data do not actually outline any physical or perceptual response, and admittedly baseball scheduling is vastly different to football.

Empirical data describing the effect of short-haul air travel on sleep, performance and the ensuing recovery in these situations is largely unknown. For instance, the sleep quantity and quality of players following away competition performance remains unclear, with short-haul air travel (1-3 h) affecting perceived sleep quality [233], whereas some football players report earlier mean bed times after short-haul air travel (~5 h) and an away match [146]. Competition performance, along with reduced physical demands, appears to be greater at home compared to away (in American football [235], baseball [234], rugby league [202] and football [146]) suggesting either a negative effect of travel or a circadian advantage [236]. However, extrapolating these effects to determinations of football match performance is difficult due to other external factors and the inter-match variability in opposition and match intensity. Whilst there have been few empirical studies, the available data suggests that short-haul travel has minimal effect on physiological and perceptual recovery (e.g. no significant effect on YYIRL1 test performance). Even though short-haul air travel appears to have negligible effects on post-match physiological recovery, the effect on perceptual markers of

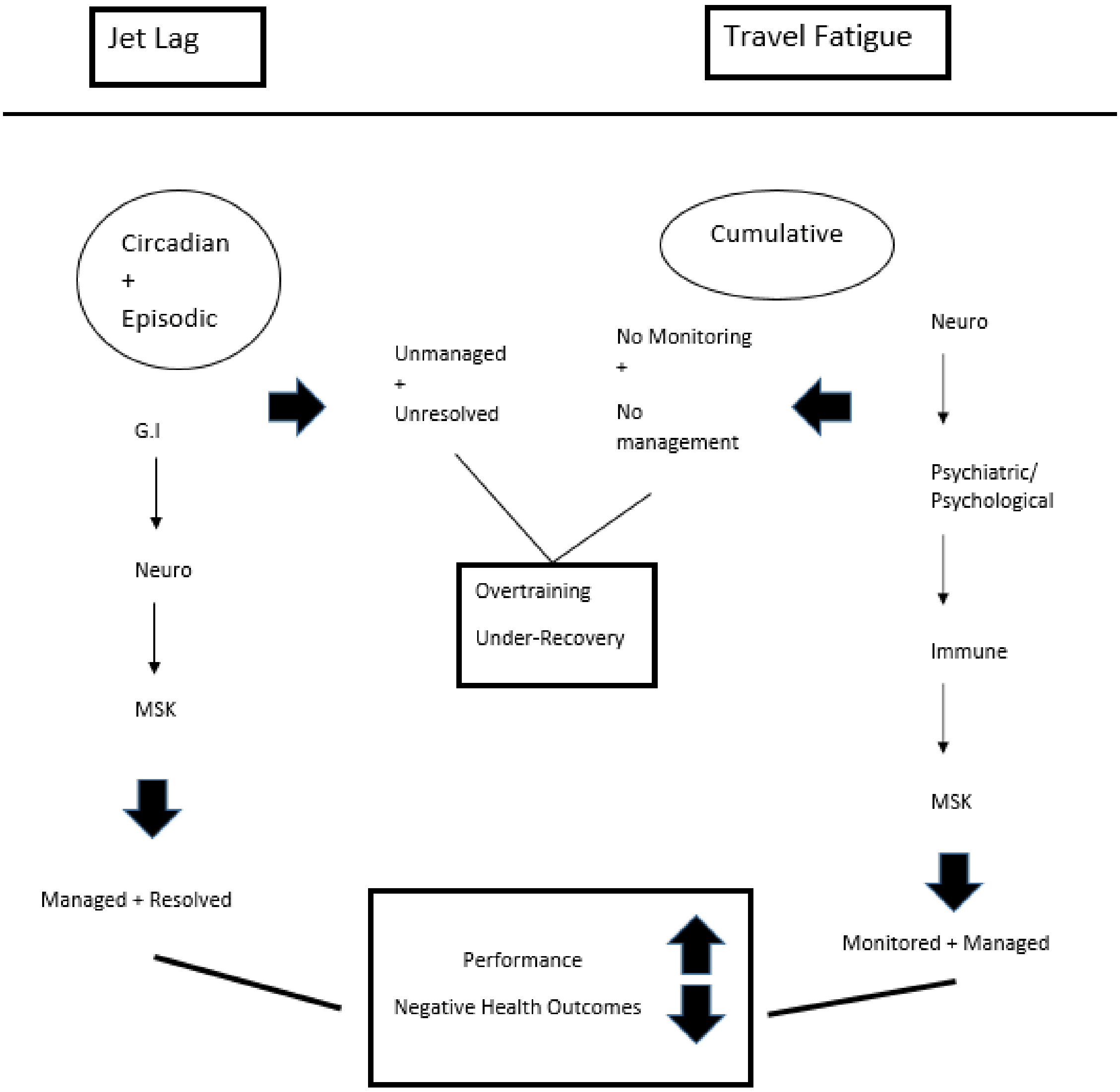


**Figure 2.2:** Jet lag and travel fatigue symptoms and management schema (reproduced from Samuels, 2012; [101]).

fatigue and sleep patterns following match play is equivocal. If these parameters decline, they can negatively influence training intensity or volume during ensuing sessions due to decreased motivation. Given the myriad of conflicting demands whilst experiencing travel and sleep loss (e.g. treatment, timing of training, recovery practices), it can be difficult for coaches to manage the most appropriate schedule for their team the day after a match. Indeed, more research is required to clarify the acute and chronic effects of cumulative domestic travel (e.g. over a season) on sleep and psychological and physiological recovery parameters of elite footballers.

There are numerous studies which report detrimental effects of long-haul air travel (> 5 h) across multiple time zones on performance [237] and physiological [238] and perceptual responses [239]. The direction of travel also plays an important role, with eastward travel reportedly more detrimental to sleep, performance and recovery outcomes [236]. The evidence supporting this proposition is surprisingly quite limited. The only study to the author's knowledge that has investigated the effects of eastward and westward long-haul air travel on physical performance relevant to team-sports is the work of Duffield and colleagues [240]. This study collected a range of data (CMJ, 20-m sprint and agility test, YYIR1) from 19 trained males for four days, one week prior to and immediately following (post four days) 21 h air travel west across eight time-zones from Australia to Qatar. After data collection in Qatar, a six day wash-out and 21 h return travel east, data was then subsequently collected at the same times of day for a further four days. The authors found that distance covered in the YYIR1 was significantly reduced at day one post travel in the PM ($P = 0.01$; $d = 2.57$), and large effect sizes were present at days two, three and four post-travel in the PM ($d > 1.00$) following eastward compared to westward travel. However, westward air travel showed a greater detrimental impact on lower-body power for 10 and 20-m sprint times. Whilst the direction of travel reveals contrasting results dependant on the type of performance parameter measured, the same authors have recently shown that the aforementioned data revealed significant reductions up to four days post long-haul transmeridian air travel [241].

Studies involving northbound and southward travel for athletes are also limited, presumably as there are minimal time-zone changes and thus less resultant effects on the aforementioned variables. The cost and intrusive nature of studies could also be reasons. Fowler et al. [242] examined the effects of 10-h northbound air travel (7800 km) across 1 time zone on sleep quantity and subjective jet lag and wellness ratings in 16 male professional football players during a pre-season tour. Sleep duration was significantly reduced the night prior to travel (due mainly to the timing of the flight) and the night of the match. In addition, subjective jet-lag remained for up to 5 days post-travel; although player wellness only reduced significantly on the day following the match. Therefore, it appears that 10 h of long haul air travel during the day with minimal time zone change has negligible effects on sleep and football player preparedness (from a wellness perspective); however the effects on the recovery of exercise performance remain unclear. Indeed, further research which investigates the effects of various durations and direction of long-haul travel on recovery in football players is required.

#### 2.4.4.3 Congested fixture scheduling

Excessive exercise loads can disturb the stress-recovery balance and result in performance decrements and injury occurrence [22]. For example, during periods of heavy match congestion in football, there is an increased injury risk for players when they play two matches per week rather than one [243]. In this regard, some major European football teams may compete in up to four competitions at once – which likely impacts on players' sleep behaviour. During these periods of high physical workloads, there is a potential for a reduction in sleep duration and quality. For example, it has been shown that as the effects of increased baseball match exposure accumulate towards the end of the season strike zone judgement is impaired, suggesting a fatigue-induced decline in performance; with sleep believed to be one of the main symptoms responsible [244]. Sleep has also been suggested to be sensitive to exercise overload, with high training volumes associated with greater sleep disruptions [245]. Although no published data is yet apparent in team-sport cases, Netzer et al. [246] found significant increases in the REM sleep onset latency and decreases in REM sleep of well-trained cyclists following training and a competitive 120-150 km race, compared to no training or competition. Following this, it is logical that when footballers compete in a greater number of matches within a short period, exercise-induced muscle damage will accumulate (dependant also on exercise intensity), characterised by decreased neuromuscular function, increased perceptual fatigue and increases in perceived soreness which can disrupt sleep [31]. Moreover, if there are several events in short succession, the continual anticipation of competition can also negate sleep [139]. However, at present, there is little research that describes or quantifies the effect of these changes on the subsequent recovery, particularly in team-sports undertaking congested fixture scheduling. Future investigations into the time course of recovery following sleep loss would be particularly pertinent to team sports such as baseball and cricket, since these athletes can play on consecutive days and could be at a high risk of cognitive impairments (e.g. slowed reaction time).

#### 2.4.4.4 Risks to training adaptation

Since sleep loss impedes muscle protein accumulation, the ability of skeletal muscle to adapt and repair can be hindered – which likely limits training adaptations [26, 89, 209]. This may be concerning during the football pre-season where training loads are higher, particularly given greater sleep disturbances are present during higher training volumes in elite swimmers [245]. Moreover, sleep efficiency has been shown to be significantly greater in during competition compared to intensive training in a group of state-level netballers [247]. Preliminary evidence also suggests that high-intensity interval training (i.e. field-based running sessions) negate sleep indices more so than strength training in well-trained athletes [248]. Since sleep loss can also affect vigour, mood and perceptual awareness [29], if training sessions are scheduled for early times this could cause reductions in motivation and consequently reduce optimal training performance and subsequent adaptations [249]. Furthermore, if the stress-recovery balance of footballers is disrupted by either an increase in training load/stress or inadequate recovery, it may lead to an overreached, or even overtrained state [22]. However, since professional football involves few prolonged periods of high intensity training due to the pure nature of modern day fixtures, it would appear elite footballers would rarely experience an overtrained state. Interestingly, disturbed sleep is believed to be one of many symptoms of either overreaching or the overtraining syndrome [22]. In a recent study by Hausswirth et al. [170], it was found that objective measures of sleep duration, efficiency and immobile time were all negatively altered in a group of functionally overreached tri-athletes. There was also a higher prevalence of upper respiratory tract infections within this group, implying an association between the two; however whether impaired sleep and illness occurrence are consequences, or simply symptoms or coincidental associations, of overreaching remains unknown [170]. Regardless, it is acknowledged that overtraining in elite football is extremely unlikely due to scheduling and coaching philosophies currently present without discounting the importance of optimising performance and match readiness.

Since sleep loss can hinder the learning of new skills, affect emotional regulation and disrupt cognitive function [89], it is likely that sleep is also important for optimising cognitive training adaptations. For instance, sleep is critical for memory retention, neural plasticity, and has been shown to improve visual discrimination and motor adaptation [105]. Therefore, it is likely that disturbing sleep during intense training or skill acquisition periods (e.g. pre-season) will encumber adaption in skill-based tasks with high neurocognitive reliance. However, objective evidence to support this suggestion is not currently present. Therefore, future research (with well controlled randomised-control trials) into the effects of sleep disruption on acute or chronic cognitive-based training adaptations in football is required.

### 2.4.5 Sleep strategies for footballers

#### 2.4.5.1 Napping

In an attempt to recover from sleep debt, a commonly utilised sleep strategy amongst footballers is the restorative nap. Naps have been shown to improve alertness, sleepiness, short-term memory and accuracy during reaction time tests [29]. Furthermore, Waterhouse et al. [29] found improvements in mean sprint performance following a 30 min post-lunch nap after 4-5 h of sleep restriction. On the basis of this, it has been proposed footballers take a post-lunch nap to ameliorate the performance deficits caused by ultradian biological rhythms that occur within the circadian cycle [250]. It appears napping behaviours have many benefits and should be undertaken where necessary in elite football environments. An example would be for players to have a nap after lunch if they are playing a match at night. However, it is critical that if naps are implemented within an elite football environment they balance the need to enhance performance whilst not disturbing subsequent sleep patterns, as this could hinder the recovery process following training or matches. For instance, Petit et al. [251] reported longer sleep onset latencies following a post-lunch nap during the subsequent night compared to a no-nap control condition in sixteen healthy young male athletes. It should be noted that these subjects were habitual ‘non-nappers’. Indeed, the high inter-individual requirement variability in napping frequency and duration was highlight recently by Lastella and colleagues whom demonstrated a group of team-sport athletes mean (± standard deviation) nap duration was 59 ± 62 min [252]. Whilst napping appears advantageous for performance (e.g. napping prior to competition), more research is required to evaluate its possible effectiveness in recovery and effects on ensuing nights’ sleep.

#### 2.4.5.2 Sleep extension

Extending sleep during normal sleep times is another strategy to alleviate the decrements in physiological and cognitive performance caused by sleep loss. Mah et al. [147] found faster sprint and reaction times and improved shooting accuracy, energy and mood following approximately three weeks of sleep extension (mean sleep duration + 110 min) in eleven basketball players, indicating its use as a viable option for enhancing performance. Moreover, extending sleep improves psychological wellbeing thus optimising athletes' mental preparedness for competition. However, obtaining extra sleep can be difficult, because increased sleep onset latency and mood effects can be nullified due to earlier bedtimes. Thus, if a player is not sleep deprived it is possible that extending sleep will reap no benefit. The timing of this sleep intervention could also influence the effects of sleep extension depending on the sleep chronotype of the player (i.e. preference for early morning or late-nights). Additionally, more research assessing whether sleep extension during periods of high-training load is a useful tool to ensure appropriate recovery is required. Such research would be pertinent in assisting players achieve higher sustained intensities in subsequent exercise bouts (i.e. during pre-season).

### 2.4.5.3 Sleep hygiene protocols

Identifying and modifying the factors that contribute to improve sleep quality (improving sleep hygiene) in footballers can also assist in ameliorating the detrimental effect of sleep loss and potentially enhance recovery. Sleep hygiene protocols are defined as a set of behavioural strategies designed to promote and improve healthy sleep [253]. They are centralised around the following principles: exercise prior to sleep, stress management, noise reduction, sleep timing, and avoidance of caffeine and alcohol. Of the few studies that have studied the effect of these strategies in non-clinical populations, the efficacy of sleep hygiene protocols remains unclear [254]. This inconsistency is most likely due to a combination of differing sleep hygiene recommendations across studies, combined with the variance between individuals in their response to these interventions. For instance, whilst sleep hygiene protocols have been shown to improve sleep quality and onset latency in university students and reduced sleep irregularity in adolescents, although the effect of numerous components of sleep hygiene in normal sleepers is mixed [253]. From a football perspective, little is known about the interaction between these sleep hygiene strategies and the recovery of exercise and psychological parameters. Preliminary evidence indicates adhering to some of the previous sleep hygiene recommendations improves sleep quantity, resulting in a reduction in perceived soreness and fatigue in elite tennis players [255]. Furthermore, regulating sleep-wake times helps synchronise the circadian timing system, improving sleep quality and quantity [256]; although evidence in non-clinical populations remains unclear. As pre-competition worry and anxiety are evident in athletes [137, 257], it may be of benefit to utilise self-confidence tools (i.e. meditation) to manage anxiety and stress, as these correlate with improved sleep. Identifying each individuals best sleep habits (e.g. bed comfort) are also pertinent, as unfamiliar environments may reduce sleep quality [256].

Such recommendations are similar to those designed for footballers who endure constant travel [101]. Fowler et al. [242] examined the effects of sleep hygiene and artificial bright light interventions on physical performance following simulated international travel in a randomized crossover design. Here 13 physically active males completed 24 h of simulated international travel with and without the interventions. Although total sleep duration during and following travel was greater following the sleep hygiene intervention (17.0 h) compared to the control condition (15.7 h), this difference was not significant ($P = 0.06$). Furthermore, there were no significant differences between conditions for the recovery of exercise performance. Such future research designs are required for further sleep and recovery compromising situations for footballers. For instance, the effect of a sleep hygiene strategy on the sleep and recovery profile for players following a late-night match is unknown.

It is well known sleep onset is prolonged by noise, light and extreme temperatures, with athletes reporting noise and light as the two most important factors to their sleep quality [137]. Since the use of technology just prior to sleeping promotes afferent signals from the retina to the pineal gland, inhibiting the secretion of melatonin and delaying sleep onset, the avoidance of bedtime technology (and thus reducing arousal and physiological excitement) has been recommended to improve sleep onset [256]. As part of a healthy sleep protocol, several nutritional recommendations have also been proposed to assist with sleep onset. For instance, a recent review by Halson proposed diets high in carbohydrates and protein may result in shorter sleep latencies and improved sleep quality, respectively [27]. Whilst there is a clear need for nutrition during the post-exercise recovery period, the interaction between foods consumed post-exercise and the ensuing sleep and recovery timeline is unclear. Indeed, the effects of nutrition are intricately complex and beyond the scope of this dissertation (see Halson [27] for further detail).

### 2.5 Future research for athletic recovery outcomes with relevance to football

Currently, there is insufficient evidence to conclusively describe the role of sleep for post-exercise recovery and resultant performance outcomes for football players. As such, the first step in understanding this contribution is for the utilisation of observational field studies through the use of subjective sleep diaries and/or actimetry in various ecologically valid situations. Once this specific context is known, it is important to understand the interaction sleep has with variables within the elite football environment during situations where sleep is an issue. This requires both randomised-cross over trials which investigate the measurement of sleep and the post-exercise recovery timeline (both physiological and psychological), and also case studies in elite football teams. Future work within this field could also focus on understanding the mechanisms involved and providing appropriate interventions to improve sleep and the ensuing recovery process. In addition to the obvious need for sleep research within professional football, future research may address the effect of combinative strategies to speed up recovery. Although many football players use more than one recovery method in order to receive additional benefit it is unclear if these multiple interventions might lead to interactions between the methods. For instance, Robey et al. [228] reported that CWI post-training does not affect subsequent sleep duration, onset or efficiency. However, the mechanisms between the interaction of sleep and other recovery protocols are difficult to determine, due to an abundance of confounding factors (e.g. protocol type, timing, facilities). Further research and practical investigation within professional environments which address whether it is more advantageous to use a recovery protocol which enhances sleep (or indeed the use of sleep as a recovery protocol itself) and/or whether a combination of these protocols enhances the recovery process is warranted.

## 2.6 Aims of the dissertation

Given the insufficient evidence to conclusively describe both observations of sleep for professional footballers and the role of sleep for post-exercise performance and recovery, this dissertation sought to address the following primary research concepts: i) what are the characteristics of sleep behaviour for elite footballers and are their instances which exist where sleep is disrupted? ii) If instances do indeed exist where sleep in hindered, is it possible to alleviate these issues through intervention-based strategies?

Therefore the aims of the thesis was to first monitor the sleeping patterns of elite football players to assess whether differences in sleep indices occurred in association with an altered perceptual recovery status. Additionally, any potential factors within the professional sporting environment (e.g. stress, physical or psychological load) which contributed to these poor sleeping patterns were identified (**Study One**). Based on such results, the sleep, travel and recovery responses of a separate group of elite footballers during and following actual long-haul international air travel was examined, with a further description of these responses over an ensuing competitive tour (including two matches; **Study Two**). Finally the aim of **Study Three** was to investigate the effect of an acute sleep hygiene strategy on physical, physiological and psychological recovery of highly trained amateur football players following a late-night match.

# 3. STUDY OVERVIEW

## 3.1 STUDY ONE: Impaired sleep and recovery following night matches in elite footballers.

**Fullagar, H.H.K.,** Skorski, S, Duffield, R, Julian, R, Bartlett, J, Meyer, T. (2016). Impaired sleep and recovery following night matches in elite football players. *Journal of Sports Sciences: Science and Medicine in Football*. 34(14):1333-9. DOI: 10.1080/02640414.2015.1135249 (Appendices 6.3).

**Introduction:** Despite the perceived importance of sleep for elite footballers, descriptions of the duration and quality of sleep, especially following match play, are limited. Moreover, recovery responses following sleep loss within match contexts remain unclear. Accordingly, the present study examined the subjective sleep and recovery responses of elite footballers across training days (TD) and both Day and Night matches (DM and NM).

**Methods:** Sixteen top division European players from three clubs completed a subjective online questionnaire twice a day for 21 days during the season. Subjective recall of sleep variables (duration, time of wake and sleep, wake episode duration), a range of perceptual variables related to recovery, mood and performance and internal training loads and non-exercise stressors were collected.

**Results:** Players reported significantly reduced subjective recall of sleep durations following NM compared to TD and DM (both $P < 0.001$; DM: $d = 3.71$; NM: $d = 4.31$). In addition, sleep restfulness (SRF) and perceived recovery (PR) were significantly poorer following NM than both TD (SRF: $P < 0.001$, $d = 3.56$; PR: $P < 0.001$, $d = 3.09$) and DM (SRF: $P = 0.002$, $d = 3.16$ PR: $P = 0.002$, $d = 1.78$), whilst PR was significantly poorer following a DM than TD ($P = 0.04$, $d = 1.31$).

**Discussion/conclusion:** The main finding of this study was the significant reduction in sleep duration and later bedtime following NM compared to both TD and DM. Following NM's, there was also a significant reduction in perceived recovery compared to both DM and TD. Players subjectively reported several individual reasons for poor sleep such as children, nervousness, pain and adrenaline following a match. Overall, our results suggest that elite football players lose sleep and report reduced perceptual recovery following night match play; however players appear to report adequate sleep durations (i.e. 7-10 h) and qualities following training days and day matches. More research is required to objectively quantify and confirm that TD results in ‘normal’ sleep durations, similarly that this sleep volume is severely hampered following NM or other sleep-compromising situations not identified here (i.e. travel). In addition, the effect of reduced sleep duration and quality on the recovery of exercise performance following NM in elite players is warranted.

## 3.2 STUDY TWO: Sleep, travel and recovery responses of national footballers during and following long-haul international air travel.

**Fullagar, H.H.K**, Duffield, R, Skorski, S, White, D, Bloomfield, J, Kolling, S, Meyer, T. (2016). *International Journal of Sports Physiology and Performance.* 11(1):86-95. DOI: 10.1123/ijspp.2015-0012 (Appendices 6.4).

**Introduction:** When long-haul international air travel is endured across multiple time-zones, numerous physiological variables are disrupted including the sleep-wake cycle, body temperature and hormonal circadian rhythms. Sleep is perhaps the more critical given sleep loss can affect athletic performance and has been shown to reduce physiological and cognitive recovery in other football codes. However, to date the interaction between these aforementioned situational disturbances and objective measurements of sleep in team sports is relatively unknown. Therefore, the present study examined the sleep, travel and recovery responses of elite footballers during and following long-haul international air travel, with a further description of these responses over the ensuing two-match competitive tour.

**Methods:** In an observational design, 15 elite male football players undertook 18 h of predominately westward international air travel from the United Kingdom to South America (-4 h time-zone shift) for a 10-day tour. During this tour, two matches were played, including against Uruguay (day 5; 20:00 local time) and Chile (day 10; 20:40 local time). Objective daily sleep parameters (Readiband actigraphy), external (global positioning systems) and internal (heart rate, rating of perceived exertion) training loads, subjective player match performance (Likert scale), technical match data (Prozone) and perceptual jet-lag on days 2, 4, 6, 10 (Liverpool John Moore's Jetlag Questionnaire) and recovery (REST-Q) measures were collected.

**Results:** Significant differences were evident between outbound travel and recovery night 1 (night of arrival; $P<0.001$) for sleep duration. Sleep efficiency was also significantly reduced during outbound travel compared to recovery nights 1 ($P = 0.001$) and 2 ($P = 0.004$). Furthermore, both match nights (5 and 10), showed significantly less sleep than non-match nights 2-4 and 7-9 (all $P < 0.001$). No significant differences were evident between baseline and any time point for all perceptual measures of jet-lag and recovery ($P > 0.05$); although large effects ($d = 1.47$) were evident for jet-lag on day 2 (two days after arrival).

**Conclusions:** Sleep duration is truncated during long-haul international travel with a 4 h time-zone delay, and even more so following night matches in elite footballers. However this lost sleep appeared to have a limited effect on perceptual recovery, which may be explained by both the direction of travel (westbound) and time zone small change (-4 h). Further the significant increase in sleep duration on the night of arrival following the long-haul flight may also alleviate any ensuing feeling or assist recovery post-travel. The confirmation of the results found in Study One of reduced sleep durations following night matches in elite footballers is concerning, if not at least from a health perspective. Further research investigating whether it is possible to: i) improve sleep parameters following night matches and/or travel ii) if so, does such an improvement result in an improvement of the recovery timeline, is required.

## 3.3 STUDY THREE: The effect of an acute sleep hygiene strategy following a late-night soccer match on recovery of players.

**Fullagar, H.H.K,** Skorski, S, Duffield, R, Meyer, T. (2016). The effect of an acute sleep hygiene strategy following a late-night soccer match on player recovery. *Chronobiology International*. 33(5):490-505. DOI: 10.3109/07420528.2016.1149190. (Appendices 6.5).

**Introduction:** Elite footballers experience reductions in sleep quantity following late-night matches, which are far less than those recommended for healthy adults. Furthermore, these players are at risk of reduced recovery following these periods of sleep disruption. However, it remains unknown whether improving sleep quality or quantity in such scenarios is i) possible and ii) whether such enhancements can improve post-match recovery. Therefore, the aim of this study was to investigate the effect of an acute sleep hygiene strategy (SHS) on sleep, physical and perceptual recovery of players following a late-night football match.

**Methods:** In a randomised cross-over design, two highly-trained amateur teams (20 players) played two late-night (20:45) friendly matches against each other seven days apart. Players completed either a SHS after the match or undertook a structured normal post-game routine (NSHS). The SHS group bedtime was at 23:45 (lights off at 0:00) and included ensuring players were in bed rooms as soon as possible with lights dimmed, and provided (optionally) with ear plugs and eye-masks in cool temperature rooms (~17°C). Further, no technological or light stimulation was allowed ~15-30 min prior to bedtime. In contrast, players in NSHS were permitted to undertake normal (supervised) activities and remained awake until they were allowed to go to bed at 02:00. Over the ensuing 48 h, objective sleep parameters (sleep duration, onset latency, efficiency, wake episodes), countermovement jump (CMJ; height, force production), YoYo Intermittent Recovery test (YYIR2; distance, maximum heart rate, lactate), venous blood (creatine kinase, urea and c-reactive protein) and perceived recovery and stress markers were collected.

**Results:** Sleep duration was significantly greater in SHS compared to NSHS on match night ($P = 0.002$, $d = 1.50$), with NSHS significantly less than baseline ($P < 0.001$, $d = 1.95$). Significantly more wake episodes occurred on match night for SHS ($P = 0.04$, $d = 1.01$), without significant differences between- or within-conditions for sleep onset latency ($P = 0.12$), efficiency ($P = 0.39$) or wake episode duration ($P = 0.07$). No significant differences were observed between conditions for any physical performance or venous blood marker (all $P > 0.05$); although maximum heart rate during the YYIR2 was significantly higher in NSHS than SHS at 36 h post-match ($P = 0.01$; $d = 0.81$). There were no significant differences between conditions for perceptual 'overall recovery' ($P = 0.47$) or 'overall stress' ($P = 0.17$).

**Discussion/conclusion:** In summary, an acute SHS increased sleep duration compared to a NSHS following a late-night football match; although there were significantly more wake episodes in the SHS and players reported similar perceived sleep quality between conditions. Thus, whilst sleep duration can be extended in a SHS following a late-night match it should be acknowledged that players may face difficulties initiating sleep when enforced with earlier bed times post-match. These difficulties could have arisen from enforcing an earlier than preferred bedtime, which may have led to a delayed sleep onset given it would've clashed with players' current preparedness for sleep, and consequentially a low sleep propensity. The SHS did not improve measures of psychological stress and recovery, or the recovery of exercise performance. Furthermore, there were no significant differences between conditions for blood-borne markers of muscle damage and inflammation or physiological responses to training (HIMS). This is in line with our previous knowledge of sleep deprivation studies where nights of complete sleep loss (e.g. 0 h), rather than partial sleep deprivation (e.g. 3-5 h) and a night of normal sleep (~8 h), are more likely to affect measures of post-exercise recovery. More research is required to assess whether a larger sleep differential (e.g. longer duration and higher quality sleep in the SHS condition) is required to affect the physical and physiological markers measured in this study. In addition, the effect of SHS on recovery in real-world elite environments requires further investigation, especially over the course of a season. For instance, there would be an increased likelihood for potential benefits if sleep behaviour was modified for more than an acute period. Taken collectively, the present findings suggest football players might consider SHS strategies where possible following a late-night match to promote restorative sleep; however there appears to be no additional benefit for the recovery of acute performance or perceptual recovery outcomes.

# 4. SUMMARY OF FINDINGS

Sleep is a vital component of human physiological and cognitive function [89], both of which are integral to peak sports performance [1]. This is especially relevant given sleeps' anecdotal importance within high performance sporting environments to recovery and offers scientific merit given the limited amount of current sleep-related research in elite football. Therefore, this thesis aimed to explore the influence of sleep on recovery within a high-performance football context. Consequently, several key contextual environments were identified that present potential sleep-related issues for professional players. These situational contexts that result in disrupted sleep may compromise recovery at various times throughout a typical season. The studies contained within this thesis showed that football players will encounter specific and re-occurring stressors throughout a season (i.e. late-night matches) which can disrupt sleep and hinder perceptual recovery. More specifically, professional players lose sleep following night matches and during extensive international air travel. That said, outside these specific contexts, players' sleep patterns appear to be within normal ranges for healthy adults. This thesis also sought to determine whether specific sleep-oriented intervention strategies could alleviate the identified sleep issues and inform improved player recovery practices. It was found that an acute sleep hygiene strategy was able to somewhat counter the reduction in sleep volume following a late-night match, despite no improvement in performance recovery. The present collection of studies offers insight into considerations necessary for understanding and interpreting these sleep-related issues in a football-specific environment. Indeed, whilst this thesis strives to further scientific knowledge, there are also critical practical outcomes that may benefit professional players and practitioners. This ensuing section will seek to integrate the findings to address the primary research concepts; i) what are the characteristics of sleep behaviour for elite footballers, and what are the instances where sleep is disrupted? ii) If instances do indeed exist where sleep in hindered, is it possible to alleviate these issues through sleep-oriented intervention strategies?

## 4.1 Normative sleep in elite footballers

The first two studies (both of which were in elite footballers) showed that sleep duration for players was primarily within normative healthy adult ranges of 7-10 h [143]. However, of pertinence, there were distinct nights where players, both individually and as a collective, slept below this range (i.e. night matches in both Studies One and Two). It could thus be suggested that professional football commitments generally do not create a significant burden on the acquisition of adequate sleep (i.e. predominance of day matches and training days). This observation is likely justified by the view that sleep in athletic populations is highly dependent on the commitments and schedules of the respective sport; in that the schedule demanded of professional footballers may not impose significant barriers to sleep in normal circumstances [139]. For instance, football players will commonly train in the late morning, allowing time to sleep past normal waking hours for the typical working adult and thus increase sleep duration. As a contrasting example, swimmers are regularly required to undertake very early wake ups to attend early morning training sessions and thus sleep durations are often truncated [249, 258]. Moreover, football players are rarely required at the club from the early afternoon onwards, imposing little restriction on the time they have to go to sleep. In addition, when players are away on camp for national duty they are often under the guidance of coaches and managers, where curfews may exist or at the very least some form of 'scheduled' time to be in rooms. Taken collectively, this would suggest that players are either well educated on the benefits of sleep, and thus obtain sufficient amounts of sleep, or they merely represent a sub-group of the normal adult population who sleep within well-established ranges [143].

On face value this lack of an overt issue regarding sleep duration in 'normal' circumstances may seem surprising, especially given the numerous reports of elite athletes having insufficient sleep durations, particularly shorter than 7 h [144, 249, 258]. For instance, it has been shown that some Olympic athletes suffer from poorer sleep durations and qualities than healthy controls [144], although this finding is biased towards swimming populations who are well known early-risers for training. Indeed, professional football training will often start later (i.e. 09:00-11:00) than many individual sports (i.e. swimming) which report reductions in sleep parameters due to these early training times (~06:00 start) [249, 258]. Indeed, the footballers in Studies One and Two reported a predominance of 'average-good' perceptual sleep quality (sleep restfulness) and sleep volumes within normal ranges of 7-10 h [143]. This reinforces the role sports-specific scheduling plays in affecting the sleep wake cycle of athletes. For footballers, it appears the major issue is when they play late-night matches, which cause an enforced disruption to the time they normally go to sleep (to be examined more closely in section 4.2) and significantly poorer sleep qualities and sleep durations, rather than training or day matches.

From the current research it seems sufficient duration of sleep was present in most players in "normal" circumstances. A conclusion that could be drawn from this is that monitoring sleep in elite footballers during the season is not necessary. However, it is important to recognise here that it is likely inevitable some players in professional football will suffer from poor sleep duration and quality during normal situations, such as match days or following training. Indeed, there was a player in Study One who continually reported problems sleeping following training and match days due to newborn children, whilst another reported high 'unrestfullness' due to regular waking to urinate (Appendices 6.3). These are some examples that support the notion of sleep being a highly variable and individualised trait, and thus considerations of the individual sleeping behaviour between players is required [259]. Thus, it would be advisable to monitor players' daily sleep patterns (either through sleep diaries or actigraphy) across a period of 1-4 weeks to give a fair indication of normative sleep behaviour. Such a practice would also presumably identify the differences in the intra-individual requirement for sleep between players. For instance, such differences were identified in both Study One and Two. Players reported vastly different sleep durations, qualities, onset latencies and perceptions of recovery (Appendices 6.3 and 6.4). In addition, whilst there were results of differences *between* players for perceptual ratings of recovery, in many instances these ratings would remain stable *within* each player. Thus, it would seem that individuals' interpretation of the numerous perceptual scales present throughout this research differs.

This is an important point for monitoring both sleep and recovery measures in the field, with a need to understand normal individualised sleep behaviour. Previous data indicate that both lifestyle choices and inter-individual differences in the requirement for sleep can dictate its volume. In addition, choosing how long to sleep for is likely affected by the ability of an individual's willingness to function under different levels of sleep debt [260]. For instance, there are reports of inter-individual differences in physiological and cognitive responses to sleep loss [261]. As an example in Study One, Player D's mean sleep duration was regularly less than Player B's. However, it is unknown what is 'optimum' sleep duration for Player B, which might be 6 h compared to 8 h of Player D. Comparatively Player A may perceive a score of 2 to be their optimum recovery state compared to Player B's 5. This would suggest that in applied practice, reliable individual baseline (normative) values be established for different stages of the season and are regularly compared to their own fluctuations in recovery state to give a true representation of when current (rolling) values fall outside the norm (i.e. smallest worthwhile change, effect size calculations) [262]. Therefore, whilst acknowledging the important findings on the collective front of this research, it also highlights the importance of interpreting data on the individual level [259].

In summary, football commitments appear to not create a significant burden on the attainment of sufficient sleep volume or quality, with footballers' sleeping habits within normative healthy adult ranges [143] following training days and day matches. However, it should be noted there are documented individual cases within this research where normal sleep is interrupted during these times. In addition, there are various 'worst case scenarios' throughout a professional footballer's typical schedule where sleep can be significantly disrupted, including sleep following late-night matches and during long-haul international air travel. Therefore, it is important to understand the potential causes of this sleep loss in these situations and the possible subsequent effect on the recovery time course.

## 4.2 Sleep loss in footballers – Potential causes and impact on recovery of sleep-compromising situations for players

### *Late-night matches*

From the results presented within this thesis, following night matches elite players struggle to fall asleep within hours normally related to high sleep propensity. Our understanding of previous research indicates that an individual's propensity to sleep is primarily the result of two processes: i) the homeostatic drive to sleep, reflecting the pressure for sleep that occurs following prolonged wakefulness and instigates the initial process of sleep and ii) circadian rhythms generated by an endogenous pacemaker regarding the flux in light [263, 264]. In normal circumstances (i.e. for a diurnally active human), the drive (need) to sleep is highest during the hours of 0:00 to 07:00 [263, 265]. In contrast, the period encompassing the early evening (i.e. 17:00-20:00) is where the drive for sleep is generally at its lowest [265]. There could be numerous mechanisms at play which may potentiate the desynchronisation between the normal sleep cycle and the endogenously derived circadian cycle. It is possible that performing vigorous exercise at what is a 'normal' bedtime is associated with this bad sleep (i.e. prolonged sleep onset and reduced sleep time [229]), an opinion widely held by members of the scientific community [219]. This premise is partially based on the exercise-induced rise in core temperature, which could potentially disrupt the thermo-physiological cascade leading to sleep initiation [266]. Other explanations include the higher HR at bedtime (delaying return of parasympathetic activity, causing excitement and prolonging sleep onset

[229]) and pain caused by perceptions of match loads [231]. Indeed, players in Study One reported 'pain' as one distinct difference for 'sleep unrestfulness' between night matches and day matches. It should be acknowledged that we were unable to derive specific physiological mechanisms from this dissertation; thus the majority of these proposed mechanisms on why performing vigorous exercise near bedtime may hinder sleep remain speculative. Nevertheless, the current findings are practically relevant, highlighting various factors which may impede sleep and induce sleep loss.

In contrast, the majority of current evidence in footballers suggests that performing high intensity exercise at night does not impact on subsequent sleep. For instance, Roach et al. [232] reported no effect of two night (19:00-21:00) matches on sleep in elite junior football players. Similarly, Robey et al. [145] found no effect of early evening high-intensity training (16:30-18:30) on the subsequent sleep quality, duration, onset latency, sleep efficiency and bedtime in elite youth football players. Therefore, alternate factors might exist that disrupt the subsequent sleep of players in Studies One and Two. The most obvious issue here is that when a player is attempting to sleep, the activity of football at night itself and post-match activities delay the time at which a player goes to bed. These later bedtimes will invariably result in lower sleep durations – especially if wake times are predetermined due to other constraints (e.g. travel, family commitments). Another possible difference between day and night matches, other than the pure timing of match activity, is the exposure to floodlights in modern stadia. Exposure to such bright light can suppress melatonin and increase alertness, possibly disrupting sleep [228]. Indeed, players reported 'adrenaline after a game' as a reason for higher 'sleep restfullness' following night matches in Study One, although this was likely in response to the match itself. Nonetheless, it is clear that players will remain exposed to light (i.e. during the match, press conferences following the match, in bus to hotel) at both a time where they would not normally be exposed to such stressors, and the homeostatic drive for sleep would be high [219]. Thus, the optimal conditions to induce sleep are prevented in these circumstances.

In addition to this extended light exposure from primary sources, players will commonly engage the use of social media and technological devices following matches (i.e. secondary light sources), which have been shown to be associated with reduced sleep volumes and difficulty falling asleep [227]. In contrast, Romyn et al. [247] reported no significant association between the amount of electronic device use and subsequent sleep parameters during a training and competition week in eight state level netballers; although a strong, negative trend between sleep efficiency and device use was present. Similarly, there was not a significant difference between sleep onset latency in players in Study Three, where players were restricted from TV or phone use 30 minutes prior to bedtime (P = 0.12; SHS: 21.1 ± 16.9; NSHS: 8.8 ± 7.1). Thus, from the limited evidence it may appear that more chronic examination of the effect of secondary light sources on sleep parameters in athletes is warranted. This will help to confirm the widely held assumption that technological devices result in reduced sleep volumes and difficulties in falling asleep. A further important consideration regarding technology use is that it realigns attention and focus, whilst providing a delay in sleep-conducive behaviour. Unfortunately, it is exceedingly unlikely that use of technological devices will cease or even reduce. However, it is possible that athletes may limit use of technological devices at an acceptable time (e.g. 30-60 min) prior to a pre-emptive sleep time. From a practical perspective, other factors may also have to be taken into account such as personal preferences. For instance, a player may wish to utilise technology to keep in contact with their family, allowing improved comfort and wellbeing, which could actually assist sleep onset. Discouraging a player whom wishes to do this could cause more harm than good, regardless of the scientific and theoretical principles behind restricting technology access.

There may also be other factors that affect sleep following night match play such as caffeine. The positive effects of caffeine on performance are well established [220, 221], although the effect of this supplement on habitual drinkers is debated, and was not measured in the present thesis. The effect of caffeine on subsequent sleep is also equivocal [26]; however it is clear that caffeine administration close to bedtime disrupts sleep [254]. Nonetheless, the premise of such debate is almost inconsequential from a football perspective, since players will almost certainly continue to take moderate to large quantities of caffeine prior to the match, regardless of effects on subsequent sleep. Invariably, a higher priority will and should be placed on the performance during the match rather than on the ensuing recovery. Similarly, napping (undertaken usually in the mid-afternoon) is commonly used for performance enhancements prior to a night match to improve alertness and physical performance [29]. Whilst this may disturb subsequent night sleep and influence recovery [219], players and coaches will always prioritise the match performance above this. Taken collectively, it would thus seem more pertinent to address the activities *following* the match in which to address sleep issues within a professional football environment. This is of course assuming the consumption of caffeine and completion of napping activity is within adequate levels of use.

With regards to activities conducted post-match, perhaps one of the most overlooked issues with sleep in elite athletes is the consumption of alcohol. For instance, two-thirds of Italian Serie A players whom were surveyed over a five year period reported themselves to be regular drinkers of alcohol [267]. Furthermore, it was found that customary behaviour following a rugby union match resulted in large amounts of alcohol consumption (~ 20 standard drinks) and sleep loss (~ 4 h) compared to a recommended behaviour group [268]. Although not recorded in this research, given the high prevalence in professional players, it is possible that at least some players in Studies One and Two (where alcohol was not controlled – unlike Study Three where it was) drank alcohol after a night match. Therefore, rather than focus on activities conducted prior to the match (e.g. caffeine consumption, napping) and those outside control of practitioners (e.g. high intensity match running, lux of floodlights), it would appear time would be better spent on addressing behavioural activity following matches to improve sleep. This may help to avoid the negative effects of alcohol on sleep and the recovery time course [269], and optimise the potential for environments conducive to sleep. It would seem pertinent to educate players on these detrimental effects (i.e. the increase in night time arousal) throughout the season as well as organise structured activities post-match. This could include the team eating together in the 1-2 h following the match in an environment which would encourage conditions conducive for sleep (e.g. dimmed lights). Whilst the scientific evidence for the detrimental effect of alcohol is strong, there are several cultural (e.g. bonding) and individual (e.g. addiction, psychological issues) factors which also need to be considered when approaching this issue.

In addition to sleep loss following the night matches, there were also significant reductions in perceptual recovery following night matches compared to training days and day matches in Study One. As no differences were evident for subjective exercise loads between day matches and night matches, it might be speculated this subsequent altered recovery state could be attributed to the reduction in sleep quantity. Indeed, sleep deprivation following exercise can lead to reductions in the recovery of psychological or perceptual performance [201]. For instance, Fowler and colleagues [146] reported significant reductions in sleep duration and quality in six professional footballers, along with an impaired stress–recovery balance, on the night of a match compared to the night prior for away matches. The present result of a reduction in perceptual recovery may represent concerns for the practitioner, especially since the competitive match load may suggest the homeostatic need for recovery sleep would be higher compared to rest days [247], and this appears to not have been provided here. Although speculative, this could have important repercussions for players during subsequent training and competition where this reduction in wellbeing could unnecessarily add to an already suppressed psychological state. For instance, Gallo et al. [270] investigated the impact of pre-training perpetual wellness (sleep quality, fatigue, stress, mood and muscle soreness) on s-RPE-training load and external load (GPS and accelerometer measures) in Australian Footballers. The authors reported that a wellness Z-score of −1 was related to a −4.9 ± 3.1 and −8.6 ± 3.9% reduction in PlayerLoad and PlayerLoad$^{slow}$, respectively. More research which focuses on the interaction between sleep loss and a suppressed psychological state is required, especially in elite footballers, and whether any subsequent associations affect the acute recovery–stress balance and ensuing performance.

*Travel*

The reduced sleep duration and qualities present during long-haul air travel (LHIT) with a 4-h time zone change in Study Two also resulted in changes in perceptual responses, with large effects of jet-lag two days after arrival, yet minimal influence thereafter. In addition, although there were significant reductions in sleep duration and efficiency during outbound travel, the nights following arrival resulted in strong rebound effects. Sleep duration is reported to be reduced during simulated LHIT [271] and after actual transmeridian travel [272]. Although we were unable to provide direct comparisons of sleep parameters to baseline in the current study, the means of ~5.5 and 5.7 h during outbound and return travel, respectively, are both far below the recommended 7 to 9 h for healthy adults [143] and the mean 8.5 h players subjectively reported before travel. Moreover, mean sleep efficiency during outbound travel was approximately 20% worse than average values for young adults who sleep for 8 h a night (~90% with PSG; [273]), indicating poor sleep quality. Previous research suggests that this poor duration and quality of sleep during travel could be due to hydration or cabin air pressure [236]. In addition, the non-supine position experienced in economy class may have hindered melatonin secretion, thus perhaps preventing the inducement of sleep [274]. In the current study, noise within the cabin, comfort, and the extensive travel schedule and timing of meals may also have played a role. Taken collectively, our results confirm the assumption that long-haul international air travel results in lower sleep durations and poorer sleep qualities than healthy recommendations.

Notwithstanding, there was a significant increase in players' sleep durations on the first night of arrival in Study Two. This acute increase in sleep duration on night 1, followed by some stability on nights 2 to 4, suggests alterations to the sleep–wake cycle due to travel. The 4-hour time-zone shift is likely to have had only minor effects compared with more extensive time-zone shifts (.i.e. 8–10 h) [236]. For example, since it is generally accepted that it takes one day per hour of time zone shifted to adjust to the new arrival time zone, it would be expected that players would adjust within the first 4 d of arrival. In addition, it is suggested that body clocks are more adept at extending the day, and thus westbound flights such as the one experienced in this study are more likely to elicit reduced severity of jet-lag symptoms (such as reduced sleep) than eastward travel [236]. Alternatively, the significantly greater sleep duration observed on the night after travel may be explained by an increased homeostatic pressure (drive) for sleep caused by the poor sleep incurred during outbound travel. However, it should be acknowledged that no marker of circadian rhythm was measured and thus we assume phase delay processes occurred.

Although perceptual jet-lag was present during the early stages of the trip, all other parameters relating to the Liverpool John Moores Jetlag Questionnaire, perceived recovery, and sleep restfulness were relatively unchanged. These results may be explained by a westbound flight and a relatively small change in time zones, in addition to the substantial increase in sleep after the long-haul flight [236]. The finding of no effect on perceptual recovery could also possibly be explained by the elite playing experience of the current players, who are accustomed to constant travel and competition. Alternatively, athletes may have intentionally not reported concerns through fears of not being chosen to play [81]. The lack of an effect in our study may also have been due to the lack of regular recovery data collection (i.e. daily). It is also important to note, there were no objective measurements of recovery (i.e. exercise performance). Nonetheless, these results were somewhat surprising given that reductions in subjective sleep quality and perceptual responses have been previously reported in athletes immediately after LHIT [275]. The presence of perceived jet-lag on day 2 was anticipated, with the players adjusting to the new light–dark cycle after travel. However, the dissipation of this effect by day 4 suggests that the timing of arrival 5 days before the first match was sufficient to alleviate symptoms of jet-lag fatigue. This sufficient readjustment may have been important given the effect that circadian readjustment can have on athletic performance [276].

In summary, there are various potential causes for the reduced sleep volume observed following night matches; including, the delay of bedtime caused by scheduling, high-intensity exercise performed close to times of high sleep propensity, caffeine and napping prior to match play, primary or secondary light sources and the consumption of alcohol post-match. These reductions in sleep volume following night matches result in reductions to the perceptual recovery state, supporting the premise that sleep deprivation following exercise can lead to reductions in the recovery of psychological or perceptual performance. However, there are also acute cases where the perceptual recovery state can be maintained following sleep reductions (e.g. the two night matches of the 10 d international tour present in Study Two). In addition, LHIT results in poor sleep volumes potentially caused by a variety of factors including hydration or cabin air pressure, a hindrance of melatonin secretion, noise within the cabin, comfort, the extensive travel schedule and the timing of meals. Taken collectively, there appear certain scenarios where several behavioural factors can affect sleep duration and quality and in turn, some aspects of the perceived state of recovery, although there remains a lack of objective performance markers. Therefore, interventions that target these specific contexts where reductions in sleep and recovery may be apparent should be further investigated.

## 4.3 Interventions focussed on improving sleep and recovery for footballers

Whilst the potential for poor sleep in elite footballers is not disputed, the efficacy of sleep hygiene strategies (SHS) to improve sleep and consequently improve physical and physiological recovery remains unknown. The acute sleep hygiene strategy in Study Three showed increased sleep duration compared to a control condition, despite significantly more wake episodes. Regardless of the ~2 h longer sleep duration, players subjectively perceived no difference in sleep quality between conditions. Furthermore, no significant improvements in perceived stress and recovery, exercise performance, or blood-borne markers of damage and inflammation were present. From the preliminary evidence it would suggest that implementing sleep hygiene strategies can improve sleep duration following night matches, but are currently ineffective in restoring physical performance or physiological and perceptual markers of recovery.

The effect of SHS on sleep quality and quantity has previously been studied in non-athletic populations, with SHS shown to improve sleep quality and onset latency in university students [253]. Comparatively, the effect of SHS in normal sleepers is equivocal [253]. Interestingly, there is limited data from athletic populations, with little known about the effect of SHS on sleep quantity or quality, let alone ensuing recovery kinetics [27]. Recently, Duffield et al. [255] investigated the effect of a SHS (21:00 bed time; low-light (8 ± 5 lux), cool (19 ± 2$^{o}$C) environment, no technology 30 min prior to bedtime) on sleep duration/quality and recovery of elite tennis players following simulated match play. SHS was shown to improve sleep quantity (increased time in bed and min asleep; [255]), which is comparable to the present study. The imposed SHS significantly improved sleep duration, likely due to the enforced earlier bedtime as part of the SHS; which was also a primary aim of the present SHS strategy in this thesis. Consequently, players were in bed as soon as realistically possible to maximise exposure to sleeping environments and then assistance to sleep was provided within this environment. Although speculative, it is also possible the removal of technology prior to bedtime aided the subsequent improvement in sleep duration, especially given the enforced earlier bed time. For example, bright light emitted from portable technological devices may suppress melatonin and disrupt ensuing subsequent sleeping quantity and quality; although, admittedly this remains in debate [277] and remains unsubstantiated from the present studies. In addition, the behavioural changes caused by the use of technology need to be considered, such as attentional resources devoted to the technology rather than on sleep, and thus delays sleep engagement. Regardless of the mechanisms responsible, given elite soccer players report large reductions in sleep quantity following night matches (Studies One and Two), this improvement in sleep duration in Study Three is both a novel and practical outcome for football players.

Despite the increased sleep duration with SHS, significantly greater wake episodes and a trend towards increased wake episode duration (38.9 ± 27.5 v 20.0 ± 18.1 for SHS and NSHS) and sleep onset latency (21.1 ± 16.9 min v 8.8 ± 7.1 min for SHS and NSHS) existed. The inverse responses of these sleep variables are likely due to the context of the players attempting sleep following the late-night match. Specifically, the homeostatic drive for sleep in the NSHS condition, given the prolonged duration of wakefulness, likely resulted in faster sleep onset times and reduced awakening [205]. Conversely, in the SHS condition players were likely to still be highly aroused when attempting to fall asleep following the night match, resulting in longer sleep onset latency [205]. That is, enforcing bedtime so soon following the match may have led to a delayed sleep onset, as this went against players' preparedness for sleep, resulting in a low sleep propensity. In one sense, this likely further justifies the need to use behavioural interventions to aid sleep at a time where players may still be reluctant to attempt sleep, thereby providing conditions which are more conducive to assisting the drive for sleep. That said, it should be noted that other reasons for the inverse response of sleep variables could also include the unfamiliar sleeping environment of the training centre or the evening exposure to light [278], even though these factors were standardised in a cross-over design model. Thus, whilst sleep duration can be extended in a SHS following a late-night match, it should be acknowledged that players may face difficulties initiating sleep when enforced bed times are relatively soon after match finish.

The results of post-match physical recovery markers reported in Study Three concur with previous sleep and recovery-based research [279]. The lack of clear differences in conditions are not unexpected considering a meta-analysis revealed that psychological mood and fatigue states are more affected by sleep disruption than either cognitive or motor performance [69, 210]. It may be speculated that a larger sleep difference between conditions (both duration and quality) is required to further retard the recovery of physical or physiological markers of recovery. As evidence, it seems sleep deprivation studies whereby nights with complete sleep loss (e.g. 0 h), as opposed to partial sleep deprivation (e.g. 4-6 h), are more likely to result in negative physical and physiological outcomes of recovery [201, 261, 280]. For example, Skein et al. [201] showed that complete deprivation negatively affected recovery after a rugby league match, specifically impairing counter movement jump distance and measures of cognitive function. Comparatively, Mougin et al. [167] found no effects of a partially disrupted night's sleep (3 h of sleep loss in the middle of the night) on the maximal sustained exercise intensity during incremental cycle ergometry (20 min at 75 % $VO_{2max}$ followed by 10 W increase every 30 s). With this evidence in mind, it may appear that improving sleep by a further ~2-3 h would be required to improve the physical recovery time course, or be more effective when the extent of sleep loss is greater. For instance, sleep extension (110.9 ± 79.7 min) has been shown to improve athletic performance; including sprint speed, basketball shooting accuracy and reaction time [147]. Extending sleep beyond 2 h, especially in a one-off instance, is difficult, and thus may be more effective when the level of sleep loss is greater. Indeed, the large standard deviation for sleep duration in the aforementioned study indicates that individuals can respond very differently to sleep interventions. At this stage this thesis confirms that it is possible to improve sleep duration through sleep interventions (to a certain degree), though our knowledge of the efficacy these interventions have on athletic performance recovery remain limited, especially over more chronic periods of time (i.e. consecutive nights of grater sleep volume and quality). .

Similar to the lack of an improvement in recovery of physical performance, there were no significant improvements in measures of psychological stress and perceived recovery in the sleep hygiene condition in Study Three. These findings differ with previous results from the aforementioned work by Duffield et al. [255] with large effect sizes evident for perceived soreness and feelings of fatigue the following morning after the sleep hygiene intervention in their study. Indeed, the results from Study Three are surprising given almost all forms of extensive sleep deprivation result in increased negative psychological mood states (e.g. fatigue, loss of vigour, sleepiness, and confusion [210]). It has been shown that sleep disturbances lead to feelings of waking unrefreshed and greater perceptual fatigue [281]. It would appear a greater sleep differential between conditions is required to improve perceptual recovery and stress. It should be further noted that the effect of the sleep hygiene condition was also only acutely assessed in Study Three (i.e. after one late-night soccer match). Elite soccer players who regularly play late-night matches may consequently enjoy greater benefit from sleep hygiene strategies if such strategies were applied regularly throughout the season, i.e. after each night soccer match.

### *The varying components of sleep hygiene strategies*

Delineating the mechanisms behind the efficacy of sleep hygiene interventions is difficult due to an abundance of confounding factors. These include exercise type/duration/intensity, stress management, noise, sleep timing, and avoidance of caffeine, nicotine, alcohol and daytime napping [256]. The contribution of each of these factors to an enhanced recovery status is likely primarily dependant on the influence of each factor on the various parameters of sleep. Sleep hygiene interventions can be used for players following match play, or simply as general guidelines to improve normative sleep. Since normative sleep across the playing groups studied within this thesis was within normal adult ranges, it seems more appropriate to address the mechanisms at play for SHS following night matches and travel. Indeed, the evidence of some forms of SHS on sleep parameters shows little benefit for sleepers whom report no sleep complaints [254]; although further research is required to examine the validity of recommendations in non-clinical populations. Thus, the following sections will address the various SHS within the context where the majority of sleep loss occurred in this dissertation i.e. late-night matches and travel.

A commonly used sleep hygiene recommendation is the encouragement of a regular sleep/wake time. This is primarily based on the intention to maximise the synchrony between homeostatic sleep drive and circadian rhythms [254]. Whilst players appear to have ample opportunity to employ this during the week, the high prevalence of night matches throughout the season will likely present challenges to implementing this type of regular scheduling following match play [219]. Indeed, whilst some individual players in Study One reported high variability, the majority reported steady and adequate sleep durations during the normal training week, before a clear reduction following night match play. Desynchronising this regularity typically results in daytime sleepiness [282] and worse self-reported sleep quality [283]. It is possible that implementing a regular sleep schedule following night match play may alleviate the ramifications of any (regular) acute reduction in sleep duration and quality. For instance, limited evidence suggests that employing better general lifestyle routines results in better sleep [284]. However, this may prove difficult as teams do not commonly have a set schedule of when they play night matches. For instance, English Premier League teams competing in domestic competition and the UEFA Champions League can play night matches on Monday, Tuesday, Wednesday or Friday night. Furthermore, they may also have to endure unpredictable travel schedules which could disrupt the effective implementation of sleep timing. More research which evaluates the ability of individuals to identify personal sources of stress and effective strategies to address these issues is required within elite footballers [254].

Strategies to improve sleep following match play may also need to consider different psychological responses arising from the match itself. Players may endure a raft of emotions following a match, such as anxiety about performance, sadness following a loss, elation or relief after a win or non-players may be angry about not playing if they were a non-starter. Indeed, it has been shown that the results of activities can generate positive emotions for winning and negative emotions when losing, with these emotions heightened when games are competitive [285]. Furthermore, Vandekerckhove and colleagues [286] reported associations between decreased sleep efficiency, total sleep time, percentage of rapid eye movement (REM) sleep, and an increased wake after sleep onset latency, total time awake, latency to slow wave sleep, number of awakenings and number of awakenings from REM sleep from polysomnography and negative stressful pre-sleep events, albeit not in football. Although speculative, players whom are susceptible to negative emotions (e.g. from losing) may sleep poorer following matches compared to those who are not. In addition, players whom are more concerned about how they thought they played may remain anxious in the hours approaching to bedtime, possibly delaying sleep onset latency. The chronic (e.g. continual) effect of sleep deprivation following night matches may also be of concern, since deprivation of sleep could make players more sensitive to emotional and stressful stimuli and events in particular [287]; although additional research is required to confirm this.

Indeed, managing stress prior to sleep onset has recently received increased attention amongst researchers and practitioners in which to improve sleep hygiene [278]. Stress responses can be of a physiological (i.e. increased heart rate and blood pressure) or psychological (i.e. anxiety, nervousness) nature. Several studies have reported associations between psychological stressors and sleep [254]. For instance, Hall et al. [288] reported increased sympathetic arousal, less restorative sleep (measured by PSG) and more wakefulness through the night following pre-sleep exposure to acute anticipatory stress. Therefore, strategies encouraging relaxation and the limitation of arousal are thought to promote effective sleep hygiene [278]. Players in Study Three did not perform relaxation techniques but refrained from technology prior to bedtime, whilst also dimming lights in preparation for bed. Although the results of this thesis are limited due to sample size, not unexpectedly players didn't report psychological stressors following simulated night matches (Studies One and Two). Interestingly, players did report such stressors during normal circumstances in Study One (i.e. after typical training days), including nervousness, personal relationship problems and confrontation with coaches. Thus, it would appear that addressing stress management as part of a healthy SHS in real-world settings is more pertinent for generalised sleep education during normal circumstances, rather than following night matches. However, given the individualised nature of these responses, targeted approaches to manage stress may be part of an effective SHS. Indeed, the sleep issues reported within this thesis are varied and are likely dependant on the individuals' sensitivity to stress. This concurs with previous research reporting that those who perceive themselves sensitive to stress perceive higher arousal states and have greater sleep stage transitions [289]. At this stage it is recommended stress relaxation techniques are implemented which are most appropriate to the needs of the individual in question.

An additional recommendation for SHS is the management of noise. The impact of noise during sleep results in an increase in arousal, increased Stage 1 and 2 NREM sleep and suppressed SWS and REM sleep [254]. With noise being a clear disturbance to sleep responses, research indicates that the relationship between noise and sleep is moderated by characteristics of the noise itself [254]. This can include the type of noise, continuity, relevance and individual habituation to noise. Although no measurements of decibels were recorded in the present study, personal opinion of the research group was that there was very little noise in Study Three, with rooms very isolated, far away from any roads or communal areas – though snoring of players within rooms was not documented. Players were provided with ear plugs, though they predominantly chose not to use the ear plugs, which have been shown to improve sleep in intensive care patients [290]. It is possible that players thought by using the ear plugs their sleep may be hindered due to comfort factors that were more concerning than the potential for noise itself. Indeed, research regarding individual preference and efficacy of various sound-attenuating strategies remains unclear [278]. Implementing strategies that minimise surrounding sounds such as traffic, music and water pipes would appear to be the most impactful to improving sleep [254]. For football teams following match play this might include staying in hotel rooms away from the main road, sleeping in single rooms or using headphones during air travel to minimise noise.

## **4.4 Limitations of the dissertation and recommendations for future research**

Despite the novel findings reported in this thesis, certain limitations need to be acknowledged when interpreting these findings. The primary limitation of this research was that PSG, the 'gold standard' of sleep quantity and quality monitoring, [26, 27] was not used. Without the use of this technique in this thesis, it is recognised as a limitation when interpreting sleep outcomes, or more specific sleep architecture. For primarily logistical reasons the use of PSG was not possible and subjective sleep diaries and actigraphy measures were used instead. Regardless, both actigraphy and subjective reports have been shown to not significantly differ to PSG data for total sleep time and sleep efficiency [124]. Given the location and methods of data collection (outside the laboratory), mechanistic inferences were difficult to delineate and thus remain unanswered. This is also true for the lack of physiological measures utilised in the first two studies. Rather the strength of the majority of this thesis was that the first two studies were conducted in real-world elite sporting environments, giving the results high ecological validity. Indeed, since the topic of this research is specific to elite football, it is argued at least some research must be undertaken in a field setting to mimic the conditions in which the research is put into practice. Furthermore, the sample size across studies was small, making it difficult to draw firm conclusions from this research. This may be especially true for recovery, which is a well-recognised multi-dimensional concept [291]. An additional limitation of the thesis was that each study was relatively acute. Thus, the influence of the majority of these highlighted issues remains unknown from a chronic standpoint. This is also true for interventions, for instance the effect of sleep hygiene on sleep and recovery over the course of a season remains unclear.

Whilst the research presented within this thesis offers novel insight into the context of sleep in elite football, there remain areas which require much additional research. Although our results suggest players lose sleep following night matches, research incorporating objective measurements of sleep during these periods in addition to more longitudinal data sets (e.g. over the length of a season) is required to confirm our findings. Indeed, the effect of these extraneous stressors on sleep in the chronic sense remains unknown. Furthermore, it is pertinent to evaluate the effect these chronic changes, if present, have on physical markers of recovery. In addition, our knowledge regarding the effect of a suppressed psychological state on the overall recovery profile through subsequent training sessions is limited, especially with regards to sleep loss. More research which focuses on the interaction between sleep loss and psychological fatigue is required, especially in elite footballers, alongside whether any subsequent associations exist between the acute recovery-stress balance and ensuing performance. The research presented in this dissertation confirmed that sleep is disrupted during long-haul westward air travel; however, the effect of this disruption on measures of physical performance and recovery remain unclear. Future research which quantifies, and where possible separates, the effects of circadian shifts, direction of air travel and length of travel on sleep and the recovery timeline of elite team-sport athletes (e.g. footballers) is warranted. In contrast, it may be prudent to evaluate the chronic effect of short haul travel on sleep, performance and recovery throughout a season in future research considering the majority of European teams will only endure flights of less than 2 h, but on a regular basis. However, with the majority of field based research in professional sporting environments, delineating the mechanisms behind these potential effects is exceedingly difficult.

It may be speculated that a larger sleep difference between conditions in Study Three (from both a duration and quality perspective) is required to affect the majority of physical or physiological measures of recovery. Thus, a priority in future work must seek to address the various factors within sleep hygiene recommendations. For example, more research which evaluates the ability of individuals to identify personal sources of stress and effective strategies to address these issues is required, especially within elite footballers. Moreover, setting regular sleep timing schedules following periods of sleep loss (i.e. late night matches, during travel) and monitoring these responses over the course of a season would appear beneficial to evaluate the chronic effect of the implementation of SHS. Since residual fatigue is suggested to be more apparent as a season progresses, it may be predicted that SHS are more effective over a longer timeline akin to the findings of Mah et al. [147] mentioned previously, where more chronic versions of SHS resulted in performance benefits. Perhaps most pertinently for elite players, the effect of SHS on recovery in real-world professional environments requires further investigation. Indeed, whilst Study Three revealed important findings, there are several additional considerations for SHS which are only present in high performance environments (e.g. press conferences, extensive recovery protocols, private air travel).

## 4.5 Practical considerations regarding sleep loss and recovery in elite football environments

Sleep loss incurred following night match play may have important repercussions for next day training. In Study One there were significant reductions in perceptual recovery following night matches. Although speculative, this reduction in wellbeing could unnecessarily add to an already suppressed psychological state during next day training. It is important to consider these risks if training the day following a match that has incurred increased sleep loss. That said, it is noted that the majority of professional European teams do not train the next day (personal communication). For night matches a number of post-match activities need to be taken into account including press conferences, recovery strategies, timing of meals, potential travel, social plans and choice of hotel. If scheduling training or recovery sessions it would appear efficacious to schedule these for later in the day, thus allowing players a time frame to increase bed time in an attempt to gain adequate amounts of sleep.

Such a premise may also be important following travel. In Study Two, players' lost significant volumes and quality of sleep during long haul travel. Training the next day may be a risk given the sleep loss incurred along with the cramped, hypoxic conditions on the aircraft. Nonetheless, elite teams seem to prefer to train immediately following travel, with both the national team present in Study Two and an elite football team in France training the day following long-haul international travel [292]. Given the nature of modern football with congested fixtures (limited time between matches) it is understandable that managers want to train their players, at least tactically, at every opportunity. However, in both cases the external training loads performed were low in distance and intensity. Indeed, balancing adequate training load with recovery and managing injury risk following constant extraneous influences such as travel and late-night matches is a constant challenge in modern football. Nonetheless, such instances are dependent on each situation and the individual in question.

Managing sleep behaviour during and following periods which may potentiate sleep loss is also dependent on the environment. For instance, whilst this section has discussed various mechanisms behind sleep hygiene protocols, there remains little knowledge of the efficacy and difficulty to implement of these interventions in comprising situations (e.g. travel). For air travel, several factors need to be considered such as time of departure/arrival, airline, seat and leg room, light, barometric pressure, timing of meals and noise. Implementing sleep hygiene strategies in these environments is obviously challenging. In Study Three the environment was representative of a hotel where players would reside following the match. However, the implementation of this type of sleep hygiene strategy, where players were in bed as short as ~ 1 h after the match concluded, is most likely not logistically possible in a professional environment. For instance, many teams will immediately travel back to their home following night matches (via air or road), presenting challenges for implementing an effective sleep hygiene strategy. Whilst no studies have yet attempted this challenge in the field, Fowler et al. [293] assessed sleep, physical performance, subjective jet-lag symptoms and mood state outcomes in the morning and evening on the day prior to and for two days post-travel (24 h of simulated international travel) with and without a sleep hygiene intervention. The authors reported a significant reduction in sleep duration during travel in both trials, with sleep duration in the sleep hygiene intervention (17.0 h) greater (although not significant: $P = 0.06$) compared to control (15.7 h). Whilst there was no effect on performance outcomes, there were significantly greater vigor the morning of day 2 in the sleep hygiene intervention and subjective jet-lag symptoms and mood states were significantly worse on day 2 in the control condition only. This limited evidence, along with the results within this thesis, shows at least the difficulty for acute sleep hygiene interventions to be efficacious in restoring physical performance. Moreover, it is likely that implementing such strategies during actual travel would face logistical challenges: provision of equipment, timing, the length of travel, player compliance and type of air travel imposed (e.g. economy versus business class). This may mitigate any potential benefit on the restoration of physical performance following training or match play. Nonetheless, with careful consideration and planning of the above factors, the implementation of sleep hygiene strategies during travel is recommended to at least improve sleep volume and perceptual recovery outcomes.

The following recommendations (Figure 4.1) are based on the results and discussion presented within this thesis. However, the author recognises that there is a lack of research examining the interactions between sleep and recovery in elite football players. Nonetheless, there seems much potential benefit, with limited associated risk, in following these schematic recommendations. Of note, it is perhaps most important to tailor interventions to individual players where possible. From a sleep perspective, this could include collecting, analysing and presenting a host of extraneous factors/influences that are of relevance to the respective athletes. Furthermore, the impact of scheduling and different behavioural patterns (i.e. caused by technology use) on sleep requires further investigation.

## 4.6 Conclusion

The outcomes arising from this thesis showed that professional football players lose sleep following night matches and during long-haul international air travel; although outside these extraneous influences players' sleep patterns appear to be within normal ranges for healthy adults. Specifically, it was determined that football players will encounter specific and re-occurring stressors throughout a season (e.g. late-night matches) which can disrupt sleep and hinder perceptual recovery. Nonetheless, it was also found that in acute cases (long-haul international air travel and a 10 d international tour) this lost sleep appeared to have a limited effect on perceptual recovery, which may be explained by both the direction of travel (westbound) and small change in time zones (-4 h). Finally, it was found that an acute sleep hygiene strategy was able to alleviate the reduction in sleep volume; although this increased sleep duration was accompanied by significantly more wake episodes in the acute sleep hygiene strategy and players reported similar sleep qualities between conditions and without subsequent improvement in physical performance. Thus, whilst sleep duration can be extended in an acute sleep hygiene strategy following a late-night match it should be acknowledged that players may face difficulties initiating sleep when enforced with earlier bed times post-match. Furthermore, there were no significant differences between conditions for blood-borne markers of muscle damage and inflammation or physiological responses to

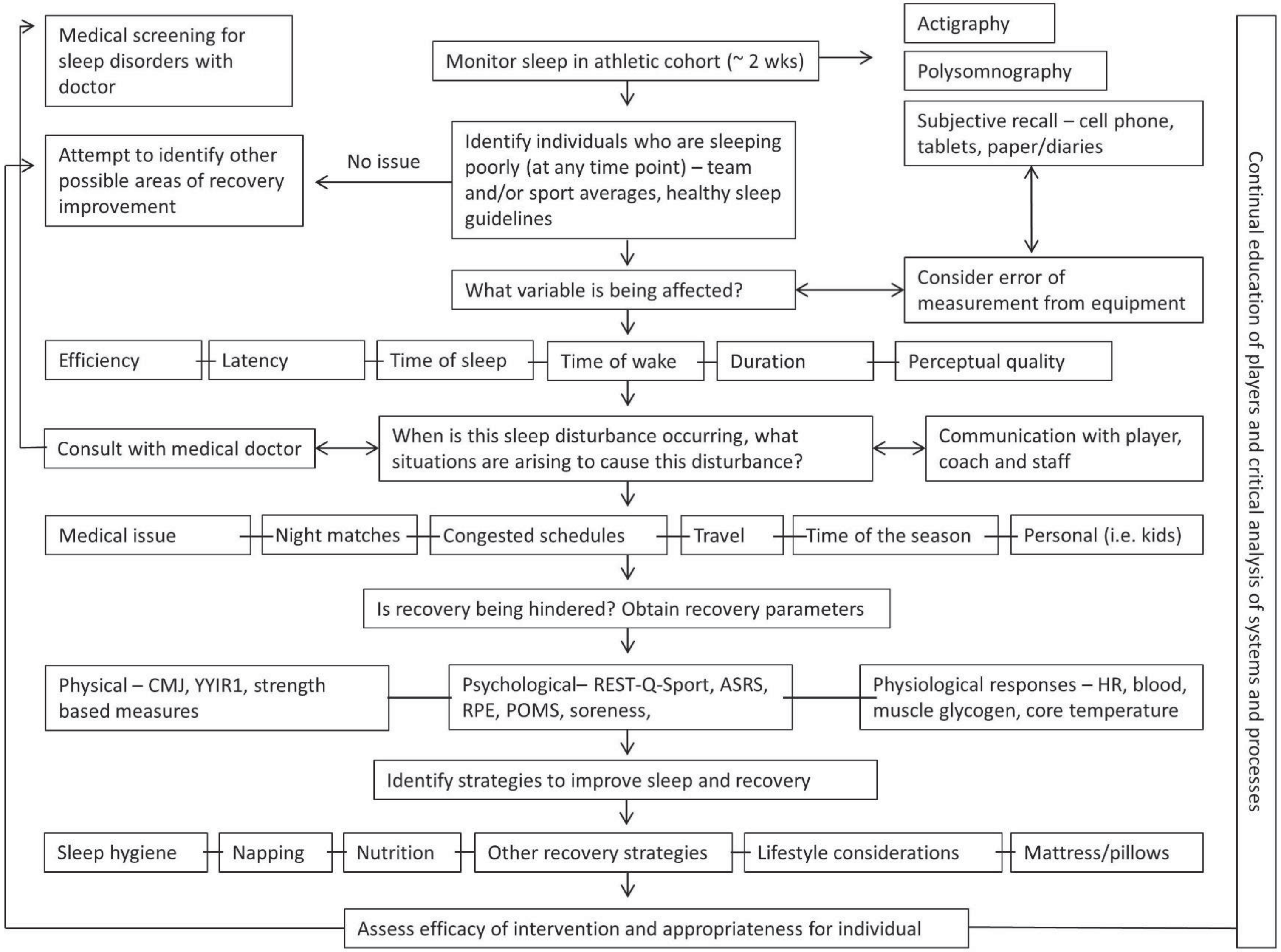


**Figure 4.1:** Flow chart schematic for monitoring sleep and managing recovery in football.

training. Taken collectively, the present findings suggest football players might consider sleep hygiene strategy strategies where possible following a late-night match to promote restorative sleep; however, there appears to be no additional benefit for the recovery of acute performance or perceptual recovery outcomes. Since sleep is a vital component of human physiological and cognitive function [89], two well established elements of sporting performance [1], it is believed this research offers novel findings into the current sleep issues professional players face, and methods which could potentially alleviate these issues. As such, this information is especially pertinent given sleeps' anecdotal criticality within sporting environments and offers scientific merit given the limited amount of current sleep-related research in elite football. Finally, this research could potentially be of importance to coaches and practitioners to factor in considerations to promote optimal sleeping patterns when designing training and recovery programs.

## 5. REFERENCES:

1. Bangsbo, J., M. Mohr, A. Poulsen, et al., Training and testing the elite athlete. *J Exerc Sci,* 2006. 1:1:1-14.
2. Bangsbo, J., The physiology of football – with special reference to intense intermittent exercise. *Acta Physiol Scand,* 1994. 151((suppl. 619)):1-15.
3. Bangsbo, J., M. Mohr, and P. Krustrup, Physical and metabolic demands of training and match-play in the elite football player. *J Sports Sci,* 2006. 24:665-674.
4. Ekblom, B., Applied physiology of soccer. *Sports Med,* 1986. 3:50-60.
5. Carling, C., J. Bloomfield, L. Nelsen, et al., The role of motion analysis in elite soccer: Contemporary performance measurement techniques and work rate data. *Sports Med,* 2008. 38:839-862.
6. Mohr, M., P. Krustrup, and J. Bangsbo, Fatigue in soccer: A brief review. *J Sports Sci,* 2005. 23:593-99.
7. Bloomfield, J., R. Polman, and P. O'Donoghue, Physical Demands of Different Positions in FA Premier League Soccer. *J Sports Sci Med,* 2007. 6(1):63-70.
8. Nédélec, M., A. McCall, C. Carling, et al., Recovery in Soccer: Part I. *Sports Med,* 2012. 42(12):997-1015.
9. Marcora, S., W. Staiano, and V. Manning, Mental fatigue impairs physical performance in humans. *J Appl Physiol,* 2009. 106:857–864.
10. Smith, M., L. Zeuwts, M. Lenoir, et al., Mental fatigue impairs soccer-specific decision-making skill. *J Sports Sci,* 2016:1-8.
11. Mohr, M., P. Krustrup, and J. Bangsbo, Match performance of high-standard soccer players with special reference to development of fatigue. *J Sports Sci,* 2003. 21:519-528.
12. Pyne, D. and D. Martin, *Fatigue-Insights from individual and team sports*. Regulation of fatigue in exercise. 2011, New York: Nova Science.
13. Halson, S., Monitoring training load to understand fatigue in athletes. *Sports Med,* 2014. 44(Suppl 2):S139-47.
14. McCall, A., M. Davison, T. Andersen, et al., Injury prevention strategies at the FIFA 2014 World Cup: perceptions and practices of the physicians from the 32 participating national teams. *Br J Sports Med,* 2015. 49(9):603-8.
15. McCall, A., C. Carling, M. Davison, et al., Injury risk factors, screening tests and preventative strategies: a systematic review of the evidence that underpins the perceptions and practices of 44 football (soccer) teams from various premier leagues. *Br J Sports Med,* 2015. 49(9):583-9.
16. Krustrup, P., M. Mohr, A. Steensberg, et al., Muscle and Blood Metabolites during a soccer game: Implications for sprint performance. *Med Sci Sports Exerc,* 2006. 38:1165-1174.
17. Di Salvo, V., R. Baron, H. Tschan, et al., Performance characteristics according to playing position in elite soccer. *Int J Sports Med,* 2007. 28(3):222-227.
18. Mohr, M., P. Krustrup, L. Nybo, et al., Muscle temperature and sprint performance during soccer matches—beneficial effects of re-warm-up at half time. *Scand J Med Sci Sports,* 2004. 14(3):156-162.
19. Minett, G. and R. Duffield, Is recovery driven by central or peripheral factors? A role for the brain in recovery following intermittent-sprint exercise. *Front Physiol,* 2014. 4(24):1-33.
20. Gandevia, S., Spinal and Supraspinal Factors in Human Muscle Fatigue. *Physiological Reviews,* 2001. 81(4):1725-1789.

21. Rampinini, E., A. Bosio, I. Ferraresi, et al., Match-related fatigue in soccer players. *Med Sci Sports Exerc,* 2011. 43(11):2161-70.
22. Kellmann, M., Preventing overtraining in athletes in high-intensity sports and stress/recovery monitoring. *Scand J Med Sci Sports,* 2010. 20 Suppl 2:95-102.
23. Kellmann, M. and K. Kallus, *Recovery-stress Questionnaire for Athletes: User Manual, Volume 1*. 2001, Champaign, IL: Human Kinetics.
24. Kellmann, M., *Enhancing recovery: preventing underperformance in athletes*, ed. M. Kellmann. 2002, Champaign, IL: Human Kinetics.
25. Durmer, J. and D.F. Dinges, Neurocognitive consequences of sleep deprivation. *Semin Neurol,* 2005. 25(1):117-129.
26. Halson, S.L., Nutrition, sleep and recovery. *Eur J Sport Sci,* 2008. 8(2):119-126.
27. Halson, S., Sleep in elite athletes and nutritional interventions to enhance sleep. *Sports Med,* 2014. 44(Suppl 1):S13-23.
28. Meney, I., J. Waterhouse, G. Atkinson, et al., The effect of one night's sleep deprivation on temperature, mood, and physical performance in subjects with different amounts of habitual physical activity. *Chronobiol Int,* 1998. 15:349–363.
29. Waterhouse, J., G. Atkinson, B. Edwards, et al., The role of a short post-lunch nap in improving cognitive, motor, and sprint performance in participants with partial sleep deprivation. *J Sports Sci,* 2007. 25(14):1557-66.
30. Mohr, M. and F. Iaia, Physiological basis of fatigue resistance training in competitive football. *Sports Science Exchange,* 2014. 27(126):1-9.
31. Nédélec, M., A. McCall, C. Carling, et al., Recovery in Soccer: Part II. *Sports Med,* 2013. 43(1):9-22.
32. Dellal, A., K. Chamari, D. Wong, et al., Comparison of physical and technical performance in European soccer match-play: FA Premier League and La Liga. *Eur J Sports Sci,* 2011. 11(1):51-59.
33. Greig, M., D. Marchant, R. Lovell, et al., A continuous mental task decreases the physiological response to soccer-specific intermittent exercise. *Br J Sports Med,* 2007. 41(12):908–913.
34. Smith, M., A. Coutts, M. Merlini, et al., Mental Fatigue Impairs Soccer-Specific Physical and Technical Performance. *Med Sci Sports Exerc,* 2016. 48(2):267-76.
35. Krustrup, P., M. Zebis, J. Jensen, et al., Game induced fatigue patterns in elite female soccer. *J Strength Cond Res,* 2010. 24(2):437–441.
36. Di Mascio, M. and P. Bradley, Evaluation of the most intense high intensity running period in English FA premier league soccer matches. *J Strength Cond Res,* 2013. 27(4):909–915.
37. Bradley, P., W. Sheldon, B. Wooster, et al., High-intensity running in English FA Premier League soccer matches. *J Sports Sci,* 2009. 27(2):159–168.
38. Akenhead, R., P. Hayes, K. Thompson, et al., Diminutions of acceleration and deceleration output during professional football match play. *J Sci Med Sport,* 2013. 16:556-561.
39. Russell, M., W. Sparkes, J. Northeast, et al., Changes in acceleration and deceleration capacity throughout professional soccer match-play. *J Strength Cond Res,* 2014. [Epub ahead of print].
40. Arruda, A., C. Carling, V. Zanetti, et al., Effects of a very congested match schedule on body load impacts, accelerations, and running measures in youth soccer players. *Int J Sports Physiol Perform,* 2015. 10(2):248-52.
41. Nedelec, M., A. McCall, C. Carling, et al., The influence of soccer playing actions on the recovery kinetics after a soccer match. *J Strength Cond Res,* 2014. 28(6):1517-23.

42. Russell, M., W. Sparkes, J. Northeast, et al., Relationships between match activities and peak power output and Creatine Kinase responses to professional reserve team soccer match-play. *Hum Mov Sci,* 2016. 45:96–101.
43. Arnason, A., S. Sigurdsson, A. Gudmundsson, et al., Physical fitness, injuries, and team performance in soccer. *Med Sci Sport Exerc,* 2004. 36(2):278-85.
44. Ascensao, A., A. Rebelo, E. Oliveira, et al., Biochemical impact of a soccer match- analysis of oxidative stress and muscle damage markers throughout recovery. *Clin Biochem,* 2008. 41((10-11)):841-51.
45. Magalhaes, J., A. Rebelo, E. Oliveira, et al., Loughborough Intermittent Shuttle Test versus soccer match on physiological, biochemical and neuromuscular parameters. *Eur J Appl Physiol,* 2010. 108(1):39-48.
46. Rahnama, N., T. Reilly, A. Lees, et al., Muscle fatigue induced by exercise simulating the work rate of competitive soccer. *J Sports Sci,* 2003. 21(11):933-42.
47. Andersson, H., T. Raastad, J. Nilsson, et al., Neuromuscular fatigue and recovery in elite female soccer: effects of active recovery. *Med Sci Sports Exerc,* 2008. 40(2):372-80.
48. Woods, C., R. Hawkins, S. Maltby, et al., The Football Association Medical Research Programme: an audit of injuries in professional football: analysis of hamstring injuries. *Br J Sports Med,* 2004. 38(1):36-41.
49. Hawkins, R., M. Hulse, C. Wilkinson, et al., The association football medical research programme: an audit of injuries in professional football. *Br J Sports Med,* 2001. 35(1):43-7.
50. Warren, G., D. Lowe, and R. Armstrong, Measurement tools used in the study of eccentric contraction-induced injury. *Sports Med,* 1998. 27(1):43-59.
51. Totsuka, M., S. Nakaji, K. Suzuki, et al., Break point of serum creatine kinase release after endurance exercise. *J App Phys,* 2002. 93(4):1280–1286.
52. Baird, M., S. Graham, J. Baker, et al., Creatine-Kinase- and Exercise-Related Muscle Damage Implications for Muscle Performance and Recovery. *J Nutr Metab,* 2012. 2012(Article ID 960363,):1-13.
53. Meyer, T. and S. Meister, Routine blood parameters in elite soccer players. *Int J Sports Med,* 2011. 32(11):875-81.
54. Nosaka, K. and P. Clarkson, Variability in serum creatine kinase response after eccentric exercise of the elbow flexors. *Int J Sports Med,* 1996. 17(2):120-127.
55. Russell, M., J. Northeast, G. Atkinson, et al., The between-match variability of peak power output and Creatine Kinase responses to soccer match-play. *J Strength Cond Res,* 2015.
56. Kendall, B. and R. Eston, Exercise-induced muscle damage and the potential protective role of estrogen. *Sports Med,* 2002. 32(2):103–123.
57. Ispirlidis, I., I. Fatouros, A. Jamurtas, et al., Time-course of changes in inflammatory and performance responses following a soccer game. *Clin J Sport Med,* 2008. 18(5):423-31.
58. Meister, S., O. Faude, T. Ammann, et al., Indicators for high physical strain and overload in elite football players. *Scand J Med Sci Sports,* 2011. 23(2):156–163.
59. Hecksteden, A., J. Kraushaar, F. Scharhag-Rosenberger, et al., Individual response to exercise training - a statistical perspective. *J Appl Physiol,* 2015. 15(118):1450-9.
60. Bangsbo, J., Physiological Demands of Football. *Sports Science Exchange,* 2014. 27(125):1-6.
61. Saltin, B., Metabolic fundamentals in exercise. *Med Sci Sports Exerc,* 1973. 5:137-146.

62. Edwards, A. and N. Clark, Thermoregulatory observations in soccer match-play: professional and recreational level applications using an intestinal pill system to measure core temperature. *Br J Sports Med,* 2006. 40:133–8.
63. Bangsbo, J., F. Iaia, and P. Krustrup, Metabolic Response and Fatigue in Soccer. *Int J Sports Physiol Perform,* 2007. 2:111-127.
64. Mohr, M., L. Nybo, J. Grantham, et al., Physiological responses and physical performance during football in the heat. *PLoS One,* 2012. 7(6):e39202.
65. Mustafa, K. and N. Mahmoud, Evaporative water loss in African soccer players. *J Sports Med Phys Fitness,* 1979. 19:181–3.
66. Edwards, M. Mann, M. Marfell-Jones, et al., Influence of moderate dehydration on soccer performance: physiological responses to 45 min of outdoor match-play and the immediate subsequent performance of sport-specific and mental concentration tests. *Br J Sports Med,* 2007. 41:385-391.
67. Duffield, R., A. McCall, A. Coutts, et al., Hydration, sweat and thermoregulatory responses to professional football training in the heat. *J Sports Sci,* 2012. 30(10):957-65.
68. Reilly, T. and B. Ekblom, The use of recovery methods post-exercise. *J Sports Sci,* 2005:619–627.
69. Rattray, B., C. Argus, K. Martin, et al., Is it time to turn our attention toward central mechanisms for post-exertional recovery strategies and performance? *Front Physiol,* 2015. 17(6):79.
70. Karageorghis, C. and P. Terry, *Inside Sport Psychology*. 2011, Champaign, IL: Human Kinetics.
71. Bradley, P., C. Carling, D. Archer, et al., The effect of playing formation on high-intensity running and technical profiles in English FA Premier League soccer matches. *J Sports Sci,* 2011. 29(8):821-830.
72. Paul, D., P. Bradley, and G. Nassis, Factors Affecting Match Running Performance of Elite Soccer Players: Shedding Some Light on the Complexity. *Int J Sports Physiol Perform,* 2015. 10:516-519.
73. Smith, M., S. Marcora, and A. Coutts, Mental Fatigue Impairs Intermittent Running Performance. *Med Sci Sports Exerc,* 2014. [Epub ahead of print].
74. Borg, G., Psychophysical bases of perceived exertion. *Med Sci Sports Exerc,* 1982. 14(5):377-81.
75. Foster, C., J. Florhaug, J. Franklin, et al., A New Approach to Monitoring Exercise Training. *J Strength Cond Res,* 2001. 15(1):109-115.
76. Impellizzeri, F., E. Rampinini, A. Coutts, et al., Use of RPE-based training load in soccer. *Med Sci Sports Exerc,* 2004. 36(6):1042-7.
77. Gabbett, T. and D. Jenkins, Relationship between training load and injury in professional rugby league players. *J Sci Med Sport,* 2011. 14:204–209.
78. Kenttä, G. and P. Hassmén, Overtraining and recovery. A conceptual model. *Sports Med,* 1998. 26(1):1-16.
79. Rushall, B., *Applied psychology in sports*. The status of psychomotor learning and sport psychology research, ed. B.S. Rushall. 1975, Dartmouth, Nova Scotia: Sports Science Associates.
80. McNair, D., M. Lorr, and L. Droppleman, *Manual for the Profile of Mood States*. 1971, San Diego, CA: Educational and Industrial Testing Services

81. Kölling, S., B. Hitzschke, T. Holst, et al., Validity of the Acute Recovery and Stress Scale – Training monitoring of the German junior national field hockey team. *Int J Sports Sci Coach,* 2014. (in press).
82. Filaire, E., X. Bernain, M. Sagnol, et al., Preliminary results on mood state, salivary testosterone:cortisol ratio and team performance in a professional soccer team. *Eur J Appl Physiol,* 2001. 86(2):179-84.
83. Coutts, A., K. Slattery, and L. Wallace, Practical tests for monitoring performance, fatigue and recovery in triathletes. *J Sci Med Sport,* 2007. 10(6):372–381.
84. Weitzman, E.D., Circadian rhythms and episodic hormone secretion in man. *Ann Rev Med,* 1976. 27:225-243.
85. Saetren, H., Diurnal variation of the first mitotic wave released among rat kidney tubule cells by partial nephrectomy. *Acta Pathol Microbial Scand,* 1972. 80:737–742.
86. Simmons, D. and M. Cohen, Postfracture linear bone growth in rats: a diurnal rhythm. *Clin Orthop,* 1980. 149:240-248.
87. Gololobova, M.T., 24-hour rhythm of cell multiplication in rat epidermis during healing of skin wounds. *B Exp Biol Med,* 1961. 50:188-122.
88. Xie, L., H. Kang, Q. Xu, et al., Sleep drives metabolite clearance from the adult brain. *Science,* 2013. 342:373-377.
89. Samuels, C., Sleep, recovery, and performance: The new frontier in high-performance athletics. *Neurol Clin,* 2008. 26(1):169-180.
90. Allada, R. and J.M. Siegel, Unearthing the phylogenetic roots of sleep. *Curr Biol,* 2008. 18:R670–R679.
91. Beersma, D.G.M. and M.C.M. Gordijn, Circadian control of the sleep–wake cycle. *Physiol Behav,* 2007. 90(2-3):190-195.
92. Vaughn, B. and P. Giallanza, Technical review of polysomnography. *Chest,* 2008. 134(6):1310-9.
93. Johnston, I., *Galen: on diseases and symptoms*. 1st ed. 2006, Cambridge, UK: Cambridge University Press.
94. Le Meur, Y., R. Duffield, and M. Skein, *Sleep: In recovery for performance in sport* ed. C. Hausswirth and I. Mujika. 2012, Champaign, IL: Human Kinetics.
95. Reilly, T. and J. Waterhouse, Sports performance: is there evidence that the body clock plays a role? *Eur J Appl Physiol,* 2009. 106(3):321-332.
96. Archer, S.N., E.E. Laing, C.S. Moller-Levet, et al., Mistimed sleep disrupts circadian regulation of the human transcriptome. *Proc Natl Acad Sci U S A,* 2014.
97. Davenne, D., Sleep of athletes – problems and possible solutions. *Biol Rhythm Res,* 2009. 40(1):45-52.
98. Crocker, A. and A. Sehgal, Genetic analysis of sleep. *Genes Dev,* 2010. 24:1220–1235.
99. Abel, T., R. Havekes, J.M. Saletin, et al., Sleep, plasticity and memory from molecules to whole-brain networks. *Curr Biol,* 2013. 23:774-788.
100. Czeisler, C.A. and E.M. Brown, Commentary: models of the effect of light on the human circadian system: current state of the art. *J Biol Rhythms,* 1999. 14(6):539-543.
101. Samuels, C., Jet lag and travel fatigue: a comprehensive management plan for sport medicine physicians and high-performance support teams. *Clin J Sport Med,* 2012. 22:268-273.
102. Sehgal, A. and E. Mignot, Genetics of sleep and sleep disorders. *Cell,* 2011. 146(2):194-207.
103. De Gennaro, L., C. Marzano, F. Fratello, et al., The electroencephalographic fingerprint of sleep is genetically determined: a twin study. *Annu Neurosci,* 2008. 64:455–460.

104. Frank, M.G. and J.H. Benington, The role of sleep in memory consolidation and brain plasticity: dream or reality? *The Neuroscientist,* 2006. 12(6):477-488.
105. Stickgold, R., Sleep-dependent memory consolidation. *Nature,* 2005. 437:1272-1278.
106. Walker, M.P., T. Brakefield, A. Morgan, et al., Practice with sleep makes perfect: sleep-dependent motor skill learning. *Neuron,* 2002. 35(1):205-11.
107. Hobson, J., Sleep is of the brain, by the brain and for the brain. *Nature,* 2005. 437(7630):1254-6.
108. Shapiro, C.M., Sleep and the athlete. *Br J Sports Med,* 1981. 15(1):51-55.
109. Lashley, F., *Measuring sleep*. Instruments for Clinical Health-care Research, ed. Frank-Stromborg and S.J. Olsen. 2004, Sudbury, M.A.: Jones and Bartlett Publishers. 715.
110. Lee-Chiong, T., *Sleep: A comprehensive handbook*. 2006, New Jersey: John Wiley and Sons, Inc. 1059.
111. Brebbia, D.R. and K.Z. Altshuler, Oxygen consumption rate and electroencephalographic stage of sleep. *Science,* 1965. 150:1621–1623.
112. Sassin, J.F., D.C. Parker, J.W. Mace, et al., Human growth hormone release: relation to slow wave sleep and sleep-waking cycles. *Science,* 1969. 165:513–515.
113. Siegel, J.M., Clues to the functions of mammalian sleep. *Nature,* 2005. 437(7063):1264-1271.
114. Hobson, J.A., Sleep is of the brain, by the brain and for the brain. *Nature,* 2005. 437(7063):1254-1256.
115. Iber, C., S. Ancoli-Israel, A. Chesson, et al., *The AASM manual for scoring of sleep and associated events: rules, terminology and technical specifications*. 2007, Westchester, IL: American Academy of Sleep Medicine.
116. Fischer, S., M. Hallschmid, A. Elsner, et al., Sleep forms memory for finger skills. *Proc Natl Acad Sci U S A,* 2002. 99(18):11987–11991.
117. Huber, R., M. Ghilardi, M. Massimini, et al., Local sleep and learning. *Nature,* 2004. 430(6995):78-81.
118. Mahoney, M. and M. Avener, Psychology of the elite athlete: An exploratory study. *Cog Ther Res,* 1977. 1(2):135-141.
119. Moran, A., *The psychology of concentration in sport performers: a cognitive analysis*. 1996 Hove: Psychology Press. 317.
120. Cooksey, J. and J. Balachandran, Portable Monitoring for the Diagnosis of Obstructive Sleep Apnea. *Chest,* 2015. [Epub ahead of print].
121. Lichstein, K., K. Stone, J. Donaldson, et al., Actigraphy validation with insomnia. *Sleep,* 2006. 29(2):232-9.
122. de Souza, L., A. Benedito-Silva, M. Pires, et al., Further validation of actigraphy for sleep studies. *Sleep,* 2003. 26(1):81-5.
123. Signal, T., J. Gale, and P. Gander, Sleep measurement in flight crew: comparing actigraphic and subjective estimates to polysomnography. *Aviat Space Environ Med,* 2005. 76(11):1058-63.
124. Kushida, C., A. Chang, C. Gadkary, et al., Comparison of actigraphic, polysomnographic, and subjective assessment of sleep parameters in sleep-disordered patients. *Sleep Med,* 2001. 2(5):389-96.
125. Kawada, T., Agreement rates for sleep/wake judgments obtained via accelerometer and sleep diary: A comparison. *Behav Res Methods,* 2008. 40:1026-1029.
126. Jackowska, M., S. Dockray, H. Hendrickx, et al., Psychosocial factors and sleep efficiency: Discrepancies between subjective and objective evaluations of sleep. *Psychosomatic Med,* 2011. 73:810-816.

127. Armitage, R., M. Trivedi, R. Hoffmann, et al., Relationship between objective and subjective sleep measures in depressed patients and healthy controls. *Depression and Anxiety,* 1997. 5:97-102.

128. Kölling, S., S. Endler, A. Ferrauti, et al., Comparing Subjective With Objective Sleep Parameters Via Multisensory Actigraphy in German Physical Education Students. *Behav Sleep Med,* 2015. 15:1-17.

129. Horne, J. and O. Ostberg, A self-assessment questionnaire to determine morningness-eveningness in human circadian rhythms. *Int J Chronobiol,* 1976. 4(2):97-110.

130. Lastella, M., G. Roach, E. Teng, et al., *Sleeping to a schedule: Does chronotype play a part?, in Australasian Chronobiology Society: Little clock, big clock: Molecular to physiological clocks*, G. Kennedy and C. Sargent, Editors. 2011, Australasian Chronobiology Society: Melbourne. p. 01-04.

131. Facer-Childs, E. and R. Brandstaetter, The impact of circadian phenotype and time since awakening on diurnal performance in athletes. *Curr Biol,* 2015. 25(4):518-22.

132. Bishop, D., An applied research model for the sports sciences. *Sports Med,* 2008. 38(3):253-263.

133. Drust, B., J. Waterhouse, G. Atkinson, et al., Circadian rhythms in sports performance: an update. *Chronobiol Int,* 2005. 22:21-40.

134. Czeisler, C.A., J.S. Allan, S.H. Strogatz, et al., Bright light resets the human circadian pacemaker independent of the timing of the sleep-wake cycle. *Science,* 1986. 233(4764):667-671.

135. Lack, L.C. and H.R. Wright, Chronobiology of sleep in humans. *Cell Mol Life Sci,* 2007. 64(10):1205-1215.

136. Banks, S. and D.F. Dinges, Behavioral and physiological consequences of sleep restriction. *J Clin Sleep Med,* 2007. 3(5):519-528.

137. Venter, R.E., Perceptions of team athletes on the importance of recovery modalities. *Eur J Sport Sci,* 2014. 14:S69-S76.

138. Erlacher, D., F. Ehrlenspiel, O.A. Adegbesan, et al., Sleep habits in German athletes before important competitions or games. *J Sports Sci,* 2011. 29(8):859-866.

139. Juliff, L.E., S.L. Halson, and J.J. Peiffer, Understanding sleep disturbance in athletes prior to important competitions. *J Sci Med Sport,* 2014:[Epub ahead of print].

140. Hanton, S., D. Fletcher, and G. Coughlan, Stress in elite sport performers: A comparative study of competitive and organizational stressors. *J Sports Sci,* 2005. 23(10):1129-1141.

141. Lastella, M., G.P. Lovell, and C. Sargent, Athletes' precompetitive sleep behaviour and its relationship with subsequent precompetitive mood and performance. *Eur J Sport Sci,* 2014:1-8.

142. Ferrara, M., How much sleep do we need? *Sleep Med Rev,* 2001. 5(2):155–79.

143. Foundation, N.S. *Sleep in America poll: Exercise and sleep*. 2013 [cited 2015 June 8]; Available from: http://sleepfoundation.org/sites/default/files/RPT336%20Summary%20of%20Findings%2002%2020%202013.pdf.

144. Leeder, J., M. Glaister, K. Pizzoferro, et al., Sleep duration and quality in elite athletes measured using wristwatch actigraphy. *J Sports Sci,* 2012. 30(6):541-5.

145. Robey, E., B. Dawson, S. Halson, et al., Sleep quantity and quality in elite youth soccer players: a pilot study. *Eur J Sport Sci,* 2014. 14(5):410-7.

146. Fowler, P., R. Duffield, and J. Vaile, Effects of domestic air travel on techincal and tactical performance and recovery in soccer. *Int J Sports Physiol Perform,* 2014. 9(3):378-86.

147. Mah, C.D., K.E. Mah, E.J. Kezirian, et al., The effects of sleep extension on the athletic performance of collegiate basketball players. *Sleep,* 2011. 34(7):943–950.

148. Eagles, A., C. Mclellan, W. Hing, et al., Changes in sleep quantity and efficiency in professional rugby union players during home based training and match-play. *J Sports Med Phys Fitness,* 2014. [Epub ahead of print].

149. Reilly, T. and M. Piercy, The effect of partial sleep deprivation on weight-lifting performance. *Ergonomics,* 1994. 37(1):107–15.

150. Symons, J., T. VanHelder, and W. Myles, Physical performance and physiological responses following 60 hours of sleep deprivation. *Med Sci Sports Exer,* 1988. 20(4):374–80.

151. Reyner, L.A. and J.A. Horne, Sleep restriction and serving accuracy in performance tennis players, and effects of caffeine. *Physiol Behav,* 2013. 120:93-96.

152. Sinnerton, S. and T. Reilly, *Effects of sleep loss and time of day in swimmers*. 1992, London, UK: E and FN Spon.

153. Edwards, B.J. and J. Waterhouse, Effects of one night of partial sleep deprivation upon diurnal rhythms of accuracy and consistency in throwing darts. *Chronobiol Int,* 2009. 26(4):756-768.

154. Souissi, N., H. Chtourou, A. Aloui, et al., Effects of time-of-day and-partial sleep deprivation on short term maximal performances of judo compeitiors. *J Strength Cond Res,* 2013. 27(9):2473-2480.

155. HajSalem, M., H. Chtourou, A. Aloui, et al., Effects of partial sleep deprivation at the end of the night on anaerobic performances in judokas. *Biol Rhythm Res,* 2014. 44(13):815–21.

156. Souissi, N., M. Souissi, H. Souissi, et al., Effect of time of day and partial sleep deprivation on short-term, high-power output. *Chronobiol Int,* 2008. 25(6):1062-76.

157. Souissi, N., B. Sesboue, A. Gauthier, et al., Effects of one night's sleep deprivation on anaerobic performance the following day. *Eur J Appl Physiol,* 2003. 89(3):359–66.

158. Abedelmalek, S., H. Chtourou, A. Aloui, et al., Effect of time of day and partial sleep deprivation on plasma concentrations of IL-6 during a short-term maximal performance. *Eur J Appl Physiol,* 2013. 113(1):241-8.

159. Reilly, T. and T. Deykin, Effects of partial sleep loss on subjective states, psychomotor and physical performance tests. *J Hum Move Stud,* 1983. 9:157–70.

160. Mejri, M., O. Hammouda, K. Zouaoui, et al., Effect of two types of partial sleep deprivation on Taekwondo players' performance during intermittent exercise. *Biol Rhythm Res,* 2014. 45(1):17–26.

161. Mougin, F., H. Bourdin, M. Simon-Rigaud, et al., Hormonal responses to exercise after partial sleep deprivation and after a hypnotic drug-induced sleep. *J Sports Sci,* 2001. 19(2):89–97.

162. Abedelmalek, S., N. Souissi, H. Chtourou, et al., Effects of partial sleep deprivation on proinflammatory cytokines, growth hormone, and steroid hormone concentrations during repeated brief sprint interval exercise. *Chronobiol Int,* 2013. 30(4):502-9.

163. Skein, M., R. Duffield, J. Edge, et al., Intermittent-sprint performance and muscle glycogen after 30 h of sleep deprivation. *Med Sci Sports Exerc,* 2011. 43(7):1301-11.

164. Poussel, M., J. Laroppe, R. Hurdiel, et al., Sleep Management Strategy and Performance in an Extreme Mountain Ultra-marathon. *Res Sports Med,* 2015. [Epub ahead of print].

165. Vincent, G., S. Ferguson, J. Tran, et al., Sleep restriction during simulated wildfire suppression: effect on physical task performance. *PLos One,* 2015. 23(10):1.

166. Halson, S. and J. Nichols, When failure is not an option: creating excellence in sport through insights from Special Forces. *Int J Sports Physiol Perform,* 2015. 10(2):137-8.
167. Mougin, F., M. Simon-Rigaud, D. Davenne, et al., Effects of sleep disturbances on subsequent physical performance. *Eur J Appl Physiol Occup Physiol,* 1991. 63(2):77-82.
168. Martin, B., Effect of sleep deprivation on tolerance of prolonged exercise. *Eur J Appl Physiol,* 1981. 47:345–54.
169. Martin, B., P. Bender, and H. Chen, Stress hormonal response to exercise after sleep loss. *Eur J Appl Physiol Occup Physiol,* 1986. 55:210–4.
170. Hausswirth, C., J. Louis, A. Aubry, et al., Evidence of disturbed sleep and increased illness in overreached endurance athletes. *Med Sci Sports Exer,* 2014. 46(5):1036-45.
171. Nimmo, M. and B. Ekblom, Fatigue and illness in athletes. *J Sports Sci,* 2007. 25(Suppl 1):S93-102.
172. Berger, R. and N. Phillips, Energy conservation and sleep. *Behav Brain Res,* 1995. 69:65–73.
173. Francesconi, R., J. Stokes, L. Banderet, et al., Sustained operations and sleep deprivation: effects on indices of stress. *Aviat Space Environ Med,* 1978. 49(11):1271-4.
174. Martin, B., Sleep loss and subsequent exercise performance. *Acta Physiol Scand,* 1988. 574:28–32.
175. Costill, D., M. Flynn, J. Kirwan, et al., Effects of repeated days of intensified training on muscle glycogen and swimming performance. *Med Sci Sports Exer,* 1988. 20:249–54.
176. Achten, J. and A. Jeukendrup, Heart rate monitoring: applications and limitations. *Sports Med,* 2003. 33:517–38.
177. Hynynen, E., A. Uusitalo, N. Konttinen, et al., Heart rate variability during night sleep and after awakening in overtrained athletes. *Med Sci Sports Exer,* 2006. 38(2):313–7.
178. Belenky, G., N. Wesensten, D. Thorne, et al., Patterns of performance degradation and restoration during sleep restriction and subsequent recovery: a sleep dose-response study. *J Sleep Res,* 2003. 12:1-12.
179. Doran, S.M., H.P.A. Van Dongen, and D.F. Dinges, Sustained attention performance during sleep deprivation: evidence of state instability. *Arch Ital Biol,* 2001. 139:253-267.
180. Dorrian, J., N.L. Rogers, and D.F. Dinges, *Psychomotor vigilance performance: neurocognitive assay sensitive to sleep loss.* . Sleep Depriv, ed. C. Kushida. 2005, New York: Marcel Dekker.
181. Dorrian, J. and D.F. Dinges, *Sleep deprivation and its effects on cognitive performance*. Encyclopedia of Sleep Medicine, ed. N.J. Hoboken. 2005: Wiley & Sons.
182. Harrison, Y. and J.A. Horne, The impact of sleep deprivation on decision making: A review. *J Expl Psychol: Appl,* 2000. 6:236-249.
183. Dinges, D.F. and N.B. Kribbs, *Performing while sleepy: effects of experimentally induced sleepiness*. 1991, Winchester, England: John Wiley & Sons.
184. Axelsson, J., G. Kecklund, T. Akerstedt, et al., Sleepiness and performance in response to repeated sleep restriction and subsequent recovery during semi-laboratory conditions. *Chronobiol Int,* 2008. 25:297-308.
185. Balkin, T.J., P.D. Bliese, and G. Belenky, Comparative utility of instruments for monitoring sleepiness-related performance decrements in the operational environmen. *J Sleep Res,* 2004. 13:219-227.

186. Bonnet, M., Effect of sleep disruption on sleep, performance and mood. *Sleep,* 1985. 8(1):11-19.
187. Roehrs, T., M.A. Carskadon, W.C. Dement, et al., *Daytime sleepiness and alertness*. Principles and Practice of Sleep Medicine 4th Edition, ed. M.H. Kryger, T. Roth, and W.C. Dement. 2005: W.B. Saunders Company.
188. Kleitman, N., *Sleep and wakefullness*. 1963, London: The University of Chicago Press.
189. Grundgeiger, T., U.J. Bayen, and S.S. Horn, Effects of sleep deprivation on prospective memory. *Memory,* 2014. 22(6):679-86.
190. Taber, K. and R. Hurley, Functional neuroanatomy of sleep and sleep deprivation. *J Neuropsychiatry Clin Neurosci,* 2006. 18(1):1-5.
191. Drummond, S.P.A. and G.G. Brown, The effects of total sleep deprivation on cerebral responses to cognitive performance. *Neuropsychopharmacology,* 2001. 25:S68–S73.
192. Thomas, M., M. Sing, and G. Belenky, Neural basis of alertness and cognitive performance impairments during sleepiness. I. Effects of 24 hour of sleep deprivation on waking human regional brain activity. *J Sleep Res,* 2000. 9:335–352.
193. Thomas, M.L., H.C. Sing, and G. Belenky, Neural basis of alertness and cognitive performance impairments during sleepiness II. Effects of 48 and 72 hour of sleep deprivation on waking human brain activity. *Thalamus Relat Syst* 2003. 2:199–229.
194. Drummond, S.P.A., G.G. Brown, J.L. Stricker, et al., Sleep deprivation-induced reduction in cortical functional response to serial subtraction. *Neuroreport,* 1999. 10:3745-3748.
195. Horne, J. and A.N. Petit, Sleep deprivation and the physiological response to exercise under steady state conditions in untrained subjects. *Sleep,* 1984. 7:168-179.
196. Khazaie, H., M. Tahmasian, M. Ghadami, et al., The effects of chronic partial sleep deprivation on cognitive functions of medical residents. *Iran J Psychiatry,* 2010. 5(2):74-7.
197. Bonnet, M.H., Performance and sleepiness following moderate sleep disruption and slow wave sleep deprivation. *Physiol Behav,* 1985. 37:915-918.
198. Jarraya, S., M. Jarraya, H. Chtourou, et al., Effect of time of day and partial sleep deprivation on the reaction time and the attentional capacities of the handball goalkeeper. *Biol Rhythm Res,* 2014. 45(2):183-191.
199. Baker, J., J. Cote, and B. Abernethy, Sport-specific practice and the development of expert decision-making in team ball sports. *J Appl Sport Psych,* 2003. 15(1):12-25.
200. Araújo, D., K. Davids, and R. Hristovski, The ecological dynamics of decision making in sport. *Psyc Sport Exerc,* 2006. 7(6):653–676.
201. Skein, R. Duffield, G. Minett, et al., The effect of overnight sleep deprivation after competitive rugby league matches on postmatch physiological and perceptual recovery. *Int J Sports Physiol Perform,* 2013. 8:556-564.
202. McGuckin, T.A., W.H. Sinclair, R.M. Sealey, et al., The effects of air travel on performance measures of elite Australian rugby league players. *Eur J Sport Sci,* 2014. 14:S116-S122.
203. Dellal, A., C. Lago-Penas, E. Rey, et al., The effects of a congested fixture period on physical performance, technical activity and injury rate during matches in a professional soccer team. *Br J Sports Med,* 2013. [Epub ahead of print].
204. Krystal, A. and J. Edinger, Measuring sleep quality. *Sleep Med,* 2008. 9(S1):S10–S7.
205. Vyazovskiy, V. and A. Delogu, NREM and REM Sleep: Complementary roles in recovery after wakefulness. *The Neuroscientist,* 2014. [Epub ahead of print].
206. Nishida, M. and M. Walker, Daytime naps, motor memory consolidation and regionally specific sleep spindles. *PLos One,* 2007. 2(4):e341.

207. Schaal, K., Y. Le Meur, J. Louis, et al., Whole-body cryostimulation limits overreaching in elite synchronized swimmers. *Med Sci Sports Exerc,* 2014. [Epub ahead of print].
208. McMurray, R. and C. Brown, The effect of sleep loss on high intensity exercise and recovery. *Aviat Space Environ Med,* 1984. 55(11):1031-5.
209. Dattilo, M., H. Antunes, A. Medeiros, et al., Sleep and muscle recovery: endocrinological and molecular basis for a new and promising hypothesis. *Med Hypotheses,* 2011. 77(2):220–2.
210. Pilcher, J. and A. Huffcutt, Effects of sleep deprivation on performance: a meta-analysis. *Sleep,* 1996. 19:318–326.
211. Walsh, N., M. Gleeson, D. Pyne, et al., Position statement. Part two: Maintaining immune health. *Exerc Immunol Rev,* 2011. 17:64-103.
212. Nieman, D., Special feature for the Olympics: effects of exercise on the immune system: exercise effects on systemic immunity. *Immunol Cell Biol,* 2000. 78(5):496-501.
213. Anglem, N., S. Lucas, E. Rose, et al., Mood, illness and injury responses and recovery with adventure racing. *Wilderness Environ Med,* 2008. 19(1):30-8.
214. Vgontzas, A., E. Zoumakis, E. Bixler, et al., Adverse effects of modest sleep restriction on sleepiness, performance, and inflammatory cytokines. *J Clin Endocrinol Metab,* 2004. 89(5):2119-26.
215. Olds, T., C. Maher, and L. Matricciani, Sleep duration or bedtime? Exploring the relationship between sleep habits and weight status and activity patterns. *Sleep,* 2011. 34(10):1299-307.
216. Luke, A., R. Lazaro, M. Bergeron, et al., Sports-related injuries in youth athletes: is overscheduling a risk factor? *Clin J Sport Med,* 2011. 21(4).
217. Costa, R., A. Smith, S. Oliver, et al., The effects of two nights of sleep deprivation with or without energy restriction on immune indices at rest and in response to cold exposure. *Eur J Appl Physiol,* 2010. 109(3):417-28.
218. Wyatt, J., Ritz-De Cecco A, C. Czeisler, et al., Circadian temperature and melatonin rhythms, sleep, and neurobehavioral function in humans living on a 20-h day. *Am J Physiol,* 1999. 277:R1152-63.
219. Nédélec, M., S. Halson, A.-E. Abaidia, et al., Stress, sleep and recovery in elite soccer: a critical review. *Sports Med,* 2015. [Epub ahead of print].
220. Burke, L., Caffeine and sports performance. *Appl Physiol Nutr Metab,* 2008. 33(6):1319-34.
221. Mujika, I. and L. Burke, Nutrition in team sports. *Ann Nutr Metab,* 2010. 57:26-35.
222. Drake, C., T. Roehrs, J. Shambroom, et al., Caffeine effects on sleep taken 0, 3, or 6 hours before going to bed. *J Clin Sleep Med,* 2013. 9(11):1195-200.
223. Pontifex, K., K. Wallman, B. Dawson, et al., Effects of caffeine on repeated sprint ability, reactive agility time, sleep and next day performance. *J Sports Med Phys Fitness,* 2010. 50(4):455-64.
224. Radonga, F., M. Diederich, and L. Ghibelli, Melatonin: a pleiotropic molecule regulating inflammation. *Biochem Pharmacol,* 2010. 80(10):1844-52.
225. Cajochen, C., Alerting effects of light on sleep. *Sleep Med Rev,* 2007. 11(6):453-64.
226. Thomée, S., M. Eklöf, E. Gustafsson, et al., Prevalence of perceived stress, symptoms of depression and sleep disturbances in relation to information and communication technology (ICT) use among young adults – an explorative prospective study. *Comput Hum Behav,* 2007. 23(3):1300–1321.

227. Arora, T., E. Broglia, G. Thomas, et al., Associations between specific technologies and adolescent sleep quantity, sleep quality, and parasomnias. *Sleep Med,* 2014. 15(2):240-7.

228. Robey, E., B. Dawson, S. Halson, et al., Effect of evening postexercise cold water immersion on subsequent sleep. *Med Sci Sports Exerc,* 2013. 45(7):1394-402.

229. Oda, S. and K. Shirakawa, Sleep onset is disrupted following pre-sleep exercise that causes large physiological excitement at bedtime. *Eur J Appl Physiol,* 2014. 114(9):1789-99.

230. Myllymaki, T., H. Kyröläinen, K. Savolainen, et al., Effects of vigorous late-night exercise on sleep quality and cardiac autonomic activity. *J Sleep Res,* 2011. 20(1):146–53.

231. Raymond, I., T. Nielsen, and G. Lavigne, Quality of sleep and its daily relationship to pain intensity in hospitalized adult burn patients. *Pain,* 2001. 92:381-8.

232. Roach, G., W. Schmidt, R. Aughey, et al., The sleep of elite athletes at sea level and high altitude: a comparison of sea-level natives and high-altitude natives (ISA3600). *Br J Sports Med,* 2013. 47:i114-i20.

233. Richmond, L., B. Dawson, S. G, et al., The effect of interstate travel on the sleep patterns and performance of elite Australian Rules footballers. *J Sci Med Sport,* 2007. 10(4):252-8.

234. Winter, W., W. Hammond, N. Green, et al., Measuring circadian advantage in Major League Baseball: a 10-year retrospective study. *Int J Sports Physiol Perform,* 2009. 4(3):394-401.

235. Smith, R., C. Guilleminault, and B. Efron, Circadian rhythms and enhanced athletic performance in the National Football League. *Sleep,* 1997. 20(5):362-5.

236. Reilly, T., How can travelling athletes deal with jet-lag? *Kinesiology,* 2009. 41:128-35.

237. Chapman, D., N. Bullock, A. Ross, et al., Detrimental effects of west to east transmeridian flight on jump performance. *Eur J Appl Physiol,* 2012. 112(5):1663–1669.

238. Beaumont, M., D. Batéjat, C. Piérard, et al., Caffeine or melatonin effects on sleep and sleepiness after rapid eastward transmeridian travel. *J Appl Physiol,* (1985) 2004. 96(1):50-8.

239. Waterhouse, J., B. Edwards, A. Nevill, et al., Do subjective symptoms predict our perception of jet-lag? *Ergonomics,* 2000. 43(10):1514-27.

240. Duffield, R., P. Fowler, S. Crowcroft, et al., *Effects of long-haul air travel on eats and west on recovery of team sport performance, in European College of Sports Science*, A. Jones, Editor. 2015: Malmo.

241. Fowler, P., S. Crowcroft, A. Mendham, et al., *Efficacy of Light Exposure & Sleep Hygiene for Improving Athletic Performance Recovery Following Long-Haul Travel, in Exercise and Sport Science Australia - Research to Practice*. April, 2016: Melbourne, Australia.

242. Fowler, P., R. Duffield, K. Howle, et al., Effects of Northbound Long-Haul International Air Travel on Sleep Quantity and Subjective Jet Lag and Wellness in Professional Australian Soccer Players. *Int J Sports Physiol Perform,* 2015. 10(5):648-54.

243. Dupont, G., M. Nedelec, A. McCall, et al., Effect of 2 soccer matches in a week on physical performance and injury rate. *Am J Sports Med,* 2010. 38(9):1752-8.

244. Kutscher, S., Y. Song, L. Wang, et al., Validation of a statistical model predicting possible fatigue effect in Major League Baseball. *Sleep,* 2013. 36:A408.

245. Taylor, S., G. Rogers, and H. Driver, Effects of training volume on sleep, psychological, and selected physiological profiles of elite female swimmers. *Med Sci Sports Exer,* 1997. 29(5):688-93.
246. Netzer, N., D. Kristo, H. Steinle, et al., REM sleep and catecholamine excretion: a study in elite athletes. *Eur J Appl Physiol,* 2001. 84(6):521-6.
247. Romyn, G., E. Robey, J. Dimmock, et al., Sleep, anxiety and electronic device use by athletes in the training and competition environments. *Eur J Sport Sci,* 2015. [Epub ahead of print].
248. Kölling, S., T. Wiewelhove, C. Raeder, et al., Sleep monitoring of a six-day microcycle in strength and high-intensity training. *Eur J Sport Sci,* 2015. [Epub ahead of print].
249. Sargent, C., S. Halson, and G. Roach, Early-morning training severely restricts the amount of sleep obtained by elite swimmers. *Eur J Sport Sci,* 2014. 14:S310-S5.
250. Reilly, T. and B. Edwards, Altered sleep–wake cycles and physical performance in athletes. *Physiol Behav,* 2007. 90(2-3):274-284.
251. Petit, E., F. Mougin, H. Bourdin, et al., A 20-min nap in athletes changes subsequent sleep architecture but does not alter physical performances after normal sleep or 5-h phase-advance conditions. *Eur J Appl Physiol,* 2014. 114(2):305-15.
252. Lastella, M., G. Roach, S. Halson, et al., Sleep/wake behaviours of elite athletes from individual and team sports. *Eur J Sport Sci,* 2015. 15(2):94-100.
253. Stepanski, E. and J. Wyatt, Use of sleep hygiene in the treatment of insomnia. *Sleep Med Rev,* 2003. 7(3):215-225.
254. Irish, L., C. Kline, H. Gunn, et al., The role of sleep hygiene in promoting public health: A review of empirical evidence. *Sleep Med Rev,* 2015. 22:23-36.
255. Duffield, R., A. Murphy, A. Kellett, et al., Recovery from repeated on-court tennis sessions: combining cold-water immersion, compression, and sleep recovery interventions. *Int J Sports Physiol Perform,* 2014. 9(2):273-82.
256. Malone, S.K., Early to bed, early to rise?: An exploration of adolescent sleep hygiene practices. *J School Nursing,* 2011. 27(5):348-54.
257. Juliff, L.E., S.L. Halson, and J.J. Peiffer, Understanding sleep disturbance in athletes prior to important competitions. *J Sci Med Sport,* 2014. 18(1):13-18.
258. Sargent, C., M. Lastella, S. Halson, et al., The impact of training schedules on the sleep and fatigue of elite athletes. *Chronobiol Int,* 2014. 31(10):1160-8.
259. Fullagar, H. and J. Bartlett, Time to wake up: individualising the approach to sleep promotion interventions. *Br J Sports Med,* 2016. 50(3):143-4.
260. Klerman, E. and D. Dijk, Interindividual variation in sleep duration and its association with sleep debt in young adults. *Sleep,* 2005. 28:1253-1259.
261. Fullagar, H., S. Skorski, R. Duffield, et al., Sleep and athletic performance: The effects of sleep loss on exercise performance, and physiological and cognitive responses to exercise. *Sports Med,* 2015:45(2):161-86.
262. Buchheit, M., The numbers will love you back in return – I promise. *Int J Sports Physiol Perform,* 2016. 11:551 – 554.
263. Sargent, C., D. Darwent, S. Ferguson, et al., Sleep restriction masks the influence of the circadian process on sleep propensity. *Chronobiol Int,* 2012. 29(5):565-71.
264. Borbély, A., A two process model of sleep regulation. *Hum Neurobiol,* 1982. 1(3):195-204.
265. Lavie, P., Ultrashort sleep-waking schedule. III. 'Gates' and 'forbidden zones' for sleep. *Electroencephalogr Clin Neurophysiol,* 1986. 63(5):414-25.
266. Krauchi, K., The thermophysiological cascade leading to sleep initiation in relation to phase of entrainment. *Sleep Med Rev,* 2007. 11(6):439–51.

267. Volpi, P. and E. Taioli, The health profile of professional soccer players: future opportunities for injury prevention. *J Strength Cond Res,* 2012. 26(12):3473–9.
268. Prentice, C., S. Stannard, and M. Barnes, The effects of binge drinking behaviour on recovery and performance after a rugby match. *J Sci Med Sport,* 2014. 17(2):244–8.
269. Murphy, A., A. Snape, G. Minett, et al., The effect of post-match alcohol ingestion on recovery from competitive rugby league matches. *J Strength Cond Res,* 2013. 27(5):1304-12.
270. Gallo, T., S. Cormack, T. Gabbett, et al., Pre-training perceived wellness impacts training output in Australian football players. *J Sports Sci,* 2015. [Epub ahead of print].
271. Lastella, M., G. Roach, S. Halson, et al., The effects of transmeridian travel and altitude on sleep: preparation for football competition. *J Sports Sci Med,* 2014. 13(3):718-20.
272. Fowler, P., R. Duffield, and J. Vaile, Effects of simulated domestic and international air travel on sleep, performance, and recovery for team sports. *Scand J Med Sci Sports,* 2015. 25(3):441-51.
273. Ohayon, M., M. Carskadon, C. Guilleminault, et al., Meta-analysis of quantitative sleep parameters from childhood to old age in healthy individuals: developing normative sleep values across the human lifespan. *Sleep,* 2004. 27(7):1255-73.
274. Cajochen, C., K. Krauchi, and A. Wirz-Justice, Role of melatonin in the regulation of human circadian rhythms and sleep. *J Neuroendocrinol,* 2003. 15:432–437.
275. Waterhouse, J., Identifying some determinants of “jet lag” and its symptoms: a study of athletes and other travellers. *Br J Sports Med,* 2002. 36(1):54–60.
276. Reilly, T., G. Atkinson, and R. Budgett, Effect of low-dose temazepam on physiological variables and performance tests following a westerly flight across five time-zones. *Int J Sports Med,* 2001. 22:166–174.
277. Lewczuk, B., G. Redlarski, A. Zak, et al., Influence of electric, magnetic, and electromagnetic fields on the circadian system: current stage of knowledge. *Biomed Res Int,* 2014. 2014:169459.
278. Malone, S.K., Early to bed, early to rise?: An exploration of adolescent sleep hygiene practices. *J School Nursing,* 2011. 27(5):348-354.
279. Duffield, R., A. Murphy, A. Kellett, et al., Recovery from repeated on-court tennis sessions; combining cold water immersion, compression and sleep recovery interventions. *Int J Sports Physiol Perform,* 2014. 9(2):273-82.
280. Fullagar, H., R. Duffield, S. Skorski, et al., Sleep and Recovery in Team Sport: Current Sleep-related Issues Facing Professional Team-sport Athletes. *Int J Sports Physiol Perform,* 2015. [Epub ahead of print].
281. Koutedakis, Y., R. Budgett, and L. Faulmann, Rest in underperforming elite competitors. *Br J Sports Med,* 1990. 24(4):248-52.
282. Billiard, M., A. Alperovitch, C. Perot, et al., Excessive daytime somnolence in young men: prevalence and contributing factors. *Sleep,* 1987. 10(4):297-305.
283. Carney, C., J. Edinger, B. Meyer, et al., Daily activities and sleep quality in college students. *Chronobiol Int,* 2006. 23(3):623-37.
284. Monk, T., C. Reynolds, D. Buysse, et al., The relationship between lifestyle regularity and subjective sleep quality. *Chronobiol Int,* 2003. 20(1):97-107.
285. Lavega, P., J. Alonso, J. Etxebeste, et al., Relationship between traditional games and the intensity of emotions experienced by participants. *Res Q Exerc Sport,* 2014. 85(4):457-67.
286. Vandekerckhove, M., R. Weiss, C. Schotte, et al., The role of presleep negative emotion in sleep physiology. *Psychophysiology,* 2011. 48(12):1738-44.

287. Vandekerckhove, M. and R. Cluydts, The emotional brain and sleep: an intimate relationship. *Sleep Med Rev,* 2010. 14(4):219-26.
288. Hall, M., R. Vasko, D. Buysse, et al., Acute stress affects heart rate variability during sleep. *Psychosom Med,* 2004. 66(1):56-62.
289. Petersen, H., G. Kecklund, P. D'Onofrio, et al., Stress vulnerability and the effects of moderate daily stress on sleep polysomnography and subjective sleepiness. *J Sleep Res,* 2013. 22(1):50-7.
290. Xie, H., J. Kang, and G. Mills, Clinical review: The impact of noise on patients' sleep and the effectiveness of noise reduction strategies in intensive care units. *Crit Care,* 2009. 13(2):208.
291. Bahrnett, A., Using recovery modalities between training sessions in elite athletes does it help? *Sports Med,* 2006. 36:781–796.
292. Buchheit, M., Y. Cholley, and P. Lambert, Psychometric and Physiological Responses to a Pre-season Competitive Camp in the Heat With a 6-hr Time Difference in Elite Soccer Players. *Int J Sports Physiol Perform,* 2015. [Epub ahead of print].
293. Fowler, P., R. Duffield, I. Morrow, et al., Effects of sleep hygiene and artificial bright light interventions on recovery from simulated international air travel. *Eur J Appl Physiol,* 2015. 115(3):541-53.

# 6. APPENDICES

## 6.1 Review: Sleep and athletic performance: the effects of sleep loss on exercise performance, and physiological and cognitive responses to exercise.

**Fullagar H.H.K.,** Skorski S, Duffield, R, Hammes, D, Coutts, A.J., Meyer T. *Sports Med*. 2015 Feb;45(2):161-86. doi: 10.1007/s40279-014-0260-0.

## 6.2 Sleep and recovery in team sport: current sleep-related issues facing professional team-sport athletes

**Fullagar, H.H.K.,** Duffield, R, Skorski, S, Coutts, A, Julian, R, Meyer, T. (2015). *International Journal of Sports Physiology and Performance*. 10(8):950-7. DOI: 10.1123/ijspp.2014-0565

## 6.3 Impaired sleep and recovery after night matches in elite football players

**Fullagar, H.H.K**., Skorski, S, Duffield, R, Julian, R, Bartlett, J, Meyer, T. (2016). *Journal of Sports Sciences: Science and Medicine in Football*. 34(14):1333-9. DOI: 10.1080/02640414.2015.1135249

## 6.4 Sleep, Travel and Recovery Responses of National Footballers During and Following Long-Haul International Air Travel.

**Fullagar H.H.K.**, Duffield R, Skorski S, White D, Bloomfield J, Kölling S, Meyer T. *International Journal of Sports Physiology and Performance.* 11(1):86-95. DOI: 10.1123/ijspp.2015-0012

## 6.5 The effect of an acute sleep hygiene strategy following a late-night soccer match on player recovery

**Fullagar, H.H.K**, Skorski, S, Duffield, R, Meyer, T. (2016). *Chronobiology International.* 33(5):490-505. DOI: 10.3109/07420528.2016.1149190

Sports Medicine

# Sleep and athletic performance: The effects of sleep loss on exercise performance, and physiological and cognitive responses to exercise

--Manuscript Draft--

| | |
|---|---|
| **Manuscript Number:** | SPOA-D-14-00068R2 |
| **Full Title:** | Sleep and athletic performance: The effects of sleep loss on exercise performance, and physiological and cognitive responses to exercise |
| **Article Type:** | Review Article |
| **Abstract:** | Although its true function remains unclear, sleep is considered critical to human physiological and cognitive function. Equally, since sleep loss is a common occurrence prior to competition in athletes, this could significantly impact upon their athletic performance. Much of the previous research has reported that exercise performance is negatively affected following sleep loss; however due to conflicting findings, it remains uncertain as to the extent, influence and mechanisms of sleep loss affecting exercise performance. For instance, research indicates some maximal physical efforts and gross motor performances can be maintained. Comparatively, the few published studies investigating the effect of sleep loss on performance in athletes report a reduction in sports-specific performance. The effects of sleep loss on physiological responses to exercise also remain equivocal; although, it appears a reduction in sleep quality and quantity could result in an autonomic nervous system imbalance, simulating symptoms of the overtraining syndrome. Additionally, increases in pro-inflammatory cytokines following sleep loss could promote immune system dysfunction. Of further concern, numerous studies investigating the effects of sleep loss on cognitive function report slower and less accurate cognitive performance. Based on this context, this review aims to evaluate the importance and prevalence of sleep in athletes and summarises the effects of sleep loss (restriction and deprivation) on exercise performance, and physiological and cognitive responses to exercise. Given the equivocal understanding of sleep and athletic performance outcomes, further research and consideration is required to obtain a greater knowledge of the interaction between sleep and performance. |
| **Corresponding Author:** | Hugh H.K. Fullagar, PhD Candidate<br>Saarland University<br>Saarbrücken, GERMANY |
| **Corresponding Author Secondary Information:** | |
| **Corresponding Author's Institution:** | Saarland University |
| **Corresponding Author's Secondary Institution:** | |
| **First Author:** | Hugh H.K. Fullagar, PhD Candidate |
| **First Author Secondary Information:** | |
| **Order of Authors:** | Hugh H.K. Fullagar, PhD Candidate |
| | Sabrina Skorski |
| | Rob Duffield |
| | Daniel Hammes |
| | Aaron Coutts |
| | Tim Meyer |
| **Order of Authors Secondary Information:** | |
| **Author Comments:** | To the editorial office<br>During the last decade, research on sleep in athletic populations has gained considerable attention, due to the belief that sleep loss has a major effect on performance in many sports. Indeed, it is widely assumed by most coaches, athletes |

and researchers that sleep is considered critical to optimal performance. However, due to the complexity of sleep function, limited availability of athletes to participate in sleep studies and the variability in the individual requirement for sleep, the effects of sleep loss on athletic performance are poorly understood. Therefore, the overall purpose of this review was to examine the effects of sleep loss on exercise performance, and physiological and cognitive responses to exercise. We believe our findings would appeal to the readership of this journal and contribute to the broader application of science in the sports medicine and exercise field. Indeed, we hope you will find it appropriate for publication in Sports Medicine.

**Response to Reviewers:**

Sleep loss and athletic performance –
Fullagar et al.
SPOA-D-14-00068
Sports Medicine re-re-submission August 2014

The following document outlines the Editor’s comments regarding the above manuscript, with the authors’ responses below each comment in italics. In the original manuscript and the adjunct Tables the amended, added or changed text appears in TRACK CHANGES RED. The authors’ thank the Editor for these comments.

Comments to Authors:
1. Section 1, paragraph 3 – please state the actual search period, e.g. January 1990 to December 2013.

Section 1, paragraph 3: Changed to “In order to accomplish this critical review a computerised literature search (Figure 1) was performed over seven months (August 2013 – March 2014) on Pub Med and Web of Science for articles within the period January 1960-March 2014”.

2. Please change ‘endocrinal’ to ‘endocrine’ or ‘endocrinological’ throughout the manuscript.

Section 4.2.2, paragraph 2: ‘Endocrinal’ changed to ‘endocrine’ as requested.

3. Section 4.2.2, paragraph 2 – ‘Interestingly, these two studies [121, 160] and others [138], which reported no differences in hormonal and endocrinal responses to exercise following SD used constant exercise protocols compared to two studies which reported significant changes following SR [95, 99] whom utilised incremental tests to exhaustion.’ Please delete the comma after ‘[138]’.

Section 4.2.2, paragraph 2: comma deleted as requested.

Then please change ‘...protocols compared to two studies which reported significant changes following SR [95, 99] whom utilised incremental tests to exhaustion.’ to ‘...protocols, whereas two studies that reported significant changes following SR [95, 99] utilised incremental tests to exhaustion.’

Section 4.2.2, paragraph 2: Amended as requested.

4. Section 4.2.2, paragraph 2 – ‘Thus, the variable load at the end of exercise appears to increases the final stress-related response.’ Please change ‘increases’ to ‘increase’.

Section 4.2.2, paragraph 2: ‘increases’ changed to ‘increase’ as requested.

5. References 55, 83, 84, 176 and 203 – please provide complete citation details.

Reference 55. This reference is a one page article. Changed to “Hicks RA, Pellegrini R. The changing sleeping habits of college students. Percept Mot Skills. 1991;72:1106.” for clarification.
Reference 83: Changed to “Ingersoll C. Editorial sleep efficiency and overreaching in swimmers. J Sport Rehab. 2003;12(1):1-12.”
Reference 84: Changed to “Oda S, Shirakawa K. Sleep onset is disrupted following pre-sleep exercise that causes large physiological excitement at bedtime. Eur J Appl Physiol. 2014;114(9):1789-99.”

| | |
|---|---|
| | Reference 176: Changed to “Taber K, Hurley R. Functional neuroanatomy of sleep and sleep deprivation. J Neuropsychiatry Clin Neurosci. 2006;18(1):1-5.”<br>Reference 203: Changed to “Hausswirth C, Louis J, Aubry A et al. Evidence of disturbed sleep and increased illness in overreached endurance athletes. Med Sci Sport Exer. 2014;46(5):1036-45.”<br><br>6. Table 1, Soussi et al. 2003, column 6 – please change ‘Peak Power’ to ‘Peak power’.<br><br>Amended as requested.<br><br>7. Table 1, Sinnerton and Reilly 1992, column 5 – please change ‘Muscular’ to ‘muscular’.<br><br>Amended as requested.<br><br>8. Table 1, abbreviation definitions beneath the table – please change ‘Maximal’ to ‘maximal’ and de-italicize ‘not significant’.<br><br>Amended as requested.<br><br>9. Thank you for the exceedingly conscientious measures you took in the previous revision to avoid exceeding the word limit. Please don’t be concerned about exceeding it in any responses to my requests here. Please also feel free, should you want to, to reinstate any or all of the text that you removed during the previous revision process to conform to the word limit. I am not really concerned about such relatively minor ‘excesses’ in relation to the word count.<br><br>Thank you for this comment. Minor previous text, where applicable, has been re-added throughout the manuscript which had previously been deleted.<br><br>Changes have also been addressed in Figure 2. Please check “Figure legends” at the end of the document and the Figure itself for approval. |
| **Suggested Reviewers:** | Yann Le Meur<br>yann.le-meur@insep.fr<br>Expert in the field |
| | Charles Samuels<br>manager@centreforsleep.com<br>Medical doctor with a long career and expertise in the field |
| | Warren Gregson<br>w.gregson@ljmu.ac.uk<br>Strong background in athletic physiology |
| | Damien Davenne<br>damien.davenne@unicaen.fr<br>Expert in the field |

**Sportmedizin**
**Saarbrücken**

**UNIVERSITÄT DES SAARLANDES**

**Institut für Sport- und Präventivmedizin**
Bereich Klinische Medizin
Ärztlicher Direktor: Univ.-Prof. Dr. med. Tim Meyer

*23.08.14*

*For the Editor-in-chief*

*Sports Medicine*

Dear Professor Olney,

Please find enclosed a revised manuscript entitled "Sleep loss and athletic performance: The effects of sleep loss on exercise performance, and physiological and cognitive responses to exercise" by Fullagar et al. which we would like to submit for publication in *Sports Medicine*.

We thank you for your insight, contribution and time to review this manuscript. The following documents outline your comments regarding the above manuscript, with the authors' responses below each comment. In the original manuscript, Tables and Figures the amended, added or changed text appears in TRACK CHANGES RED. Clean copies of amended documents are also provided. Taken collectively, we believe our findings would appeal to the readership of this journal and contribute to the broader application of science in the sports medicine and exercise field. Indeed, we hope you will find it appropriate for publication in *Sports Medicine*.

This manuscript represents original unpublished material, and does not contain any previously published material in the text, illustrations or tables without proper reference citation and permission to reprint, where required. It is not under consideration for publication elsewhere, and further, has not been posted to the Internet for public access. All listed co-authors have read and approved the manuscript and meet the requirements of co-authorship as specified in the guidelines for submission of *Sports Medicine*. All co-authors declare that there are no conflicts of interest. Please address all correspondence to myself (Hugh Fullagar), as you have done previously with our contact between one another, at the email address hugh.fullagar@uni-saarland.de. Thank you once again for considering this manuscript for publication. We look forward to hearing from you at your earliest convenience.

Sincerely,

Hugh Fullagar

**Sleep loss and athletic performance – Fullagar et al. SPOA-D-14-00068**
**Sports Medicine re-re-submission August 2014**

**The following document outlines the Editor's comments regarding the above manuscript, with the authors' responses below each comment in italics. In the original manuscript and the adjunct Tables the amended, added or changed text appears in TRACK CHANGES RED. The authors' thank the Editor for these comments.**

Comments to Authors:

1. Section 1, paragraph 3 – please state the actual search period, e.g. January 1990 to December 2013.

*Section 1, paragraph 3: Changed to "In order to accomplish this critical review a computerised literature search (Figure 1) was performed over seven months (August 2013 – March 2014) on Pub Med and Web of Science for articles within the period January 1960-March 2014".*

2. Please change 'endocrinal' to 'endocrine' or 'endocrinological' throughout the manuscript.

*Section 4.2.2, paragraph 2: 'Endocrinal' changed to 'endocrine' as requested.*

3. Section 4.2.2, paragraph 2 – 'Interestingly, these two studies [121, 160] and others [138], which reported no differences in hormonal and endocrinal responses to exercise following SD used constant exercise protocols compared to two studies which reported significant changes following SR [95, 99] whom utilised incremental tests to exhaustion.' Please delete the comma after '[138]'.

*Section 4.2.2, paragraph 2: comma deleted as requested.*

Then please change '...protocols compared to two studies which reported significant changes following SR [95, 99] whom utilised incremental tests to exhaustion.' to '...protocols, whereas two studies that reported significant changes following SR [95, 99] utilised incremental tests to exhaustion.'

*Section 4.2.2, paragraph 2: Amended as requested.*

4. Section 4.2.2, paragraph 2 – 'Thus, the variable load at the end of exercise appears to increases the final stress-related response.' Please change 'increases' to 'increase'.

*Section 4.2.2, paragraph 2: 'increases' changed to 'increase' as requested.*

5. References 55, 83, 84, 176 and 203 – please provide complete citation details.

*Reference 55. This reference is a one page article. Changed to "Hicks RA, Pellegrini R. The changing sleeping habits of college students. Percept Mot Skills. 1991;72:1106." for clarification.*
*Reference 83: Changed to "Ingersoll C. Editorial sleep efficiency and overreaching in swimmers. J Sport Rehab. 2003;12(1):1-12."*
*Reference 84: Changed to "Oda S, Shirakawa K. Sleep onset is disrupted following pre-sleep exercise that causes large physiological excitement at bedtime. Eur J Appl Physiol. 2014;114(9):1789-99."*
*Reference 176: Changed to "Taber K, Hurley R. Functional neuroanatomy of sleep and sleep deprivation. J Neuropsychiatry Clin Neurosci. 2006;18(1):1-5."*
*Reference 203: Changed to "Hausswirth C, Louis J, Aubry A et al. Evidence of disturbed sleep and increased illness in overreached endurance athletes. Med Sci Sport Exer. 2014;46(5):1036-45."*

6. Table 1, Soussi et al. 2003, column 6 – please change 'Peak Power' to 'Peak power'.

*Amended as requested.*

7. Table 1, Sinnerton and Reilly 1992, column 5 – please change 'Muscular' to 'muscular'.

*Amended as requested.*

8. Table 1, abbreviation definitions beneath the table – please change 'Maximal' to 'maximal' and de-italicize 'not significant'.

*Amended as requested.*

9. Thank you for the exceedingly conscientious measures you took in the previous revision to avoid exceeding the word limit. Please don't be concerned about exceeding it in any responses to my requests here. Please also feel free, should you want to, to reinstate any or all of the text that you removed during the previous revision process to conform to the word limit. I am not really concerned about such relatively minor 'excesses' in relation to the word count.

*Thank you for this comment. Minor previous text, where applicable, has been re-added throughout the manuscript which had previously been deleted.*

*Changes have also been addressed in Figure 2. Please check "Figure legends" at the end of the document and the Figure itself for approval.*

# Sleep and athletic performance: The effects of sleep loss on exercise performance, and physiological and cognitive responses to exercise

Hugh H.K. Fullagar[1], Sabrina Skorski[1], Rob Duffield[2], Daniel Hammes[1], Aaron J. Coutts[2], Tim Meyer[1]

Affiliations

1. Institute of Sport and Preventive Medicine, Saarland University, Germany
2. Sport & Exercise Discipline Group, UTS: Health, University of Technology Sydney, Australia

**Corresponding author and reprint requests**

Hugh Fullagar
Institute of Sport and Preventive Medicine
Saarland University, GEB. B82
66123 Saarbrucken
Germany
Email: hugh.fullagar@uni-saarland.de
Phone: 0681-302 70400
Fax: 0681-302 4296

**Conflicts of interest:**

The authors declare that there are no conflicts of interest.

**Running head:**

Sleep loss and athletic performance

## Abstract

Although its true function remains unclear, sleep is considered critical to human physiological and cognitive function. Equally, since sleep loss is a common occurrence prior to competition in athletes, this could significantly impact upon their athletic performance. Much of the previous research has reported that exercise performance is negatively affected following sleep loss; however due to conflicting findings, it remains uncertain as to the extent, influence and mechanisms of sleep loss affecting exercise performance. For instance, research indicates some maximal physical efforts and gross motor performances can be maintained. Comparatively, the few published studies investigating the effect of sleep loss on performance in athletes report a reduction in sports-specific performance. The effects of sleep loss on physiological responses to exercise also remain equivocal; although, it appears a reduction in sleep quality and quantity could result in an autonomic nervous system imbalance, simulating symptoms of the overtraining syndrome. Additionally, increases in pro-inflammatory cytokines following sleep loss could promote immune system dysfunction. Of further concern, numerous studies investigating the effects of sleep loss on cognitive function report slower and less accurate cognitive performance. Based on this context, this review aims to evaluate the importance and prevalence of sleep in athletes and summarises the effects of sleep loss (restriction and deprivation) on exercise performance, and physiological and cognitive responses to exercise. Given the equivocal understanding of sleep and athletic performance outcomes, further research and consideration is required to obtain a greater knowledge of the interaction between sleep and performance.

## Key points (2 to 3 key points summarising the main findings and implication of the review)

- Although sleep is considered critical to optimal performance, many athletes appear to lose sleep prior to competition due to various reasons including noise, light, anxiety and nervousness.

- Whilst there appears sufficient evidence to imply complete sleep deprivation can have significant negative effects on athletic performance, the effects of sleep restriction (partial disturbance of the sleep-wake cycle) are more conflicting; a concerning issue given athletes are more likely to experience this mode of sleep loss.

- The detrimental effect of sleep loss on most aspects of cognitive function remains unequivocal, with only minor conflicting findings present for the extent of the effects of mild sleep restriction; findings which would predictably suggest negative consequences for athletes requiring high neurocognitive reliance.

## 1. Introduction

Reoccurring at habitual intervals throughout a 24 hour (h) period in humans, sleep is a homeostatically controlled behavioural state of reduced movement and sensory responsiveness [1, 2]. The process of sleep is widely regarded as critical to both cognitive and physiological function [2-7]. In spite of this perceived importance, the consensus regarding the rationale as to why humans sleep remains equivocal, if not robustly debated [2, 8]. Recent studies have shown sleep to regulate key molecular mechanisms (i.e. transcriptional regulatory proteins [1, 9, 10]), and have demonstrated that sleep has an integral role in metabolic homeostasis [11]. Whilst the duration and quality of sleep is manipulated by numerous environmental factors, among them light [12], jetlag [13] and nutrition [14]), it has also been shown to be influenced by genetic traits [15, 16]. Notwithstanding the complexity surrounding the need, rationale and outcome of sleep, it seemingly must serve an important purpose for humans because it has survived so many years of evolution [15].

The ability of humans to cope with physiological and psychological stressors is critical to athletic performance outcomes [17], and is affected by numerous factors including experience, fitness, motivation and the natural fluctuation of physiological and behavioural processes across a 24 h period (i.e. sleep-wake cycle, body temperature, hormone regulation [18]). These *circadian rhythms* are primarily controlled by the suprachiasmatic nucleus (SN) within the hypothalamus [2]. However, the SN is unable to always maintain control over these patterns, as humans are highly sensitive to alterations to their natural environment [2, 19], most notably through the light-dark cycle [20]. When athletes encounter disruptions to their environments (e.g. through travel or training/playing at night), endogenous circadian rhythms and normal sleep-wake cycles can become desynchronised [2, 21]. Such perturbations in sleeping patterns can cause an increase in homeostatic pressure and affect emotional regulation, core temperature and circulating levels of melatonin, causing a delay in sleep onset [22]. Following these periods there is potential for sleep loss and neurocognitive and physiological performance to be compromised [7, 14, 23, 24]. Thus, since sleep disruption prior to important events are commonly found in elite athletes [25-27], there are numerous instances where the subsequent performance could be compromised [25, 28, 29].

However, due to the complexity of sleep function, limited availability of athletes to participate in sleep studies and the variability in the individual requirement for sleep [21, 30], the effects of sleep loss on athletic performance are poorly understood. Furthermore, the increase in recent literature since past reviews [21, 31, 32] highlights a need to re-evaluate the effects of sleep loss on athletic performance, in particular allowing for a greater focus on sport-specific outcomes. Accordingly, the overall purpose of this review is to examine the effects of sleep loss on exercise performance, and physiological and cognitive responses to exercise. As a result, this communication reviews the current literature on the theoretical components of sleep and importance for athletes, the quality and quantity of ‘normal’ sleep compared to athletes, and the effects of sleep loss on exercise performance and physiological and cognitive responses (including mood) to exercise. In order to accomplish this critical review a computerised literature search (Figure 1) was performed over seven months (August 2013 – March 2014) on Pub Med and Web of Science for articles within the period January 1960-March 2014. Keywords used in different combinations were “sleep”, “deprivation”, “loss”, “restriction”, “team”, “exercise”, “cognition”, physiological”, “sport”, “athlete”, “player” and “performance”. In addition, articles were sourced manually from the reference lists of original manuscripts, and previous critical, systematic and meta-analytical reviews. The previous work within this field, and the multi-dimensional components of sleep and their role in athletic performance, are duly recognised. Notwithstanding these critical components, their roles are too extensive to be discussed here. The reader is advised to consult previous work regarding the effects of nutrition [14], jetlag [13, 33, 34] and Ramadan [35] on sleep for further detail.

INSERT FIGURE 1

## 2. The theoretical components of sleep and their importance for athletes

A recent review by Frank [8] identified several theories of the function of sleep, including: 1) the restorative effects on the immune and the endocrine systems, 2) a neurometabolic theory suggesting that sleep assists in the recovery of the nervous and metabolic cost imposed by the waking state, and 3) cognitive development, supposing that sleep has a vital role in learning, memory, and synaptic plasticity. An interaction between these theories is likely to contribute to the construct of several stages during sleep [8]. These respective stages not only differ in depth, but also in the frequency and intensity of dreaming, eye movements, muscle tone, regional brain activation and communication between memory systems [36]. A typical night's sleep is composed of approximately 90 min cycles divided into periods of rapid-eye-movement sleep (REM; associated with dreams), and non-REM sleep (NREM) [37]. NREM sleep is further divided into four different stages (Figure 2). All stages are classified according to parameters such as electrical brain activity, blood pressure, and eye movement [38, 39].

Specifically, the role for NREM sleep is proposed to assist with energy conservation and nervous system recuperation. For example, it has been shown that growth hormone (GH; fundamental to tissue regeneration and growth) is released [40] and oxygen consumption is lowered [41] during phases of NREM sleep. Moreover, NREM sleep seems to be a stimulus for anabolic hormones that increase the synthesis of protein and mobilise free fatty acids to provide energy, thereby preventing amino acid catabolism [42]. Such processes would seem particularly pertinent for athletic populations requiring accelerated rates of healing to repair peripheral muscular damage [43]. Comparatively, theories of REM sleep have suggested a role for this state in periodic brain activation, localized recuperative processes and emotional regulation [44]. Especially in the early stages of mammalian life, REM sleep is assumed to be critical in establishing brain connections [44], since neuronal activity is similar to waking in REM sleep [45]. Hence, sleep can be rather defined as an actively regulated process than a passive result of diminished waking, and can be seen as a reorganisation of neuronal activity [45].

The importance of sleep in athletes has also been discussed in regards to memory consolidation, especially to motor learning. REM, NREM stage 2 and slow-wave (SWS) sleep have all been implicated in sleep dependent memory procession [36]. For example, several studies showed improvements in motor task tests after a night of sleep, whereas this was not the case in subjects having an equivalent period of being awake [36, 46-48]. Since sleep loss reduces the overnight improvement in motor learning, it seems that motor task learning may correlate with the amount of specific sleep stages/events, rather than just one specific aspect of sleep [36]. With the ongoing motor learning and cognitive adaptation required for elite athletes to perform [49], combined with the numerous neurocognitive components of many sports [50], it seems ascertaining an optimal brain state for a range of distinct memory consolidation processes are pertinent for athletes prior to and following competition [49].

INSERT FIGURE 2

## 3. What is the quantity and quality of 'normal' sleep and how do athletes compare?

### 3.1 What is 'normal' sleep?

Subjective average total sleep duration has fallen in healthy adults since the mid-20th century from approximately 8-9 h per night in 1959 to 7-8 h in 1980 [51]. In a nationwide survey of the United States in 2013, data indicate adults slept for an average of 6 h:51 min on 'workdays' and 7 h:37 min on 'non-workdays' [52]. A mean 7 h:17 min total sleep time was required for respondents to 'operate at their best the next day' [52] which corresponds with the 7-9 h recommended by the National Sleep Foundation for healthy sleep [51-53]. Despite such recommendations, almost a quarter of adults who have similar sleep durations to these recommendations reported 'fairly-very bad' subjective sleep quality [52]. Others have reported that university/college students demonstrate even poorer patterns of sleep than other healthy adults. Many studies indicate this cohort suffers from chronic sleep problems and disruptions [54-56], with some adolescent athletes sleeping 2 h less than recommended daily sleep volumes [57]. These discrepancies are attributed to the rising melatonin levels of the adolescent cohort [58] and the rapid advances of 21st century technology prolonging human exposure to light [59-61]. Overall, sleep architecture, quality and quantity varies drastically across individuals and occupations [62], mainly due to a vast array of physiological and cultural differences [63, 64]. Such variety makes the interpretation of generic sleep recommendations (7-9 h, abide by sleep hygiene protocols to optimise sleep quality; [51, 52, 65]) difficult, especially for athletes [30].

### 3.2 Sleep in athletes

Since both athletes and coaches rate sleep as critical to optimal performance [14, 25], it is peculiar that relatively few studies have investigated the sleep quality and quantity of the athletic cohort. Early research suggests athletes possess similar or even superior sleep quality and quantity than nonathletic subjects [66, 67], with aerobically fit subjects tending to experience more SWS sleep and longer sleep duration than non-fit controls [68]. However, these findings may have been due to the enduring habitual, genetic and behavioural patterns of sleep, rather than the greater endurance status *per se* [15, 69]. Regardless, the longer sleep duration found in certain aerobically fit individuals has been attributed to the restorative and energy conservation theories for sleep (e.g. athletes require greater recovery; [69, 70]. Accordingly, some authors suggest athletes should sleep for between 9-10 h [71], whilst 7-9 h is recommended enough for healthy adults [51, 52]. Recent evidence suggests athletes sleep far less than either of these recommendations [72]. For example, a survey of 890 elite South African athletes showed that three quarters of athletes reported an average sleep duration between 6-8 h per night [73], while on weekends 11% reported sleeping less than 6 h. Moreover, 41% stated they had problems falling asleep, with these discrepancies attributed to interference by noise and light [25, 74]. Additionally, pre-competition anxiety can also play a role in worsening sleep patterns [26, 75, 76]. For instance, sleep quality [76], efficiency [77] and duration [78, 79] have all been found to dramatically decrease just prior to competition. Juliff and colleagues found that within a sample of 283 elite Australian athletes, 64% reported poor sleep prior to an important competition [27]. The primary reasons for these poor sleep patterns could be due to nervousness, deteriorations in mood and/or confidence [80] and elevations in physical and mental stress [77].

Recently, Leeder et al. [81] found Olympic athletes slept for a lower mean total duration (6 h:55 min compared to 7 h:11 min using actigraphy) and had poorer sleep quality compared to non-athletic controls. Given the short sampling period (4 d), it is difficult to generalise the findings from this study to all athletes; however there is supportive evidence of training disrupting sleep quality and duration in other athletes. For instance, Taylor and colleagues [80] reported training volume to alter movements during sleep (greater movements were found; defined as occupying ≥ 4 s of any 20 s epoch within the polysomnographic recording [80]). The effect of training volume on sleep patterns is supported by others [82, 83], with early-morning training severely restricting sleep duration compared to normal (5.4 h to 7-8 h) in a group of world-class swimmers [72]. In addition to exercise volume, intensity may also negatively affect sleep, with a recent study reporting increases in sleep onset and physiological excitement following high-intensity exercise conducted prior to bed time (40 min treadmill running at 80% heart rate reserve commencing at 21h:20) compared to a non-exercise control condition in active young men [84]. Other possible disruptions of athletes' sleep include altitude, which appears to disrupt REM sleep and impair breathing [85]. Disrupted sleep is also prevalent in numerous extreme adventure and boat sports [86-88]. Despite these findings, further evidence of the sleeping patterns of elite athletes during various scenarios is very rare within the current literature. In summary, the sleep patterns of athletes remain unclear, mainly due to a vast array of physiological differences [63, 64], training [80, 89] and competition [26, 27] stressors. More research is required to assess the sleeping patterns of elite athletes across various scenarios which could potentially influence subsequent performance.

## 4. Effects of sleep loss on exercise performance and physiological and cognitive responses

Sleep restriction (SR) occurs when humans fall asleep later or wake earlier than normal; that is, their normal sleep wake cycle is partially disturbed [90]. In contrast, sleep deprivation (SD) generally refers to extreme cases of sleep loss, whereby humans do not sleep at all for a prolonged period (i.e. whole nights) [90]. The following sections of this article will review the effects of sleep loss (restriction and deprivation) on exercise performance (Table 1), and physiological (Table 2) and cognitive (Table 3) responses to exercise. However, due to an abundance of conflicting results some of the effects of sleep loss on these indices remain uncertain. These varied results are mainly attributed to differences in exercise protocols, participants' fitness and the experimental environment. For instance, variations in thermoregulatory responses, habituation to sleep loss and the time of day activities are performed have a complex interaction with exercise performance [65, 91, 92], and thus may potentially mask the effects of sleep loss [93]. Furthermore, being unable to blind subjects can potentially result in nocebo effects [94].

## 4.1 Sleep loss and exercise performance

### *4.1.1. Sleep restriction and exercise performance*

Early work from Mougin et al. [95] found no effects of a partially disrupted night's sleep (3 h of sleep loss in the middle of the night) on the maximal sustained exercise intensity during incremental cycle ergometry (20 min at 75% maximum oxygen uptake ($VO_{2max}$) followed by 10 watt (W) increase every 30 s ). The same authors [96] found also no change in mean or peak power or peak velocity during a Wingate cycling test after similar SR compared to normal baseline values in highly trained participants. With regard to more prolonged running exercise modes, Reilly and Deykin [97] reported no decrements in endurance running performance (time to exhaustion) following partial sleep loss (3 h of sleep per night for three nights). Furthermore, the total distance covered in a YoYo intermittent-recovery test level one was not different following SR [98]. In contrast to this maintenance of exercise performance, maximal work rate has been found to decrease (~15 W decrease following SR) during incremental cycling to exhaustion (30 min at 75% $VO_{2max}$ followed by 10 W increase every min [99]). Similarly, mean and peak power during Wingate anaerobic cycle tests have been shown to decrease in students [100], footballers [101], and judo competitors [92] following 4 h of SR for one night. Theories on the reasons for this restricted exercise tolerance following SR are attributed to either the impairment of aerobic pathways [102] or perceptual changes (i.e. increased perceived exertion), as physiological responses often remain largely unaltered [94, 103]. Indeed, increases in perceived effort accompanied by a reduction in power output would support neuromuscular causes of fatigue [104], possibly indicating an association between a reduction in central drive and the neural theory of sleep [36, 103, 105]. However, studies investigating perceived effort following SR report mixed results [98, 106, 107], so such theories remain unclear. These conflicting results are attributed to a large body of evidence reporting a vast array of effects on emotional regulation (i.e. mood) following SR [106, 108-111]. Indeed, variations in perceived effort are likely a result of these emotional modifications [112]. Given the widespread use of rating of perceived exertion in monitoring the training load of elite athletes [113, 114], further research is required to investigate the interaction between these responses to standardised training or match stimuli following sleep loss.

Similar to maximal aerobic demands, a variety of conclusions have been reported for the effects of SR on muscular strength and power. Studies have shown back and grip strength are maintained following SR [93]. In contrast, others have demonstrated 3 h of nocturnal SR to negatively affect both maximal and submaximal weightlifting tasks, with greater effects on the submaximal tasks [106]. Given the high motivational component of weightlifting, this decline in work rate was attributed to the coinciding decline in mood state. However, whilst these perturbations in submaximal work outputs may be due to fluctuations in mood state, or even neurological alterations [104], the central and local muscular fatigue mechanisms behind such outcomes remain unknown [106]. Collectively, these observations indicate that whilst athletes may be able to perform singular, maximal efforts following SR, it is unclear whether they are able to cope with repeated bouts of physical activity such as those required during intensive training or matches [21].

INSERT TABLE 1

An example of the susceptibility of sport-specific performance following SR in athletes is the reduction in sport-specific skill execution in dart players [115], tennis players [116] and handball goalkeepers [117]. In contrast, swimming performance (lap times) did not differ between SR (2.5 h of sleep per night for four nights) and normal sleep for 8 trained swimmers [111]. These differing findings could be attributed to the additional cognitive dimension of the aforementioned fine motor skills. For instance, since loss of sleep can result in reductions in decision making and accuracy (see section 4.3), SR would presumably be more likely to affect sports performance incorporating a high cognitive reliance (i.e. fine motor movements in the serve accuracy of a tennis player [116]) rather than one involving gross-motor execution (i.e. the stroke rate of a swimmer [111]). Furthermore, since professional sport comprises many environmental components which can influence sleep [14], it has been argued athletes may be more susceptible to performance decrements following SR than normal healthy participants [81], although this is debated [69, 81, 118, 119].

Overall, the effects of SR on exercise performance are mixed. SR does not appear to affect singular bouts of aerobic performance (neither endurance running nor cycling modes for 20-30 min) or maximal measures of strength, although admittedly conflicting results still exist. A possible reason for this discrepancy is that many studies reporting no effect of sleep restriction on endurance exercise have sample sizes less than ten participants (e.g. [97, 99], Table 1), making it difficult to extrapolate the results of these studies due to the underpowered nature of the study. In contrast, sports-specific skill execution, submaximal strength and muscular and anaerobic power seem to decline following SR. Given these findings, whilst it seems that SR impedes some aspects of athletic performance; it is still not clear whether sleep is critical to performance for *all* athletes who experience small one-off SR periods.

### *4.1.2 Sleep deprivation and exercise performance*

Similar to SR, the effects of total SD on exercise performance are varied [120]. Mean time to exhaustion for prolonged treadmill walking (80% of $VO_{2max}$) is reduced by ~11% following 36 h of SD [94]. These results are supported by other studies highlighting reduced time to exhaustion (mean ~20% [121]) during incremental exercise protocols following SD [122]. In addition, mean distance covered has been found to decline (6224 to

6037 m) following SD during 30 min of self-paced treadmill running [123]. It appears time to exhaustion decreases because of either perceptual changes or reductions in arousal and impaired muscle fibre coordination (e.g. decreases in vertical jump performance and knee extension torque [124]) following prolonged SD, although the mechanisms behind this are unclear [94]. Indeed, it is proposed increased muscular and central fatigue is unlikely to explain decreases in prolonged exercise performance following SD [112]; however this warrants further investigation.

Despite the popularity of sports that require high intermittent-sprint performance (i.e. team sports [125]), there is a relatively poor understanding of the effect of SD on these activities. Skein et al. [126] recently reported slower mean sprint times, reduced muscle glycogen concentration, voluntary force and activation during maximal isometric knee extensions along with an increased perceptual effort following 30 h of SD in ten team-sport athletes [126]. Similarly, several other studies have shown the detrimental effects of SD on muscular strength [30, 124, 127], power [128] and speed [129]. In contrast, Symons et al. [130] reported no effect of 60 h of SD on a range of muscular and submaximal isometric strength tests. Indeed, several studies have shown that grip strength performance is maintained regardless of the amount of sleep loss [131, 132] and shuttle runs scores remain unaffected [133]. Indeed, submaximal strength tasks may be more susceptible to SD than maximal tasks due to the sustained effort required to complete the task, whereby perception of effort could increase exponentially with time to task completion [123]. In addition, differences in reported muscle contractility (i.e. voluntary activation) between studies could be explained by the sensitivity and accuracy of electromyography measurements. Older studies (i.e. [130, Table 1]) may have been limited in comparison to the equipment used in recent research [126, 134].

In summary, although the effect of SD on exercise performance remains somewhat unclear, there appears sufficient evidence to imply SD can have a significant effect on aspects of athletic performance. This seems particularly pertinent for time to exhaustion in running activities lasting longer than 30 min. Nonetheless, whilst these studies reveal important physiological mechanisms, conceptually it is debatable whether the findings are applicable to elite athletic populations given it would be rare for an athlete to endure a night(s) of complete total SD.

### 4.2 Sleep loss and physiological responses to exercise

#### *4.2.1 Sleep restriction and physiological responses to exercise*

Examples of the susceptibility of physiological responses to exercise following SR are the increase in heart rate, minute ventilation and plasma lactate concentration during submaximal and maximal exercise after a partially disrupted night's sleep (3 h of sleep loss in the middle of the night) [95]. These responses are attributed to the increased metabolic demand [135], perceived effort [94] and catecholamine concentrations following SR [136]. This could be interpreted as SR acting as an additional stress to the stress imposed by exercise itself [137]. In contrast, Martin and colleagues [138] showed that two nights of fragmented sleep (eight 'wake up' calls ranging 30-75 min) had no significant effect on heart rate, oxygen consumption, minute ventilation and core body temperature during 30 min of heavy treadmill walking. Similarly, these findings support other results, suggesting no alterations to physiological responses following SR i.e. lung function and power unaffected by minor sleep loss [97, 111]. Whilst the error sensitivity across metabolic collection systems could perhaps explain some differences across studies [139-142], these differences are perhaps more attributable to the exercise mode and protocol administered (running [98] versus cycling [95]; free-paced exercise [111] versus time to exhaustion [102]).

Although various hormonal concentrations (e.g. plasma cortisol) will typically increase during exercise-induced stress, the interaction between these responses and sleep loss is inconclusive [31]. For instance, there have been reports by some [99, 143], but not all [138, 144, 145] studies that cortisol concentration might be lowered following sleep loss. These varied results are likely attributed to the fact that cortisol secretion is dependent on the timing, intensity and duration of the stimulus [146] and is highly driven by circadian rhythms [147]. As an example of the sensitivity of hormonal and additionally immune responses to SR and exercise stimuli, GH, prolactin and interleukin-6 (IL-6) have been shown to increase following SR and 4 x 250-m treadmill runs at 80% maximum speed [101]. This is supported by findings of next-day increases in IL-6 (three-fold) and tumor necrosis factor (TNF-α; two-fold) following SR [148], although others have reported these variables to remain unchanged at rest [149]. Since increases in these pro-inflammatory cytokines (e.g. IL-6; mean 4.11 ±SD 0.99 $pg.ml^{-1}$ rising to 5.44 ±1.1 $pg.ml^{-1}$ [144] and TNF-α [143] following SR and exercise)) might be associated with unfavourable metabolic profiles [143] and inflammatory disease risk [147, 150], there is concern about obtaining sufficient quality and duration of sleep in all individuals from an overall health perspective [14, 143].

### *4.2.2 Sleep deprivation and physiological responses to exercise*

Energy substrate balance appears vulnerable to sleep loss, with 30 h of SD shown to blunt the full restoration of muscle glycogen stores in team-sport athletes [126]. Without adequate intake, this could hinder the ability of athletes to compete for sustained periods, as muscle glycogen shortage is known to reduce muscle function and total work capacity [3, 151]. Indeed, energy imbalances are associated with SD, potentially leading to decreased aerobic and anaerobic power production [21, 152]. Prolonged periods of SD (36 h) are further associated with increased sympathetic and decreased parasympathetic cardiovascular modulation, and spontaneous baroreflex sensitivity during sitting and vigilance testing in healthy adults [153]. Since disruptions to the sympathetic-parasympathetic balance are associated with overtraining [154], it is possible these disturbances to the autonomic nervous system following SD could support the development of an overreaching or overtraining status [3, 155]. Indeed, of importance to athletes, maintaining this autonomic balance is critical for producing optimal performance [156]. Notwithstanding this, most [94, 103, 122], but not all [122] studies have reported that SD does not alter cardiorespiratory variables during incremental exercise (e.g. $VO_{2max}$, minute ventilation). Further to these results, there were no significant effects on cardiorespiratory or thermoregulatory function despite a reduction in distance covered during 30 min of self-paced treadmill running following SD [123]. Taken with other results [94, 123, 157, 158], these findings suggest that SD has minimal effect on cardiorespiratory function during intermittent submaximal exercise, despite observations of a reduction in performance. Oliver et al. [123] hypothesise this could be due to the influence of the perception of effort during the end stages of prolonged high-intensity exercise. More extreme periods of sleep loss (100 h without sleep), are more likely to negatively affect cardiorespiratory variables compared to acute SD (24-36 h) [159].

Similar to the effects of SR, the effects of SD on hormonal and endocrine responses to exercise are unclear. It has been shown that SD (50 h) does not affect blood parameters such as blood lactate, epinephrine, norepinephrine and dopamine during treadmill walking to exhaustion [121], nor in cases where subjects exercised (28% $VO_2$ max for 1 h every 3 h for 64 h of SD) during the SD period (i.e. blood lactate concentration (12.1 vs. 11.8 $mmol.l^{-1}$) [160])). However, such responses are heavily influenced by circadian fluctuations [40], making the effect of SD on these parameters difficult to determine. Interestingly, these two studies [121, 160] and others [138] which reported no differences in hormonal and endocrine responses to exercise following SD used constant exercise protocols, whereas two studies that reported significant changes following SR [95, 99] utilised incremental tests to exhaustion. Thus, the variable load at the end of exercise appears to increase the final stress-related response. The response of blood-cortisol concentrations to SD are similar to SR, with inconsistent findings presented [138, 149, 161]. Theoretically, if increased cortisol concentrations do occur [161], this could lead to increased muscle catabolism and a reduction in protein synthesis [3]. As such, this would lend support to the restorative theory that sleep is required for muscular recovery [162]; however such hypotheses require further research for clarification. For instance, whilst SD can initially blunt the secretion of GH [163], possibly hindering growth [42] and recovery [162], this deficiency is compensated for by increasing GH secretion during waking hours [164].

INSERT TABLE 2

### 4.3 Sleep loss, cognitive performance and mood responses

Numerous studies report that when sleep is reduced to less than 7 h in healthy adults, cognitive performance is poorer in tests for alertness, reaction time, memory and decision making [23, 109, 165-170]. Heightened levels of sleepiness, depression, confusion and poorer overall mood states have also been reported [171-174]. Decrements in cognitive performance have previously been attributed to disruptions to pre-frontal cortex functioning, as cognitive deficiencies which occur outside this area of the brain malfunction in qualitatively different ways [169]. Recently, a more universal effect of sleep disruption on cognition has been proposed [175], due to the sensitivity of cognitive performance to both arousal (not limited to pre-frontal activity) and attention in a sleep disrupted state [166]. The neuroanatomical mechanisms behind this state are intricately complex [176]. For instance, when the quality and quantity of human sleep is reduced, it appears the largest decreases in cerebral metabolism (compared to the awake-rested state) are apparent in the thalamus, cerebellum and prefrontal, posterior parietal, and temporal cortices [176, 177]. The reduced metabolic rates within these regions have been correlated with decreased cognitive performance [178, 179], highlighting their influence on optimum cognitive functioning [176, 180]. Based on these collective findings, some support suggested sleep benefits from models related to neural mechanisms, rather than peripheral tissues [103].

### *4.3.1 Cognitive performance and mood responses following sleep restriction*

As an example of the sensitivity of cognitive function to sleep disruption, simple reaction time (RT) has been shown to increase in individuals following 1 h of SR for two nights [108] and 4 h per night for five nights [109]. In addition, Jarraya et al. [117] found increases in RT and decreases in selective and constant attention in 12 handball goalkeepers following 4-5 h of SR at both the beginning and end of the night [117]. With RT slower following even minor disruptions to both sleep quality [108] and duration [117], it would seem pertinent for athletes with a high reliance on this cognitive component to ensure optimum sleep conditions prior to competing (e.g. baseball, cricket). This may be particularly challenging for baseball teams who play more than 80 away matches per season, where sleep conditions will change on an almost daily basis. These recommendations might be extrapolated to a host of individual and team-sport athletes, as many sports also involve critical decision making [181, 182], which is also susceptible following SR [169]. Although the majority of literature supports the impairment of decision making following sleep loss [169], others have reported no effects [183]. Khazaie et al. [183] reported no change in abstract reasoning, time reproduction skills or decision-making ability in 26 sleep-restricted (< 6 h sleep for five nights) medical residents. Whilst this was most likely due to a lack of an effect of partial SR on pre-frontal cognition or the interaction between the type of SR and type of cognitive task, it does show that optimum sleep may not always be critical for maintenance of decision-making performance over an acute period.

INSERT TABLE 3

The understanding of the effect of SR on memory and recall is also equivocal with some authors reporting decrements in short-term memory following SR [184], whilst others report no change [185]. For instance, Drummond et al. [185] found no changes in visual working memory or filtering efficiency following 3.5-4 h of sleep. Whilst SR is unlikely to affect elite players' memory of *how* a (motor) skill is executed, it could potentially affect the recall and understanding of tactical awareness or positioning. From this perspective, it seems sufficient sleep should be obtained following training sessions, as the perceptual and motor learning processes continue into and throughout subsequent sleep [186]. Another example of the detrimental effects of SR on cognitive performance is the plethora of evidence which reports poorer mood states after SR, with decreases in vigour along with increases in depression, sleepiness and confusion [106, 109, 115, 172, 187]. These negative mood states have been linked to overreaching and overtraining [188-190]. Indeed, this increase in psychological fatigue following SR would appear to create a neurocognitive state not conducive for either engaging in physical activity requiring a high motivational component or employing optimal decision making; however such concepts still require further substantiation.

### 4.3.2 Cognitive performance and mood responses following sleep deprivation

The effects of SD on cognitive performance are quite clear with many studies showing that greater total sleep loss results in poorer overall mood states with increased fatigue, sleepiness, confusion and decreased vigour [30, 138, 191], liveliness [126] and heightened depression [192]. In addition, decreases in logical reasoning, coding, decision making and filtering efficiency have also been reported [185, 191, 193]. The speed and accuracy at which these tasks are performed are also negatively affected by SD [194, 195]. Moreover, previous studies show participants perform poorer in tests for auditory vigilance [192], simple and complex reaction time [191, 192, 196] and memory [175, 194, 197, 198] following complete sleep loss. Limited data is available for cognitive functioning during sporting events, although during extreme sports (i.e. long-haul yacht racing), it appears cognitive impairments present following extensive SD [86]. These findings potentially have severe repercussions for athletic performance (Table 4). Nonetheless, conflicting results do exist with no significant differences in simple and complex responses to an altered Stroop test for decision making during 96-125 h of adventure racing (~100 h of SD [199]). These differences are most likely attributable to the intra-individual variability in personality and mood state and sleep requirement, in addition to sample size and task familiarity [200]. For instance, Edinger et al. [201] found vastly different responses for sleepiness and mood when investigating the daytime functioning of two players during a 146 h marathon tennis match. Indeed, humans are sometimes unaware of their increasing cognitive deficits and declining neurobehavioral function following SD [65]. In summary, SD results in relatively unequivocal decrements in most aspects of cognitive function and mood responses.

INSERT TABLE 4

## 5. Future Research

Currently, there is insufficient evidence to clarify the importance of sleep for athletes and the effects of sleep loss on exercise performance, alongside physiological and cognitive responses to exercise. Indeed, more research is required to confirm what dimensions of exercise performance are affected by sleep loss, especially those with a focus on repeated bouts of intermittent exercise and sport-specific performance. Admittedly, very little of the current literature has been conducted in team-sport athletes making the extrapolation of assumptions regarding sleep and performance to team sports difficult. Furthermore, there is little to no statistical analysis in the majority of previous studies with regard to magnitudes of effect, which may cloud some statistical inferences as to the effect on performance with respect to practical relevance [202]. Moreover, the majority of studies which assess the effect of sleep loss on athletic performance are those involving SD, a scenario which is very rare in real-world scenarios. For athletes, it would seem more pertinent in future research to investigate the effect of SR on parameters related to athletic performance. Future research may also focus on the interaction between sleep and acute and chronic training adaptations. Further research is also required to confirm if reduced sleep in elite athletic populations is associated with illness and injury occurrence, and whether such disturbances can partly explain the overtraining state. Preliminary evidence indicates that athletes who are at least functionally overreached present with sleep disturbances and illness prevalence during high-volume training [203]. From a purely scientific perspective, it is pertinent certain factors are considered in future endeavours when defining the effect of sleep on athletic performance within an experimental protocol [21, 204], including isolating homeostatic and circadian components, utilising an externally valid competitive event and minimising the many confounding variables which affect sports performance [205].

## 6. Practical recommendations

The following recommendations (Table 5) are based on the literature within this review. However, the authors recognise that given the equivocal findings for most summaries, future research is required to confirm these recommendations. Most importantly, it is recommended to understand the intra-individual differences with regards to sleeping patterns. Practitioners should strive to identify where sleep problems exist, and if necessary employ ethical interventions. If problems persist, these should be dealt with by medical professionals [7]. Whilst there are numerous examples of the interaction between sleep and performance which may aid practitioners, there is little literature confirming the importance of sleep to physiological and psychological recovery. In particular, evidence of the role and importance sleep plays within the professional sporting environment during various scenarios is lacking. Thus, although sport science personnel and researchers should be aware of the complex effects of sleep loss on athletic performance, such knowledge needs to be supplemented with sufficient understanding of sleep's role in recovery, and possible sleep hygiene strategies to alleviate these issues. Accordingly, future examination of the evidence of sleep and the potential role it may play in recovery for athletes is warranted.

INSERT TABLE 5

## 7. Conclusion

Although sleep is generally considered critical for human and athletic performance, there are mixed results regarding objective performance decrements in the current scientific literature. Individual athletes appear to lose sleep just prior to competing or if forced to train at early times; however evidence for such instances in team sports is lacking. Exercise performance seems to be negatively affected during periods of SD (specifically endurance and repeated exercise bouts), although conflicting results exist for the effect of acute SR, as performance during maximal one-off efforts (in particular for maximal strength) is generally maintained.

Possible reasons for these differences could be due to contrasting research designs and statistical power. The effects of sleep loss on physiological responses to exercise could potentially hinder muscular recovery and lead to a reduction in immune defence, although this still remains speculative. The majority of studies focussing on sleep loss and cognitive performance and mood responses have found detriments to most aspects of cognitive function (i.e. reaction time) and mood stability, results which potentially could hinder the neurocognitive components of many sports. Despite common assumptions of the importance of sleep, the lack of scientific evidence (especially in elite athletes) suggests future research into the examination of sleep and athletic performance is warranted.

## Acknowledgements

No funding was provided which contributed to the development of this manuscript. The authors declare that there are no conflicts of interest. Hugh Fullagar is supported by a “Science and Health in Soccer” scholarship funded by the DAAD (German Academic Exchange Centre). The preceding manuscript is a critical review of the literature, thus does not include any original research pertaining clinical studies or patient data that required ethical approval. However, both affiliated institutions were aware of the construction of this manuscript and supported such a practice. This critical review was conducted in good faith and in accordance with best current practice, whereby the quality, suitability and significance of each article was evaluated by the experience and expertise of the body of authors prior to final collection and reporting.

## Figure Legends

Figure 1: Flow diagram and results of the literature search to address the aim of the article to evaluate the importance and prevalence of sleep in athletes and review the effects of sleep loss on exercise performance, and physiological and cognitive responses to exercise.

Figure 2: The behavioural states of humans and phase changes throughout the sleep wake cycle, including states of waking, non-rapid-eye-movement sleep (NREM sleep) and rapid-eye-movement sleep (REM). The first row depicts a visual representation of movements throughout the sleep night. The second row illustrates REM sleep and the four stages of NREM sleep. The third row includes sample polysomnography tracings (each ~ 20 s) of an electromyogram (EMG), an electroencephalogram (EEG) and an electrooculogram (EOG) to help determine the presence or absence of each stage. Rows four, five and six portray a range of subjective and objective state variables. Although unable to replicate the sensitivity of these measurement techniques, other sleep indices (i.e. duration, latency) can also be measured by subjective sleep diaries and or/ wristwatch actigraphy. Reproduced from Hobson [45], with permission.

## References

1. Allada R, Siegel JM. Unearthing the phylogenetic roots of sleep. Curr Biol. 2008;18:R670–R9.

2. Beersma DGM, Gordijn MCM. Circadian control of the sleep–wake cycle. Physiol Behav. 2007;90(2-3):190-5.

3. Le Meur Y, Duffield R, Skein M. Sleep: In recovery for performance in sport Champaign, IL: Human Kinetics; 2012.

4. Reilly T, Waterhouse J. Sports performance: is there evidence that the body clock plays a role? Eur J Appl Physiol. 2009;106(3):321-32.

5. Archer SN, Laing EE, Moller-Levet CS, et al. Mistimed sleep disrupts circadian regulation of the human transcriptome. Proc Natl Acad Sci U S A. 2014.

6. Davenne D. Sleep of athletes – problems and possible solutions. Biol Rhythm Res. 2009;40(1):45-52.

7. Samuels C. Sleep, recovery, and performance: The new frontier in high-performance athletics. Neurol Clin. 2008;26(1):169-80.

8. Frank MG, Benington JH. The role of sleep in memory consolidation and brain plasticity: dream or reality? The Neuroscientist. 2006;12(6):477-88.

9. Crocker A, Sehgal A. Genetic analysis of sleep. Genes Dev. 2010;24:1220–35.

10. Abel T, Havekes R, Saletin JM, et al. Sleep, plasticity and memory from molecules to whole-brain networks. Curr Biol. 2013;23:774-88.

11. Xie L, Kang H, Xu Q, et al. Sleep drives metabolite clearance from the adult brain. Science. 2013;342:373-7.

12. Czeisler CA, Brown EM. Commentary: models of the effect of light on the human circadian system: current state of the art. J Biol Rhythms. 1999;14(6):539-43.

13. Samuels C. Jet lag and travel fatigue: a comprehensive management plan for sport medicine physicians and high-performance support teams. Clin J Sport Med. 2012;22:268-73.

14. Halson SL. Nutrition, sleep and recovery. Eur J Sport Sci. 2008;8(2):119-26.

15. Sehgal A, Mignot E. Genetics of sleep and sleep disorders. Cell. 2011;146(2):194-207.

16. De Gennaro L, Marzano C, Fratello F, et al. The electroencephalographic fingerprint of sleep is genetically determined: a twin study. Annu Neurosci. 2008;64:455–60.

17. Bishop D. An applied research model for the sports sciences. Sports Med. 2008;38(3):253-63.

18. Drust B, Waterhouse J, Atkinson G, et al. Circadian rhythms in sports performance: an update. Chronobiol Int. 2005;22:21-40.

19. Reilly T, Waterhouse J. Sport, exercise and environmental physiology. Edinburgh: Elsevier; 2005.

20. Czeisler CA, Allan JS, Strogatz SH, et al. Bright light resets the human circadian pacemaker independent of the timing of the sleep-wake cycle. Science. 1986;233(4764):667-71.

21. Reilly T, Edwards B. Altered sleep–wake cycles and physical performance in athletes. Physiol Behav. 2007;90(2-3):274-84.

22. Lack LC, Wright HR. Chronobiology of sleep in humans. Cell Mol Life Sci. 2007;64(10):1205-15.

23. Durmer J, Dinges DF. Neurocognitive consequences of sleep deprivation. Semin Neurol. 2005;25(1):117-29.

24. Banks S, Dinges DF. Behavioral and physiological consequences of sleep restriction. J Clin Sleep Med. 2007;3(5):519-28.

25. Venter RE. Perceptions of team athletes on the importance of recovery modalities. Eur J Sport Sci. 2014;14:S69-S76.

26. Erlacher D, Ehrlenspiel F, Adegbesan OA, et al. Sleep habits in German athletes before important competitions or games. J Sports Sci. 2011;29(8):859-66.

27. Juliff LE, Halson SL, Peiffer JJ. Understanding sleep disturbance in athletes prior to important competitions. J Sci Med Sport. 2014:[Epub ahead of print].

28. Hanton S, Fletcher D, Coughlan G. Stress in elite sport performers: A comparative study of competitive and organizational stressors. J Sports Sci. 2005;23(10):1129-41.

29. Lastella M, Lovell GP, Sargent C. Athletes' precompetitive sleep behaviour and its relationship with subsequent precompetitive mood and performance. Eur J Sport Sci. 2014:1-8.

30. Meney I, Waterhouse J, Atkinson G, et al. The effect of one night’s sleep deprivation on temperature, mood, and physical performance in subjects with different amounts of habitual physical activity. Chronobiol Int. 1998;15(4):349–63.

31. Van Helder T, Radomski M. Sleep deprivation and the effect on exercise performance. Sports Med. 1989;7:235-47.

32. Pilcher JJ, Hoffcutt AI. Effect of sleep deprivation on performance: a meta-analysis. Sleep. 1996;19(4):318-26.

33. Leatherwood W, Dragoo J. Effect of airline travel on performance: a review of the literature. Br J Sports Med. 2013;47:561-7.

34. Waterhouse J, Reilly T, Atkinson G, et al. Jet lag: trends and coping strategies. The Lancet. 2007;369(9567):1117-29.

35. Drust B, Ahmed Q, Roky R. Circadian variation and soccer performance: Implications for training and match-play during Ramadan. J Sports Sci. 2012;30(sup1):S43-S52.

36. Stickgold R. Sleep-dependent memory consolidation. Nature. 2005;437:1272-8.

37. Shapiro CM. Sleep and the athlete. Br J Sports Med. 1981;15(1):51-5.

38. Lashley F. Measuring sleep. Sudbury, M.A.: Jones and Bartlett Publishers; 2004.

39. Lee-Chiong T. Sleep: A comprehensive handbook. New Jersey: John Wiley and Sons, Inc; 2006.

40. Weitzman ED. Circadian rhythms and episodic hormone secretion in man. Ann Rev Med. 1976;27:225-43.

41. Brebbia DR, Altshuler KZ. Oxygen consumption rate and electroencephalographic stage of sleep. Science. 1965;150:1621–3.

42. Sassin JF, Parker DC, Mace JW, et al. Human growth hormone release: relation to slow wave sleep and sleep-waking cycles. Science. 1969;165:513–5.

43. Gololobova MT. 24-hour rhythm of cell multiplication in rat epidermis during healing of skin wounds. B Exp Biol Med. 1961;50:188-22.

44. Siegel JM. Clues to the functions of mammalian sleep. Nature. 2005;437(7063):1264-71.

45. Hobson JA. Sleep is of the brain, by the brain and for the brain. Nature. 2005;437(7063):1254-6.

46. Walker MP, Brakefield T, Morgan A, et al. Practice with sleep makes perfect: sleep-dependent motor skill learning. Neuron. 2002;35(1):205-11.

47. Fischer S, Hallschmid M, Elsner A, et al. Sleep forms memory for finger skills. Proc Natl Acad Sci U S A. 2002;99(18):11987–91.

48. Huber R, Ghilardi M, Massimini M, et al. Local sleep and learning. Nature. 2004;430(6995):78-81.

49. Mahoney M, Avener M. Psychology of the elite athlete: An exploratory study. Cog Ther Res. 1977;1(2):135-41.

50. Moran A. The psychology of concentration in sport performers: a cognitive analysis. Hove: Psychology Press; 1996

51. Ferrara M. How much sleep do we need? Sleep Med Rev. 2001;5(2):155-79.

52. 2013 Sleep in America poll: Exercise and sleep. Crofton, MD: National Sleep Foundation; 2013.

53. Natale V, Adan A, Fabbri M. Season of birth, gender, and social-cultural effects on sleep timing preferences in humans. Sleep. 2009;32(3):423-6.

54. Yu Q, Ma W, Zou Y, et al. Impact of evening exercise on college students' sleep quality. Chin J Prev Med. 2013;47(6):542-6.

55. Hicks RA, Pellegrini R. The changing sleeping habits of college students. Percept Mot Skills. 1991;72:1106.

56. Hicks R, Fernandez C, Pellegrini RJ. Striking changes in the sleep satisfaction of university students over the last two decades. Percept Mot Skills. 2001;93(3):660.

57. Aerenhouts D, Zinzen E, Clarys P. Energy expenditure and habitual physical activities in adolescent sprint athletes. J Sports Sci Med. 2011;10:362-8.

58. Carskadon MA. Adolescent sleep patterns: Biological, social, and psychological influences. Cambridge, UK: Cambridge University Press; 2002.

59. Carney CE, Edinger JD, Meyer B, et al. Daily activities and sleep quality in college students. Chronobiol Int. 2006;23:623-37.

60. Shenghui L, Xinming J, Shenghu W, et al. The impact of media use on sleep patterns and sleep disorders among school-aged children in China. Sleep. 2007;30:361-7.

61. Derks D, van Mierlo H, Schmitz EB. A diary study on work-related smartphone use, psychological detachment and exhaustion: Examining the role of the perceived segmentation norm. J Occup Health Psychol. 2014;19(1):74-84.

62. Klerman EB, Dijk DJ. Interindividual variation in sleep duration and its association with sleep debt in young adults. Sleep. 2005;28:1253–59.

63. Aeschbach D, Cajochen C, Landolt H, et al. Homeostatic sleep regulation in habitual short sleepers and long sleepers. Am J Physiol. 1996;270:41–53.

64. Aeschbach D, Sher L, Postolache TT, et al. A longer biological night in long sleepers than in short sleepers. J Clin Endocrinol Metab. 2003;88:26-30.

65. Van Dongen HPA, Maislin G, Mullington JM, et al. The cumulative cost of additional wakefulness: dose-response effects on neurobehavioural functions and sleep physiology from chronic sleep restriction and total sleep deprivation. Sleep. 2003;2:117-26.

66. Porter JM, Horne JA. Exercise and sleep behaviour - a questionnaire approach. Ergonomics. 1981;24:511-21.

67. Shapiro CM, Catterall J, Warren P, et al. Lean body mass and non-rapid eye movement sleep. Br Med J. 1986;294:22.

68. Baekeland F, Lasky R. Exercise and sleep patterns in college athletes. Percept Mot Skills. 1966;23:1203-7.

69. Paxton SJ, Trinder J, Montgomery I. Does aerobic fitness affect sleep? Psychophysiology. 1983;20(3):320-4.

70. Shapiro CM, Bortz R, Mitchell D. Slow wave sleep: a recovery period after exercise. Science. 1981;214(11):1253-4.

71. Calder A. Recovery strategies for sports performance. USOC Olympic Coach E-Magazine 2003 [cited 2013 December 15]; Available from: http://coaching.usolympicteam.com/coaching/kpub.nsf/v/3Sept03

72. Sargent C, Halson S, Roach GD. Sleep or swim? Early-morning training severely restricts the amount of sleep obtained by elite swimmers. Eur J Sport Sci. 2014;14:S310-S5.

73. Venter RE. Role of sleep in performance and recovery of athletes : a review article. SA J Res Sport Phys Ed Rec. 2012;34(1):167-84.

74. Öhrstrom E, Skanberg A. Sleep disturbances from road traffic and ventilation noiselaboratory and field experiments. J Sound Vibr. 2004;271(1-2):279-96.

75. de Queiroz SS, Silva A, Winckler C, et al. Evaluation of the quality of sleep and chronotype of brazilian athletes: Paralympic Games in Beijing 2008. 3rd International Congress of the Association of Sleep Medicine: Sleep Medicine 2009. p. S04.

76. Silva A, Queiroz S, Winckler C, et al. Sleep quality evaluation, chronotype, sleepiness and anxiety of Paralympic Brazilian athletes: Beijing 2008 Paralympic Games. Br J Sports Med. 2012;46:150-4.

77. Fietze I, Strauch J, Holzhausen M, et al. Sleep quality in professional ballet dancers. Chronobiol Int. 2009;26(6):1249-62.

78. Forndran A, Lastella M, Roach GD, et al. Training schedules in elite swimmers: No time to rest? In: Zhou X SCE, editor. Sleep of different populations. Adelaide: Australasian Chronobiology Society; 2012. p. 6-10.

79. Anglem N, Lucas SJE, Rose E, et al. Mood, illness and injury responses and recovery with adventure racing. Wild Envion Med. 2008;19:30-8.

80. Taylor SR, Rogers GG, Driver HS. Effects of training volume on sleep, psychological, and selected physiological profiles of elite female swimmers. Med Sci Sport Exer. 1997;29(5):688-93.

81. Leeder J, Glaister M, Pizzoferro K, et al. Sleep duration and quality in elite athletes measured using wristwatch actigraphy. J Sports Sci. 2012;30(6):541-5.

82. Matos NF, Winsley RJ, Williams CA. Prevalence of nonfunctional overreaching/overtraining in young English athletes. Med Sci Sport Exer. 2011;43(7):1287-94.

83. Ingersoll C. Editorial sleep efficiency and overreaching in swimmers. J Sport Rehab. 2003;12(1):1-12.

84. Oda S, Shirakawa K. Sleep onset is disrupted following pre-sleep exercise that causes large physiological excitement at bedtime. Eur J Appl Physiol. 2014;114(9):1789-99.

85. Sargent C, Schmidt WF, Aughey RJ, et al. The impact of altitude on the sleep of young elite soccer players (ISA3600). Br J Sports Med. 2013;47(Suppl_1):i86-i92.

86. Hurdiel R, Van Dongen HPA, Aron C, et al. Sleep restriction and degraded reaction-time performance in Figaro solo sailing races. J Sports Sci. 2014;32(2):172-4.

87. Léger D, Elbaz M, Raffray T, et al. Sleep management and the performance of eight sailors in the Tour de France à la voile yacht race. J Sports Sci. 2008;26(1):21-8.

88. Hurdiel R, Monaca C, Mauvieux B, et al. Field study of sleep and functional impairments in solo sailing races. Sleep Biol Rhythms. 2012;10(4):270-7.

89. Sargent C, Halson S, Roach GD. Sleep or swim? Early-morning training severely restricts the amount of sleep obtained by elite swimmers. Eur J Sport Sci. 2012:1-6.

90. Boonstra TW, Stins JF, Daffertshofer A, et al. Effects of sleep deprivation on neural functioning: an integrative review. Cell Mol Life Sci. 2007;64(7-8):934-46.

91. Waterhouse JM, Minors DS, Waterhouse ME, et al. Keeping in time with your body clock. Oxford: Oxford University Press; 2002.

92. Souissi N, Chtourou H, Aloui A, et al. Effects of time-of-day and-partial sleep deprivation on short term maximal performances of judo compeitiors. J Strength Cond Res. 2013;27(9):2473-80.

93. Reilly T, Hales A. Effects of partial sleep deprivation on performance measures in females. London Taylor and Francis; 1988.

94. Martin B. Effect of sleep deprivation on tolerance of prolonged exercise. Eur J Appl Physiol. 1981;47:345-54.

95. Mougin F, Simon-Rigaud ML, Davenne D, et al. Effects of sleep disturbances on subsequent physical performance. Eur J Appl Physiol Occup Physiol. 1991;63:77-83.

96. Mougin F, Bourdin H, Simon-Rigaud ML, et al. Effects of a selective sleep deprivation on subsequent anaerobic performance. Int J Sports Med. 1996;17(2):115-9.

97. Reilly T, Deykin T. Effects of partial sleep loss on subjective states, psychomotor and physical performance tests. J Hum Move Stud. 1983;9:157–70.

98. Mejri MA, Hammouda O, Zouaoui K, et al. Effect of two types of partial sleep deprivation on Taekwondo players' performance during intermittent exercise. Biol Rhythm Res. 2014;45(1):17-26.

99. Mougin F, Bourdin H, Simon-Rigaud ML, et al. Hormonal responses to exercise after partial sleep deprivation and after a hypnotic drug-induced sleep. J Sports Sci. 2001;19(2):89-97.

100. Souissi N, Souissi M, Souissi H, et al. Effect of time of day and partial sleep deprivation on short-term, high-power output. Chronobiol Int. 2008;25(6):1062-76.

101. Abedelmalek S, Souissi N, Chtourou H, et al. Effects of partial sleep deprivation on proinflammatory cytokines, growth hormone, and steroid hormone concentrations during repeated brief sprint interval exercise. Chronobiol Int. 2013;30(4):502-9.

102. Mougin F, Davenne D, Simon-Rigaud ML, et al. Disturbance of sports performance after partial sleep deprivation. C R Seances Soc Biol Fil. 1989;183(5):461-6.

103. Horne J, Petit AN. Sleep deprivation and the physiological response to exercise under steady state conditions in untrained subjects. Sleep. 1984;7:168-79.

104. Abbiss CR, Laursen PB. Models to explain fatigue during prolonged endurance cycling. Sports Med. 2005;35(10):865-98.

105. Walker MP, Stickgold R. Its practice, with sleep, that makes perfect: implications of sleep dependent learning and plasticity for skill performance. . Clin J Sports Med. 2005;24(2):310-7.

106. Reilly T, Piercy M. The effect of partial sleep deprivation on weight-lifting performance. Ergonomics. 1994;37(1):107-15.

107. HajSalem M, Chtourou H, Aloui A, et al. Effects of partial sleep deprivation at the end of the night on anaerobic performances in judokas. Biol Rhythm Res. 2013;44(13):815-21.

108. Bonnet MH. Performance and sleepiness following moderate sleep disruption and slow wave sleep deprivation. Physiol Behav. 1985;37:915-8.

109. Axelsson J, Kecklund G, Akerstedt T, et al. Sleepiness and performance in response to repeated sleep restriction and subsequent recovery during semi-laboratory conditions. Chronobiol Int. 2008;25:297-308.

110. Koboyashi F, Yamamoto K, Tsubi H, et al. Five-hour sleep restriction for 7 days increases subjective sleepiness. Ind Health. 2007;45:160-4.

111. Sinnerton S, Reilly T. Effects of sleep loss and time of day in swimmers. London: E and FN Spon; 1992.

112. Temesi J, Arnal PJ, Davranche K, et al. Does central fatigue explain reduced cycling after complete sleep deprivation? Med Sci Sport Exer. 2013;45(12):2243-53.

113. Brink MS, Nederhof E, Visscher C, et al. Monitoring load, recovery, and performance in young elite soccer players. J Strength Cond Res. 2010;24(3):597-603.

114. Foster C. Monitoring training in athletes with reference to overtraining syndrome. Med Sci Sport Exer. 1998;30(7):1164-8.

115. Edwards BJ, Waterhouse J. Effects of one night of partial sleep deprivation upon diurnal rhythms of accuracy and consistency in throwing darts. Chronobiol Int. 2009;26(4):756-68.

116. Reyner LA, Horne JA. Sleep restriction and serving accuracy in performance tennis players, and effects of caffeine. Physiol Behav. 2013;120:93-6.

117. Jarraya S, Jarraya M, Chtourou H, et al. Effect of time of day and partial sleep deprivation on the reaction time and the attentional capacities of the handball goalkeeper. Biol Rhythm Res. 2014;45(2):183-91.

118. Brand S, Gerber M, Beck J, et al. High exercise levels are related to favorable sleep patterns and psychological functioning in adolescents: a comparison of athletes and controls. J Adolesc Health. 2010;46(2):133-41.

119. Driver HS, Taylor SR. Exercise and sleep. Sleep Med Rev. 2000;4(4):387-402.

120. Hill DW, Borden DO, Darnaby KM, et al. Aerobic and anaerobic contributions to exhaustive high-intensity exercise after sleep deprivation. J Sports Sci. 1994;12(5):455-61.

121. Martin BJ, Chen H. Sleep loss and the sympathoadrenal response to exercise. Med Sci Sport Exer. 1984;16:56-9.

122. Azboy O, Kaygisiz Z. Effects of sleep deprivation on cardiorespiratory functions of the runners and volleyball players during rest and exercise. Acta Physiol Hung. 2009;96(1):29-36.

123. Oliver SJ, Costa RJS, Laing SJ, et al. One night of sleep deprivation decreases treadmill endurance performance. Eur J Appl Physiol. 2009;107(2):155-61.

124. Takeuchi L, Davis GM, Plyley MJ, et al. Sleep deprivation, chronic exercise and muscular performance. Ergonomics. 1985;28:591–601.

125. Coutts AJ, Duffield R. Validity and reliability of GPS devices for measuring movement demands of team sports. J Sci Med Sport. 2010;13(1):133–5.

126. Skein M, Duffield R, Edge J, et al. Intermittent-sprint performance and muscle glycogen after 30 h of sleep deprivation. Med Sci Sport Exer. 2011;43(7):1301-11.

127. Bulbulian R, Heaney JH, Leake CN, et al. The effect of sleep deprivation and exercise load on isokinetic leg strength and endurance. Eur J Appl Physiol. 1996;73:273-7.

128. Souissi N, Sesboüé B, Gauthier A, et al. Effects of one night's sleep deprivation on anaerobic performance the following day. Eur J Appl Physiol. 2003;89(3):359-66.

129. How JM, Foo SC, Low EC, et al. Effect of sleep deprivation on performance of Naval seamen: I. Total sleep deprivation on performance. Ann of Acad Med Singapore. 1994;23:669-75.

130. Symons JD, VanHelder T, Myles WS. Physical performance and physiological responses following 60 hours of sleep deprivation. Med Sci Sport Exer. 1988;20(4):374-80.

131. Reilly T, Walsh TJ. Physiological, psychological and performance measures duraing an endurance record for 5-a-side soccer play. Br J Sports Med. 1981;15:122-8.

132. Reilly T, George A. Urinary phenylethamine levels during three days of indoor soccer play. J Sports Sci. 1983;1:70.

133. Racinais S, Hue O, Blonc S, et al. Effect of sleep deprivation on shuttle run score in middle-aged amateur athletes. J Sports Med Phys Fitness. 2004;44(3):246-8.

134. Katirji B. Clinical neurophysiology: clinical electromyography. Philadelphia, Pa: Saunders Elsevier; 2012.

135. Berger RJ, Phillips NH. Energy conservation and sleep. Behav Brain Res. 1995;69:65-73.

136. Francesconi RP, Stokes JW, Banderet LE, et al. Sustained operations and sleep deprivation: effects on indices of stress. Aviat Space Environ Med. 1978;49:1271-4.

137. Martin BJ. Sleep loss and subsequent exercise performance. Acta Physiol Scand. 1988;574:28-32.

138. Martin BJ, Bender PR, Chen H. Stress hormonal response to exercise after sleep loss. Eur J Appl Physiol Occup Physiol. 1986;55:210-4.

139. Rossiter H. Exercise: Kinetic considerations for gas exchange. Compr Physiol. 2011;1:203-44.

140. Ashley E, Myers J, Froelicher V. Exercise testing in clinical medicine. The Lancet. 2000;356(4):1592-97.

141. Beaver W, Lamarra N, Wasserman K. Breath by breath measurement of true alveolar gas exchange. J Appl Physiol: Respirat Environ Exercise Physiol Behav. 1981;51(6):1662-75.

142. Wilmore J, Costill DL. Semiautomated systems approach to the assessment of oxygen uptake during exercise. J Appl Physiol. 1974;36(5):618-20.

143. Vgontzas AN, Zoumakis E, Bixler EO, et al. Adverse effects of modest sleep restriction on sleepiness, performance, and inflammatory cytokines. J Clin Endocrinol Metab. 2004;89(5):2119-26.

144. Abedelmalek S, Chtourou H, Aloui A, et al. Effect of time of day and partial sleep deprivation on plasma concentrations of IL-6 during a short-term maximal performance. Eur J Appl Physiol. 2013;113(1):241-8.

145. Goh VH, Tong TY, Lim CL, et al. Effects of one night of sleep deprivation on hormone profiles and performance efficiency. Military Medicine. 2001;166(5):427-31.

146. Urhausen A, Kindermann W. The endocrine system in overtraining. Totowa, NJ: Humana Press; 2000.

147. Redwine L, Hauger RL, Christian Gillin J, et al. Effects of sleep and sleep deprivation on interleukin-6, growth hormone, cortisol, and melatonin levels in humans. J Clin Endocrinol Metab. 2000;85(10):3597–603.

148. Irwin MR, Wang M, Campomayor CO, et al. Sleep deprivation and activation of morning levels of cellular and genomic markers of inflammation. Arch Intern Med. 2006;166:1756–62.

149. Costa RJS, Smith AH, Oliver SJ, et al. The effects of two nights of sleep deprivation with or without energy restriction on immune indices at rest and in response to cold exposure. Eur J Appl Physiol. 2010;109(3):417-28.

150. Papanicolaou DA, Wilder RL, Manolagas SC, et al. The pathophysiologic roles of interleukin-6 in human disease. Ann Intern Med. 1998;128:127–37.

151. Costill DL, Flynn MG, Kirwan JP, et al. Effects of repeated days of intensified training on muscle glycogen and swimming performance. Med Sci Sport Exer. 1988;20:249-54.

152. Guezennec CY, Sabatin P, Legrand H, et al. Physical performance and metabolic changes induced by combined prolonged exercise and different energy intake in humans. Eur J Appl Physiol. 1994;68:525-30.

153. Zhong X, Hilton HJ, Gates GJ, et al. Increased sympathetic and decreased parasympathetic cardiovascular modulation in normal humans with acute sleep deprivation. J Appl Physiol. 2005;98:2024-32.

154. Achten J, Jeukendrup AE. Heart rate monitoring: Applications and limitations. Sports Med. 2003;33:517-38.

155. Hynynen ESA, Uusitalo A, Konttinen N, et al. Heart rate variability during night sleep and after awakening in overtrained athletes. Med Sci Sport Exer. 2006;38(2):313-7.

156. Garet M, Tournaire N, Roche F, et al. Individual interdependence between nocturnal ANS activity and performance in swimmers. Med Sci Sport Exer. 2004;36:2112-8.

157. Martin BJ, Haney R. Self-selected exercise intensity is unchanged by sleep loss. Eur J Appl Physiol Occup Physiol. 1982;49:79-86.

158. Martin BJ, Gaddis GM. Exercise after sleep deprivation. Med Sci Sport Exer. 1981;13:220-3.

159. Thomas V, Reilly T. Circulatory, psychological and performance variables during 100 hours of continuous exercise under conditions of controlled energy intake and work output. J Hum Move Stud. 1975;1:149-55.

160. Plyley MJ, Shephard RJ, Davis GM, et al. Sleep deprivation and cardiorespiratory function. Influence of intermittent submaximal exercise. Eur J Appl Physiol Occup Physiol. 1987;56:338-44.

161. Obal F, Krueger JM. GHRH and sleep. Sleep Med Rev. 2004;8:367-77.

162. Dattilo M, Antunes HKM, Medeiros A, et al. Sleep and muscle recovery: Endocrinological and molecular basis for a new and promising hypothesis. Med Hypotheses. 2011;77(2):220-2.

163. Everson CA, Crowley WR. Reductions in circulating anabolic hormones induced by sustained sleep deprivation in rats. Am J Physiol Endocrinol Metab. 2004;286:1060-70.

164. Brandenberger G, Gronfier C, Chapotota F, et al. Effect of sleep deprivation on overall 24 h growth-hormone secretion. The Lancet. 2000;356(9239):1408.

165. Belenky G, Wesensten N, Thorne D, et al. Patterns of performance degradation and restoration during sleep restriction and subsequent recovery: a sleep dose-response study. J Sleep Res. 2003;12:1-12.

166. Doran SM, Van Dongen HPA, Dinges DF. Sustained attention performance during sleep deprivation: evidence of state instability. Arch Ital Biol. 2001;139:253-67.

167. Dorrian J, Rogers NL, Dinges DF. Psychomotor vigilance performance: neurocognitive assay sensitive to sleep loss. . New York: Marcel Dekker; 2005.

168. Dorrian J, Dinges DF. Sleep deprivation and its effects on cognitive performance: Wiley & Sons; 2005.

169. Harrison Y, Horne JA. The impact of sleep deprivation on decision making: A review. J Expl Psychol: Appl. 2000;6:236-49.

170. Dinges DF, Kribbs NB. Performing while sleepy: effects of experimentally induced sleepiness. Winchester, England: John Wiley & Sons; 1991.

171. Balkin TJ, Bliese PD, Belenky G. Comparative utility of instruments for monitoring sleepiness-related performance decrements in the operational environmen. J Sleep Res. 2004;13:219-27.

172. Bonnet M. Effect of sleep disruption on sleep, performance and mood. Sleep. 1985;8(1):11-9.

173. Roehrs T, Carskadon MA, Dement WC, et al. Daytime sleepiness and alertness: W.B. Saunders Company; 2005.

174. Kleitman N. Sleep and wakefullness. London: The University of Chicago Press; 1963.

175. Grundgeiger T, Bayen UJ, Horn SS. Effects of sleep deprivation on prospective memory. Memory. 2014;22(6):679-86.

176. Taber K, Hurley R. Functional neuroanatomy of sleep and sleep deprivation. J Neuropsychiatry Clin Neurosci. 2006;18(1):1-5.

177. Drummond SPA, Brown GG. The effects of total sleep deprivation on cerebral responses to cognitive performance. Neuropsychopharmacology. 2001;25:S68–S73.

178. Thomas M, Sing M, Belenky G. Neural basis of alertness and cognitive performance impairments during sleepiness. I. Effects of 24 hour of sleep deprivation on waking human regional brain activity. J Sleep Res. 2000;9:335–52.

179. Thomas ML, Sing HC, Belenky G. Neural basis of alertness and cognitive performance impairments during sleepiness II. Effects of 48 and 72 hour of sleep deprivation on waking human brain activity. Thalamus Relat Syst 2003;2:199–229.

180. Drummond SPA, Brown GG, Stricker JL, et al. Sleep deprivation-induced reduction in cortical functional response to serial subtraction. Neuroreport. 1999;10:3745-8.

181. Baker J, Cote J, Abernethy B. Sport-specific practice and the development of expert decision-making in team ball sports. J Appl Sport Psych. 2003;15(1):12-25.

182. Araújo D, Davids K, Hristovski R. The ecological dynamics of decision making in sport. Psyc Sport Exerc. 2006;7(6):653–76.

183. Khazaie H, Tahmasian M, Ghadami M, et al. Theeffects of chronic partial sleep deprivation on cognitive functions of medical residents. Iran J Psych. 2010;5(2):74-7.

184. Waterhouse J, Atkinson G, Edwards B, et al. The role of a short post-lunch nap in improving cognitive, motor, and sprint performance in participants with partial sleep deprivation. J Sports Sci. 2007;25(14):1557-66.

185. Drummond SPA, Anderson D, Straus L, et al. The effects of two types of sleep deprivation on visual working memory capacity and filtering efficiency. PLoS ONE. 2012;7(4):e35653.

186. Laureys S, Peigneux P, Perrin F, et al. Sleep and motor skill learning. Neuron. 2002;35(1):5-7.

187. Otmani S, Pebayle T, Roge J, et al. Effect of driving duration and partial sleep deprivation on subsequent alertness and performance of car drivers. Physiol Behav. 2005;84(5):715-24.

188. Jurimae J, Maestu J, Purge P, et al. Changes in stress and recovery after heavy training in rowers. J Sci Med Sport. 2004;7(3):334-9.

189. Jurimae J, Maestu J, Purge P, et al. Relations among heavy training stress, mood state, and performance for male junior rowers. Percept Mot Skills. 2001;95:520-6.

190. Coutts AJ, Reaburn P, Piva TJ, et al. Monitoring for overreaching in rugby league players. Eur J Appl Physiol. 2007;99(3):313-24.

191. Angus RG, Heslegrave R, Myles WS. Effects of prolonged sleep duration, with and without chronic physical exercise, on mood and performance. Psychophysiology. 1985;22:276-82.

192. Scott JPR, McNaughton LR, Polman RCJ. Effects of sleep deprivation and exercise on cognitive, motor performance and mood. Physiol Behav. 2006;87(2):396-408.

193. Harrison Y, Horne JA. One night of sleep loss impairs innovative thinking and flexible decision making. Organ Behav Hum Dec Process. 1999;78(2):128-45.

194. Williamson AM. Moderate sleep deprivation produces impairments in cognitive and motor performance equivalent to legally prescribed levels of alcohol intoxication. Occup Environ Med. 2000;57(10):649-55.

195. Froberg JE, Karlsson C, Levi L, et al. Circadian rhythms of catecholamine excretion, shooting range performance and self-ratings of fatigue during sleep deprivation. Biol Psychol. 1975;2:175-88.

196. Taheri M, Arabameri E. The effect of sleep deprivation on choice reaction time and anaerobic power of college student athletes. Asia J Sport Med. 2011;3(1):15-20.

197. Rosa R, Bonnet MH, Warm J. Recovery of performance during sleep following sleep deprivation. Psychophysiology. 1983;20(2):152-9.

198. Wimmer F, Hoffmann RF, Bonato RA. The effects of sleep deprivation on divergent thinking and attention processes. J Sleep Res. 1992;1:223–30.

199. Lucas SJE, Anson JG, Palmer CD, et al. The impact of 100 hours of exercise and sleep deprivation on cognitive function and physical capacities. J Sports Sci. 2009;27(7):719-28.

200. Olsen OK, Pallesen S, Eid J. The impact of partial sleep deprivation on moral reasoning in military officers. Sleep. 2010;33(8):1086-90.

201. Edinger JD, Marsh GR, Vaughn McCall W, et al. Daytime fuctioning and nighttime sleep before, during, and after a 146 hour tennis match. Sleep. 1990;13(6):526-32.

202. Hopkins WG. Linear models and effect magnitudes for research, clinical and practical applications. wwwsportscienceorg. 2010;14:49-58.

203. Hausswirth C, Louis J, Aubry A, et al. Evidence of disturbed sleep and increased illness in overreached endurance athletes. Med Sci Sport Exer. 2014;46(5):1036-45.

204. Sawka MN, Gonzalez RR, Pandolf KB. Effects of sleep deprivation on thermoregulation during exercise. Am Journal of Physiology. 1984;246:R72–R7.

205. Smith RS, Reilly T. Athletic performance. New York: Marcel Dekker; 2005.

# Sleep and athletic performance: The effects of sleep loss on exercise performance, and physiological and cognitive responses to exercise

Hugh H.K. Fullagar[1], Sabrina Skorski[1], Rob Duffield[2], Daniel Hammes[1], Aaron J. Coutts[2], Tim Meyer[1]

Affiliations

1. Institute of Sport and Preventive Medicine, Saarland University, Germany
2. Sport & Exercise Discipline Group, UTS: Health, University of Technology Sydney, Australia

**Corresponding author and reprint requests**

Hugh Fullagar
Institute of Sport and Preventive Medicine
Saarland University, GEB. B82
66123 Saarbrucken
Germany
Email: hugh.fullagar@uni-saarland.de
Phone: 0681-302 70400
Fax: 0681-302 4296

**Conflicts of interest:**

The authors declare that there are no conflicts of interest.

**Running head:**

Sleep loss and athletic performance

## Abstract

Although its true function remains unclear, sleep is considered critical to human physiological and cognitive function. Equally, since sleep loss is a common occurrence prior to competition in athletes, this could significantly impact upon their athletic performance. Much of the previous research has reported that exercise performance is negatively affected following sleep loss; however due to conflicting findings, it remains uncertain as to the extent, influence and mechanisms of sleep loss affecting exercise performance. For instance, research indicates some maximal physical efforts and gross motor performances can be maintained. Comparatively, the few published studies investigating the effect of sleep loss on performance in athletes report a reduction in sports-specific performance. The effects of sleep loss on physiological responses to exercise also remain equivocal; although, it appears a reduction in sleep quality and quantity could result in an autonomic nervous system imbalance, simulating symptoms of the overtraining syndrome. Additionally, increases in pro-inflammatory cytokines following sleep loss could promote immune system dysfunction. Of further concern, numerous studies investigating the effects of sleep loss on cognitive function report slower and less accurate cognitive performance. Based on this context, this review aims to evaluate the importance and prevalence of sleep in athletes and summarises the effects of sleep loss (restriction and deprivation) on exercise performance, and physiological and cognitive responses to exercise. Given the equivocal understanding of sleep and athletic performance outcomes, further research and consideration is required to obtain a greater knowledge of the interaction between sleep and performance.

## Key points (2 to 3 key points summarising the main findings and implication of the review)

- Although sleep is considered critical to optimal performance, many athletes appear to lose sleep prior to competition due to various reasons including noise, light, anxiety and nervousness.

- Whilst there appears sufficient evidence to imply complete sleep deprivation can have significant negative effects on athletic performance, the effects of sleep restriction (partial disturbance of the sleep-wake cycle) are more conflicting; a concerning issue given athletes are more likely to experience this mode of sleep loss.

- The detrimental effect of sleep loss on most aspects of cognitive function remains unequivocal, with only minor conflicting findings present for the extent of the effects of mild sleep restriction; findings which would predictably suggest negative consequences for athletes requiring high neurocognitive reliance.

## 1. Introduction

Reoccurring at habitual intervals throughout a 24 hour (h) period in humans, sleep is a homeostatically controlled behavioural state of reduced movement and sensory responsiveness [1, 2]. The process of sleep is widely regarded as critical to both cognitive and physiological function [2-7]. In spite of this perceived importance, the consensus regarding the rationale as to why humans sleep remains equivocal, if not robustly debated [2, 8]. Recent studies have shown sleep to regulate key molecular mechanisms (i.e. transcriptional regulatory proteins [1, 9, 10]), and have demonstrated that sleep has an integral role in metabolic homeostasis [11]. Whilst the duration and quality of sleep is manipulated by numerous environmental factors, among them light [12], jetlag [13] and nutrition [14]), it has also been shown to be influenced by genetic traits [15, 16]. Notwithstanding the complexity surrounding the need, rationale and outcome of sleep, it seemingly must serve an important purpose for humans because it has survived so many years of evolution [15].

The ability of humans to cope with physiological and psychological stressors is critical to athletic performance outcomes [17], and is affected by numerous factors including experience, fitness, motivation and the natural fluctuation of physiological and behavioural processes across a 24 h period (i.e. sleep-wake cycle, body temperature, hormone regulation [18]). These *circadian rhythms* are primarily controlled by the suprachiasmatic nucleus (SN) within the hypothalamus [2]. However, the SN is unable to always maintain control over these patterns, as humans are highly sensitive to alterations to their natural environment [2, 19], most notably through the light-dark cycle [20]. When athletes encounter disruptions to their environments (e.g. through travel or training/playing at night), endogenous circadian rhythms and normal sleep-wake cycles can become desynchronised [2, 21]. Such perturbations in sleeping patterns can cause an increase in homeostatic pressure and affect emotional regulation, core temperature and circulating levels of melatonin, causing a delay in sleep onset [22]. Following these periods there is potential for sleep loss and neurocognitive and physiological performance to be compromised [7, 14, 23, 24]. Thus, since sleep disruption prior to important events are commonly found in elite athletes [25-27], there are numerous instances where the subsequent performance could be compromised [25, 28, 29].

However, due to the complexity of sleep function, limited availability of athletes to participate in sleep studies and the variability in the individual requirement for sleep [21, 30], the effects of sleep loss on athletic performance are poorly understood. Furthermore, the increase in recent literature since past reviews [21, 31, 32] highlights a need to re-evaluate the effects of sleep loss on athletic performance, in particular allowing for a greater focus on sport-specific outcomes. Accordingly, the overall purpose of this review is to examine the effects of sleep loss on exercise performance, and physiological and cognitive responses to exercise. As a result, this communication reviews the current literature on the theoretical components of sleep and importance for athletes, the quality and quantity of 'normal' sleep compared to athletes, and the effects of sleep loss on exercise performance and physiological and cognitive responses (including mood) to exercise. In order to accomplish this critical review a computerised literature search (Figure 1) was performed over ~~a period of~~ seven months (August 2013 – ~~February~~ March 2014) on Pub Med and Web of Science for articles within the period January 1960-March 2014. Keywords used in different combinations were "sleep", "deprivation", "loss", "restriction", "team", "exercise", "cognition", physiological", "sport", "athlete", "player" and "performance". In addition, articles were sourced manually from the reference lists of original manuscripts, and previous critical, systematic and meta-analytical reviews. The previous work within this field, and the multi-dimensional components of sleep and their role in athletic performance, are duly recognised. Notwithstanding these critical components, their roles are too extensive to be discussed here. The reader is advised to consult previous work regarding the effects of nutrition [14], jetlag [13, 33, 34] and Ramadan [35] on sleep for further detail.

INSERT FIGURE 1

## 2. The theoretical components of sleep and their importance for athletes

A recent review by Frank [8] identified several theories of the function of sleep, including: 1) the restorative effects on the immune and the endocrine systems, 2) a neurometabolic theory suggesting that sleep assists in the recovery of the nervous and metabolic cost imposed by the waking state, and 3) cognitive development, supposing that sleep has a vital role in learning, memory, and synaptic plasticity. An interaction between these theories is likely to contribute to the construct of several stages during sleep [8]. These respective stages not only differ in depth, but also in the frequency and intensity of dreaming, eye movements, muscle tone, regional brain activation and communication between memory systems [36]. A typical night's sleep is composed of approximately 90 min cycles divided into periods of rapid-eye-movement sleep (REM; associated with dreams), and non-REM sleep (NREM) [37]. NREM sleep is further divided into four different stages (Figure 2). All stages are classified according to parameters such as electrical brain activity, blood pressure, and eye movement [38, 39].

Specifically, the role for NREM sleep is proposed to assist with energy conservation and nervous system recuperation. For example, it has been shown that growth hormone (GH; fundamental to tissue regeneration and growth) is released [40] and oxygen consumption is lowered [41] during phases of NREM sleep. Moreover, NREM sleep seems to be a stimulus for anabolic hormones that increase the synthesis of protein and mobilise free fatty acids to provide energy, thereby preventing amino acid catabolism [42]. Such processes would seem particularly pertinent for athletic populations requiring accelerated rates of healing to repair peripheral muscular damage [43]. Comparatively, theories of REM sleep have suggested a role for this state in periodic brain activation, localized recuperative processes and emotional regulation [44]. Especially in the early stages of mammalian life, REM sleep is assumed to be critical in establishing brain connections [44], since neuronal activity is similar to waking in REM sleep [45]. Hence, sleep can be rather defined as an actively regulated process than a passive result of diminished waking, and can be seen as a reorganisation of neuronal activity [45].

The importance of sleep in athletes has also been discussed in regards to memory consolidation, especially to motor learning. REM, NREM stage 2 and slow-wave (SWS) sleep have all been implicated in sleep dependent memory procession [36]. For example, several studies showed improvements in motor task tests after a night of sleep, whereas this was not the case in subjects having an equivalent period of being awake [36, 46-48]. Since sleep loss reduces the overnight improvement in motor learning, it seems that motor task learning may correlate with the amount of specific sleep stages/events, rather than just one specific aspect of sleep [36]. With the ongoing motor learning and cognitive adaptation required for elite athletes to perform [49], combined with the numerous neurocognitive components of many sports [50], it seems ascertaining an optimal brain state for a range of distinct memory consolidation processes are pertinent for athletes prior to and following competition [49].

INSERT FIGURE 2

## 3. What is the quantity and quality of 'normal' sleep and how do athletes compare?

### 3.1 What is 'normal' sleep?

Subjective average total sleep duration has fallen in healthy adults since the mid-20th century from approximately 8-9 h per night in 1959 to 7-8 h in 1980 [51]. In a nationwide survey of the United States in 2013, data indicate adults slept for an average of 6 h:51 min on 'workdays' and 7 h:37 min on 'non-workdays' [52]. A mean 7 h:17 min total sleep time was required for respondents to 'operate at their best the next day' [52] which corresponds with the 7-9 h recommended by the National Sleep Foundation for healthy sleep [51-53]. Despite such recommendations, almost a quarter of adults who have similar sleep durations to these recommendations reported 'fairly-very bad' subjective sleep quality [52]. Others have reported that university/college students demonstrate even poorer patterns of sleep than other healthy adults. Many studies indicate this cohort suffers from chronic sleep problems and disruptions [54-56], with some adolescent athletes sleeping 2 h less than recommended daily sleep volumes [57]. These discrepancies are attributed to the rising melatonin levels of the adolescent cohort [58] and the rapid advances of 21st century technology prolonging human exposure to light [59-61]. Overall, sleep architecture, quality and quantity varies drastically across individuals and occupations [62], mainly due to a vast array of physiological and cultural differences [63, 64]. Such variety makes the interpretation of generic sleep recommendations (7-9 h, abide by sleep hygiene protocols to optimise sleep quality; [51, 52, 65]) difficult, especially for athletes [30].

### 3.2 Sleep in athletes

Since both athletes and coaches rate sleep as critical to optimal performance [14, 25], it is peculiar that relatively few studies have investigated the sleep quality and quantity of the athletic cohort. Early research suggests athletes possess similar or even superior sleep quality and quantity than nonathletic subjects [66, 67], with aerobically fit subjects tending to experience more SWS sleep and longer sleep duration than non-fit controls [68]. However, these findings may have been due to the enduring habitual, genetic and behavioural patterns of sleep, rather than the greater endurance status *per se* [15, 69]. Regardless, the longer sleep duration found in certain aerobically fit individuals has been attributed to the restorative and energy conservation theories for sleep (e.g. athletes require greater recovery; [69, 70]. Accordingly, some authors suggest athletes should sleep for between 9-10 h [71], whilst 7-9 h is recommended enough for healthy adults [51, 52]. Recent evidence suggests athletes sleep far less than either of these recommendations [72]. For example, a survey of 890 elite South African athletes showed that three quarters of athletes reported an average sleep duration between 6-8 h per night [73], while on weekends 11% reported sleeping less than 6 h. Moreover, 41% stated they had problems falling asleep, with these discrepancies attributed to interference by noise and light [25, 74]. Additionally, pre-competition anxiety can also play a role in worsening sleep patterns [26, 75, 76]. For instance, sleep quality [76], efficiency [77] and duration [78, 79] have all been found to dramatically decrease just prior to competition. Juliff and colleagues found that within a sample of 283 elite Australian athletes, 64% reported poor sleep prior to an important competition [27]. The primary reasons for these poor sleep patterns could be due to nervousness, deteriorations in mood and/or confidence [80] and elevations in physical and mental stress [77].

Recently, Leeder et al. [81] found Olympic athletes slept for a lower mean total duration (6 h:55 min compared to 7 h:11 min using actigraphy) and had poorer sleep quality compared to non-athletic controls. Given the short sampling period (4 d), it is difficult to generalise the findings from this study to all athletes; however there is supportive evidence of training disrupting sleep quality and duration in other athletes. For instance, Taylor and colleagues [80] reported training volume to alter movements during sleep (greater movements were found; defined as occupying ≥ 4 s of any 20 s epoch within the polysomnographic recording [80]). The effect of training volume on sleep patterns is supported by others [82, 83], with early-morning training severely restricting sleep duration compared to normal (5.4 h to 7-8 h) in a group of world-class swimmers [72]. In addition to exercise volume, intensity may also negatively affect sleep, with a recent study reporting increases in sleep onset and physiological excitement following high-intensity exercise conducted prior to bed time (40 min treadmill running at 80% heart rate reserve commencing at 21h:20) compared to a non-exercise control condition in active young men [84]. Other possible disruptions of athletes' sleep include altitude, which appears to disrupt REM sleep and impair breathing [85]. Disrupted sleep is also prevalent in numerous extreme adventure and boat sports [86-88]. Despite these findings, further evidence of the sleeping patterns of elite athletes during various scenarios is very rare within the current literature. In summary, the sleep patterns of athletes remain unclear, mainly due to a vast array of physiological differences [63, 64], training [80, 89] and competition [26, 27] stressors. More research is required to assess the sleeping patterns of elite athletes across various scenarios which could potentially influence subsequent performance.

## 4. Effects of sleep loss on exercise performance and physiological and cognitive responses

Sleep restriction (SR) occurs when humans fall asleep later or wake earlier than normal; that is, their normal sleep wake cycle is partially disturbed [90]. In contrast, sleep deprivation (SD) generally refers to extreme cases of sleep loss, whereby humans do not sleep at all for a prolonged period (i.e. whole nights) [90]. The following sections of this article will review the effects of sleep loss (restriction and deprivation) on exercise performance (Table 1), and physiological (Table 2) and cognitive (Table 3) responses to exercise. However, due to an abundance of conflicting results some of the effects of sleep loss on these indices remain uncertain. These varied results are mainly attributed to differences in exercise protocols, participants' fitness and the experimental environment. For instance, variations in thermoregulatory responses, habituation to sleep loss and the time of day activities are performed have a complex interaction with exercise performance [65, 91, 92], and thus may potentially mask the effects of sleep loss [93]. Furthermore, being unable to blind subjects can potentially result in nocebo effects [94].

### 4.1 Sleep loss and exercise performance

#### *4.1.1. Sleep restriction and exercise performance*

Early work from Mougin et al. [95] found no effects of a partially disrupted night's sleep (3 h of sleep loss in the middle of the night) on the maximal sustained exercise intensity during incremental cycle ergometry (20 min at 75% maximum oxygen uptake ($VO_{2max}$) followed by 10 watt (W) increase every 30 s ). The same authors [96] found also no change in mean or peak power or peak velocity during a Wingate cycling test after similar SR compared to normal baseline values in highly trained participants. With regard to more prolonged running exercise modes, Reilly and Deykin [97] reported no decrements in endurance running performance (time to exhaustion) following partial sleep loss (3 h of sleep per night for three nights). Furthermore, the total distance covered in a YoYo intermittent-recovery test level one was not different following SR [98]. In contrast to this maintenance of exercise performance, maximal work rate has been found to decrease (~15 W decrease following SR) during incremental cycling to exhaustion (30 min at 75% $VO_{2max}$ followed by 10 W increase every min [99]). Similarly, mean and peak power during Wingate anaerobic cycle tests have been shown to decrease in students [100], footballers [101], and judo competitors [92] following 4 h of SR for one night. Theories on the reasons for this restricted exercise tolerance following SR are attributed to either the impairment of aerobic pathways [102] or perceptual changes (i.e. increased perceived exertion), as physiological responses often remain largely unaltered [94, 103]. Indeed, increases in perceived effort accompanied by a reduction in power output would support neuromuscular causes of fatigue [104], possibly indicating an association between a reduction in central drive and the neural theory of sleep [36, 103, 105]. However, studies investigating perceived effort following SR report mixed results [98, 106, 107], so such theories remain unclear. These conflicting results are attributed to a large body of evidence reporting a vast array of effects on emotional regulation (i.e. mood) following SR [106, 108-111]. Indeed, variations in perceived effort are likely a result of these emotional modifications [112]. Given the widespread use of rating of perceived exertion in monitoring the training load of elite athletes [113, 114], further research is required to investigate the interaction between these responses to standardised training or match stimuli following sleep loss.

Similar to maximal aerobic demands, a variety of conclusions have been reported for the effects of SR on muscular strength and power. Studies have shown back and grip strength are maintained following SR [93]. In contrast, others have demonstrated 3 h of nocturnal SR to negatively affect both maximal and submaximal weightlifting tasks, with greater effects on the submaximal tasks [106]. Given the high motivational component of weightlifting, this decline in work rate was attributed to the coinciding decline in mood state. However, whilst these perturbations in submaximal work outputs may be due to fluctuations in mood state, or even neurological alterations [104], the central and local muscular fatigue mechanisms behind such outcomes remain unknown [106]. Collectively, these observations indicate that whilst athletes may be able to perform singular, maximal efforts following SR, it is unclear whether they are able to cope with repeated bouts of physical activity such as those required during intensive training or matches [21].

INSERT TABLE 1

An example of the susceptibility of sport-specific performance following SR in athletes is the reduction in sport-specific skill execution in dart players [115], tennis players [116] and handball goalkeepers [117]. In contrast, swimming performance (lap times) did not differ between SR (2.5 h of sleep per night for four nights) and normal sleep for 8 trained swimmers [111]. These differing findings could be attributed to the additional cognitive dimension of the aforementioned fine motor skills. For instance, since loss of sleep can result in reductions in decision making and accuracy (see section 4.3), SR would presumably be more likely to affect sports performance incorporating a high cognitive reliance (i.e. fine motor movements in the serve accuracy of a tennis player [116]) rather than one involving gross-motor execution (i.e. the stroke rate of a swimmer [111]). Furthermore, since professional sport comprises many environmental components which can influence sleep [14], it has been argued athletes may be more susceptible to performance decrements following SR than normal healthy participants [81], although this is debated [69, 81, 118, 119].

Overall, the effects of SR on exercise performance are mixed. SR does not appear to affect singular bouts of aerobic performance (neither endurance running nor cycling modes for 20-30 min) or maximal measures of strength, although admittedly conflicting results still exist. A possible reason for this discrepancy is that many studies reporting no effect of sleep restriction on endurance exercise have sample sizes less than ten participants (e.g. [97, 99], Table 1), making it difficult to extrapolate the results of these studies due to the underpowered nature of the study. In contrast, sports-specific skill execution, submaximal strength and muscular and anaerobic power seem to decline following SR. Given these findings, whilst it seems that SR impedes some aspects of athletic performance; it is still not clear whether sleep is critical to performance for *all* athletes who experience small one-off SR periods.

### *4.1.2 Sleep deprivation and exercise performance*

Similar to SR, the effects of total SD on exercise performance are varied [120]. Mean time to exhaustion for prolonged treadmill walking (80% of $VO_{2max}$) is reduced by ~11% following 36 h of SD [94]. These results are supported by other studies highlighting reduced time to exhaustion (mean ~20% [121]) during incremental exercise protocols following SD [122]. In addition, mean distance covered has been found to decline (6224 to

6037 m) following SD during 30 min of self-paced treadmill running [123]. It appears time to exhaustion decreases because of either perceptual changes or reductions in arousal and impaired muscle fibre coordination (e.g. decreases in vertical jump performance and knee extension torque [124]) following prolonged SD, although the mechanisms behind this are unclear [94]. Indeed, it is proposed increased muscular and central fatigue is unlikely to explain decreases in prolonged exercise performance following SD [112]; however this warrants further investigation.

Despite the popularity of sports that require high intermittent-sprint performance (i.e. team sports [125]), there is a relatively poor understanding of the effect of SD on these activities. Skein et al. [126] recently reported slower mean sprint times, reduced muscle glycogen concentration, voluntary force and activation during maximal isometric knee extensions along with an increased perceptual effort following 30 h of SD in ten team-sport athletes [126]. Similarly, several other studies have shown the detrimental effects of SD on muscular strength [30, 124, 127], power [128] and speed [129]. In contrast, Symons et al. [130] reported no effect of 60 h of SD on a range of muscular and submaximal isometric strength tests. Indeed, several studies have shown that grip strength performance is maintained regardless of the amount of sleep loss [131, 132] and shuttle runs scores remain unaffected [133]. Indeed, submaximal strength tasks may be more susceptible to SD than maximal tasks due to the sustained effort required to complete the task, whereby perception of effort could increase exponentially with time to task completion [123]. In addition, differences in reported muscle contractility (i.e. voluntary activation) between studies could be explained by the sensitivity and accuracy of electromyography measurements. Older studies (i.e. [130, Table 1]) may have been limited in comparison to the equipment used in recent research [126, 134].

In summary, although the effect of SD on exercise performance remains somewhat unclear, there appears sufficient evidence to imply SD can have a significant effect on aspects of athletic performance. This seems particularly pertinent for time to exhaustion in running activities lasting longer than 30 min. Nonetheless, whilst these studies reveal important physiological mechanisms, conceptually it is debatable whether the findings are applicable to elite athletic populations given it would be rare for an athlete to endure a night(s) of complete total SD.

## 4.2 Sleep loss and physiological responses to exercise

### *4.2.1 Sleep restriction and physiological responses to exercise*

Examples of the susceptibility of physiological responses to exercise following SR are the increase in heart rate, minute ventilation and plasma lactate concentration during submaximal and maximal exercise after a partially disrupted night's sleep (3 h of sleep loss in the middle of the night) [95]. These responses are attributed to the increased metabolic demand [135], perceived effort [94] and catecholamine concentrations following SR [136]. This could be interpreted as SR acting as an additional stress to the stress imposed by exercise itself [137]. In contrast, Martin and colleagues [138] showed that two nights of fragmented sleep (eight 'wake up' calls ranging 30-75 min) had no significant effect on heart rate, oxygen consumption, minute ventilation and core body temperature during 30 min of heavy treadmill walking. Similarly, these findings support other results, suggesting no alterations to physiological responses following SR i.e. lung function and power unaffected by minor sleep loss [97, 111]. Whilst the error sensitivity across metabolic collection systems could perhaps explain some differences across studies [139-142], these differences are perhaps more attributable to the exercise mode and protocol administered (running [98] versus cycling [95]; free-paced exercise [111] versus time to exhaustion [102]).

Although various hormonal concentrations (e.g. plasma cortisol) will typically increase during exercise-induced stress, the interaction between these responses and sleep loss is inconclusive [31]. For instance, there have been reports by some [99, 143], but not all [138, 144, 145] studies that cortisol concentration might be lowered following sleep loss. These varied results are likely attributed to the fact that cortisol secretion is dependent on the timing, intensity and duration of the stimulus [146] and is highly driven by circadian rhythms [147]. As an example of the sensitivity of hormonal and additionally immune responses to SR and exercise stimuli, GH, prolactin and interleukin-6 (IL-6) have been shown to increase following SR and 4 x 250-m treadmill runs at 80% maximum speed [101]. This is supported by findings of next-day increases in IL-6 (three-fold) and tumor necrosis factor (TNF-α; two-fold) following SR [148], although others have reported these variables to remain unchanged at rest [149]. Since increases in these pro-inflammatory cytokines (e.g. IL-6; mean 4.11 ±SD 0.99 $pg.ml^{-1}$ rising to 5.44 ±1.1 $pg.ml^{-1}$ [144] and TNF-α [143] following SR and exercise)) might be associated with unfavourable metabolic profiles [143] and inflammatory disease risk [147, 150], there is concern about obtaining sufficient quality and duration of sleep in all individuals from an overall health perspective [14, 143].

### *4.2.2 Sleep deprivation and physiological responses to exercise*

Energy substrate balance appears vulnerable to sleep loss, with 30 h of SD shown to blunt the full restoration of muscle glycogen stores in team-sport athletes [126]. Without adequate intake, this could hinder the ability of athletes to compete for sustained periods, as muscle glycogen shortage is known to reduce muscle function and total work capacity [3, 151]. Indeed, energy imbalances are associated with SD, potentially leading to decreased aerobic and anaerobic power production [21, 152]. Prolonged periods of SD (36 h) are further associated with increased sympathetic and decreased parasympathetic cardiovascular modulation, and spontaneous baroreflex sensitivity during sitting and vigilance testing in healthy adults [153]. Since disruptions to the sympathetic-parasympathetic balance are associated with overtraining [154], it is possible these disturbances to the autonomic nervous system following SD could support the development of an overreaching or overtraining status [3, 155]. Indeed, of importance to athletes, maintaining this autonomic balance is critical for producing optimal performance [156]. Notwithstanding this, most [94, 103, 122], but not all [122] studies have reported that SD does not alter cardiorespiratory variables during incremental exercise (e.g. $VO_{2max}$, minute ventilation). Further to these results, there were no significant effects on cardiorespiratory or thermoregulatory function despite a reduction in distance covered during 30 min of self-paced treadmill running following SD [123]. Taken with other results [94, 123, 157, 158], these findings suggest that SD has minimal effect on cardiorespiratory function during intermittent submaximal exercise, despite observations of a reduction in performance. Oliver et al. [123] hypothesise this could be due to the influence of the perception of effort during the end stages of prolonged high-intensity exercise. More extreme periods of sleep loss (100 h without sleep), are more likely to negatively affect cardiorespiratory variables compared to acute SD (24-36 h) [159].

Similar to the effects of SR, the effects of SD on hormonal and endocrine responses to exercise are unclear. It has been shown that SD (50 h) does not affect blood parameters such as blood lactate, epinephrine, norepinephrine and dopamine during treadmill walking to exhaustion [121], nor in cases where subjects exercised (28% $VO_2$ max for 1 h every 3 h for 64 h of SD) during the SD period (i.e. blood lactate concentration (12.1 vs. 11.8 $mmol.l^{-1}$) [160])). However, such responses are heavily influenced by circadian fluctuations [40], making the effect of SD on these parameters difficult to determine. Interestingly, these two studies [121, 160] and others [138]~~,~~ which reported no differences in hormonal and endocrine~~endocrinal~~ responses to exercise following SD used constant exercise protocols, whereas two studies that reported significant changes following SR ~~protocols compared to two studies which reported significant changes following SR~~ [95, 99] utilised incremental tests to exhaustion~~whom utilised incremental tests to exhaustion~~. Thus, the variable load at the end of exercise appears to increase~~s~~ the final stress-related response. The response of blood-cortisol concentrations to SD are similar to SR, with inconsistent findings presented [138, 149, 161]. Theoretically, if increased cortisol concentrations do occur [161], this could lead to increased muscle catabolism and a reduction in protein synthesis [3]. As such, this would lend support to the restorative theory that sleep is required for muscular recovery [162]; however such hypotheses require further research for clarification. For instance, whilst SD can initially blunt the secretion of GH [163], possibly hindering growth [42] and recovery [162], this deficiency is compensated for by increasing GH secretion during waking hours [164].

INSERT TABLE 2

### 4.3 Sleep loss, cognitive performance and mood responses

Numerous studies report that when sleep is reduced to less than 7 h in healthy adults, cognitive performance is poorer in tests for alertness, reaction time, memory and decision making [23, 109, 165-170]. Heightened levels of sleepiness, depression, confusion and poorer overall mood states have also been reported [171-174]. Decrements in cognitive performance have previously been attributed to disruptions to pre-frontal cortex functioning, as cognitive deficiencies which occur outside this area of the brain malfunction in qualitatively different ways [169]. Recently, a more universal effect of sleep disruption on cognition has been proposed [175], due to the sensitivity of cognitive performance to both arousal (not limited to pre-frontal activity) and attention in a sleep disrupted state [166]. The neuroanatomical mechanisms behind this state are intricately complex [176]. For instance, when the quality and quantity of human sleep is reduced, it appears the largest decreases in cerebral metabolism (compared to the awake-rested state) are apparent in the thalamus, cerebellum and prefrontal, posterior parietal, and temporal cortices [176, 177]. The reduced metabolic rates within these regions have been correlated with decreased cognitive performance [178, 179], highlighting their influence on optimum cognitive functioning [176, 180]. Based on these collective findings, some support suggested sleep benefits from models related to neural mechanisms, rather than peripheral tissues [103].

### *4.3.1 Cognitive performance and mood responses following sleep restriction*

As an example of the sensitivity of cognitive function to sleep disruption, simple reaction time (RT) has been shown to increase in individuals following 1 h of SR for two nights [108] and 4 h per night for five nights [109]. In addition, Jarraya et al. [117] found increases in RT and decreases in selective and constant attention in 12 handball goalkeepers following 4-5 h of SR at both the beginning and end of the night [117]. With RT slower following even minor disruptions to both sleep quality [108] and duration [117], it would seem pertinent for athletes with a high reliance on this cognitive component to ensure optimum sleep conditions prior to competing (e.g. baseball, cricket). This may be particularly challenging for baseball teams who play more than 80 away matches per season, where sleep conditions will change on an almost daily basis. These recommendations might be extrapolated to a host of individual and team-sport athletes, as many sports also involve critical decision making [181, 182], which is also susceptible following SR [169]. Although the majority of literature supports the impairment of decision making following sleep loss [169], others have reported no effects [183]. Khazaie et al. [183] reported no change in abstract reasoning, time reproduction skills or decision-making ability in 26 sleep-restricted (< 6 h sleep for five nights) medical residents. Whilst this was most likely due to a lack of an effect of partial SR on pre-frontal cognition or the interaction between the type of SR and type of cognitive task, it does show that optimum sleep may not always be critical for maintenance of decision-making performance over an acute period.

INSERT TABLE 3

The understanding of the effect of SR on memory and recall is also equivocal with some authors reporting decrements in short-term memory following SR [184], whilst others report no change [185]. For instance, Drummond et al. [185] found no changes in visual working memory or filtering efficiency following 3.5-4 h of sleep. Whilst SR is unlikely to affect elite players' memory of *how* a (motor) skill is executed, it could potentially affect the recall and understanding of tactical awareness or positioning. From this perspective, it seems sufficient sleep should be obtained following training sessions, as the perceptual and motor learning processes continue into and throughout subsequent sleep [186]. Another example of the detrimental effects of SR on cognitive performance is the plethora of evidence which reports poorer mood states after SR, with decreases in vigour along with increases in depression, sleepiness and confusion [106, 109, 115, 172, 187]. These negative mood states have been linked to overreaching and overtraining [188-190]. Indeed, this increase in psychological fatigue following SR would appear to create a neurocognitive state not conducive for either engaging in physical activity requiring a high motivational component or employing optimal decision making; however such concepts still require further substantiation.

### *4.3.2 Cognitive performance and mood responses following sleep deprivation*

The effects of SD on cognitive performance are quite clear with many studies showing that greater total sleep loss results in poorer overall mood states with increased fatigue, sleepiness, confusion and decreased vigour [30, 138, 191], liveliness [126] and heightened depression [192]. In addition, decreases in logical reasoning, coding, decision making and filtering efficiency have also been reported [185, 191, 193]. The speed and accuracy at which these tasks are performed are also negatively affected by SD [194, 195]. Moreover, previous studies show participants perform poorer in tests for auditory vigilance [192], simple and complex reaction time [191, 192, 196] and memory [175, 194, 197, 198] following complete sleep loss. Limited data is available for cognitive functioning during sporting events, although during extreme sports (i.e. long-haul yacht racing), it appears cognitive impairments present following extensive SD [86]. These findings potentially have severe repercussions for athletic performance (Table 4). Nonetheless, conflicting results do exist with no significant differences in simple and complex responses to an altered Stroop test for decision making during 96-125 h of adventure racing (~100 h of SD [199]). These differences are most likely attributable to the intra-individual variability in personality and mood state and sleep requirement, in addition to sample size and task familiarity [200]. For instance, Edinger et al. [201] found vastly different responses for sleepiness and mood when investigating the daytime functioning of two players during a 146 h marathon tennis match. Indeed, humans are sometimes unaware of their increasing cognitive deficits and declining neurobehavioral function following SD [65]. In summary, SD results in relatively unequivocal decrements in most aspects of cognitive function and mood responses.

INSERT TABLE 4

## 5. **Future Research**

Currently, there is insufficient evidence to clarify the importance of sleep for athletes and the effects of sleep loss on exercise performance, alongside physiological and cognitive responses to exercise.  Indeed, more research is required to confirm what dimensions of exercise performance are affected by sleep loss, especially those with a focus on repeated bouts of intermittent exercise and sport-specific performance. Admittedly, very little of the current literature has been conducted in team-sport athletes making the extrapolation of assumptions regarding sleep and performance to team sports difficult. Furthermore, there is little to no statistical analysis in the majority of previous studies with regard to magnitudes of effect, which may cloud some statistical inferences as to the effect on performance with respect to practical relevance [202]. Moreover, the majority of studies which assess the effect of sleep loss on athletic performance are those involving SD, a scenario which is very rare in real-world scenarios. For athletes, it would seem more pertinent in future research to investigate the effect of SR on parameters related to athletic performance. Future research may also focus on the interaction between sleep and acute and chronic training adaptations. Further research is also required to confirm if reduced sleep in elite athletic populations is associated with illness and injury occurrence, and whether such disturbances can partly explain the overtraining state. Preliminary evidence indicates that athletes who are at least functionally overreached present with sleep disturbances and illness prevalence during high-volume training [203]. From a purely scientific perspective, it is pertinent certain factors are considered in future endeavours when defining the effect of sleep on athletic performance within an experimental protocol [21, 204], including isolating homeostatic and circadian components, utilising an externally valid competitive event and minimising the many confounding variables which affect sports performance [205].

## 6. Practical recommendations

The following recommendations (Table 5) are based on the literature within this review. However, the authors recognise that given the equivocal findings for most summaries, future research is required to confirm these recommendations. Most importantly, it is recommended to understand the intra-individual differences with regards to sleeping patterns. Practitioners should strive to identify where sleep problems exist, and if necessary employ ethical interventions. If problems persist, these should be dealt with by medical professionals [7]. Whilst there are numerous examples of the interaction between sleep and performance which may aid practitioners, there is little literature confirming the importance of sleep to physiological and psychological recovery. In particular, evidence of the role and importance sleep plays within the professional sporting environment during various scenarios is lacking. Thus, although sport science personnel and researchers should be aware of the complex effects of sleep loss on athletic performance, such knowledge needs to be supplemented with sufficient understanding of sleep's role in recovery, and possible sleep hygiene strategies to alleviate these issues. Accordingly, future examination of the evidence of sleep and the potential role it may play in recovery for athletes is warranted.

INSERT TABLE 5

## 7. Conclusion

Although sleep is generally considered critical for human and athletic performance, there are mixed results regarding objective performance decrements in the current scientific literature. Individual athletes appear to lose sleep just prior to competing or if forced to train at early times; however evidence for such instances in team sports is lacking. Exercise performance seems to be negatively affected during periods of SD (specifically endurance and repeated exercise bouts), although conflicting results exist for the effect of acute SR, as performance during maximal one-off efforts (in particular for maximal strength) is generally maintained. Possible reasons for these differences could be due to contrasting research designs and statistical power. The effects of sleep loss on physiological responses to exercise could potentially hinder muscular recovery and lead to a reduction in immune defence, although this still remains speculative. The majority of studies focussing on sleep loss and cognitive performance and mood responses have found detriments to most aspects of cognitive function (i.e. reaction time) and mood stability, results which potentially could hinder the neurocognitive components of many sports. Despite common assumptions of the importance of sleep, the lack of scientific evidence (especially in elite athletes) suggests future research into the examination of sleep and athletic performance is warranted.

## Acknowledgements

No funding was provided which contributed to the development of this manuscript. The authors declare that there are no conflicts of interest. Hugh Fullagar is supported by a “Science and Health in Soccer” scholarship funded by the DAAD (German Academic Exchange Centre). The preceding manuscript is a critical review of the literature, thus does not include any original research pertaining clinical studies or patient data that required ethical approval. However, both affiliated institutions were aware of the construction of this manuscript and supported such a practice. This critical review was conducted in good faith and in accordance with best current practice, whereby the quality, suitability and significance of each article was evaluated by the experience and expertise of the body of authors prior to final collection and reporting.

## Figure Legends

Figure 1: Flow diagram and results of the literature search to address the aim of the article to evaluate the importance and prevalence of sleep in athletes and review the effects of sleep loss on exercise performance, and physiological and cognitive responses to exercise.

Figure 2: The behavioural states of humans and phase changes throughout the sleep wake cycle, including states of waking, non-rapid-eye-movement sleep (NREM sleep) and rapid-eye-movement sleep (REM). The first row depicts a visual representation of movements throughout the sleep night. The second row illustrates REM sleep and the four stages of NREM sleep. The third row includes sample polysomnography tracings (each ~ 20 s) of an electromyogram (EMG), an electroencephalogram (EEG) and an electrooculogram (EOG) to help determine the presence or absence of each stage. Rows four, five and six portray a range of subjective and objective state variables. Although unable to replicate the sensitivity of these measurement techniques, other sleep indices (i.e. duration, latency) can also be measured by subjective sleep diaries and or/ wristwatch actigraphy. Reproduced from Hobson [45], with permission.

## References

1. Allada R, Siegel JM. Unearthing the phylogenetic roots of sleep. Curr Biol. 2008;18:R670–R9.

2. Beersma DGM, Gordijn MCM. Circadian control of the sleep–wake cycle. Physiol Behav. 2007;90(2-3):190-5.

3. Le Meur Y, Duffield R, Skein M. Sleep: In recovery for performance in sport Champaign, IL: Human Kinetics; 2012.

4. Reilly T, Waterhouse J. Sports performance: is there evidence that the body clock plays a role? Eur J Appl Physiol. 2009;106(3):321-32.

5. Archer SN, Laing EE, Moller-Levet CS, et al. Mistimed sleep disrupts circadian regulation of the human transcriptome. Proc Natl Acad Sci U S A. 2014.

6. Davenne D. Sleep of athletes – problems and possible solutions. Biol Rhythm Res. 2009;40(1):45-52.

7. Samuels C. Sleep, recovery, and performance: The new frontier in high-performance athletics. Neurol Clin. 2008;26(1):169-80.

8. Frank MG, Benington JH. The role of sleep in memory consolidation and brain plasticity: dream or reality? The Neuroscientist. 2006;12(6):477-88.

9. Crocker A, Sehgal A. Genetic analysis of sleep. Genes Dev. 2010;24:1220–35.

10. Abel T, Havekes R, Saletin JM, et al. Sleep, plasticity and memory from molecules to whole-brain networks. Curr Biol. 2013;23:774-88.

11. Xie L, Kang H, Xu Q, et al. Sleep drives metabolite clearance from the adult brain. Science. 2013;342:373-7.

12. Czeisler CA, Brown EM. Commentary: models of the effect of light on the human circadian system: current state of the art. J Biol Rhythms. 1999;14(6):539-43.

13. Samuels C. Jet lag and travel fatigue: a comprehensive management plan for sport medicine physicians and high-performance support teams. Clin J Sport Med. 2012;22:268-73.

14. Halson SL. Nutrition, sleep and recovery. Eur J Sport Sci. 2008;8(2):119-26.

15. Sehgal A, Mignot E. Genetics of sleep and sleep disorders. Cell. 2011;146(2):194-207.

16. De Gennaro L, Marzano C, Fratello F, et al. The electroencephalographic fingerprint of sleep is genetically determined: a twin study. Annu Neurosci. 2008;64:455–60.

17. Bishop D. An applied research model for the sports sciences. Sports Med. 2008;38(3):253-63.

18. Drust B, Waterhouse J, Atkinson G, et al. Circadian rhythms in sports performance: an update. Chronobiol Int. 2005;22:21-40.

19. Reilly T, Waterhouse J. Sport, exercise and environmental physiology. Edinburgh: Elsevier; 2005.

20. Czeisler CA, Allan JS, Strogatz SH, et al. Bright light resets the human circadian pacemaker independent of the timing of the sleep-wake cycle. Science. 1986;233(4764):667-71.

21. Reilly T, Edwards B. Altered sleep–wake cycles and physical performance in athletes. Physiol Behav. 2007;90(2-3):274-84.

22. Lack LC, Wright HR. Chronobiology of sleep in humans. Cell Mol Life Sci. 2007;64(10):1205-15.

23. Durmer J, Dinges DF. Neurocognitive consequences of sleep deprivation. Semin Neurol. 2005;25(1):117-29.

24. Banks S, Dinges DF. Behavioral and physiological consequences of sleep restriction. J Clin Sleep Med. 2007;3(5):519-28.

25. Venter RE. Perceptions of team athletes on the importance of recovery modalities. Eur J Sport Sci. 2014;14:S69-S76.

26. Erlacher D, Ehrlenspiel F, Adegbesan OA, et al. Sleep habits in German athletes before important competitions or games. J Sports Sci. 2011;29(8):859-66.

27. Juliff LE, Halson SL, Peiffer JJ. Understanding sleep disturbance in athletes prior to important competitions. J Sci Med Sport. 2014:[Epub ahead of print].

28. Hanton S, Fletcher D, Coughlan G. Stress in elite sport performers: A comparative study of competitive and organizational stressors. J Sports Sci. 2005;23(10):1129-41.

29. Lastella M, Lovell GP, Sargent C. Athletes' precompetitive sleep behaviour and its relationship with subsequent precompetitive mood and performance. Eur J Sport Sci. 2014:1-8.

30. Meney I, Waterhouse J, Atkinson G, et al. The effect of one night’s sleep deprivation on temperature, mood, and physical performance in subjects with different amounts of habitual physical activity. Chronobiol Int. 1998;15(4):349–63.

31. Van Helder T, Radomski M. Sleep deprivation and the effect on exercise performance. Sports Med. 1989;7:235-47.

32. Pilcher JJ, Hoffcutt AI. Effect of sleep deprivation on performance: a meta-analysis. Sleep. 1996;19(4):318-26.

33. Leatherwood W, Dragoo J. Effect of airline travel on performance: a review of the literature. Br J Sports Med. 2013;47:561-7.

34. Waterhouse J, Reilly T, Atkinson G, et al. Jet lag: trends and coping strategies. The Lancet. 2007;369(9567):1117-29.

35. Drust B, Ahmed Q, Roky R. Circadian variation and soccer performance: Implications for training and match-play during Ramadan. J Sports Sci. 2012;30(sup1):S43-S52.

36. Stickgold R. Sleep-dependent memory consolidation. Nature. 2005;437:1272-8.

37. Shapiro CM. Sleep and the athlete. Br J Sports Med. 1981;15(1):51-5.

38. Lashley F. Measuring sleep. Sudbury, M.A.: Jones and Bartlett Publishers; 2004.

39. Lee-Chiong T. Sleep: A comprehensive handbook. New Jersey: John Wiley and Sons, Inc; 2006.

40. Weitzman ED. Circadian rhythms and episodic hormone secretion in man. Ann Rev Med. 1976;27:225-43.

41. Brebbia DR, Altshuler KZ. Oxygen consumption rate and electroencephalographic stage of sleep. Science. 1965;150:1621–3.

42. Sassin JF, Parker DC, Mace JW, et al. Human growth hormone release: relation to slow wave sleep and sleep-waking cycles. Science. 1969;165:513–5.

43. Gololobova MT. 24-hour rhythm of cell multiplication in rat epidermis during healing of skin wounds. B Exp Biol Med. 1961;50:188-22.

44. Siegel JM. Clues to the functions of mammalian sleep. Nature. 2005;437(7063):1264-71.

45. Hobson JA. Sleep is of the brain, by the brain and for the brain. Nature. 2005;437(7063):1254-6.

46. Walker MP, Brakefield T, Morgan A, et al. Practice with sleep makes perfect: sleep-dependent motor skill learning. Neuron. 2002;35(1):205-11.

47. Fischer S, Hallschmid M, Elsner A, et al. Sleep forms memory for finger skills. Proc Natl Acad Sci U S A. 2002;99(18):11987–91.

48. Huber R, Ghilardi M, Massimini M, et al. Local sleep and learning. Nature. 2004;430(6995):78-81.

49. Mahoney M, Avener M. Psychology of the elite athlete: An exploratory study. Cog Ther Res. 1977;1(2):135-41.

50. Moran A. The psychology of concentration in sport performers: a cognitive analysis. Hove: Psychology Press; 1996

51. Ferrara M. How much sleep do we need? Sleep Med Rev. 2001;5(2):155-79.

52. 2013 Sleep in America poll: Exercise and sleep. Crofton, MD: National Sleep Foundation; 2013.

53. Natale V, Adan A, Fabbri M. Season of birth, gender, and social-cultural effects on sleep timing preferences in humans. Sleep. 2009;32(3):423-6.

54. Yu Q, Ma W, Zou Y, et al. Impact of evening exercise on college students' sleep quality. Chin J Prev Med. 2013;47(6):542-6.

55. Hicks RA, Pellegrini R. The changing sleeping habits of college students. Percept Mot Skills. 1991;72:1106.

56. Hicks R, Fernandez C, Pellegrini RJ. Striking changes in the sleep satisfaction of university students over the last two decades. Percept Mot Skills. 2001;93(3):660.

57. Aerenhouts D, Zinzen E, Clarys P. Energy expenditure and habitual physical activities in adolescent sprint athletes. J Sports Sci Med. 2011;10:362-8.

58. Carskadon MA. Adolescent sleep patterns: Biological, social, and psychological influences. Cambridge, UK: Cambridge University Press; 2002.

59. Carney CE, Edinger JD, Meyer B, et al. Daily activities and sleep quality in college students. Chronobiol Int. 2006;23:623-37.

60. Shenghui L, Xinming J, Shenghu W, et al. The impact of media use on sleep patterns and sleep disorders among school-aged children in China. Sleep. 2007;30:361-7.

61. Derks D, van Mierlo H, Schmitz EB. A diary study on work-related smartphone use, psychological detachment and exhaustion: Examining the role of the perceived segmentation norm. J Occup Health Psychol. 2014;19(1):74-84.

62. Klerman EB, Dijk DJ. Interindividual variation in sleep duration and its association with sleep debt in young adults. Sleep. 2005;28:1253–59.

63. Aeschbach D, Cajochen C, Landolt H, et al. Homeostatic sleep regulation in habitual short sleepers and long sleepers. Am J Physiol. 1996;270:41–53.

64. Aeschbach D, Sher L, Postolache TT, et al. A longer biological night in long sleepers than in short sleepers. J Clin Endocrinol Metab. 2003;88:26-30.

65. Van Dongen HPA, Maislin G, Mullington JM, et al. The cumulative cost of additional wakefulness: dose-response effects on neurobehavioural functions and sleep physiology from chronic sleep restriction and total sleep deprivation. Sleep. 2003;2:117-26.

66. Porter JM, Horne JA. Exercise and sleep behaviour - a questionnaire approach. Ergonomics. 1981;24:511-21.

67. Shapiro CM, Catterall J, Warren P, et al. Lean body mass and non-rapid eye movement sleep. Br Med J. 1986;294:22.

68. Baekeland F, Lasky R. Exercise and sleep patterns in college athletes. Percept Mot Skills. 1966;23:1203-7.

69. Paxton SJ, Trinder J, Montgomery I. Does aerobic fitness affect sleep? Psychophysiology. 1983;20(3):320-4.

70. Shapiro CM, Bortz R, Mitchell D. Slow wave sleep: a recovery period after exercise. Science. 1981;214(11):1253-4.

71. Calder A. Recovery strategies for sports performance. USOC Olympic Coach E-Magazine 2003 [cited 2013 December 15]; Available from: http://coaching.usolympicteam.com/coaching/kpub.nsf/v/3Sept03

72. Sargent C, Halson S, Roach GD. Sleep or swim? Early-morning training severely restricts the amount of sleep obtained by elite swimmers. Eur J Sport Sci. 2014;14:S310-S5.

73. Venter RE. Role of sleep in performance and recovery of athletes : a review article. SA J Res Sport Phys Ed Rec. 2012;34(1):167-84.

74. Öhrstrom E, Skanberg A. Sleep disturbances from road traffic and ventilation noiselaboratory and field experiments. J Sound Vibr. 2004;271(1-2):279-96.

75. de Queiroz SS, Silva A, Winckler C, et al. Evaluation of the quality of sleep and chronotype of brazilian athletes: Paralympic Games in Beijing 2008. 3rd International Congress of the Association of Sleep Medicine: Sleep Medicine 2009. p. S04.

76. Silva A, Queiroz S, Winckler C, et al. Sleep quality evaluation, chronotype, sleepiness and anxiety of Paralympic Brazilian athletes: Beijing 2008 Paralympic Games. Br J Sports Med. 2012;46:150-4.

77. Fietze I, Strauch J, Holzhausen M, et al. Sleep quality in professional ballet dancers. Chronobiol Int. 2009;26(6):1249-62.

78. Forndran A, Lastella M, Roach GD, et al. Training schedules in elite swimmers: No time to rest? In: Zhou X SCE, editor. Sleep of different populations. Adelaide: Australasian Chronobiology Society; 2012. p. 6-10.

79. Anglem N, Lucas SJE, Rose E, et al. Mood, illness and injury responses and recovery with adventure racing. Wild Envion Med. 2008;19:30-8.

80. Taylor SR, Rogers GG, Driver HS. Effects of training volume on sleep, psychological, and selected physiological profiles of elite female swimmers. Med Sci Sport Exer. 1997;29(5):688-93.

81. Leeder J, Glaister M, Pizzoferro K, et al. Sleep duration and quality in elite athletes measured using wristwatch actigraphy. J Sports Sci. 2012;30(6):541-5.

82. Matos NF, Winsley RJ, Williams CA. Prevalence of nonfunctional overreaching/overtraining in young English athletes. Med Sci Sport Exer. 2011;43(7):1287-94.

83. Ingersoll C. Editorial sleep efficiency and overreaching in swimmers. J Sport Rehab. 2003;12(1):1-12.

84. Oda S, Shirakawa K. Sleep onset is disrupted following pre-sleep exercise that causes large physiological excitement at bedtime. Eur J Appl Physiol. 2014;114(9):1789-99.

85. Sargent C, Schmidt WF, Aughey RJ, et al. The impact of altitude on the sleep of young elite soccer players (ISA3600). Br J Sports Med. 2013;47(Suppl_1):i86-i92.

86. Hurdiel R, Van Dongen HPA, Aron C, et al. Sleep restriction and degraded reaction-time performance in Figaro solo sailing races. J Sports Sci. 2014;32(2):172-4.

87. Léger D, Elbaz M, Raffray T, et al. Sleep management and the performance of eight sailors in the Tour de France à la voile yacht race. J Sports Sci. 2008;26(1):21-8.

88. Hurdiel R, Monaca C, Mauvieux B, et al. Field study of sleep and functional impairments in solo sailing races. Sleep Biol Rhythms. 2012;10(4):270-7.

89. Sargent C, Halson S, Roach GD. Sleep or swim? Early-morning training severely restricts the amount of sleep obtained by elite swimmers. Eur J Sport Sci. 2012:1-6.

90. Boonstra TW, Stins JF, Daffertshofer A, et al. Effects of sleep deprivation on neural functioning: an integrative review. Cell Mol Life Sci. 2007;64(7-8):934-46.

91. Waterhouse JM, Minors DS, Waterhouse ME, et al. Keeping in time with your body clock. Oxford: Oxford University Press; 2002.

92. Souissi N, Chtourou H, Aloui A, et al. Effects of time-of-day and-partial sleep deprivation on short term maximal performances of judo compeitiors. J Strength Cond Res. 2013;27(9):2473-80.

93. Reilly T, Hales A. Effects of partial sleep deprivation on performance measures in females. London Taylor and Francis; 1988.

94. Martin B. Effect of sleep deprivation on tolerance of prolonged exercise. Eur J Appl Physiol. 1981;47:345-54.

95. Mougin F, Simon-Rigaud ML, Davenne D, et al. Effects of sleep disturbances on subsequent physical performance. Eur J Appl Physiol Occup Physiol. 1991;63:77-83.

96. Mougin F, Bourdin H, Simon-Rigaud ML, et al. Effects of a selective sleep deprivation on subsequent anaerobic performance. Int J Sports Med. 1996;17(2):115-9.

97. Reilly T, Deykin T. Effects of partial sleep loss on subjective states, psychomotor and physical performance tests. J Hum Move Stud. 1983;9:157–70.

98. Mejri MA, Hammouda O, Zouaoui K, et al. Effect of two types of partial sleep deprivation on Taekwondo players' performance during intermittent exercise. Biol Rhythm Res. 2014;45(1):17-26.

99. Mougin F, Bourdin H, Simon-Rigaud ML, et al. Hormonal responses to exercise after partial sleep deprivation and after a hypnotic drug-induced sleep. J Sports Sci. 2001;19(2):89-97.

100. Souissi N, Souissi M, Souissi H, et al. Effect of time of day and partial sleep deprivation on short-term, high-power output. Chronobiol Int. 2008;25(6):1062-76.

101. Abedelmalek S, Souissi N, Chtourou H, et al. Effects of partial sleep deprivation on proinflammatory cytokines, growth hormone, and steroid hormone concentrations during repeated brief sprint interval exercise. Chronobiol Int. 2013;30(4):502-9.

102. Mougin F, Davenne D, Simon-Rigaud ML, et al. Disturbance of sports performance after partial sleep deprivation. C R Seances Soc Biol Fil. 1989;183(5):461-6.

103. Horne J, Petit AN. Sleep deprivation and the physiological response to exercise under steady state conditions in untrained subjects. Sleep. 1984;7:168-79.

104. Abbiss CR, Laursen PB. Models to explain fatigue during prolonged endurance cycling. Sports Med. 2005;35(10):865-98.

105. Walker MP, Stickgold R. Its practice, with sleep, that makes perfect: implications of sleep dependent learning and plasticity for skill performance. . Clin J Sports Med. 2005;24(2):310-7.

106. Reilly T, Piercy M. The effect of partial sleep deprivation on weight-lifting performance. Ergonomics. 1994;37(1):107-15.

107. HajSalem M, Chtourou H, Aloui A, et al. Effects of partial sleep deprivation at the end of the night on anaerobic performances in judokas. Biol Rhythm Res. 2013;44(13):815-21.

108. Bonnet MH. Performance and sleepiness following moderate sleep disruption and slow wave sleep deprivation. Physiol Behav. 1985;37:915-8.

109. Axelsson J, Kecklund G, Akerstedt T, et al. Sleepiness and performance in response to repeated sleep restriction and subsequent recovery during semi-laboratory conditions. Chronobiol Int. 2008;25:297-308.

110. Koboyashi F, Yamamoto K, Tsubi H, et al. Five-hour sleep restriction for 7 days increases subjective sleepiness. Ind Health. 2007;45:160-4.

111. Sinnerton S, Reilly T. Effects of sleep loss and time of day in swimmers. London: E and FN Spon; 1992.

112. Temesi J, Arnal PJ, Davranche K, et al. Does central fatigue explain reduced cycling after complete sleep deprivation? Med Sci Sport Exer. 2013;45(12):2243-53.

113. Brink MS, Nederhof E, Visscher C, et al. Monitoring load, recovery, and performance in young elite soccer players. J Strength Cond Res. 2010;24(3):597-603.

114. Foster C. Monitoring training in athletes with reference to overtraining syndrome. Med Sci Sport Exer. 1998;30(7):1164-8.

115. Edwards BJ, Waterhouse J. Effects of one night of partial sleep deprivation upon diurnal rhythms of accuracy and consistency in throwing darts. Chronobiol Int. 2009;26(4):756-68.

116. Reyner LA, Horne JA. Sleep restriction and serving accuracy in performance tennis players, and effects of caffeine. Physiol Behav. 2013;120:93-6.

117. Jarraya S, Jarraya M, Chtourou H, et al. Effect of time of day and partial sleep deprivation on the reaction time and the attentional capacities of the handball goalkeeper. Biol Rhythm Res. 2014;45(2):183-91.

118. Brand S, Gerber M, Beck J, et al. High exercise levels are related to favorable sleep patterns and psychological functioning in adolescents: a comparison of athletes and controls. J Adolesc Health. 2010;46(2):133-41.

119. Driver HS, Taylor SR. Exercise and sleep. Sleep Med Rev. 2000;4(4):387-402.

120. Hill DW, Borden DO, Darnaby KM, et al. Aerobic and anaerobic contributions to exhaustive high-intensity exercise after sleep deprivation. J Sports Sci. 1994;12(5):455-61.

121. Martin BJ, Chen H. Sleep loss and the sympathoadrenal response to exercise. Med Sci Sport Exer. 1984;16:56-9.

122. Azboy O, Kaygisiz Z. Effects of sleep deprivation on cardiorespiratory functions of the runners and volleyball players during rest and exercise. Acta Physiol Hung. 2009;96(1):29-36.

123. Oliver SJ, Costa RJS, Laing SJ, et al. One night of sleep deprivation decreases treadmill endurance performance. Eur J Appl Physiol. 2009;107(2):155-61.

124. Takeuchi L, Davis GM, Plyley MJ, et al. Sleep deprivation, chronic exercise and muscular performance. Ergonomics. 1985;28:591–601.

125. Coutts AJ, Duffield R. Validity and reliability of GPS devices for measuring movement demands of team sports. J Sci Med Sport. 2010;13(1):133–5.

126. Skein M, Duffield R, Edge J, et al. Intermittent-sprint performance and muscle glycogen after 30 h of sleep deprivation. Med Sci Sport Exer. 2011;43(7):1301-11.

127. Bulbulian R, Heaney JH, Leake CN, et al. The effect of sleep deprivation and exercise load on isokinetic leg strength and endurance. Eur J Appl Physiol. 1996;73:273-7.

128. Souissi N, Sesboüé B, Gauthier A, et al. Effects of one night's sleep deprivation on anaerobic performance the following day. Eur J Appl Physiol. 2003;89(3):359-66.

129. How JM, Foo SC, Low EC, et al. Effect of sleep deprivation on performance of Naval seamen: I. Total sleep deprivation on performance. Ann of Acad Med Singapore. 1994;23:669-75.

130. Symons JD, VanHelder T, Myles WS. Physical performance and physiological responses following 60 hours of sleep deprivation. Med Sci Sport Exer. 1988;20(4):374-80.

131. Reilly T, Walsh TJ. Physiological, psychological and performance measures duraing an endurance record for 5-a-side soccer play. Br J Sports Med. 1981;15:122-8.

132. Reilly T, George A. Urinary phenylethamine levels during three days of indoor soccer play. J Sports Sci. 1983;1:70.

133. Racinais S, Hue O, Blonc S, et al. Effect of sleep deprivation on shuttle run score in middle-aged amateur athletes. J Sports Med Phys Fitness. 2004;44(3):246-8.

134. Katirji B. Clinical neurophysiology: clinical electromyography. Philadelphia, Pa: Saunders Elsevier; 2012.

135. Berger RJ, Phillips NH. Energy conservation and sleep. Behav Brain Res. 1995;69:65-73.

136. Francesconi RP, Stokes JW, Banderet LE, et al. Sustained operations and sleep deprivation: effects on indices of stress. Aviat Space Environ Med. 1978;49:1271-4.

137. Martin BJ. Sleep loss and subsequent exercise performance. Acta Physiol Scand. 1988;574:28-32.

138. Martin BJ, Bender PR, Chen H. Stress hormonal response to exercise after sleep loss. Eur J Appl Physiol Occup Physiol. 1986;55:210-4.

139. Rossiter H. Exercise: Kinetic considerations for gas exchange. Compr Physiol. 2011;1:203-44.

140. Ashley E, Myers J, Froelicher V. Exercise testing in clinical medicine. The Lancet. 2000;356(4):1592-97.

141. Beaver W, Lamarra N, Wasserman K. Breath by breath measurement of true alveolar gas exchange. J Appl Physiol: Respirat Environ Exercise Physiol Behav. 1981;51(6):1662-75.

142. Wilmore J, Costill DL. Semiautomated systems approach to the assessment of oxygen uptake during exercise. J Appl Physiol. 1974;36(5):618-20.

143. Vgontzas AN, Zoumakis E, Bixler EO, et al. Adverse effects of modest sleep restriction on sleepiness, performance, and inflammatory cytokines. J Clin Endocrinol Metab. 2004;89(5):2119-26.

144. Abedelmalek S, Chtourou H, Aloui A, et al. Effect of time of day and partial sleep deprivation on plasma concentrations of IL-6 during a short-term maximal performance. Eur J Appl Physiol. 2013;113(1):241-8.

145. Goh VH, Tong TY, Lim CL, et al. Effects of one night of sleep deprivation on hormone profiles and performance efficiency. Military Medicine. 2001;166(5):427-31.

146. Urhausen A, Kindermann W. The endocrine system in overtraining. Totowa, NJ: Humana Press; 2000.

147. Redwine L, Hauger RL, Christian Gillin J, et al. Effects of sleep and sleep deprivation on interleukin-6, growth hormone, cortisol, and melatonin levels in humans. J Clin Endocrinol Metab. 2000;85(10):3597–603.

148. Irwin MR, Wang M, Campomayor CO, et al. Sleep deprivation and activation of morning levels of cellular and genomic markers of inflammation. Arch Intern Med. 2006;166:1756–62.

149. Costa RJS, Smith AH, Oliver SJ, et al. The effects of two nights of sleep deprivation with or without energy restriction on immune indices at rest and in response to cold exposure. Eur J Appl Physiol. 2010;109(3):417-28.

150. Papanicolaou DA, Wilder RL, Manolagas SC, et al. The pathophysiologic roles of interleukin-6 in human disease. Ann Intern Med. 1998;128:127–37.

151. Costill DL, Flynn MG, Kirwan JP, et al. Effects of repeated days of intensified training on muscle glycogen and swimming performance. Med Sci Sport Exer. 1988;20:249-54.

152. Guezennec CY, Sabatin P, Legrand H, et al. Physical performance and metabolic changes induced by combined prolonged exercise and different energy intake in humans. Eur J Appl Physiol. 1994;68:525-30.

153. Zhong X, Hilton HJ, Gates GJ, et al. Increased sympathetic and decreased parasympathetic cardiovascular modulation in normal humans with acute sleep deprivation. J Appl Physiol. 2005;98:2024-32.

154. Achten J, Jeukendrup AE. Heart rate monitoring: Applications and limitations. Sports Med. 2003;33:517-38.

155. Hynynen ESA, Uusitalo A, Konttinen N, et al. Heart rate variability during night sleep and after awakening in overtrained athletes. Med Sci Sport Exer. 2006;38(2):313-7.

156. Garet M, Tournaire N, Roche F, et al. Individual interdependence between nocturnal ANS activity and performance in swimmers. Med Sci Sport Exer. 2004;36:2112-8.

157. Martin BJ, Haney R. Self-selected exercise intensity is unchanged by sleep loss. Eur J Appl Physiol Occup Physiol. 1982;49:79-86.

158. Martin BJ, Gaddis GM. Exercise after sleep deprivation. Med Sci Sport Exer. 1981;13:220-3.

159. Thomas V, Reilly T. Circulatory, psychological and performance variables during 100 hours of continuous exercise under conditions of controlled energy intake and work output. J Hum Move Stud. 1975;1:149-55.

160. Plyley MJ, Shephard RJ, Davis GM, et al. Sleep deprivation and cardiorespiratory function. Influence of intermittent submaximal exercise. Eur J Appl Physiol Occup Physiol. 1987;56:338-44.

161. Obal F, Krueger JM. GHRH and sleep. Sleep Med Rev. 2004;8:367-77.

162. Dattilo M, Antunes HKM, Medeiros A, et al. Sleep and muscle recovery: Endocrinological and molecular basis for a new and promising hypothesis. Med Hypotheses. 2011;77(2):220-2.

163. Everson CA, Crowley WR. Reductions in circulating anabolic hormones induced by sustained sleep deprivation in rats. Am J Physiol Endocrinol Metab. 2004;286:1060-70.

164. Brandenberger G, Gronfier C, Chapotota F, et al. Effect of sleep deprivation on overall 24 h growth-hormone secretion. The Lancet. 2000;356(9239):1408.

165. Belenky G, Wesensten N, Thorne D, et al. Patterns of performance degradation and restoration during sleep restriction and subsequent recovery: a sleep dose-response study. J Sleep Res. 2003;12:1-12.

166. Doran SM, Van Dongen HPA, Dinges DF. Sustained attention performance during sleep deprivation: evidence of state instability. Arch Ital Biol. 2001;139:253-67.

167. Dorrian J, Rogers NL, Dinges DF. Psychomotor vigilance performance: neurocognitive assay sensitive to sleep loss. . New York: Marcel Dekker; 2005.

168. Dorrian J, Dinges DF. Sleep deprivation and its effects on cognitive performance: Wiley & Sons; 2005.

169. Harrison Y, Horne JA. The impact of sleep deprivation on decision making: A review. J Expl Psychol: Appl. 2000;6:236-49.

170. Dinges DF, Kribbs NB. Performing while sleepy: effects of experimentally induced sleepiness. Winchester, England: John Wiley & Sons; 1991.

171. Balkin TJ, Bliese PD, Belenky G. Comparative utility of instruments for monitoring sleepiness-related performance decrements in the operational environmen. J Sleep Res. 2004;13:219-27.

172. Bonnet M. Effect of sleep disruption on sleep, performance and mood. Sleep. 1985;8(1):11-9.

173. Roehrs T, Carskadon MA, Dement WC, et al. Daytime sleepiness and alertness: W.B. Saunders Company; 2005.

174. Kleitman N. Sleep and wakefullness. London: The University of Chicago Press; 1963.

175. Grundgeiger T, Bayen UJ, Horn SS. Effects of sleep deprivation on prospective memory. Memory. 2014;22(6):679-86.

176. Taber K, Hurley R. Functional neuroanatomy of sleep and sleep deprivation. J Neuropsychiatry Clin Neurosci. 2006;18(1):1-5.

177. Drummond SPA, Brown GG. The effects of total sleep deprivation on cerebral responses to cognitive performance. Neuropsychopharmacology. 2001;25:S68–S73.

178. Thomas M, Sing M, Belenky G. Neural basis of alertness and cognitive performance impairments during sleepiness. I. Effects of 24 hour of sleep deprivation on waking human regional brain activity. J Sleep Res. 2000;9:335–52.

179. Thomas ML, Sing HC, Belenky G. Neural basis of alertness and cognitive performance impairments during sleepiness II. Effects of 48 and 72 hour of sleep deprivation on waking human brain activity. Thalamus Relat Syst 2003;2:199–229.

180. Drummond SPA, Brown GG, Stricker JL, et al. Sleep deprivation-induced reduction in cortical functional response to serial subtraction. Neuroreport. 1999;10:3745-8.

181. Baker J, Cote J, Abernethy B. Sport-specific practice and the development of expert decision-making in team ball sports. J Appl Sport Psych. 2003;15(1):12-25.

182. Araújo D, Davids K, Hristovski R. The ecological dynamics of decision making in sport. Psyc Sport Exerc. 2006;7(6):653–76.

183. Khazaie H, Tahmasian M, Ghadami M, et al. Theeffects of chronic partial sleep deprivation on cognitive functions of medical residents. Iran J Psych. 2010;5(2):74-7.

184. Waterhouse J, Atkinson G, Edwards B, et al. The role of a short post-lunch nap in improving cognitive, motor, and sprint performance in participants with partial sleep deprivation. J Sports Sci. 2007;25(14):1557-66.

185. Drummond SPA, Anderson D, Straus L, et al. The effects of two types of sleep deprivation on visual working memory capacity and filtering efficiency. PLoS ONE. 2012;7(4):e35653.

186. Laureys S, Peigneux P, Perrin F, et al. Sleep and motor skill learning. Neuron. 2002;35(1):5-7.

187. Otmani S, Pebayle T, Roge J, et al. Effect of driving duration and partial sleep deprivation on subsequent alertness and performance of car drivers. Physiol Behav. 2005;84(5):715-24.

188. Jurimae J, Maestu J, Purge P, et al. Changes in stress and recovery after heavy training in rowers. J Sci Med Sport. 2004;7(3):334-9.

189. Jurimae J, Maestu J, Purge P, et al. Relations among heavy training stress, mood state, and performance for male junior rowers. Percept Mot Skills. 2001;95:520-6.

190. Coutts AJ, Reaburn P, Piva TJ, et al. Monitoring for overreaching in rugby league players. Eur J Appl Physiol. 2007;99(3):313-24.

191. Angus RG, Heslegrave R, Myles WS. Effects of prolonged sleep duration, with and without chronic physical exercise, on mood and performance. Psychophysiology. 1985;22:276-82.

192. Scott JPR, McNaughton LR, Polman RCJ. Effects of sleep deprivation and exercise on cognitive, motor performance and mood. Physiol Behav. 2006;87(2):396-408.

193. Harrison Y, Horne JA. One night of sleep loss impairs innovative thinking and flexible decision making. Organ Behav Hum Dec Process. 1999;78(2):128-45.

194. Williamson AM. Moderate sleep deprivation produces impairments in cognitive and motor performance equivalent to legally prescribed levels of alcohol intoxication. Occup Environ Med. 2000;57(10):649-55.

195. Froberg JE, Karlsson C, Levi L, et al. Circadian rhythms of catecholamine excretion, shooting range performance and self-ratings of fatigue during sleep deprivation. Biol Psychol. 1975;2:175-88.

196. Taheri M, Arabameri E. The effect of sleep deprivation on choice reaction time and anaerobic power of college student athletes. Asia J Sport Med. 2011;3(1):15-20.

197. Rosa R, Bonnet MH, Warm J. Recovery of performance during sleep following sleep deprivation. Psychophysiology. 1983;20(2):152-9.

198. Wimmer F, Hoffmann RF, Bonato RA. The effects of sleep deprivation on divergent thinking and attention processes. J Sleep Res. 1992;1:223–30.

199. Lucas SJE, Anson JG, Palmer CD, et al. The impact of 100 hours of exercise and sleep deprivation on cognitive function and physical capacities. J Sports Sci. 2009;27(7):719-28.

200. Olsen OK, Pallesen S, Eid J. The impact of partial sleep deprivation on moral reasoning in military officers. Sleep. 2010;33(8):1086-90.

201. Edinger JD, Marsh GR, Vaughn McCall W, et al. Daytime fuctioning and nighttime sleep before, during, and after a 146 hour tennis match. Sleep. 1990;13(6):526-32.

202. Hopkins WG. Linear models and effect magnitudes for research, clinical and practical applications. wwwsportscienceorg. 2010;14:49-58.

203. Hausswirth C, Louis J, Aubry A, et al. Evidence of disturbed sleep and increased illness in overreached endurance athletes. Med Sci Sport Exer. 2014;46(5):1036-45.

204. Sawka MN, Gonzalez RR, Pandolf KB. Effects of sleep deprivation on thermoregulation during exercise. Am Journal of Physiology. 1984;246:R72–R7.

205. Smith RS, Reilly T. Athletic performance. New York: Marcel Dekker; 2005.

**Table 1:** Studies examining the effect of sleep loss (restriction and deprivation) on various parameters of exercise performance

| | Study | Subjects and fitness status if provided | Sleep intervention | Exercise protocol | Performance outcome | Results[a] |
|---|---|---|---|---|---|---|
| **Endurance/aerobic** | Azboy et al. 2009 [122] | Runners and volleyballers[b] | 25-30 h of SD | Incremental cycling test to exhaustion | Time to exhaustion | ↓ in VB players |
| | Hill et al. 1993 [120] | 14 college students | 25-30 h of SD | Incremental cycling test to exhaustion | Total work (kJ)<br>Anaerobic contribution<br>Aerobic contribution | NS<br>NS<br>NS |
| | Martin 1981 [94] | 8 subjects in 'excellent' health | 36 h of SD | Prolonged walking to exhaustion at 80% $VO_{2max}$ | Time to exhaustion | ↓ by ~11%[c] |
| | Martin and Chen 1984 [121] | 8 graduate students | 50 h of SD | Walking at steady-state then walking to exhaustion | Time to exhaustion | ↓ |
| | Mejri et al. 2014 [98] | 10 taekwondo athletes | Partial disruptions at the beginning and end of the night (SR) | YoYo intermittent recovery test level one | Total distance covered | NS |
| | Mougin et al. 1991 [95] | 7 cyclists | 3 h of SR during the night | 20 min steady state work (75% $VO_{2max}$) on a cycle ergometer followed by an incremental test to exhaustion | Maximal sustained exercise intensity | NS |
| | Oliver at al. 2009 [123] | 11 recreationally active participants | 30 h of SD | 30 min pre-load treadmill run at 60% $VO_{2max}$ then 30 min self-paced treadmill run | Distance ran | ↓ |
| | Racinais et al. 2004 [133] | 22 athletes | 38 h of SD | Leger and Gadoury shuttle run test | Shuttle run score | NS |
| | Reilly and Deykin 1983 [97] | 8 trained participants | 2.5 h of sleep obtained per night for three nights (SR) | Incremental treadmill test to exhaustion | Endurance running performance | NS |
| **Anaerobic** | Abedelmalek et al. 2013 [144] | 12 footballers | Restricted to 4.5 h for one night (SR) | Wingate anaerobic test | Mean power<br>Peak power | ↓<br>↓ |
| | HajSalem et al. 2013 [107] | 21 judokas | Partial disruptions at the end of one night (SR) | Wingate anaerobic test | Mean power<br>Peak power | ↓<br>↓ |
| | Mougin et al. 1996 [96] | 8 highly trained participants | ~4 h of sleep obtained (SR) | Wingate anaerobic test | Mean power<br>Peak power<br>Peak velocity | NS<br>NS<br>NS |
| | Soussi et al. 2003 [128] | 13 physical education students | 36 h of SD | Wingate anaerobic test | Maximal power<br>Peak power<br>Mean power | ↓ at 36 h<br>↓ at 36h<br>↓ at 36h |
| | Soussi et al. 2008 [100] | 11 physical education students | ~3-4 h of sleep obtained per night for two nights (one at beginning and one at end of night; SR) | Wingate anaerobic test | Maximal power<br>Peak power<br>Mean power<br>Force velocity | ↓[d]<br>↓<br>↓<br>↓ |
| | Soussi et al. 2013 [92] | 12 judo competitors | 3 h of sleep per night over for two nights (one at the beginning and one at the end of the night; SR) | Wingate anaerobic test | Mean power | ↓[e] |

**Table 1:** *continued*

| | Study | Subjects and fitness status if provided | Sleep intervention | Exercise protocol | Performance outcome | Results |
|---|---|---|---|---|---|---|
| | Symons et al. 1988 [130] | 11 volunteers | 60 h of SD | Wingate anaerobic test | Peak power | NS |
| | | | | | Mean power | NS |
| | Taheri et al. 2011 [196] | 18 student athletes | Whole night of SD | Wingate anaerobic test | Mean power | NS |
| | | | | | Peak power | NS |
| **Intermittent/RSA** | Skein et al. 2011 [126] | 10 team-sport athletes | 30 h of SD | 30 min graded exercise run, 50 min intermittent sprint exercise (15-m maximal sprint per min and self paced after) | 15-m sprint performance | ↓ |
| | Takeuchi et al. 1985 [124] | 12 healthy volunteers | 64 h of SD | Intermittent treadmill walking at 28% $VO_{2max}$ and 40m sprint | 40-m sprint performance | NS |
| **Muscular strength** | Bulbulian et al. 1996 [127] | 24 U.S Marine Corps | 30 h of SD | Walking at low intensity; 45 consecutive maximal reciprocal contraction at a pre-determined isokinetic speed ($3.14\ rad/s^{-1}$) | Knee extension peak torque | ↓ |
| | | | | | Knee flexion peak torque | ↓ |
| | HajSalem et al. 2013 [107] | 21 judokas | Partial disruptions at the end of one night (SR) | Muscular strength tests prior to and following a judo match | Handgrip test | NS |
| | Meney et al. 1998 [30] | 14 healthy participants | Whole night of SD | 5 min of self-paced cycling; | Self-paced work rate | NS |
| | | | | Muscular strength tests | Grip, leg, back strength | NS |
| | Reilly and Deykin 1983 [97] | 8 trained participants | 2.5 h of sleep obtained per night for three nights (SR) | Muscular strength tests | Isometric handgrip test | NS |
| | Reilly and Piercy 1994 [106] | 8 healthy participants | 3 h of sleep obtained per night for three nights (SR) | Maximal and submaximal weight lifting tasks | Biceps curl | Submaximal = ↓, maximal= NS |
| | | | | | Bench press | Both NS |
| | | | | | Leg press | Both NS |
| | | | | | Dead lift | Both NS |
| | Skein et al. 2011 [126] | 10 team-sport athletes | 30 h of SD | Muscular strength tests | MVC (right quadriceps) | ↓ |
| | | | | | Voluntary activation | ↓ |
| | Soussi et al. 2013 [92] | 12 judo competitors | 3 h of sleep per night over for two nights (one at the beginning and one at the end of the night; SR) | Muscular strengths tests prior to judo combat | Handgrip test | ↓[e] |
| | | | | | MVC (elbow flexors) | ↓ |
| | Symons et al. 1988 [130] | 11 volunteers | 60 h of SD | Muscular strength tests | Maximal isometric strength (forearm flexors, leg extensors) | NS |
| | | | | | Mean torque (endurance) | NS |
| | | | | | MVC (leg and arm) | NS |
| | | | | | Rate of force development | NS |
| | Takeuchi et al. 1985 [124] | 12 healthy volunteers | 64 h of SD | Muscular and balance strength tests | Handgrip | NS |
| | | | | | Balance (stabilometer test) | NS |
| | | | | | Vertical jump | ↓ |
| | | | | | Isokinetic knee extension force | ↓ |

**Table 1**: *continued*

| | Study | Subjects and fitness status if provided | Sleep intervention/condition | Exercise protocol | Performance outcome | Results |
|---|---|---|---|---|---|---|
| **Sport-specific performance** | Edwards et al. 2009 [115] | 60 differently experienced dart players | 3-4 h of sleep obtained (SR) | Dart performance | Mean score<br>Number of zeros<br>Variability of dart score | ↓<br>↑<br>↑ |
| | Fröberg et al. 1975 [195] | 29 Army corporal officers | 72 h of SD | Military shooting drills | Number of shots<br>Number of hits | ↓<br>↓ |
| | Goh et al. 2001 [145] | 14 military service members | Whole night of SD | Military pursuit drills | Drill performance<br>Handgrip test | NS<br>NS |
| | Léger et al. 2008 [87] | 8 healthy young sailors | 2 h of sleep obtained per night | Four Tour de France yacht racing legs (90, 244, 56 and 75 nautical miles respectively) | Global performance (final official race ranking | It was found that the "final ranking in the race related to the sleep management strategy of the participants" |
| | Otmani et al. 2005 [187] | 20 healthy volunteers | 4 h of sleep obtained for one night (SR) | Simulated car driving protocol | Driving performance measures | NS<br>(except for "number of right edge line crossings" (↓ in alertness)) |
| | Reyner and Horne 2013 [116] | 16 tennis players | Delay bedtime 2-2.5 (e.g. ~5 h obtained for one night; SR) | Tennis serving drills | Serving accuracy | ↓ |
| | Sinnerton and Reilly 1992 [111] | 8 swimmers | 2.5 h obtained sleep per night for four nights (SR) | Swimming performance test (50m and 400m); muscular strength tests | Lap times<br>Back strength<br>Grip strength | NS<br>NS<br>NS |

↓ (Decrease), ↑ (Increase), [a] All changes signified by ↑ and ↓ were statistically significant ($p < 0.05$), [b] Full text unavailable, [c] $p = 0.05$, [d] When measurements were obtained at 18:00 and SD was at the end of the night, [e] When measurements were obtained at 16:00 and SD was at the end of the night, *MVC* maximal voluntary contraction, *NS* not significant, *RSA* repeated sprint ability, *SD* sleep deprivation, *SR* sleep restriction, *VB* volleyball players, $VO_{2max}$ maximal oxygen uptake.

**Table 1:** Studies examining the effect of sleep loss (restriction and deprivation) on various parameters of exercise performance

| | **Study** | **Subjects and fitness status if provided** | **Sleep intervention** | **Exercise protocol** | **Performance outcome** | **Results**[a] |
|---|---|---|---|---|---|---|
| **Endurance/aerobic** | Azboy et al. 2009 [122] | Runners and volleyballers[b] | 25-30 h of SD | Incremental cycling test to exhaustion | Time to exhaustion | ↓ in VB players |
| | Hill et al. 1993 [120] | 14 college students | 25-30 h of SD | Incremental cycling test to exhaustion | Total work (kJ)<br>Anaerobic contribution<br>Aerobic contribution | NS<br>NS<br>NS |
| | Martin 1981 [94] | 8 subjects in 'excellent' health | 36 h of SD | Prolonged walking to exhaustion at 80% $VO_{2max}$ | Time to exhaustion | ↓ by ~11%[c] |
| | Martin and Chen 1984 [121] | 8 graduate students | 50 h of SD | Walking at steady-state then walking to exhaustion | Time to exhaustion | ↓ |
| | Mejri et al. 2014 [98] | 10 taekwondo athletes | Partial disruptions at the beginning and end of the night (SR) | YoYo intermittent recovery test level one | Total distance covered | NS |
| | Mougin et al. 1991 [95] | 7 cyclists | 3 h of SR during the night | 20 min steady state work (75% $VO_{2max}$) on a cycle ergometer followed by an incremental test to exhaustion | Maximal sustained exercise intensity | NS |
| | Oliver at al. 2009 [123] | 11 recreationally active participants | 30 h of SD | 30 min pre-load treadmill run at 60% $VO_{2max}$ then 30 min self-paced treadmill run | Distance ran | ↓ |
| | Racinais et al. 2004 [133] | 22 athletes | 38 h of SD | Leger and Gadoury shuttle run test | Shuttle run score | NS |
| | Reilly and Deykin 1983 [97] | 8 trained participants | 2.5 h of sleep obtained per night for three nights (SR) | Incremental treadmill test to exhaustion | Endurance running performance | NS |
| **Anaerobic** | Abedelmalek et al. 2013 [144] | 12 footballers | Restricted to 4.5 h for one night (SR) | Wingate anaerobic test | Mean power<br>Peak power | ↓<br>↓ |
| | HajSalem et al. 2013 [107] | 21 judokas | Partial disruptions at the end of one night (SR) | Wingate anaerobic test | Mean power<br>Peak power | ↓<br>↓ |
| | Mougin et al. 1996 [96] | 8 highly trained participants | ~4 h of sleep obtained (SR) | Wingate anaerobic test | Mean power<br>Peak power<br>Peak velocity | NS<br>NS<br>NS |
| | Soussi et al. 2003 [128] | 13 physical education students | 36 h of SD | Wingate anaerobic test | Maximal power<br>Peak power<br>Mean power | ↓ at 36 h<br>↓ at 36h<br>↓ at 36h |
| | Soussi et al. 2008 [100] | 11 physical education students | ~3-4 h of sleep obtained per night for two nights (one at beginning and one at end of night; SR) | Wingate anaerobic test | Maximal power<br>Peak power<br>Mean power<br>Force velocity | ↓[d]<br>↓<br>↓<br>↓ |
| | Soussi et al. 2013 [92] | 12 judo competitors | 3 h of sleep per night over for two nights (one at the beginning and one at the end of the night; SR) | Wingate anaerobic test | Mean power | ↓[e] |

**Table 1:** *continued*

| | Study | Subjects and fitness status if provided | Sleep intervention | Exercise ~~Protocol~~ protocol | Performance outcome | Results |
|---|---|---|---|---|---|---|
| | Symons et al. 1988 [130] | 11 volunteers | 60 h of SD | Wingate anaerobic test | Peak power | NS |
| | | | | | Mean power | NS |
| | Taheri et al. 2011 [196] | 18 student athletes | Whole night of SD | Wingate anaerobic test | Mean power | NS |
| | | | | | Peak power | NS |
| **Intermittent/RSA** | Skein et al. 2011 [126] | 10 team-sport athletes | 30 h of SD | 30 min graded exercise run, 50 min intermittent sprint exercise (15-m maximal sprint per min and self paced after) | 15-m sprint performance | ↓ |
| | Takeuchi et al. 1985 [124] | 12 healthy volunteers | 64 h of SD | Intermittent treadmill walking at 28% $VO_{2max}$ and 40m sprint | 40-m sprint performance | NS |
| **Muscular strength** | Bulbulian et al. 1996 [127] | 24 U.S Marine Corps | 30 h of SD | Walking at low intensity; 45 consecutive maximal reciprocal contraction at a pre-determined isokinetic speed (3.14 rad/s$^{-1}$) | Knee extension peak torque | ↓ |
| | | | | | Knee flexion peak torque | ↓ |
| | HajSalem et al. 2013 [107] | 21 judokas | Partial disruptions at the end of one night (SR) | Muscular strength tests prior to and following a judo match | Handgrip test | NS |
| | Meney et al. 1998 [30] | 14 healthy participants | Whole night of SD | 5 min of self-paced cycling; Muscular strength tests | Self-paced work rate | NS |
| | | | | | Grip, leg, back strength | NS |
| | Reilly and Deykin 1983 [97] | 8 trained participants | 2.5 h of sleep obtained per night for three nights (SR) | Muscular strength tests | Isometric handgrip test | NS |
| | Reilly and Piercy 1994 [106] | 8 healthy participants | 3 h of sleep obtained per night for three nights (SR) | Maximal and submaximal weight lifting tasks | Biceps curl | Submaximal = ↓, maximal= NS |
| | | | | | Bench press | Both NS |
| | | | | | Leg press | Both NS |
| | | | | | Dead lift | Both NS |
| | Skein et al. 2011 [126] | 10 team-sport athletes | 30 h of SD | Muscular strength tests | MVC (right quadriceps) | ↓ |
| | | | | | Voluntary activation | ↓ |
| | Soussi et al. 2013 [92] | 12 judo competitors | 3 h of sleep per night over for two nights (one at the beginning and one at the end of the night; SR) | Muscular strengths tests prior to judo combat | Handgrip test | ↓[e] |
| | | | | | MVC (elbow flexors) | ↓ |
| | Symons et al. 1988 [130] | 11 volunteers | 60 h of SD | Muscular strength tests | Maximal isometric strength (forearm flexors, leg extensors) | NS |
| | | | | | Mean torque (endurance) | NS |
| | | | | | MVC (leg and arm) | NS |
| | | | | | Rate of force development | NS |
| | Takeuchi et al. 1985 [124] | 12 healthy volunteers | 64 h of SD | Muscular and balance strength tests | Handgrip | NS |
| | | | | | Balance (stabilometer test) | NS |
| | | | | | Vertical jump | ↓ |
| | | | | | Isokinetic knee extension force | ↓ |

**Table 1**: *continued*

| | Study | Subjects and fitness status if provided | Sleep intervention/condition | Exercise ~~Protocol~~ protocol | Performance outcome | Results |
|---|---|---|---|---|---|---|
| **Sport-specific performance** | Edwards et al. 2009 [115] | 60 differently experienced dart players | 3-4 h of sleep obtained (SR) | Dart performance | Mean score<br>Number of zeros<br>Variability of dart score | ↓<br>↑<br>↑ |
| | Fröberg et al. 1975 [195] | 29 Army corporal officers | 72 h of SD | Military shooting drills | Number of shots<br>Number of hits | ↓<br>↓ |
| | Goh et al. 2001 [145] | 14 military service members | Whole night of SD | Military pursuit drills | Drill performance<br>Handgrip test | NS<br>NS |
| | Léger et al. 2008 [87] | 8 healthy young sailors | 2 h of sleep obtained per night | Four Tour de France yacht racing legs (90, 244, 56 and 75 nautical miles respectively) | Global performance (final official race ranking | It was found that the "final ranking in the race related to the sleep management strategy of the participants" |
| | Otmani et al. 2005 [187] | 20 healthy volunteers | 4 h of sleep obtained for one night (SR) | Simulated car driving protocol | Driving performance measures | NS (except for "number of right edge line crossings" (↓ in alertness)) |
| | Reyner and Horne 2013 [116] | 16 tennis players | Delay bedtime 2-2.5 (e.g. ~5 h obtained for one night; SR) | Tennis serving drills | Serving accuracy | ↓ |
| | Sinnerton and Reilly 1992 [111] | 8 swimmers | 2.5 h obtained sleep per night for four nights (SR) | Swimming performance test (50m and 400m); ~~Muscular~~ muscular strength tests | Lap times<br>Back strength<br>Grip strength | NS<br>NS<br>NS |

↓ (Decrease), ↑ (Increase), [a] All changes signified by ↑ and ↓ were statistically significant ($p < 0.05$), [b] Full text unavailable, [c] $p = 0.05$, [d] When measurements were obtained at 18:00 and SD was at the end of the night, [e] When measurements were obtained at 16:00 and SD was at the end of the night, *MVC* ~~Maximal~~ maximal voluntary contraction, *NS* not significant, *RSA* repeated sprint ability, *SD* sleep deprivation, *SR* sleep restriction, *VB* volleyball players, $VO_{2max}$ maximal oxygen uptake.

**Table 2:** Studies examining the effects of sleep loss (restriction and deprivation) on physiological responses to exercise

| | **Study** | **Subjects and fitness status if provided** | **Sleep intervention** | **Exercise protocol** | **Outcome measures** | **Results**[a] |
|---|---|---|---|---|---|---|
| **Respiratory/cardiovascular** | Azboy et al. 2009 [122] | Runners and volleyballers[b] | 25-30 h of SD | Incremental cycling exercise test to exhaustion | *At rest* | |
| | | | | | $VO_2$ | ↑ in runners |
| | | | | | $VCO_2$ | ↑ in both groups |
| | | | | | HR | NS |
| | | | | | $V_E$ | NS |
| | | | | | $SaO_2$ | NS |
| | | | | | RQ | NS |
| | | | | | *During exercise* | |
| | | | | | HR | NS |
| | | | | | $VO_2$ | NS |
| | | | | | $VCO_2$ | NS |
| | | | | | RQ | NS |
| | | | | | $SaO_2$ | NS |
| | | | | | $V_E$ | ↓ in both groups |
| | Horne and Petit 1984 [103] | 7 physically trained participants | 72 h of SD | 40 min (total) cycling at 40%, 60%, 80% of $VO_{2max}$ | $VO_2$ | NS |
| | Martin and Gaddis 1981 [158] | 6 healthy participants | 30 h of SD | 8 min of cycling at 25%, 50% and 75% of $VO_{2max}$ | RPE | ↑ |
| | | | | | $VO_2$ | NS |
| | | | | | $VCO_2$ | NS |
| | | | | | HR | NS |
| | | | | | $V_E$ | NS |
| | | | | | BP | NS |
| | Martin and Chen 1984 [121] | 8 graduate students | 50 h of SD | Walking at steady-state then walking to exhaustion | $VO_2$ | NS |
| | | | | | $VCO_2$ | NS |
| | | | | | HR | NS |
| | | | | | $V_E$ | NS |
| | Martin et al. 1986 [138] | 8 healthy participants | 36 h of SD (preceded by 2 nights of partial sleep disruption) | 30 min of high intensity treadmill walking and 3 h of treadmill walking | HR | NS |
| | | | | | $VO_2$ | NS |
| | | | | | $V_E$ | NS |
| | Mejri et al. 2014 [98] | 10 taekwondo athletes | Partial disruptions at the beginning and end of the night (SR) | YoYo intermittent recovery test level one | $HR_{peak}$ | NS |
| | | | | | RPE | NS |
| | Meney et al. 1998 [30] | 14 healthy participants | Whole night of SD | 5 min of self-paced cycling | HR | NS |
| | | | | | RPE | NS |
| | | | | | Self-paced work rate | NS |
| | Mougin et al. 1989 [102] | 7 endurance athletes | Partial disruption during the middle of the night for one night (SR) | Submaximal (75%) cycling test and maximal incremental test on a cycle ergometer | HR | ↑ at submaximal |
| | | | | | Ventilation rate | ↑ at submaximal |
| | | | | | $V_E/VO_2$ | ↑ at submaximal |
| | | | | | $VO_{2max}$ | ↓ at submaximal |
| | Mougin et al. 1991 [95] | 7 cyclists | 3 h of SR during the night | 20 min steady state work (75% $VO_{2max}$) on a cycle ergometer, followed by incremental test to exhaustion | HR | ↑ during both phases |
| | | | | | $V_E$ | ↑ during both phases |
| | | | | | $VO_{2peak}$ | ↓ during incremental |
| | Mougin et al. 1996 [96] | 8 highly trained participants | 4 h sleep obtained for one night (SR) | Wingate anaerobic test | $V_{E\,max}$ | NS |
| | | | | | VT | NS |
| | | | | | $VO_{2peak}$ | NS |

**Table 2**: *continued*

| | Study | Subjects and fitness status if provided | Sleep intervention | Exercise protocol | Outcome measures | Results |
|---|---|---|---|---|---|---|
| **Respiratory/cardiovascular *continued*** | Oliver at al. 2009 [123] | 11 recreationally active participants | 30 h of SD | 30 min at 60% VO$_{2max}$ followed by 30 min self-paced treadmill run | RPE<br>HR<br>VO$_2$ | NS<br>NS<br>↑ at 30min at 60% VO$_{2max}$ |
| | Plyley et al. 1987 [160] | 11 healthy volunteers | 64 h of SD | VO$_{2max}$ test, with an additional group completing 1 h of treadmill walking every 3 h | VO$_{2max}$<br>V$_{Emax}$<br>RER<br>HR | ↓<br>↓<br>NS<br>NS |
| | Reilly and Deakin 1983 [97] | 8 trained participants | 2.5 h of sleep obtained per night for three nights (SR) | Incremental treadmill test to exhaustion | FEV$_1$<br>VC | NS<br>NS |
| | Sinnerton and Reilly 1992 [111] | 8 swimmers | 2.5 h obtained sleep per night for four nights (SR) | Muscular strength measures; Swimming performance test | Lung function | NS |
| | Symons et al. 1988 [128] | 11 volunteers | 60 h of SD | 20 min at 75% VO$_{2max}$ on cycle ergometer; Wingate anaerobic test; Intermittent cycle test; Treadmill running at 70%-80% VO2max | HR during SSE<br>RPE during SSE<br>BF during SSE<br>All other respiratory variables | ↑<br>↑<br>↑<br>NS |
| **Hormonal and immunological** | Abedelmalek et al. 2013 [101] | 30 footballers | 4.5 h obtained for one night | 4 × 250m runs on treadmill at 80% of the personal maximal speed (3 min rest in between sets) | Plasma cortisol<br>Testosterone<br>Growth hormone<br>IL-6<br>TNF-α | NS<br>↑<br>↑<br>↑<br>↑ |
| | Abedelmalek et al. 2013 [144] | 12 footballers | 4 h obtained for one night | Wingate anaerobic test | IL-6 | ↑<br>Measured at 1800h |
| | Costa et al. 2010 [149] | 10 recreationally active participants | 30 h of SD | 30 min steady state treadmill exercise at 60% VO$_{2max}$; followed by a 30 min treadmill time trial | Circulating leukocytes<br>T-lymphocyte subset<br>Bacterially-stimulated neutrophil degranulation<br>Saliva secretory immunoglobulin A<br>Plasma cortisol | NS<br>NS<br>NS<br>NS<br>NS |
| | Goh et al. 2001 [145] | 14 military service members | Whole night | Military pursuit drills | Melatonin<br>Plasma cortisol | ↑<br>NS |
| | Martin and Chen 1984 [121] | 8 graduate students | 50 h of SD | Walking at steady-state then walking to exhaustion | Blood lactate<br>Epinephrine<br>Dopamine | NS<br>NS<br>NS |
| | Martin et al. 1986 [138] | 8 healthy participants | 36 h of SD (preceded by 2 nights of partial sleep disruption) | 30min of high intensity treadmill walking and 3h of treadmill walking | Plasma cortisol<br>ß-endorphins | NS<br>NS |
| | Mougin et al. 1991 [95] | 7 cyclists | 3 h of SR during the night | 20 min steady state work (75% VO$_{2max}$) on a cycle ergometer, followed by incremental test to exhaustion | Blood lactate | ↑ during both phases |
| | Mougin et al. 1996 [96] | 8 highly trained participants | ~4 h obtained for one night (SR) | Wingate anaerobic test | Plasma concentrations of lactate | NS |

**Table 2**: *continued*

| | Study | Subjects and fitness status if provided | Sleep intervention | Exercise protocol | Outcome measures | Results |
|---|---|---|---|---|---|---|
| **Hormonal and immunological *continued*** | Mougin et al. 2001 [99] | 8 well-trained endurance athletes | 4.5 h obtained for two nights (SR) | 30 min steady state cycling at 75% of $VO_{2max}$ then progressive increases to exhaustion | Growth hormone<br>Prolactin<br>Plasma cortisol<br>Catecholamines<br>Blood lactate | NS<br>↑<br>↓<br>NS<br>↑ |
| | Plyley et al. 1987 [160] | 11 healthy volunteers | 64 h of SD | $VO_{2max}$ test, with an additional group completing 1 h of treadmill walking every 3 h | Blood lactate | NS |
| | Soussi et al. 2003 [128] | 13 physical education students | 24 h of SD | Wingate anaerobic test | Blood lactate | NS |
| **Energy substrate storage** | Skein et al. 2011 [126] | 10 team-sport athletes | 30 h of SD | 30 min graded exercise run; 50 min intermittent-sprint exercise protocol (15 m maximal sprint every minute and self-paced exercise for remainder of minute) | Muscle glycogen | ↓ |
| **Thermoregulation** | Martin et al. 1986 [138] | 8 healthy participants | 36 h of SD (preceded by 2 nights of partial sleep disruption) | 30 min of high intensity treadmill walking and 3 h of treadmill walking | Core temperature | NS |
| | Meney et al. 1998 [30] | 14 healthy participants | Whole night of SD | 5 min of self-paced cycling | Core temperature (tympanic membrane) | NS |
| | Sawka et al. 1984 [204] | 5 fit participants | 33 h of SD | 40 min on cycle ergometer (50% of $VO_{2max}$) in 28°C 'ambient' conditions | Core temperature (Esophageal)<br>Local sweat rate<br>Chest thermal conductance | NS<br>↓<br>↓ |

↓ (Decrease), ↑ *(*Increase), [a] All changes signified by ↑ and ↓ were statistically significant ($p < 0.05$), [b] Full text unavailable, *BF* breathing frequency, *BP* blood pressure, $FEV_1$ forced expiratory volume, *HR* heart rate, $HR_{max}$ maximal heart rate, *IL-6* interleukin six, *NS* not significant, *RER* respiratory exchange ratio, *RPE* rating of perceived exertion, *RQ* respiratory quotient, $SaO_2$ arterial oxygen saturation, *SD* sleep deprivation, *SR* sleep restriction, *SSE* steady state exercise, *TNF*-α tumor necrosis factor, *VC* vital capacity, $VCO_2$ carbon dioxide production, $V_E$ minute ventilation, $V_{Emax}$ maximal minute ventilation, $VO_2$ oxygen uptake, $VO2_{peak}$ peak oxygen consumption, $VO_{2max}$ maximal oxygen uptake, *VT* tidal volume.

**Table 3:** Studies examining the effects of sleep loss (restriction and deprivation) on cognitive performance and mood state

| | Study | Subjects and fitness status if provided | Sleep intervention | Exercise condition if applicable | Performance measure | Results$^{a,b}$ |
|---|---|---|---|---|---|---|
| **Cognitive performance** | Angus et al. 1985 [191] | 12 fit young subjects | 60 h of SD | N/A | Auditory vigilance<br>Logical reasoning<br>Visual search<br>Mental addition<br>Coding<br>RT | ↓<br>↓<br>↓<br>↓<br>↓<br>↑ |
| | Axelsson et al. 2008 [109] | 9 healthy participants | 4 h obtained per night for five nights | N/A | RT | ↑ |
| | Bonnet 1985 [172] | 11 healthy adults | Continuous disruption for two nights, ~ 1 h lost per night (SR) | N/A | RT | ↑ |
| | Drummond et al. 2012 [185] | 44 healthy participants | 3.5-4 h obtained per night for 4 nights (SR) | N/A | Visual working memory performance<br>Filtering efficiency performance | NS<br>NS |
| | Drummond et al. 2012 [185] | 44 healthy participants | Whole night of SD | N/A | Visual working memory performance<br>Filtering efficiency performance | NS<br>↓ |
| | Grundgeiger et al. 2014 [175] | 60 first-year university students | 25 h of SD | N/A | Two prospective memory tasks (more demanding and less demanding combinations of German 'living' and 'non-living' words) | ↓ in both |
| | Harrison and Horne 1999 [193] | 10 trained participants | 36 h of SD | N/A | Critical reasoning<br>Game involving decision making and innovative thinking | NS<br>↓ |
| | Hurdiel et al. 2014 [86] | 12 professional competitive sailors | 22 ± 30 min , 92 ± 34 min and 172 ± 122 min during the race | 150, 300 and 350 nautical mile races | 5 min serial reaction time test | ↑ |
| | Jarraya et al. 2014 [117] | 12 handball goalkeepers | 4-5 h obtained for two nights (one with deprivation at the start, one with deprivation at end; SR) | N/A | RT<br>Stroop test (selective attention and reading ability)<br>Barrage test (visual-spatial ability and recognition) | ↑<br>↓<br>↓ |
| | Khazaie et al. 2010 [183] | 26 medical residents | < 6 h obtained per night for five nights (SR) | N/A | Wisconsin Card Sorting Test<br>Time Perception Task<br>Iowa Gambling Test | NS<br>NS<br>NS |
| | Lucas et al. 2009 [199] | 9 adventure racers | 100 h of SD | 96-125 h of adventure racing | Altered Stroop test (simple and complex response/decision making) | NS |
| | Olsen et al. 2010 [200] | 71 army and navy cadets | 2.5 h obtained per night for five nights (SR) | Combat simulation drills | Defining issues test (moral reasoning) | ↓ |

**Table 3:** *continued*

| | Study | Subjects and fitness status if provided | Sleep intervention | Exercise condition if applicable | Performance measure | Results |
|---|---|---|---|---|---|---|
| **Cognitive performance** ***continued*** | Rosa et al. 1983 [197] | 12 healthy participants | 40-64 h of SD | N/A | Williams Word Memory test<br>RT | ↓ |
| | Scott et al. 2006 [192] | 6 students | 30 h of SD | Rest and cycle ergometry at 50% $VO_{2max}$ for 20 min every 2 h for 30 h of SD | Tracking task<br>Number cancellation task<br>2 choice reaction time and simple reaction time | NS<br>NS<br>↑ at rest |
| | Symons et al. 1988 [130] | 11 volunteers | 60 h of SD | 20 min at 75% $VO_{2max}$ on cycle erg; Wingate anaerobic test; Intermittent cycle test; Treadmill running at 70-80% $VO_{2max}$; Muscular isometric strength tests | RT | NS |
| | Taheri et al. 2011 [196] | 18 student athletes | Whole night of SD | Wingate anaerobic test | Choice reaction time | ↑ |
| | Vgontzas et al. 2004 [143] | 25 normally active participants | 6 h per night (2 h less than normal) for eight nights (SR) | N/A | Psychomotor vigilance test | ↓ |
| | Williamson et al. 2000 [194] | 39 volunteers from transport industry and the army | 17-19 h of SD | N/A | RT<br>Mackworth clock (passive vigilance test)<br>Tracking (hand-eye coordination)<br>Dual task (divided attention)<br>Symbol digit test (coding)<br>Spatial memory search<br>Memory and search test | Speed and accuracy for all tasks were generally poorer with results at the end of the SD period equivalent to blood alcohol concentrations of 0.01-0.05. |
| | Wimmer et al. 1992 [198] | 12 undergraduate students | Whole night of SD | N/A | Torrence test of creative thinking<br>Trail marking test (attention)<br>Letter recognition task (attention)<br>Working memory performance | ↓<br>↓<br>↓<br>↓ |
| **Mood state** | Angus et al. 1985 [191] | 12 fit young subjects | 60 h of SD | N/A | Subjective Fatigue Checklist<br>Stanford Sleepiness Scale<br>Mood state<br>Auditory vigilance<br>Logical reasoning<br>Visual search<br>Mental addition<br>Coding<br>RT | ↑<br>↑<br>↓<br>↓<br>↓<br>↓<br>↓<br>↓<br>↑ |
| | Axelsson et al. 2008 [109] | 9 healthy participants | 4 h obtained per night for five nights (SR) | N/A | RT<br>Karolinksa Sleepiness Scale | ↑<br>↑ |
| | Bonnet 1985 [172] | 11 healthy adults | Continuous disruption for two nights, ~ 1h lost per night (SR) | N/A | Clyde Mood Scale<br>Stanford Sleepiness Scale | ↓<br>↑ |
| | Edwards and Waterhouse 2009 [115] | 60 differently experienced dart players | 3-4 h obtained for one night (SR) | Dart throwing | Subjective alertness<br>Subjective fatigue | ↓<br>↑ |

**Table 3:** *continued*

| | Study | Subjects and fitness status if provided | Sleep intervention | Exercise condition if applicable | Performance measure | Results |
|---|---|---|---|---|---|---|
| **Mood state *continued*** | Koboyashi et al. 2007 [110] | 13 healthy university students | 5 h obtained per night for seven nights (SR) | N/A | Subjective sleepiness | ↑ |
| | Meney et al. 1998 [30] | 14 healthy participants | Whole night of SD | 5 min of self-paced cycling; | *POMS* | |
| | | | | | Fatigue | ↑ |
| | | | | | Confusion | ↑ |
| | | | | | Vigour | ↓ |
| | Olsen et al. 2010 [200] | 71 army and navy cadets | 2.5 h obtained per night for five nights (SR) | Combat simulation drills | Stanford Sleepiness Scale | ↑ |
| | | | | | Defining Issues test (moral reasoning) | ↓ |
| | Reilly and Piercy 1994 [106] | 8 healthy participants | 3 h obtained per night for three nights (SR) | Weight lifting tasks | *POMS* | |
| | | | | | Fatigue | ↑ |
| | | | | | Confusion | ↑ |
| | | | | | Vigour | ↓ |
| | | | | | Depression | NS |
| | | | | | Anger | NS |
| | | | | | Tension | NS |
| | | | | | Sleepiness | ↑ |
| | | | | | Perceived effort | ↑ |
| | Scott et al. 2006 [192] | 6 students | 30 h of SD | Rest and cycle ergometry at 50% $VO_{2max}$ for 20 min every 2 h for 30 h of SD | *POMS* | |
| | | | | | Fatigue | ↑ |
| | | | | | Confusion | ↑ |
| | | | | | Vigour | ↓ |
| | | | | | Depression | ↑ |
| | | | | | Tension | NS |
| | | | | | Anger | NS |
| | | | | | Tracking task | NS |
| | | | | | Number cancellation task | NS |
| | | | | | 2 choice reaction time and simple reaction time | ↑ at rest |
| | Sinnerton and Reilly 1992 [111] | 8 swimmers | 2.5 h obtained per night for four nights (SR) | Muscular strength measures; Swimming performance test | *POMS* | |
| | | | | | Fatigue | ↑ |
| | | | | | Confusion | ↑ |
| | | | | | Vigour | ↓ |
| | | | | | Depression | ↑ |
| | | | | | Tension | ↑ |
| | | | | | Anger | ↑ |
| | Skein et al. 2011 [126] | 10 team-sport athletes | 30 h of SD | 30 min graded exercise run, 50 min intermittent sprint exercise (15 m maximal sprint per min and self-paced after) | *POMS* | |
| | | | | | Liveliness | ↓ |
| | | | | | Alertness | NS |
| | | | | | Energetic | NS |
| | | | | | Fatigue | NS |
| | Vgontzas et al. 2004 [143] | 25 normally active participants | 6 h per night for eight nights | N/A | Multiple Sleep Latency Test | ↑ |

↓ (Decrease), ↑ (Increase), [a] All changes signified by ↑ and ↓ were statistically significant ($p < 0.05$), [b] Note that, for RT, ↑ represents a slowing down of reaction time, *N/A* not applicable, *NS* not significant, *POMS* Profile of Mood States, *RT* simple reaction time, *SD* sleep deprivation, *SR* sleep restriction, $VO_{2max}$ maximal oxygen uptake.

**Table 4:** Effects of sleep loss on cognitive functioning and possible extrapolations to sport performance (column 1 adapted from Durmer and Dinges [23], with permission)

| Effects of sleep loss on cognitive performance | Possible effects on professional athletes |
|---|---|
| Time pressure increases error rate | More errors in time-affected sports (e.g. shotclock in basketball) |
| Response time slows | Decreased reaction time could be especially pertinent for sprinters, baseballers, cricketers, goalkeepers, tennis and handball players |
| Both short-term recall and working memory performances decline | Effects the messages coaches can deliver to athletes, this will have a flow-on effect on tactical awareness (may be pertinent for teams with set plays e.g. American football, ice hockey, rugby league, basketball and soccer) |
| Reduced learning (acquisition) of cognitive tasks | Blunt cognitive-induced training adaptations during periods of high intensity learning (e.g. players will struggle whilst learning new tactics and formations during pre-season, Australian rules football) |
| Response perseveration on ineffective solutions is more likely | If an athlete continually tries to perform a task in the wrong manner from a reduced proprioceptive state, this could lead to an increase in injury [3] |
| Tasks may be begun well, but performance deteriorates as task duration increases | Fatigue can lead to an increase in decision making errors. Could affect all sports played over prolonged periods (e.g. decathlon, American football, baseball, Australian rules football) |
| Increased compensatory effort is required to remain behaviourally effective | This would suggest a decrease in time to fatigue, affecting numerous sports which experience intermittent and repeated exercise bouts |

**Table 5:** Practical recommendations for sporting practitioners

---

Identify if sleep problems exist within your athletic population – collect and compare to longitudinal data across a variety of situations and competitions. Where possible, collect performance and/or match data to detect possible associations. There may be instances where there are no sleep issues apparent.

If issues are present, identify poor practice; how, when and why do these issues occur. If problems persist, treat it in conjunction with a trained medical professional from the team to improve the quantity and quality of sleep (follow sleep hygiene practice i.e. no technology 30 min before bedtime, no TV or use of laptops in bed, dark, cool and quiet rooms)

Understand that the effect of a poor night's sleep (acute sleep restriction) before a match or training may not necessarily affect athletic (exercise) performance. Theoretical principles and limited evidence would suggest it is more likely to affect illness and injury occurrence.

Avoid early morning training sessions following sleep disruption where possible, as these can be more detrimental to muscle strength and power performance than late bedtimes.

Be aware that poor sleep prior to training could influence motivation and may hinder both cognitive and physiological induced training adaptations.

Where possible align training sessions to game times to adjust circadian rhythms. However, such practices have logistical issues and should not be at the risk of the quality of training

Practitioners, where possible, should supplement this understanding of sleep loss and performance with an increased knowledge of the relationship between sleep and recovery. Despite a widely held assumption that sleep is crucial for recovery, the interaction between sleep and recovery remains poorly understood. Limited evidence indicates sleep has a role to play in athletic recovery; however the mechanisms behind this remain uncertain, so this assumption should be treated with caution.

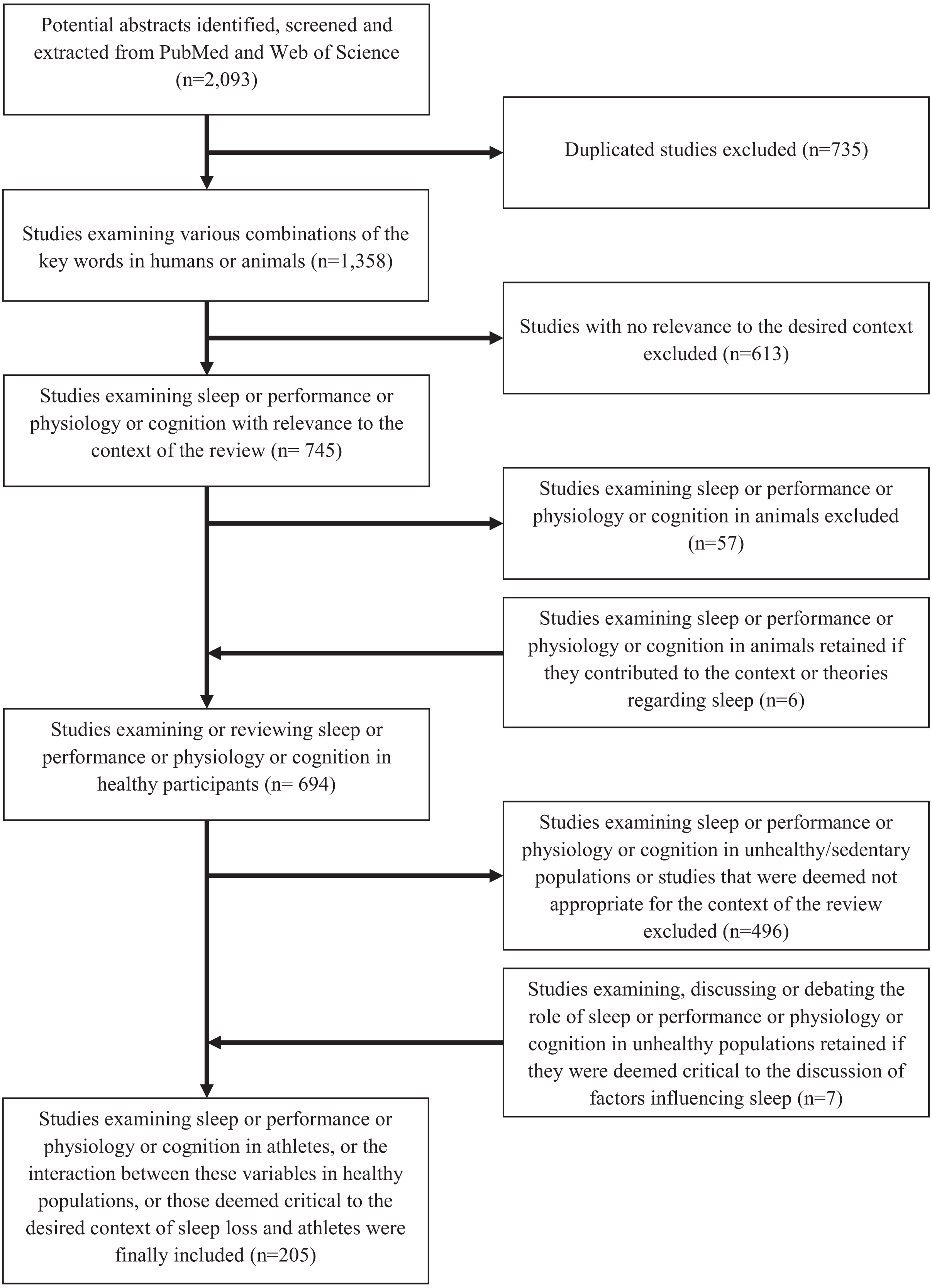


**Figure 1:** Flow diagram and results of the literature search to address the aim of the article to evaluate the importance and prevalence of sleep in athletes and review the effects of sleep loss on exercise performance, and physiological and cognitive responses to exercise.

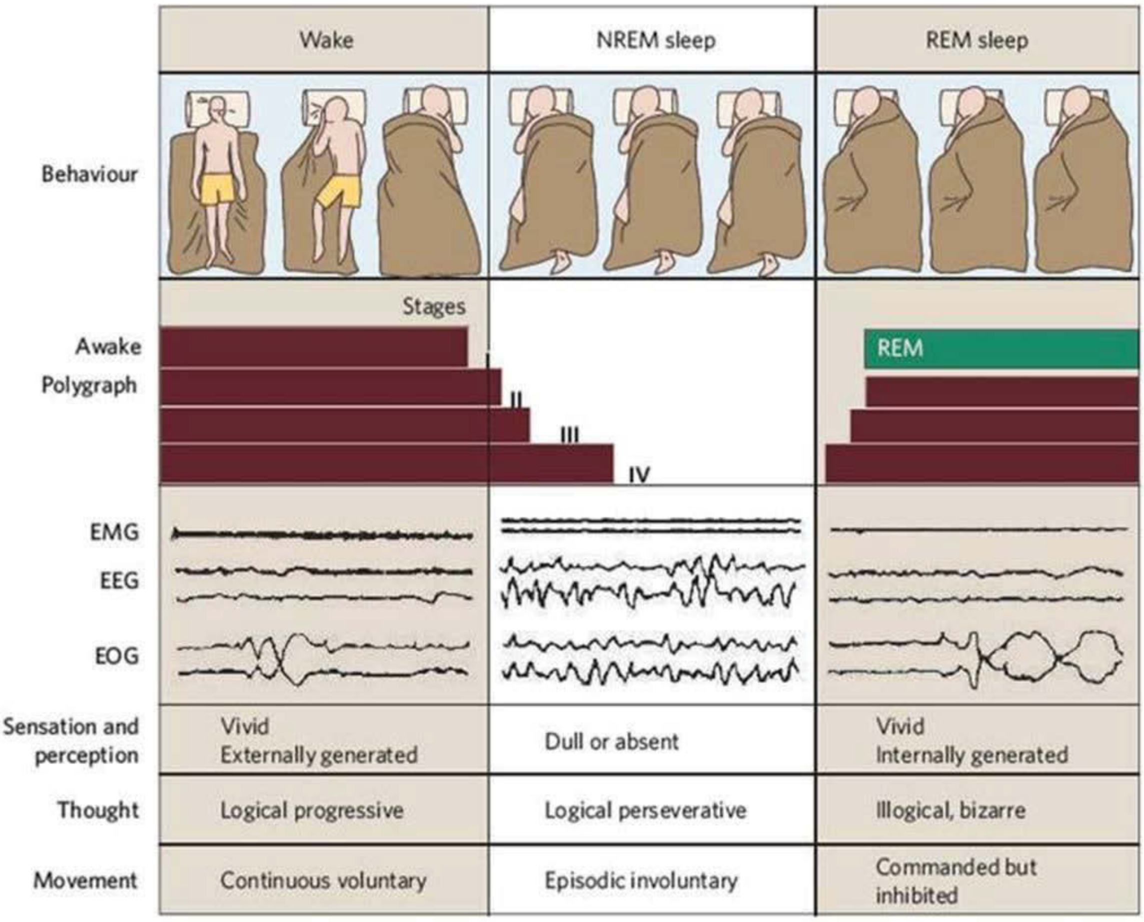


**Figure 2**: The behavioural states of humans and phase changes throughout the sleep wake cycle, including states of waking, non-rapid-eye-movement sleep (NREM sleep) and rapid-eye-movement sleep (REM). The first row depicts a visual representation of movements throughout the sleep night. The second row illustrates REM sleep and the four stages of NREM sleep. The third row includes sample polysomnography tracings (each ~ 20 s) of an electromyogram (EMG), an electroencephalogram (EEG) and an electrooculogram (EOG) to help determine the presence or absence of each stage. Rows four, five and six portray a range of subjective and objective state variables. Although unable to replicate the sensitivity of these measurement techniques, other sleep indices (i.e. duration, latency) can also be measured by subjective sleep diaries and or/ wristwatch actigraphy. Reproduced from Hobson [45], with permission.

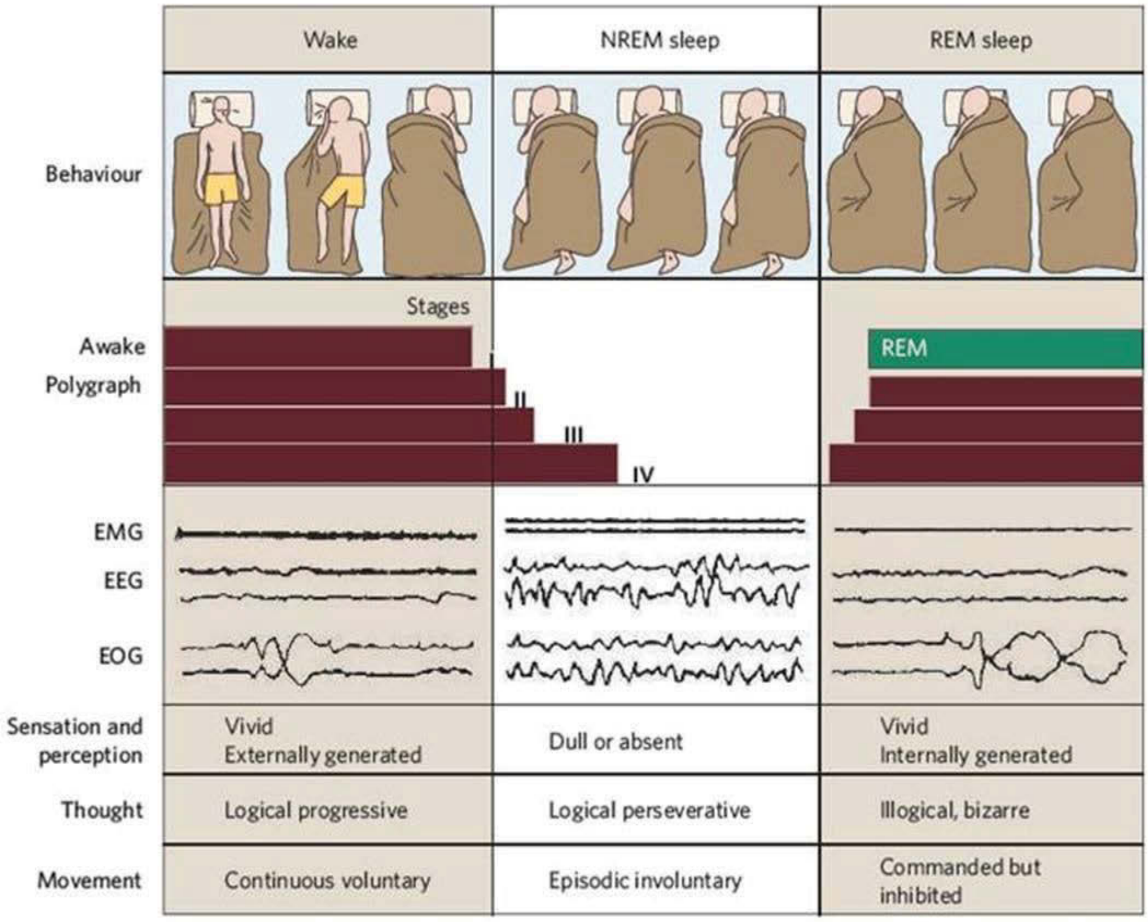


**Figure 2**: The behavioural states of humans and phase changes throughout the sleep wake cycle, including states of waking, non-rapid-eye-movement sleep (NREM sleep) and rapid-eye-movement sleep (REM). The first row depicts a visual representation of movements throughout the sleep night. The second row illustrates REM sleep and the four stages of NREM sleep. The third row includes sample polysomnography tracings (each ~ 20 s) of an electromyogram (EMG), an electroencephalogram (EEG) and an electrooculogram (EOG) to help determine the presence or absence of each stage. Rows four, five and six portray a range of subjective and objective state variables. Although unable to replicate the sensitivity of these measurement techniques, other sleep indices (i.e. duration, latency) can also be measured by subjective sleep diaries and or/ wristwatch actigraphy. Reproduced from Hobson [45], with permission.

Adis

## CONFLICT OF INTEREST DISCLOSURE FORM

At submission, **EVERY AUTHOR** listed in the manuscript must **READ** and **COMPLETE** the following statements on: (A) Authorship Responsibility, (B) Authorship Criteria, (C) Authorship Contribution, (D) Funding Disclosures, (E) Contributor Disclosures/Acknowledgments, and (F) Conflicts of Interest Disclosures.

It is important that you return this form as early as possible in the publication process. **EVERY AUTHOR MUST COMPLETE AN INDIVIDUAL COPY OF THE FORM, AND EVERY SECTION OF THE FORM MUST BE COMPLETED.** We will **NOT** consider your manuscript for publication until every author has completed the form and returned it to us.

Your name (please print): Hugh Fullagar E-mail: hugh.fullagar@uni-saarland.de

Journal name: Sports Medicine Corresponding author: Hugh Fullagar

Manuscript title: Sleep and athletic performance: The effect of sleep loss on exercise performance, and physiological & cognitive responses to exercise.

### A. AUTHORSHIP RESPONSIBILITY

☑ I certify that **ALL** of the following statements are correct **(PLEASE CHECK THE BOX)**.

- The manuscript represents valid work; neither this manuscript nor one with substantially similar content under my authorship has been published or is being considered for publication elsewhere (except as described in the manuscript submission); and copies of any closely related manuscripts are enclosed in the manuscript submission; ***AND***
- For manuscripts with more than one author, I agree to allow the corresponding author to serve as the primary correspondent with the editorial office and to review and sign off on the final proofs prior to publication; or, if I am the only author, I will be the corresponding author and agree to serve in the roles described above.
- Any change in authors and/or contributors after initial submission must be approved by all authors. This applies to additions, deletions, change in order of the authors, or contributions being attributed differently. Any alterations must be explained.
- For manuscripts that are a report of a study, I confirm that this work is an accurate representation of the trial results.

### B. AUTHORSHIP CRITERIA

To fulfil all of the criteria for authorship, every author of the manuscript must have made substantial contributions to **ALL** of the following aspects of the work:

- Conception and planning of the work that led to the manuscript or acquisition, analysis and interpretation of the data, or both; ***AND***
- Drafting and/or critical revision of the manuscript for important intellectual content; ***AND***
- Approval of the final submitted version of the manuscript.

☑ I certify that I fulfill **ALL** of the above criteria for authorship **(PLEASE CHECK THE BOX)**.

### C. AUTHORSHIP CONTRIBUTION

I certify that I have participated sufficiently in the work to take public responsibility for **(PLEASE CHECK 1 OF THE 2 BOXES BELOW)**:

☐ Part of the content of the manuscript; ***OR***

☑ The entire content of the manuscript.

### D. FUNDING DISCLOSURES

All sources of funding should be declared in the Acknowledgements section of the manuscript. Authors must describe the role of the study sponsor(s), if any, in: (i) the study design; (ii) the collection, analysis and interpretation of data; (iii) the writing of the report; and (iv) the decision to submit the paper for publication. If the authors' work was independent of the funders, the authors should state this.

**PLEASE CHECK 1 OF THE 2 BOXES BELOW**:

☑ I certify that no funding has been received for the conduct of this study and/or preparation of this manuscript; ***OR***

☐ I certify that all financial and material support for the conduct of this study and/or preparation of this manuscript is clearly described in the Acknowledgments section of the manuscript.

### E. CONTRIBUTOR DISCLOSURES (complete if applicable)

All persons who have made substantial contributions to the work reported in the manuscript (e.g. data collection, data analysis, or writing or editing assistance) but who do not fulfill the authorship criteria **MUST** be named with their specific contributions in the Acknowledgments section of the manuscript. Groups of persons who have contributed may be listed under a heading such as 'Clinical investigators' and their function described. Because readers may infer their endorsement of the manuscript, all persons named in the Acknowledgments section **MUST** give the authors their written permission to be named in the manuscript.

☑ I certify that all persons who have made substantial contributions to this manuscript but who do not fulfill the authorship criteria are listed with their specific contributions in the Acknowledgments section in the manuscript, and that all persons named in the Acknowledgments section have given me written permission to be named in the manuscript.

**F. CONFLICT OF INTEREST DISCLOSURES**

A conflict of interest exists when professional judgment concerning a primary interest (such as patients' welfare or the validity of research) may be influenced by a secondary interest (such as financial gain or personal rivalry). A conflict of interest may arise for authors when they have a financial interest that may influence – probably without their knowing – their interpretation of their results or those of others. We believe that to make the best decision on how to deal with a manuscript we should know about any such conflict of interest that the authors may have. We are not aiming to eradicate conflicts of interests – they are almost inevitable. We will not reject manuscripts simply because the authors have a conflict of interest, but we will publish a declaration in the manuscript as to whether or not the authors have conflicts of interests.

All authors **MUST** complete the following checklist:

| | | | |
|---|---|---|---|
| **Category of potential conflict of interest** | If you have had any of the listed relationships with an entity that has a financial interest in the subject matter discussed in this manuscript, please check the appropriate "Yes" box below and provide details. If you do not have a listed relationship, please check the appropriate "No" box. When completing this section, please take into account the last 36 months through to the foreseeable future. | | |
| | **No (√)** | **Yes (√)** | **Details** |
| Employment | ✓ | | |
| Grant received/grants pending | ✓ | | |
| Consulting fees or honorarium | ✓ | | |
| Support for travel to meetings for the study, manuscript preparation or other purposes | ✓ | | |
| Fees for participation in review activities such as data monitoring boards, etc | ✓ | | |
| Payment for writing or reviewing the manuscript | ✓ | | |
| Provision of writing assistance, medicines, equipment or administrative support | ✓ | | |
| Payment for lectures including service on speakers bureaus | ✓ | | |
| Stock/stock options | ✓ | | |
| Expert testimony | ✓ | | |
| Patents (planned, pending or issued) | ✓ | | |
| Royalties | ✓ | | |
| Other (err on the side of full disclosure) | ✓ | | |

Every author **MUST** complete option 1 or option 2 as appropriate below. If you answered "Yes" to any of the questions relating to financial conflicts of interests in the table above (or if you wish to disclose a non-financial conflict of interest), you **MUST** write a suitable statement in the box below. This statement will be published in the Acknowledgments section of the manuscript.

☑ I have no conflicts of interest to declare; ***OR***

☐ Please insert the following statement regarding conflicts of interest and financial support for conduct of this study and/or preparation of this manuscript in the Acknowledgments section of the manuscript:

**Declaration:** I certify that I have fully read and fully understood this form, and that the information that I have presented here is accurate and complete to the best of my knowledge.

Your name (please print): Hugh Fullagar

Signature (please **HAND-WRITE**): [redacted]

Date: 14/3/14

Springer

http://www.springer.com/journal/40279

Sports Medicine
Associate Editor: McMillan, S. - Editor: Olney, R.
ISSN: 0112-1642 (print version)
ISSN: 1179-2035 (electronic version)
Journal no. 40279

# CONFLICT OF INTEREST DISCLOSURE FORM

At submission, **EVERY AUTHOR** listed in the manuscript must **READ** and **COMPLETE** the following statements on: (A) Authorship Responsibility, (B) Authorship Criteria, (C) Authorship Contribution, (D) Funding Disclosures, (E) Contributor Disclosures/Acknowledgments, and (F) Conflicts of Interest Disclosures.

It is important that you return this form as early as possible in the publication process. **EVERY AUTHOR MUST COMPLETE AN INDIVIDUAL COPY OF THE FORM, AND EVERY SECTION OF THE FORM MUST BE COMPLETED.** We will **NOT** consider your manuscript for publication until every author has completed the form and returned it to us.

Your name (please print): Sabrina Skorski
E-mail: s.skorski@mx.uni-saarland.de

Journal name: Sports Medicine
Corresponding author: Hugh Fullagar

Manuscript title: Sleep and athletic performance: The effects of sleep loss on exercise performance, and physiological and cognitive responses to exercise

## A. AUTHORSHIP RESPONSIBILITY

☑ I certify that **ALL** of the following statements are correct **(PLEASE CHECK THE BOX)**.

- The manuscript represents valid work; neither this manuscript nor one with substantially similar content under my authorship has been published or is being considered for publication elsewhere (except as described in the manuscript submission); and copies of any closely related manuscripts are enclosed in the manuscript submission; ***AND***
- For manuscripts with more than one author, I agree to allow the corresponding author to serve as the primary correspondent with the editorial office and to review and sign off on the final proofs prior to publication; or, if I am the only author, I will be the corresponding author and agree to serve in the roles described above.
- Any change in authors and/or contributors after initial submission must be approved by all authors. This applies to additions, deletions, change in order of the authors, or contributions being attributed differently. Any alterations must be explained.
- For manuscripts that are a report of a study, I confirm that this work is an accurate representation of the trial results.

## B. AUTHORSHIP CRITERIA

To fulfil all of the criteria for authorship, every author of the manuscript must have made substantial contributions to **ALL** of the following aspects of the work:

- Conception and planning of the work that led to the manuscript or acquisition, analysis and interpretation of the data, or both; ***AND***
- Drafting and/or critical revision of the manuscript for important intellectual content; ***AND***
- Approval of the final submitted version of the manuscript.

☑ I certify that I fulfill **ALL** of the above criteria for authorship **(PLEASE CHECK THE BOX)**.

## C. AUTHORSHIP CONTRIBUTION

I certify that I have participated sufficiently in the work to take public responsibility for **(PLEASE CHECK 1 OF THE 2 BOXES BELOW)**:

☐ Part of the content of the manuscript; ***OR***
☑ The entire content of the manuscript.

## D. FUNDING DISCLOSURES

All sources of funding should be declared in the Acknowledgements section of the manuscript. Authors must describe the role of the study sponsor(s), if any, in: (i) the study design; (ii) the collection, analysis and interpretation of data; (iii) the writing of the report; and (iv) the decision to submit the paper for publication. If the authors' work was independent of the funders, the authors should state this.

**PLEASE CHECK 1 OF THE 2 BOXES BELOW**:

☐ I certify that no funding has been received for the conduct of this study and/or preparation of this manuscript; ***OR***
☑ I certify that all financial and material support for the conduct of this study and/or preparation of this manuscript is clearly described in the Acknowledgments section of the manuscript.

## E. CONTRIBUTOR DISCLOSURES (complete if applicable)

All persons who have made substantial contributions to the work reported in the manuscript (e.g. data collection, data analysis, or writing or editing assistance) but who do not fulfill the authorship criteria **MUST** be named with their specific contributions in the Acknowledgments section of the manuscript. Groups of persons who have contributed may be listed under a heading such as 'Clinical investigators' and their function described. Because readers may infer their endorsement of the manuscript, all persons named in the Acknowledgments section **MUST** give the authors their written permission to be named in the manuscript.

☑ I certify that all persons who have made substantial contributions to this manuscript but who do not fulfill the authorship criteria are listed with their specific contributions in the Acknowledgments section in the manuscript, and that all persons named in the Acknowledgments section have given me written permission to be named in the manuscript.

## F. CONFLICT OF INTEREST DISCLOSURES

A conflict of interest exists when professional judgment concerning a primary interest (such as patients' welfare or the validity of research) may be influenced by a secondary interest (such as financial gain or personal rivalry). A conflict of interest may arise for authors when they have a financial interest that may influence – probably without their knowing – their interpretation of their results or those of others. We believe that to make the best decision on how to deal with a manuscript we should know about any such conflict of interest that the authors may have. We are not aiming to eradicate conflicts of interests – they are almost inevitable. We will not reject manuscripts simply because the authors have a conflict of interest, but we will publish a declaration in the manuscript as to whether or not the authors have conflicts of interests.

All authors **MUST** complete the following checklist:

| **Category of potential conflict of interest** | If you have had any of the listed relationships with an entity that has a financial interest in the subject matter discussed in this manuscript, please check the appropriate "Yes" box below and provide details. If you do not have a listed relationship, please check the appropriate "No" box. When completing this section, please take into account the last 36 months through to the foreseeable future. | | |
|---|---|---|---|
| | **No (√)** | **Yes (√)** | **Details** |
| Employment | √ | | |
| Grant received/grants pending | √ | | |
| Consulting fees or honorarium | √ | | |
| Support for travel to meetings for the study, manuscript preparation or other purposes | √ | | |
| Fees for participation in review activities such as data monitoring boards, etc | √ | | |
| Payment for writing or reviewing the manuscript | √ | | |
| Provision of writing assistance, medicines, equipment or administrative support | √ | | |
| Payment for lectures including service on speakers bureaus | √ | | |
| Stock/stock options | √ | | |
| Expert testimony | √ | | |
| Patents (planned, pending or issued) | √ | | |
| Royalties | √ | | |
| Other (err on the side of full disclosure) | | | |

Every author **MUST** complete option 1 or option 2 as appropriate below. If you answered "Yes" to any of the questions relating to financial conflicts of interests in the table above (or if you wish to disclose a non-financial conflict of interest), you **MUST** write a suitable statement in the box below. This statement will be published in the Acknowledgments section of the manuscript.

☑ I have no conflicts of interest to declare; ***OR***

☐ Please insert the following statement regarding conflicts of interest and financial support for conduct of this study and/or preparation of this manuscript in the Acknowledgments section of the manuscript:

**Declaration:** I certify that I have fully read and fully understood this form, and that the information that I have presented here is accurate and complete to the best of my knowledge.

Your name (please print): Sabrina Skorski

Signature (please **HAND-WRITE**):

Date: 09.03.2014

.

http://www.springer.com/journal/40279

Sports Medicine
Associate Editor: McMillan, S. – Editor: Olney, R.
ISSN: 0112-1642 (print version)
ISSN: 1179-2035 (electronic version)
Journal no. 40279

Adis

# CONFLICT OF INTEREST DISCLOSURE FORM

At submission, **EVERY AUTHOR** listed in the manuscript must **READ** and **COMPLETE** the following statements on: (A) Authorship Responsibility, (B) Authorship Criteria, (C) Authorship Contribution, (D) Funding Disclosures, (E) Contributor Disclosures/Acknowledgments, and (F) Conflicts of Interest Disclosures.

It is important that you return this form as early as possible in the publication process. **EVERY AUTHOR MUST COMPLETE AN INDIVIDUAL COPY OF THE FORM, AND EVERY SECTION OF THE FORM MUST BE COMPLETED.** We will **NOT** consider your manuscript for publication until every author has completed the form and returned it to us.

Your name (please print): Rob Duffield E-mail: Rob.Duffield@uts.edu.au

Journal name: Sports Medicine Corresponding author: Hugh Fullagar

Manuscript title: Sleep and athletic performance: The effects of sleep on exercise performance, and physiological and cognitive responses to exercise.

## A. AUTHORSHIP RESPONSIBILITY

☒ I certify that **ALL** of the following statements are correct **(PLEASE CHECK THE BOX).**

- The manuscript represents valid work; neither this manuscript nor one with substantially similar content under my authorship has been published or is being considered for publication elsewhere (except as described in the manuscript submission); and copies of any closely related manuscripts are enclosed in the manuscript submission; ***AND***
- For manuscripts with more than one author, I agree to allow the corresponding author to serve as the primary correspondent with the editorial office and to review and sign off on the final proofs prior to publication; or, if I am the only author, I will be the corresponding author and agree to serve in the roles described above.
- Any change in authors and/or contributors after initial submission must be approved by all authors. This applies to additions, deletions, change in order of the authors, or contributions being attributed differently. Any alterations must be explained.
- For manuscripts that are a report of a study, I confirm that this work is an accurate representation of the trial results.

## B. AUTHORSHIP CRITERIA

To fulfil all of the criteria for authorship, every author of the manuscript must have made substantial contributions to **ALL** of the following aspects of the work:

- Conception and planning of the work that led to the manuscript or acquisition, analysis and interpretation of the data, or both; ***AND***
- Drafting and/or critical revision of the manuscript for important intellectual content; ***AND***
- Approval of the final submitted version of the manuscript.

☒ I certify that I fulfill **ALL** of the above criteria for authorship **(PLEASE CHECK THE BOX).**

## C. AUTHORSHIP CONTRIBUTION

I certify that I have participated sufficiently in the work to take public responsibility for **(PLEASE CHECK 1 OF THE 2 BOXES BELOW):**

☐ Part of the content of the manuscript; ***OR***
☒ The entire content of the manuscript.

## D. FUNDING DISCLOSURES

All sources of funding should be declared in the Acknowledgements section of the manuscript. Authors must describe the role of the study sponsor(s), if any, in: (i) the study design; (ii) the collection, analysis and interpretation of data; (iii) the writing of the report; and (iv) the decision to submit the paper for publication. If the authors' work was independent of the funders, the authors should state this.

**PLEASE CHECK 1 OF THE 2 BOXES BELOW:**

☒ I certify that no funding has been received for the conduct of this study and/or preparation of this manuscript; ***OR***
☐ I certify that all financial and material support for the conduct of this study and/or preparation of this manuscript is clearly described in the Acknowledgments section of the manuscript.

## E. CONTRIBUTOR DISCLOSURES (complete if applicable)

All persons who have made substantial contributions to the work reported in the manuscript (e.g. data collection, data analysis, or writing or editing assistance) but who do not fulfill the authorship criteria **MUST** be named with their specific contributions in the Acknowledgments section of the manuscript. Groups of persons who have contributed may be listed under a heading such as 'Clinical investigators' and their function described. Because readers may infer their endorsement of the manuscript, all persons named in the Acknowledgments section **MUST** give the authors their written permission to be named in the manuscript.

☒ I certify that all persons who have made substantial contributions to this manuscript but who do not fulfill the authorship criteria are listed with their specific contributions in the Acknowledgments section in the manuscript, and that all persons named in the Acknowledgments section have given me written permission to be named in the manuscript.

## F. CONFLICT OF INTEREST DISCLOSURES

A conflict of interest exists when professional judgment concerning a primary interest (such as patients' welfare or the validity of research) may be influenced by a secondary interest (such as financial gain or personal rivalry). A conflict of interest may arise for authors when they have a financial interest that may influence – probably without their knowing – their interpretation of their results or those of others. We believe that to make the best decision on how to deal with a manuscript we should know about any such conflict of interest that the authors may have. We are not aiming to eradicate conflicts of interests – they are almost inevitable. We will not reject manuscripts simply because the authors have a conflict of interest, but we will publish a declaration in the manuscript as to whether or not the authors have conflicts of interests.

All authors **MUST** complete the following checklist:

| **Category of potential conflict of interest** | If you have had any of the listed relationships with an entity that has a financial interest in the subject matter discussed in this manuscript, please check the appropriate "Yes" box below and provide details. If you do not have a listed relationship, please check the appropriate "No" box. When completing this section, please take into account the last 36 months through to the foreseeable future. | | |
|---|---|---|---|
| | **No (√)** | **Yes (√)** | **Details** |
| Employment | ✓ | | |
| Grant received/grants pending | ✓ | | |
| Consulting fees or honorarium | ✓ | | |
| Support for travel to meetings for the study, manuscript preparation or other purposes | ✓ | | |
| Fees for participation in review activities such as data monitoring boards, etc | ✓ | | |
| Payment for writing or reviewing the manuscript | ✓ | | |
| Provision of writing assistance, medicines, equipment or administrative support | ✓ | | |
| Payment for lectures including service on speakers bureaus | ✓ | | |
| Stock/stock options | ✓ | | |
| Expert testimony | ✓ | | |
| Patents (planned, pending or issued) | ✓ | | |
| Royalties | ✓ | | |
| Other (err on the side of full disclosure) | ✓ | | |

Every author **MUST** complete option 1 or option 2 as appropriate below. If you answered "Yes" to any of the questions relating to financial conflicts of interests in the table above (or if you wish to disclose a non-financial conflict of interest), you **MUST** write a suitable statement in the box below. This statement will be published in the Acknowledgments section of the manuscript.

☒ I have no conflicts of interest to declare; ***OR***

☐ Please insert the following statement regarding conflicts of interest and financial support for conduct of this study and/or preparation of this manuscript in the Acknowledgments section of the manuscript:

**Declaration:** I certify that I have fully read and fully understood this form, and that the information that I have presented here is accurate and complete to the best of my knowledge.

Your name (please print): Rob Duffield

Signature (please **HAND-WRITE**):

Date: 13/3/14

Adis

# CONFLICT OF INTEREST DISCLOSURE FORM

At submission, **EVERY AUTHOR** listed in the manuscript must **READ** and **COMPLETE** the following statements on: (A) Authorship Responsibility, (B) Authorship Criteria, (C) Authorship Contribution, (D) Funding Disclosures, (E) Contributor Disclosures/Acknowledgments, and (F) Conflicts of Interest Disclosures.

It is important that you return this form as early as possible in the publication process. **EVERY AUTHOR MUST COMPLETE AN INDIVIDUAL COPY OF THE FORM, AND EVERY SECTION OF THE FORM MUST BE COMPLETED.** We will **NOT** consider your manuscript for publication until every author has completed the form and returned it to us.

Your name (please print): Daniel Hammes E-mail: d.hammes@mx.uni-saarland.de

Journal name: Sports Medicine Corresponding author: Hugh Fullagar

Manuscript title: Sleep and athletic performance: The effects of sleep loss on exercise performance and physiological and cognitive responses to exercise

## A. AUTHORSHIP RESPONSIBILITY

☑ I certify that **ALL** of the following statements are correct **(PLEASE CHECK THE BOX)**.

- The manuscript represents valid work; neither this manuscript nor one with substantially similar content under my authorship has been published or is being considered for publication elsewhere (except as described in the manuscript submission); and copies of any closely related manuscripts are enclosed in the manuscript submission; ***AND***
- For manuscripts with more than one author, I agree to allow the corresponding author to serve as the primary correspondent with the editorial office and to review and sign off on the final proofs prior to publication; or, if I am the only author, I will be the corresponding author and agree to serve in the roles described above.
- Any change in authors and/or contributors after initial submission must be approved by all authors. This applies to additions, deletions, change in order of the authors, or contributions being attributed differently. Any alterations must be explained.
- For manuscripts that are a report of a study, I confirm that this work is an accurate representation of the trial results.

## B. AUTHORSHIP CRITERIA

To fulfil all of the criteria for authorship, every author of the manuscript must have made substantial contributions to **ALL** of the following aspects of the work:

- Conception and planning of the work that led to the manuscript or acquisition, analysis and interpretation of the data, or both; ***AND***
- Drafting and/or critical revision of the manuscript for important intellectual content; ***AND***
- Approval of the final submitted version of the manuscript.

☑ I certify that I fulfill **ALL** of the above criteria for authorship **(PLEASE CHECK THE BOX)**.

## C. AUTHORSHIP CONTRIBUTION

I certify that I have participated sufficiently in the work to take public responsibility for **(PLEASE CHECK 1 OF THE 2 BOXES BELOW)**:

☐ Part of the content of the manuscript; ***OR***

☑ The entire content of the manuscript.

## D. FUNDING DISCLOSURES

All sources of funding should be declared in the Acknowledgements section of the manuscript. Authors must describe the role of the study sponsor(s), if any, in: (i) the study design; (ii) the collection, analysis and interpretation of data; (iii) the writing of the report; and (iv) the decision to submit the paper for publication. If the authors' work was independent of the funders, the authors should state this.

**PLEASE CHECK 1 OF THE 2 BOXES BELOW:**

☑ I certify that no funding has been received for the conduct of this study and/or preparation of this manuscript; ***OR***

☑ I certify that all financial and material support for the conduct of this study and/or preparation of this manuscript is clearly described in the Acknowledgments section of the manuscript.

## E. CONTRIBUTOR DISCLOSURES (complete if applicable)

All persons who have made substantial contributions to the work reported in the manuscript (e.g. data collection, data analysis, or writing or editing assistance) but who do not fulfill the authorship criteria **MUST** be named with their specific contributions in the Acknowledgments section of the manuscript. Groups of persons who have contributed may be listed under a heading such as 'Clinical investigators' and their function described. Because readers may infer their endorsement of the manuscript, all persons named in the Acknowledgments section **MUST** give the authors their written permission to be named in the manuscript.

☑ I certify that all persons who have made substantial contributions to this manuscript but who do not fulfill the authorship criteria are listed with their specific contributions in the Acknowledgments section in the manuscript, and that all persons named in the Acknowledgments section have given me written permission to be named in the manuscript.

## F. CONFLICT OF INTEREST DISCLOSURES

A conflict of interest exists when professional judgment concerning a primary interest (such as patients' welfare or the validity of research) may be influenced by a secondary interest (such as financial gain or personal rivalry). A conflict of interest may arise for authors when they have a financial interest that may influence – probably without their knowing – their interpretation of their results or those of others. We believe that to make the best decision on how to deal with a manuscript we should know about any such conflict of interest that the authors may have. We are not aiming to eradicate conflicts of interests – they are almost inevitable. We will not reject manuscripts simply because the authors have a conflict of interest, but we will publish a declaration in the manuscript as to whether or not the authors have conflicts of interests.

All authors **MUST** complete the following checklist:

| **Category of potential conflict of interest** | If you have had any of the listed relationships with an entity that has a financial interest in the subject matter discussed in this manuscript, please check the appropriate "Yes" box below and provide details. If you do not have a listed relationship, please check the appropriate "No" box. When completing this section, please take into account the last 36 months through to the foreseeable future. | | |
|---|---|---|---|
| | **No (√)** | **Yes (√)** | **Details** |
| Employment | ✓ | | |
| Grant received/grants pending | ✓ | | |
| Consulting fees or honorarium | ✓ | | |
| Support for travel to meetings for the study, manuscript preparation or other purposes | ✓ | | |
| Fees for participation in review activities such as data monitoring boards, etc | ✓ | | |
| Payment for writing or reviewing the manuscript | ✓ | | |
| Provision of writing assistance, medicines, equipment or administrative support | ✓ | | |
| Payment for lectures including service on speakers bureaus | ✓ | | |
| Stock/stock options | ✓ | | |
| Expert testimony | ✓ | | |
| Patents (planned, pending or issued) | ✓ | | |
| Royalties | ✓ | | |
| Other (err on the side of full disclosure) | ✓ | | |

Every author **MUST** complete option 1 or option 2 as appropriate below. If you answered "Yes" to any of the questions relating to financial conflicts of interests in the table above (or if you wish to disclose a non-financial conflict of interest), you **MUST** write a suitable statement in the box below. This statement will be published in the Acknowledgments section of the manuscript.

☑ I have no conflicts of interest to declare; ***OR***

☐ Please insert the following statement regarding conflicts of interest and financial support for conduct of this study and/or preparation of this manuscript in the Acknowledgments section of the manuscript:

**Declaration:** I certify that I have fully read and fully understood this form, and that the information that I have presented here is accurate and complete to the best of my knowledge.

Your name (please print): Daniel Hammes

Signature (please **HAND-WRITE**): [redacted]

Date: 14.03.14

Springer

http://www.springer.com/journal/40279

Sports Medicine
Associate Editor: McMillan, S. - Editor: Olney, R.
ISSN: 0112-1642 (print version)
ISSN: 1179-2035 (electronic version)
Journal no. 40279

Adis

# CONFLICT OF INTEREST DISCLOSURE FORM

At submission, **EVERY AUTHOR** listed in the manuscript must **READ** and **COMPLETE** the following statements on: (A) Authorship Responsibility, (B) Authorship Criteria, (C) Authorship Contribution, (D) Funding Disclosures, (E) Contributor Disclosures/Acknowledgments, and (F) Conflicts of Interest Disclosures.

It is important that you return this form as early as possible in the publication process. **EVERY AUTHOR MUST COMPLETE AN INDIVIDUAL COPY OF THE FORM, AND EVERY SECTION OF THE FORM MUST BE COMPLETED.** We will **NOT** consider your manuscript for publication until every author has completed the form and returned it to us.

Your name (please print): Aaron COutts E-mail: aaron.coutts@uts.edu.au

Journal name: Sports Medicine Corresponding author: Hugh Fullagar

Manuscript title: Sleep and athletic performance: The effects of sleep loss on exercise performance, and physiological and cognitive responses to exercise

## A. AUTHORSHIP RESPONSIBILITY

☒ I certify that **ALL** of the following statements are correct **(PLEASE CHECK THE BOX)**.

- The manuscript represents valid work; neither this manuscript nor one with substantially similar content under my authorship has been published or is being considered for publication elsewhere (except as described in the manuscript submission); and copies of any closely related manuscripts are enclosed in the manuscript submission; ***AND***
- For manuscripts with more than one author, I agree to allow the corresponding author to serve as the primary correspondent with the editorial office and to review and sign off on the final proofs prior to publication; or, if I am the only author, I will be the corresponding author and agree to serve in the roles described above.
- Any change in authors and/or contributors after initial submission must be approved by all authors. This applies to additions, deletions, change in order of the authors, or contributions being attributed differently. Any alterations must be explained.
- For manuscripts that are a report of a study, I confirm that this work is an accurate representation of the trial results.

## B. AUTHORSHIP CRITERIA

To fulfil all of the criteria for authorship, every author of the manuscript must have made substantial contributions to **ALL** of the following aspects of the work:

- Conception and planning of the work that led to the manuscript or acquisition, analysis and interpretation of the data, or both; ***AND***
- Drafting and/or critical revision of the manuscript for important intellectual content; ***AND***
- Approval of the final submitted version of the manuscript.

☒ I certify that I fulfill **ALL** of the above criteria for authorship **(PLEASE CHECK THE BOX)**.

## C. AUTHORSHIP CONTRIBUTION

I certify that I have participated sufficiently in the work to take public responsibility for **(PLEASE CHECK 1 OF THE 2 BOXES BELOW)**:

☒ Part of the content of the manuscript; ***OR***

☐ The entire content of the manuscript.

## D. FUNDING DISCLOSURES

All sources of funding should be declared in the Acknowledgements section of the manuscript. Authors must describe the role of the study sponsor(s), if any, in: (i) the study design; (ii) the collection, analysis and interpretation of data; (iii) the writing of the report; and (iv) the decision to submit the paper for publication. If the authors' work was independent of the funders, the authors should state this.

**PLEASE CHECK 1 OF THE 2 BOXES BELOW**:

☐ I certify that no funding has been received for the conduct of this study and/or preparation of this manuscript; ***OR***

☒ I certify that all financial and material support for the conduct of this study and/or preparation of this manuscript is clearly described in the Acknowledgments section of the manuscript.

## E. CONTRIBUTOR DISCLOSURES (complete if applicable)

All persons who have made substantial contributions to the work reported in the manuscript (e.g. data collection, data analysis, or writing or editing assistance) but who do not fulfill the authorship criteria **MUST** be named with their specific contributions in the Acknowledgments section of the manuscript. Groups of persons who have contributed may be listed under a heading such as 'Clinical investigators' and their function described. Because readers may infer their endorsement of the manuscript, all persons named in the Acknowledgments section **MUST** give the authors their written permission to be named in the manuscript.

☒ I certify that all persons who have made substantial contributions to this manuscript but who do not fulfill the authorship criteria are listed with their specific contributions in the Acknowledgments section in the manuscript, and that all persons named in the Acknowledgments section have given me written permission to be named in the manuscript.

## F. CONFLICT OF INTEREST DISCLOSURES

A conflict of interest exists when professional judgment concerning a primary interest (such as patients' welfare or the validity of research) may be influenced by a secondary interest (such as financial gain or personal rivalry). A conflict of interest may arise for authors when they have a financial interest that may influence – probably without their knowing – their interpretation of their results or those of others. We believe that to make the best decision on how to deal with a manuscript we should know about any such conflict of interest that the authors may have. We are not aiming to eradicate conflicts of interests – they are almost inevitable. We will not reject manuscripts simply because the authors have a conflict of interest, but we will publish a declaration in the manuscript as to whether or not the authors have conflicts of interests.

All authors **MUST** complete the following checklist:

| **Category of potential conflict of interest** | If you have had any of the listed relationships with an entity that has a financial interest in the subject matter discussed in this manuscript, please check the appropriate "Yes" box below and provide details. If you do not have a listed relationship, please check the appropriate "No" box. When completing this section, please take into account the last 36 months through to the foreseeable future. | | |
|---|---|---|---|
| | **No (√)** | **Yes (√)** | **Details** |
| Employment | X | | |
| Grant received/grants pending | X | | |
| Consulting fees or honorarium | X | | |
| Support for travel to meetings for the study, manuscript preparation or other purposes | X | | |
| Fees for participation in review activities such as data monitoring boards, etc | X | | |
| Payment for writing or reviewing the manuscript | X | | |
| Provision of writing assistance, medicines, equipment or administrative support | x | | |
| Payment for lectures including service on speakers bureaus | x | | |
| Stock/stock options | x | | |
| Expert testimony | x | | |
| Patents (planned, pending or issued) | x | | |
| Royalties | X | | |
| Other (err on the side of full disclosure) | | | |

Every author **MUST** complete option 1 or option 2 as appropriate below. If you answered "Yes" to any of the questions relating to financial conflicts of interests in the table above (or if you wish to disclose a non-financial conflict of interest), you **MUST** write a suitable statement in the box below. This statement will be published in the Acknowledgments section of the manuscript.

☒ I have no conflicts of interest to declare; ***OR***

☐ Please insert the following statement regarding conflicts of interest and financial support for conduct of this study and/or preparation of this manuscript in the Acknowledgments section of the manuscript:

**Declaration:** I certify that I have fully read and fully understood this form, and that the information that I have presented here is accurate and complete to the best of my knowledge.

Your name (please print): Aaron Coutts

Signature (please **HAND-WRITE**): __________

Date: 07/03/2014

.

http://www.springer.com/journal/40279

Sports Medicine
Associate Editor: McMillan, S. - Editor: Olney, R.
ISSN: 0112-1642 (print version)
ISSN: 1179-2035 (electronic version)
Journal no. 40279

Conflict of Interest Form MEYER

Adis

# CONFLICT OF INTEREST DISCLOSURE FORM

At submission, **EVERY AUTHOR** listed in the manuscript must **READ** and **COMPLETE** the following statements on: (A) Authorship Responsibility, (B) Authorship Criteria, (C) Authorship Contribution, (D) Funding Disclosures, (E) Contributor Disclosures/Acknowledgments, and (F) Conflicts of Interest Disclosures.

It is important that you return this form as early as possible in the publication process. **EVERY AUTHOR MUST COMPLETE AN INDIVIDUAL COPY OF THE FORM, AND EVERY SECTION OF THE FORM MUST BE COMPLETED.** We will **NOT** consider your manuscript for publication until every author has completed the form and returned it to us.

Your name (please print): Tim Meyer E-mail: tim.meyer@mx.uni-saarland.de

Journal name: Sports Medicine Corresponding author: Hugh Fullagar

Manuscript title: Sleep and athletic performance: The effect of sleep loss on exercise performance, and physiological and cognitive responses to exercise

## A. AUTHORSHIP RESPONSIBILITY

☒ I certify that **ALL** of the following statements are correct **(PLEASE CHECK THE BOX).**

- The manuscript represents valid work; neither this manuscript nor one with substantially similar content under my authorship has been published or is being considered for publication elsewhere (except as described in the manuscript submission); and copies of any closely related manuscripts are enclosed in the manuscript submission; ***AND***
- For manuscripts with more than one author, I agree to allow the corresponding author to serve as the primary correspondent with the editorial office and to review and sign off on the final proofs prior to publication; or, if I am the only author, I will be the corresponding author and agree to serve in the roles described above.
- Any change in authors and/or contributors after initial submission must be approved by all authors. This applies to additions, deletions, change in order of the authors, or contributions being attributed differently. Any alterations must be explained.
- For manuscripts that are a report of a study, I confirm that this work is an accurate representation of the trial results.

## B. AUTHORSHIP CRITERIA

To fulfil all of the criteria for authorship, every author of the manuscript must have made substantial contributions to **ALL** of the following aspects of the work:

- Conception and planning of the work that led to the manuscript or acquisition, analysis and interpretation of the data, or both; ***AND***
- Drafting and/or critical revision of the manuscript for important intellectual content; ***AND***
- Approval of the final submitted version of the manuscript.

☒ I certify that I fulfill **ALL** of the above criteria for authorship **(PLEASE CHECK THE BOX).**

## C. AUTHORSHIP CONTRIBUTION

I certify that I have participated sufficiently in the work to take public responsibility for **(PLEASE CHECK 1 OF THE 2 BOXES BELOW):**

☐ Part of the content of the manuscript; ***OR***

☒ The entire content of the manuscript.

## D. FUNDING DISCLOSURES

All sources of funding should be declared in the Acknowledgements section of the manuscript. Authors must describe the role of the study sponsor(s), if any, in: (i) the study design; (ii) the collection, analysis and interpretation of data; (iii) the writing of the report; and (iv) the decision to submit the paper for publication. If the authors' work was independent of the funders, the authors should state this.

**PLEASE CHECK 1 OF THE 2 BOXES BELOW:**

☒ I certify that no funding has been received for the conduct of this study and/or preparation of this manuscript; ***OR***

☐ I certify that all financial and material support for the conduct of this study and/or preparation of this manuscript is clearly described in the Acknowledgments section of the manuscript.

## E. CONTRIBUTOR DISCLOSURES (complete if applicable)

All persons who have made substantial contributions to the work reported in the manuscript (e.g. data collection, data analysis, or writing or editing assistance) but who do not fulfill the authorship criteria **MUST** be named with their specific contributions in the Acknowledgments section of the manuscript. Groups of persons who have contributed may be listed under a heading such as 'Clinical investigators' and their function described. Because readers may infer their endorsement of the manuscript, all persons named in the Acknowledgments section **MUST** give the authors their written permission to be named in the manuscript.

☒ I certify that all persons who have made substantial contributions to this manuscript but who do not fulfill the authorship criteria are listed with their specific contributions in the Acknowledgments section in the manuscript, and that all persons named in the Acknowledgments section have given me written permission to be named in the manuscript.

## F. CONFLICT OF INTEREST DISCLOSURES

A conflict of interest exists when professional judgment concerning a primary interest (such as patients' welfare or the validity of research) may be influenced by a secondary interest (such as financial gain or personal rivalry). A conflict of interest may arise for authors when they have a financial interest that may influence – probably without their knowing – their interpretation of their results or those of others. We believe that to make the best decision on how to deal with a manuscript we should know about any such conflict of interest that the authors may have. We are not aiming to eradicate conflicts of interests – they are almost inevitable. We will not reject manuscripts simply because the authors have a conflict of interest, but we will publish a declaration in the manuscript as to whether or not the authors have conflicts of interests.

All authors **MUST** complete the following checklist:

| **Category of potential conflict of interest** | If you have had any of the listed relationships with an entity that has a financial interest in the subject matter discussed in this manuscript, please check the appropriate "Yes" box below and provide details. If you do not have a listed relationship, please check the appropriate "No" box. When completing this section, please take into account the last 36 months through to the foreseeable future. | | |
|---|---|---|---|
| | **No (√)** | **Yes (√)** | **Details** |
| Employment | X | | |
| Grant received/grants pending | X | | |
| Consulting fees or honorarium | X | | |
| Support for travel to meetings for the study, manuscript preparation or other purposes | X | | |
| Fees for participation in review activities such as data monitoring boards, etc | X | | |
| Payment for writing or reviewing the manuscript | X | | |
| Provision of writing assistance, medicines, equipment or administrative support | X | | |
| Payment for lectures including service on speakers bureaus | X | | |
| Stock/stock options | X | | |
| Expert testimony | X | | |
| Patents (planned, pending or issued) | X | | |
| Royalties | X | | |
| Other (err on the side of full disclosure) | X | | |

Every author **MUST** complete option 1 or option 2 as appropriate below. If you answered "Yes" to any of the questions relating to financial conflicts of interests in the table above (or if you wish to disclose a non-financial conflict of interest), you **MUST** write a suitable statement in the box below. This statement will be published in the Acknowledgments section of the manuscript.

☒ I have no conflicts of interest to declare; ***OR***

☐ Please insert the following statement regarding conflicts of interest and financial support for conduct of this study and/or preparation of this manuscript in the Acknowledgments section of the manuscript:

**Declaration:** I certify that I have fully read and fully understood this form, and that the information that I have presented here is accurate and complete to the best of my knowledge.

Your name (please print): Tim Meyer

Signature (please **HAND-WRITE**): [redacted]

Date: March, 10, 2014

Springer

http://www.springer.com/journal/40279

Sports Medicine
Associate Editor: McMillan, S. - Editor: Olney, R.
ISSN: 0112-1642 (print version)
ISSN: 1179-2035 (electronic version)
Journal no. 40279

Order Completed
Thank you very much for your order.

This is a License Agreement between Hugh Fullagar ("You") and Nature Publishing Group ("Nature Publishing Group"). The license consists of your order details, the terms and conditions provided by Nature Publishing Group, and the payment terms and conditions.

Get the printable license.

| | |
|---|---|
| License Number | 3345371116004 |
| License date | Mar 10, 2014 |
| Licensed content publisher | Nature Publishing Group |
| Licensed content publication | Nature |
| Licensed content title | Sleep is of the brain, by the brain and for the brain |
| Licensed content author | J. Allan Hobson |
| Licensed content date | Oct 26, 2005 |
| Type of Use | reuse in a journal/magazine |
| Volume number | 437 |
| Issue number | 7063 |
| Requestor type | academic/university or research institute |
| Format | electronic |
| Portion | figures/tables/illustrations |
| Number of figures/tables/illustrations | 1 |
| High-res required | no |
| Figures | Figure 1 from "Sleep is of the brain, by the brain and for the brain" |
| Author of this NPG article | no |
| Your reference number | |
| Title of the article | Sleep and athletic performance: The effects of sleep loss on exercise performance, and physiological and cognitive responses to exercise |
| Publication the new article is in | Sports Medicine |
| Publisher of your article | Springer |
| Author of the article | Hugh H.K. Fullagar1, 2, Sabrina Skorski1, Rob Duffield2, Daniel Hammes1, Aaron J. Coutts2, Tim Meyer1 |
| Expected publication date | Apr 2014 |
| Estimated size of new article (number of pages) | 25 |
| Total | 0.00 USD |

Other - permission for table 4

# Confirmation Number: 11166660
# Order Date: 03/13/2014

If you paid by credit card, your order will be finalized and your card will be charged within 24 hours. If you choose to be invoiced, you can change or cancel your order until the invoice is generated.

## Payment Information

Hugh Fullagar
hugh.fullagar@uni-saarland.de
+49 [redacted]
Payment Method: n/a

Order Details

**Seminars in neurology**

- **Order detail ID:** 64522521
- **Order License Id:** 3347060219017
- **Article Title:** Neurocognitive Consequences of Sleep Deprivation
- **Author(s):** Durmer, Jeffrey S ; Dinges, David F
- **DOI:** 10.1055/S-2005-867080
- **Date:** Mar 01, 2005
- **ISSN:** 0271-8235
- **Publication Type:** Journal
- **Volume:** 25
- **Issue:** 01
- **Start page:** 117
- **Publisher:** THIEME MEDICAL PUBLISHERS

- **Permission Status:** ✓ **Granted**
- **Permission type:** Republish or display content
- **Type of use:** reuse in a journal/magazine/newspaper
- View details

**Section:** Brief Review

**Article Title:** Sleep and Recovery in Team Sport: Current Sleep-related Issues Facing Professional Team-sport Athletes

**Authors:** Hugh H.K. Fullagar[1], Rob Duffield[2], Sabrina Skorski[1], Aaron J Coutts[2], Ross Julian[1] and Tim Meyer[1]

**Affiliations:** [1]Institute of Sport and Preventive Medicine, Saarland University, Germany. [2]Sport & Exercise Discipline Group, UTS: Health, University of Technology, Australia.

**Journal:** *International Journal of Sports Physiology and Performance*

**Acceptance Date:** February 18, 2015

**DOI**: http://dx.doi.org/10.1123/ijspp.2014-0565

| | |
|---|---|
| **Title:** | Sleep and recovery in team sport: current sleep-related issues facing professional team-sport athletes |
| **Submission Type:** | Brief Review |
| **Authors:** | Hugh H.K. Fullagar[1],<br>Rob Duffield[2],<br>Sabrina Skorski[1],<br>Aaron J Coutts[2],<br>Ross Julian[1]<br>and Tim Meyer[1] |
| **Institutions:** | [1] Institute of Sport and Preventive Medicine, Saarland University, Germany<br>[2] Sport & Exercise Discipline Group, UTS: Health, University of Technology, Australia |
| **Corresponding author** | [1] Hugh Fullagar<br>Institute of Sport and Preventive Medicine, Saarland University, GEB. B82<br>66123 Saarbrucken, Germany<br>Email:<br>hughfullagar@uni-saarland.de<br>Phone: 0681-302 70400<br>Fax: 0681-302 4296 |
| **Running head:** | Sleep and recovery in team sport |
| **Abstract word count:** | 241 |
| **Text only word count:** | 4497 |
| **References:** | 49 |
| **Number of Figures:** | 2 |
| **Number of Tables:** | 1 |

## ABSTRACT

Whilst the effects of sleep loss on performance have previously been reviewed, the effects of disturbed sleep on recovery following exercise are less reported. Specifically, the interaction between sleep and physiological and psychological recovery in team-sport athletes is not well understood. Accordingly, the aim of the present review is to examine the current evidence of sleep and the potential role it may play in post-exercise recovery, with a tailored focus on professional team-sport athletes. Recent studies show that team-sport athletes are at high risk of poor sleep during and following competition. Although limited published data is available, these athletes also appear particularly susceptible to reductions in both sleep quality and duration following night competition and periods of heavy training. However, studies examining the relationship between sleep and recovery in such situations are lacking. Indeed, further observational sleep studies in team-sport athletes are required to confirm these concerns. Naps, sleep extension and sleep hygiene practices appear advantageous to performance; however, future proof of concept studies are now required to determine the efficacy of these interventions on the post-exercise recovery. Moreover, more research is required to understand how sleep interacts with numerous recovery responses within team-sport environments. This is pertinent given the regularity at which these teams encounter challenging scenarios during the course of a season. Therefore, this review will examine the factors that compromise sleep during a season and following competition, and discuss strategies which may help improve sleep in team-sport athletes.

**KEYWORDS:** Regeneration, exercise, stress, soccer, circadian rhythms,

## 1. Introduction

High performance team-sport athletes endure numerous physiological, psychological and neuromuscular stressors during training and competition.[1] It is logical that these athletes balance these stressors with appropriate recovery to maximise performance and adaptation, whilst also minimising the injury risk.[2] A crucial part of this stress-recovery balance is the management of an athlete’s sleep, especially during intense training and competition.[3] However, whilst the interest afforded to the relationship between sleep and athletic performance is well documented,[4] the evidence underpinning the role of sleep in recovery is less understood. This is surprising from both a scientific and applied perspective given athletes often rate sleep as their most important recovery strategy.[5]

There are three key factors which determine the recuperative outcome of sleep; the duration (total sleep time), quality and phase (circadian timing) of sleep.[6] A ‘healthy’ night of sleep has been suggested to be 7-9 h.[7] In addition to duration, sleep quality is also critical for optimal health and restorative functioning.[7] Although a clear definition is not readily available, sleep quality can best be outlined as the personal satisfaction of the sleep experience.[7] Further, the timing of sleep will also influence the effectiveness of the sleep bout. The timing of an individual’s preferred bedtime in turn affects their circadian rhythms (i.e. body temperature, hormone regulation), which can impact both sleep duration and quality.[6] From an athletic perspective, disturbances to one or all of these collective aspects of sleep are suggested to affect the post-exercise recovery process.[6] For instance, it has been shown that a reduction in the quantity and quality of sleep hinders the capacity of rugby-league footballers to recover for the demands of ensuing training and competitive bouts.[8] Thus, it may be paramount for team-sport athletes to be aware of situations where disturbed sleep duration, quality or phase may affect ensuing recovery.

A reduction in sleep duration and/or quality in individual athletes prior to,[9-11] and during competition[12] has been recently documented. Whilst there is less information available on team-sport athletes, Lastella et al[13] reported a mean sleep duration of 7.0 h per night in 58 elite Australian team-sport athletes during a typical training phase, ~ one hour less than the recommended 8 h per night. Further to these findings, sleep disruption or deprivation can occur for team-sport athletes, particularly during short- or long-haul travel,[14-16] congested competition schedules,[1] and training or playing at night,[17] presenting the potential for compromised recovery.[3,8] Indeed, sleep loss in team-sport athletes is often affected by these situational factors,[18] with many professional teams currently facing the challenge of coping with these specific, but recurring stressors. For example, Major League Baseballers play every two days combined with repeated travel across the United States, which provide conditions that are not conducive to optimal sleep.[19] Similarly, the majority of European soccer tournaments are commonly played at night, resulting in late night finishes and players subjectively reporting sleep loss.[20] These observations of altered sleep in team-sport athletes are also supported by objective evidence of post-competitive sleep disturbance in elite rugby union players[17] and professional Australian soccer players,[16] and a recent report that 52.3% of elite (individual and team sport) athletes experience sleep disturbances following late matches or training sessions.[18] Collectively, these data suggest that although 'normal' sleep patterns may be sufficient, under specific, recurring circumstances there are cases for reduced sleep durations and quality in team-sport athletes.

At present, the importance of sleep as a recovery method in team-sport athletes (i.e. return to baseline of psycho-physiological and performance parameters following exercise and disrupted sleep) is unclear. In particular, there is little analysis of the role sleep plays in the post-exercise recovery process during various situations where sleep is compromised. Whilst the literature examining the interaction between sleep and recovery in athletes is increasing (Figure 1), there have been no critical reviews of these factors in the context of training and competition demands of team-sport athletes. Accordingly, the aim of the current study was to examine the evidence of the potential role sleep may play in post-exercise recovery, with a specific focus on professional team-sport athletes. As such, an analysis of situations which may continually compromise sleep throughout a season and/or one-off post-competition sleep disturbance is provided. Strategies to alleviate such issues facing team-sport athletes are also addressed. For this review, it is important to discern the difference between *recovery* and *performance*. From an athletic perspective, *performance* in absolute terms refers to the context and magnitude to which the athlete completes certain tasks within their sporting domain.[21] These can include but are not limited to competition performance (e.g. goals scored by a footballer), predictors of performance (e.g. sprinting speed) and surrogate measures of performance (e.g. counter movement jump score). The effects of sleep loss on performance trials involve baseline performance measures followed by a sleep loss intervention/sleep control condition and then final performance measures the next morning/days. Comparatively, *recovery* refers to the degree at which parameters *return* to baseline following a distinct exercise bout and disrupted sleep (e.g. return of creatine kinase to baseline values following a rugby match or the return of YoYo test performance to baseline values following a training session).[6,8] Thus, the main discernible difference between performance and recovery is that recovery experiments follow a distinct time-course analysis from a prior stressor (i.e. match play). This makes them suitable for the assessment of the health, wellbeing and readiness to perform of team-sport athletes.

## 2. Sleep and recovery for team-sport athletes

A typical night of sleep is comprised of approximately 90-min cycles divided into periods of rapid-eye-movement (REM), and non-REM (NREM) sleep. Whilst REM sleep has a role in periodic brain activation, localized recuperative processes and emotional regulation, the role for NREM sleep is proposed to assist with energy conservation and nervous system recuperation.[22] Taken collectively, there is considerable evidence supporting the recuperative nature of sleep in restoring molecular homeostasis, cellular maintenance and synaptic plasticity.[6,22,23] From an athletic perspective, this implicates that disturbances to either the timing of sleep phases, or the quality and duration of sleep within these phases, can result in the hindrance of psychological and physical recovery following an exercise bout.[6] This would seem especially pertinent for field-based team sports that are typically exposed to prolonged bouts of intermittent-sprint activity during both high-intensity training and competition. Logically, exposure to such activity will increase the need for recovery and subsequently increase the overall requirement for sleep.[13]

From this perspective, it seems rational to first investigate the sleep-wake behaviour of team-sport athletes during and following training, and competition periods. Mah et al[24] reported mean average sleep durations of 6.7±1.0 h in collegiate basketballers during a competitive season. Similarly, Lastella et al[13] found a sample of 58 elite Australian team-sport athletes slept for a mean duration of 7.0±1.2 h during a regular training phase. With regard to sleep following competition, Eagles et al[17] found a significant reduction in sleep duration on game nights compared to non-game nights.[17] Juliff et al[18] reported that more than half of a sample of 283 elite individual and team-sport elite athletes (of which 210 were from team sports) endured sleep disturbances following a late training session or match.[18] In support of this, sleep duration and quality were significantly reduced on the night of away matches compared to the night prior in elite Australian soccer players.[16] Whilst caution needs to be taken in comparing these studies (i.e. due to differences in sleep-assessment methodologies), it seems reasonable to assume sleep in team-sport athletes is dependent on many factors. These could include the type of sport, training demands, age, time of season and team culture.[13] Overall, high performance team-sport athletes are considered susceptible to sleep loss during training periods and following match play (especially at night). Whilst such insight is important, further descriptive research of sleep with high performance team-sport athletes is required to confirm this, most importantly for the nights following competition.

Recent studies have also shown that sleep restriction following team-sport competition affects the time course of recovery for both performance and psychophysiological measures. For instance, Skein and colleagues[8] investigated the effect of sleep deprivation (0 h sleep) compared with normal sleep (~8 h) on the physiological and perceptual recovery of eleven rugby-league footballers following competitive matches in a randomised cross-over design. Overall, sleep deprivation negatively affected recovery with significant impairments observed in mean and peak countermovement jump height and cognitive reaction time. Although sleep deprivation was excessive, this study highlights the increased physiological load during wakefulness following sleep loss in team sports, and in turn, suppression of cognitive function and lower body power. Similarly, Fowler et al[16] reported significant reductions in sleep duration and quality, along with an impaired stress-recovery balance, on the night of a match compared to the night prior for away matches. Whilst additional literature is lacking in team-sport athletes, there is further evidence of this relationship in individual athletes. For instance, significant reductions in sleep quantity and efficiency were associated with increased fatigue and impaired exercise capacity in a group of ten functionally-overreached elite synchronized swimmers.[25] Furthermore, McMurray and Brown[26] investigated the cardiovascular and metabolic responses of five participants during submaximal exercise following 24 h of sleep deprivation. They reported increased minute ventilation and oxygen uptake during the recovery period, suggesting negative effects of sleep loss on physiological recovery.[26] Nonetheless, the evidence as to how sleep interacts with multi-factorial recovery responses within high performance team-sport environments is currently lacking. In particular, there is little longitudinal objective sleep data available in the scientific literature. This is surprising given this would appear the first step in understanding the relationship between sleep and recovery.

Finally, since a variety of other recovery strategies are utilised in sport, some studies have also examined the interaction between sleep and these protocols. For instance, Robey et al[27] reported that cold water immersion post-training does not affect subsequent sleep duration, onset or efficiency. However, the mechanisms between the interaction of sleep and other recovery protocols are difficult to determine, due to an abundance of confounding factors (e.g. protocol type, timing, facilities). Further research and practical investigation within professional environments which address whether it is more advantageous to use a recovery protocol which enhances sleep and/or whether a combination of these protocols enhances the recovery process is warranted. This is especially pertinent given the wide prevalence of these methods in team sports.

## 3. Sleep-related issues facing team-sport athletes

As summarised in Figure 2, the following section outlines particular situations where sleep is at risk of compromise in team sport athletes. Whilst acknowledging the previous work done in this area but also recognising the absence of published data over prolonged periods, this gives particular relevance to situations during a season and/or one-off post-competition sleep disturbance.

### 3.1Team-sport matches played at night

As often determined by television scheduling, numerous team-sports schedule the completion of matches at night. Indeed, the pure timing of matches (i.e. some matches in the Spanish La Liga commence at 22:00) will force players into later bedtimes.[1] Furthermore, since physical activity promotes arousal, it has long been assumed exercising during the evening hours produces a greater number of sleep disturbances than exercising during daylight.[20] Team-sport athletes also have extensive post-game commitments such as press conferences, recovery practises and social functions, which could lead to later bedtimes and disrupt sleep duration and quality.[1] As alluded to previously, Juliff et al[18] found 52.3% of a sample of 283 elite individual (n=73) and team-sport (n=210) athletes reported sleep disturbances following a night training session/match. Moreover, 59.1% of team-sport athletes reported that that did not use a strategy to overcome these sleep disturbances.[18] Furthermore, a recent review on regenerative interventions used in professional soccer explains that many medical doctors report players lose sleep following night matches, which include findings on elite Bundesliga soccer players subjectively reporting reduced sleep duration and quality.[20] Notwithstanding these findings, the anecdotal evidence of athletes reporting sleep disturbances following night competition outweighs that documented in the literature; thus, further research in elite athletic populations is required to confirm this.

Recent data shows that performing maximal aerobic exercise in the evening results in elevated sleep onset latency, awakenings, and REM sleep latency - suggesting poorer overall sleep quality in judo competitors.[28] Whilst several physiological variables are elevated prior to sleep onset following late-night vigorous exercise (suggesting possible effects on cardiac autonomic control and metabolic function[29]), delayed sleep onset can also be caused by mental stimulation or cognitive fatigue.[23] Moreover, given pain is a significant predictor of a poor night’s sleep,[30] it is likely prolonged late-night, high-intensity exercise (equivalent to match situations) will incur sleep disturbances throughout the night as a result of pain and soreness. This is of particular relevance for heavy contact sports such as American football, ice hockey, and rugby union. It should be noted that there is opposing evidence on the effect of competing at night on sleep. For instance, Roach et al[31] reported no effect of two night

(19:00-21:00) matches on sleep in elite junior soccer players. Similarly, Robey et al[32] found no effect of early evening high-intensity training on the subsequent sleep quality or duration in elite youth soccer players.

In light of this, it should be recognised that the mechanisms behind the effect of exercise (and timing) on sleep are complex due to the main confounding variable (amongst others) of the stress induced by the exercise itself. From an applied perspective, future research must first focus on providing objective evidence (e.g. acute and chronic measurements of actigraphy) on whether disturbances following match play at night occur. Researchers might also focus on the effects of disrupted sleep following match play in team-sport athletes and attempt to delineate the mechanisms responsible. At present, practitioners should also be aware of the intra-individual variability in sleep requirement and chronotype (those who arise early in the morning vs. those who prefer later bedtimes). Accommodating these differences within a team environment is difficult as it may require more individualised approaches. Indeed, this would be even more pertinent for team scheduling training the day after a game. For instance, training in the absence of sufficient sleep following late night matches may potentiate the negative outcomes. This may create recovery concerns given players will sleep differently after these matches, whilst also possibly placing those whom are training at an unnecessary injury risk.

### 3.2 Sleep and travel fatigue

Cumulative sleep loss occurs as a consequence of travel during busy periods, which tends to lead to accumulative fatigue over a season.[33] Travel fatigue is dependent on the distance and frequency of travel, and the length of the season. It should be noted that travel-induced fatigue is separate to jet-lag fatigue, with the main difference being jet-lag comprises an effect of time-zone change.[33] The influences of jet-lag arising from long-haul international travel in elite athletes have been discussed previously[33,34] and thus will not be further addressed here. Sleep disturbances during or following travel can result in reductions in mood, acute fatigue and difficulty in initiating sleep at the arrival destination.[33] For team-sports, the method, mode, distance and timing of travel varies greatly and is largely dependent on scheduling, team budget and the coach’s preference.[35] Many teams, particularly in America and Australia, endure one-way short haul domestic or international travel up to 6 h prior to or following competition.[19,36,37] In addition to sleep disturbances, travelling can result in detrimental health, impaired mood, dehydration and loss of motivation all of which can affect recovery.[33] Of further concern, it has been shown that baseball teams whose circadian rhythms are more synchronised to optimal performance times are more likely to be successful, indicating either a negative effect of travel and/or desynchronised body-clock functioning.[19] However, it should be noted that these data do not actually outline any physical or perceptual response to the travel, limiting its implication in athlete recovery.

Empirical data describing the effect of short-haul air travel on sleep, performance and the ensuing recovery in these situations is largely unknown. For instance, the sleep quantity and quality of players following away competition performance remains unclear, with short-haul air travel (1-3 h) affecting perceived sleep quality,[36] whereas some soccer players report earlier mean bed times after short-haul air travel (~5 h) and an away match.[16] Competition performance, along with reduced physical demands, appears to be greater at home compared to away (in American football[37], baseball[19], rugby league[14] and soccer[16]) suggesting either a negative effect of travel or a circadian advantage.[34] However, extrapolating these effects to determinations of match performance is difficult due to other external factors and the inter-match variability in opposition and match intensity. Whilst there have been few empirical studies, the available data suggests that short-haul travel has minimal effect on physiological and perceptual recovery (e.g. no significant effect on YoYo Intermittent Recovery level 1 test performance), with more regular or longer periods of travel (e.g. 24-h international transfers) more likely to result in negative responses.[15] Whilst short-haul air travel appears to have negligible effects on post-match physiological recovery, the effect on perceptual markers of fatigue and sleep patterns following competition performance is equivocal. If these parameters decline, they can negatively influence training intensity or volume during ensuing sessions due to decreased motivation.[38] Given the myriad of conflicting demands whilst experiencing travel and sleep loss (e.g. treatment, timing of training, recovery practices), it can be difficult for coaches to manage the most appropriate schedule for their team the day after a match. Indeed more research is required to clarify the acute and chronic effects of cumulative travel (e.g. over a season) on sleep and psychological and physiological recovery parameters of professional team-sport athletes.

### 3.3 Sleep and congested competition schedules

Excessive exercise loads can disturb the stress-recovery balance and result in performance decrements and injury occurrence.[2] For example, during periods of heavy match congestion in soccer, there is an increased injury risk for players when they play two matches per week rather than one.[39] In this regard, some major European football teams may compete in up to four competitions at once – which likely impacts on players' sleep behaviour. Congested schedules are also present throughout American sports such as baseball, hockey and basketball. During these periods of high physical workloads, there is a potential for a reduction in sleep duration and quality. For example, it has been shown that as the effects of increased baseball match exposure accumulate towards the end of the season strike zone judgement is impaired, which suggests a fatigue-induced decline in performance; with sleep believed to be one of the main symptoms responsible.[40]

Sleep has also been suggested to be sensitive to exercise overload - with high training volumes associated with greater sleep disruptions.[41] Although no published data is yet apparent in team-sport cases, Netzer et al[42] found significant increases in the REM sleep onset latency and decreases in REM sleep of well trained cyclists following training and a competitive 120-150 km race, compared to no training or competition. Following this, it is logical that when team-sport athletes compete in a greater number of matches within a short period, exercise-induced muscle damage will accumulate (dependant also on exercise intensity), characterised by decreased neuromuscular function, increased perceptual fatigue and increases in perceived soreness which can disrupt sleep.[1] Moreover, if there are several events in short succession, the continual anticipation of competition can also negate sleep.[18] However, at present, there is little research that describes or quantifies the effect of these changes on the subsequent recovery, particularly in team-sports undertaking congested fixture scheduling. Future investigations into the time course of recovery following sleep loss would be particularly pertinent to team sports such as baseball and cricket, since these athletes can play on consecutive days and could be at a high risk of cognitive impairments (e.g. slowed reaction time).

### 3.4 Sleep and disturbances to training adaptation

Since sleep loss impedes muscle protein accumulation, the ability of skeletal muscle to adapt and repair can be hindered – which likely limits training adaptations.[3,6,43] This may be concerning during the pre-season for team-sport athletes given sleep disturbances are present during higher training volumes.[41] Since sleep loss can also affect vigour, mood and perceptual awareness,[38] early training sessions could cause reductions in motivation and consequently reduce optimal training performance and subsequent adaptations.[44] Furthermore, if the stress-recovery balance of team-sport athletes is disrupted by either an increase in training load/stress or inadequate recovery, it may lead to an overreached, or even overtrained state.[2] Interestingly, disturbed sleep is believed to be one of many symptoms of either overreaching or the overtraining syndrome.[2] In a recent study by Hausswirth et al[45], it was found that objective measures of sleep duration, efficiency and immobile time were all negatively altered in a group of functionally overreached tri-athletes. There was also a higher prevalence of upper respiratory tract infections within this group, implying an association between the two; however whether impaired sleep and illness occurrence are consequences, or simply symptoms or coincidental associations, of overreaching remains unknown.[45] In light of this, practitioners are encouraged to monitor the sleeping patterns of their athletes in high periods of stress either through subjective sleep diaries and/or wristwatch actigraphy.[5]

Since sleep loss can hinder the learning of new skills, affect emotional regulation and disrupt cognitive function,[6] it is likely that sleep is also important for optimising cognitive training adaptations in team-sport athletes. For instance, sleep is critical for memory retention, neural plasticity, and has been shown to improve visual discrimination and motor adaptation.[23] Therefore, it is likely that disturbing sleep during intense training or skill acquisition periods (e.g. pre-season) will encumber adaption in skill-based tasks with high neurocognitive reliance.[4] However, objective evidence to support this suggestion is not currently present. Therefore, future research (with well controlled randomised-control trials) into the effects of sleep disruption on acute or chronic cognitive-based training adaptations in athletic populations is required.

## 4. Sleep strategies for team-sport athletes

### 4.1. Napping

In an attempt to recover from sleep debt, a commonly utilised sleep strategy amongst team-sport athletes is the restorative nap. Naps have been shown to improve alertness, sleepiness, short-term memory and accuracy during reaction time tests.[46] Furthermore, Waterhouse et al[46] found improvements in mean sprint performance following a 30 min post-lunch nap after 4-5 h of sleep restriction. On the basis of this, it has been proposed athletes take a post-lunch nap to ameliorate the performance deficits caused by ultradian biological rhythms that occur within the circadian cycle.[38,46] As such, it appears napping behaviours have many benefits and should be undertaken where necessary in team-sport environments. An example would be for soccer players to have a nap after lunch if they are playing a match at night. However, it is critical that if naps are implemented within a team-sport environment they balance the need to enhance performance whilst not disturbing subsequent sleep patterns, as this could hinder the recovery process following training or competition. Indeed, whilst napping appears advantageous for performance (e.g. napping prior to competition), more research is required to evaluate its possible effectiveness in recovery.

### 4.2 Sleep extension

Extending sleep during normal sleep times is another strategy to alleviate the decrements in physiological and cognitive performance caused by sleep loss. Mah et al[24] found faster sprint and reaction times and improved shooting accuracy, energy and mood following approximately three weeks of sleep extension (mean + 110 min) in eleven basketball players, indicating its use as a viable option for enhancing team-sport performance. Moreover, extending sleep improves psychological wellbeing thus optimising athletes’ mental preparedness for competition.[24] However, obtaining extra sleep can be difficult, because increased sleep onset latency and mood effects can be nullified due to earlier bedtimes. Thus, if an athlete is not sleep deprived it is possible that extending sleep will reap no benefit. The timing of this sleep intervention could also influence the effects of sleep extension depending on the sleep chronotype of the athlete. Additionally, more research assessing whether sleep extension during periods of high-training load is a useful tool to ensure appropriate recovery is required. Such research would be pertinent in assisting players achieve higher sustained intensities in subsequent exercise bouts (i.e. during pre-season).

### 4.3 Sleep hygiene protocols

Identifying and modifying the factors that contributes to improve sleep quality (improving sleep hygiene) in team-sport athletes can also assist in ameliorating the detrimental effect of sleep loss and potentially enhance recovery. Sleep hygiene strategies have been shown to improve sleep quality and onset latency in university students and reduced sleep irregularity in adolescents, although the effect of numerous components of sleep hygiene in normal sleepers is mixed.[47] From an athletic perspective, little is known about the interaction between these sleep hygiene strategies and the recovery of exercise and psychological parameters. Preliminary evidence indicates adhering to some of the previous sleep hygiene recommendations improves sleep quantity, resulting in a reduction in perceived soreness and fatigue in elite tennis players.[48] Furthermore, regulating sleep-wake times helps synchronise the circadian timing system, improving sleep quality and quantity.[49] As pre-competition worry and anxiety are evident in athletes,[10,18] it may be of benefit to utilise self-confidence tools (i.e. meditation) to manage anxiety and stress, as these correlate with improved sleep.[49] Identifying each individuals best sleep habits (e.g. bed comfort) are also pertinent, as unfamiliar environments may reduce sleep quality.[49] Such recommendations are similar to those designed for team-sport athletes who endure constant travel.[33] It is well known sleep onset is prolonged by noise, light and extreme temperatures, with athletes reporting noise and light as the two most important factors to their sleep quality.[10] Since the use of technology just prior to sleeping promotes afferent signals from the retina to the pineal gland, inhibiting the secretion of melatonin and delaying sleep onset, the avoidance of bedtime technology (and thus reducing arousal and physiological excitement) has been recommended to improve sleep onset.[49] As part of a healthy sleep protocol, several nutritional recommendations have also been proposed to assist with sleep onset. For instance, a recent review by Halson[5] proposed diets high in carbohydrates and protein may result in shorter sleep latencies and improved sleep quality, respectively.[5] Whilst there is a clear need for nutrition during the post-exercise recovery period, the interaction between foods consumed post-exercise and the ensuing sleep and recovery timeline is unclear. Indeed, the effects of nutrition are intricately complex and beyond the scope of this review (see Halson[5] for further detail).

## 5. Future research

Currently, there is insufficient evidence to conclusively describe the role of sleep for post-exercise recovery and resultant performance outcomes. As such, the first step in understanding this contribution is for the utilisation of long-term observational field studies through the use of subjective sleep diaries and/or actimetry in various situations. This will help to identify areas where sleep may be an issue in team-sport athletes. Once this specific context is known, it is important to understand the interaction sleep has with variables within the high performance athletic environment during situations where sleep is an issue. This requires both randomised-cross over trials which investigate the measurement of sleep and the post-exercise recovery timeline (both physiological and psychological), and also case studies in high performance team-sport athletes. Future work within this field could also focus on understanding the mechanisms involved and providing appropriate interventions to improve sleep and the ensuing recovery process.

## 6. Practical recommendations for team-sport athletes

The following recommendations (Table 1) are based on the literature within this review. However, the authors recognise that there is a lack of research examining the interactions between sleep and recovery in athletes. Nonetheless, there seems little risk but much (potential) benefit in following these recommendations. It is perhaps most important to tailor interventions toward individual athletes.

## 7. Conclusion

While sleep is commonly reported to be critical for recovery from intense exercise and/or competition by athletes, coaches and scientists, the current understanding of the effect of sleep on the recovery profile, especially in athletic populations, remains unclear. There is evidence to suggest elite athletes lose sleep prior to and during competition periods. Further, although limited published data is available, team-sport athletes appear to be susceptible to reductions in sleep quality and duration during and following competition (especially at night), during periods of congested fixture scheduling and longer forms of travel. Given the regularity at which numerous professional teams might encounter these situations throughout a season, they may encumber the players sleep and recovery. The efficacy of interventions to improve sleep, such as sleep hygiene protocols and sleep extension appear advantageous - but require further investigation in situations relevant to professional team sports. These interventions may be suited to specific situations when the risk of compromised sleep is higher (i.e. playing at home or away, at night and/or inclusive of travel). This is especially pertinent with regards to the recovery of exercise parameters. Indeed, since research in this area is lacking, further research into the role of sleep and recovery in team sports is warranted.

## Acknowledgments:

No funding was provided which contributed to the development of this manuscript. The authors declare that there are no conflicts of interest. Hugh Fullagar is supported by a "Science and Health in Soccer" scholarship funded by the DAAD (German Academic Exchange Service).

## REFERENCES:

1. Nédélec M, McCall A, Carling C, et al. Recovery in Soccer. *Sports Med*. 2012;43(1):9-22.
2. Kellmann M. Preventing overtraining in athletes in high-intensity sports and stress/recovery monitoring. *Scand J Med Sci Sports*. 2010;20:95-102.
3. Halson SL. Nutrition, sleep and recovery. *Eur J Sport Sci*. 2008;8(2):119-26.
4. Fullagar HHK, Skorski S, Duffield R, et al. Sleep and athletic performance: The effects of sleep loss on exercise performance, and physiological and cognitive responses to exercise. *Sports Med*. 2014:[Epub ahead of print].
5. Halson SL. Sleep in elite athletes and nutritional interventions to enhance sleep. *Sports Med*. 2014;44(Suppl 1):S13–S23.
6. Samuels C. Sleep, recovery, and performance: The new frontier in high-performance athletics. *Neurol Clin*. 2008;26(1):169-80.
7. Krystal AD, Edinger JD. Measuring sleep quality. *Sleep Med*. 2008;9(S1):S10–S7.
8. Skein M, Duffield R, Minett G, et al. The effect of overnight sleep deprivation after competitive rugby league matches on postmatch physiological and perceptual recovery. *Int J Sport Physiol Perform*. 2013;8:556-64.
9. Erlacher D, Ehrlenspiel F, Adegbesan OA, et al. Sleep habits in German athletes before important competitions or games. *J Sports Sci*. 2011;29(8):859-66.
10. Venter RE. Perceptions of team athletes on the importance of recovery modalities. *Eur J Sport Sci*. 2014;14:S69-S76.
11. Lastella M, Lovell GP, Sargent C. Athletes' precompetitive sleep behaviour and its relationship with subsequent precompetitive mood and performance. *Eur J Sport Sci*. 2014:1-8.
12. Lastella M, Roach G, Halson SL, et al. Sleep/wake behaviour of endurance cyclists before and during competition. *J Sports Sci*. 2014;8:1-7.
13. Lastella M, Roach G, Halson SL, et al. Sleep/wake behaviours of elite athletes from individual and team sports. *Eur J Sport Sci*. 2014;[Epub ahead of print].
14. McGuckin TA, Sinclair WH, Sealey RM, et al. The effects of air travel on performance measures of elite Australian rugby league players. *Eur J Sport Sci*. 2014;14:S116-S22.
15. Fowler P, Duffield R, Vaile J. Effects of simulated domestic and international air travel on sleep, performance and recovery. *Scand J Med Sci Sports*. 2014;[Epub ahead of print].
16. Fowler P, Duffield R, Vaile J. Effects of domestic air travel on techincal and tactical performance and recovery in soccer. *Int J Sport Physiol Perform*. 2014;9(3):378-86.

17. Eagles A, Mclellan C, Hing W, et al. Changes in sleep quantity and efficiency in professional rugby union players during home based training and match-play. *J Sports Med Phys Fitness*. 2014;[Epub ahead of print].

18. Juliff LE, Halson SL, Peiffer JJ. Understanding sleep disturbance in athletes prior to important competitions. *J Sci Med Sport*. 2014:[Epub ahead of print].

19. Winter WC, Hammond WR, Green NH, et al. Measuring circadian advantage in Major League Baseball: a 10-year retrospective study. *Int J Sports Physiol Perform*. 2009;4(3):394-401.

20. Meyer T, Wegmann M, Poppendieck W, et al. Regenerative interventions in professional football. *Sport Orthop Traumatol*. 2014;30:112-8.

21. Brukner P, Khan K. *Clinical sports medicine* Sydney: McGraw Hill 2006.

22. Vyazovskiy VV, Delogu A. NREM and REM Sleep: Complementary roles in recovery after wakefulness. *The Neuroscientist*. 2014;[Epub ahead of print].

23. Stickgold R. Sleep-dependent memory consolidation. *Nature*. 2005;437:1272-8.

24. Mah CD, Mah KE, Kezirian EJ, et al. The effects of sleep extension on the athletic performance of collegiate basketball players. *Sleep*. 2011;34(7):943–50.

25. Schaal K, Le Meur Y, Louis J, et al. Whole-body cryostimulation limits overreaching in elite synchronized swimmers. *Med Sci Sports Exerc*. 2014;[Epub ahead of print].

26. McMurray RG, Brown CF. The effect of sleep loss on high intensity exercise and recovery. *Aviat Space Environ Med*. 1984;55(11):1031-5.

27. Robey E, Dawson B, Halson S, et al. Effect of evening postexercise cold water immersion on subsequent sleep. *Med Sci Sport Exer*. 2013;45(7):1394-402.

28. Souissi N, Chtourou H, Aloui A, et al. Effects of time-of-day and-partial sleep deprivation on short term maximal performances of judo compeitiors. *J Strength Cond Res*. 2013;27(9):2473-80.

29. Myllymaki T, Kyröläinen H, Savolainen K, et al. Effects of vigorous late-night exercise on sleep quality and cardiac autonomic activity. *J Sleep Res*. 2011;20(1):146–53.

30. Raymond I, Nielsen TA, Lavigne G. Quality of sleep and its daily relationship to pain intensity in hospitalized adult burn patients. *Pain*. 2001;92:381-8.

31. Roach GD, Schmidt WF, Aughey RJ, et al. The sleep of elite athletes at sea level and high altitude: a comparison of sea-level natives and high-altitude natives (ISA3600). *Br J Sports Med*. 2013;47:i114-i20.

32. Robey E, Dawson B, Halson S, et al. Sleep quantity and quality in elite youth soccer players: A pilot study. *Eur J Sport Sci*. 2013:1-8.

33. Samuels C. Jet lag and travel fatigue: a comprehensive management plan for sport medicine physicians and high-performance support teams. *Clin J Sport Med*. 2012;22:268-73.

34. Reilly T. How can travelling athletes deal with jet-lag? *Kinesiology*. 2009;41:128-35.

35. Bishop D. The effects of travel on team performance in the Australian national netball competition. *J Sci Med Sport*. 2004;7(1):118-22.

36. Richmond LK, Dawson B, Stewart G, et al. The effect of interstate travel on the sleep patterns and performance of elite Australian Rules footballers. *J Sci Med Sport*. 2007;10(4):252-8.

37. Smith RS, Guilleminault C, Efron B. Circadian rhythms and enhanced athletic performance in the National Football League. *Sleep*. 1997;20(5):362-5.

38. Reilly T, Edwards B. Altered sleep–wake cycles and physical performance in athletes. *Physiol Behav*. 2007;90(2-3):274-84.

39. Dupont G, Nedelec M, McCall A, et al. Effect of 2 soccer matches in a week on physical performance and injury rate. *Am J Sport Med*. 2010;38(9):1752-8.

40. Kutscher S, Song Y, Wang L, et al. Validation of a statistical model predicting possible fatigue effect in Major League Baseball. *Sleep*. 2013;36:A408.

41. Taylor SR, Rogers GG, Driver HS. Effects of training volume on sleep, psychological, and selected physiological profiles of elite female swimmers. *Med Sci Sport Exer*. 1997;29(5):688-93.

42. Netzer N, Kristo D, Steinle H, et al. REM sleep and catecholamine excretion: a study in elite athletes. *Eur J Appl Physiol*. 2001;84:521-6.

43. Dattilo M, Antunes HKM, Medeiros A, et al. Sleep and muscle recovery: Endocrinological and molecular basis for a new and promising hypothesis. *Med Hypotheses*. 2011;77(2):220-2.

44. Sargent C, Halson S, Roach GD. Sleep or swim? Early-morning training severely restricts the amount of sleep obtained by elite swimmers. *Eur J Sport Sci*. 2014;14:S310-S5.

45. Hausswirth C, Louis J, Aubry A, et al. Evidence of disturbed sleep and increased illness in overreached endurance athletes. *Med Sci Sport Exer*. 2014;46(5):1036-45.

46. Waterhouse J, Atkinson G, Edwards B, et al. The role of a short post-lunch nap in improving cognitive, motor, and sprint performance in participants with partial sleep deprivation. *J Sports Sci*. 2007;25(14):1557-66.

47. Stepanski E, Wyatt J. Use of sleep hygiene in the treatment of insomnia. *Sleep Med Rev*. 2003;7(3):215-25.

48. Duffield R, Murphy A, Kellett A, et al. Recovery from repeated on-court tennis sessions; combining cold water immersion, compression and sleep recovery interventions. *Int J Sport Physiol Perform*. 2013:[Epub ahead of print].

49. Malone SK. Early to bed, early to rise?: An exploration of adolescent sleep hygiene practices. *J School Nursing*. 2011;27(5):348-54.

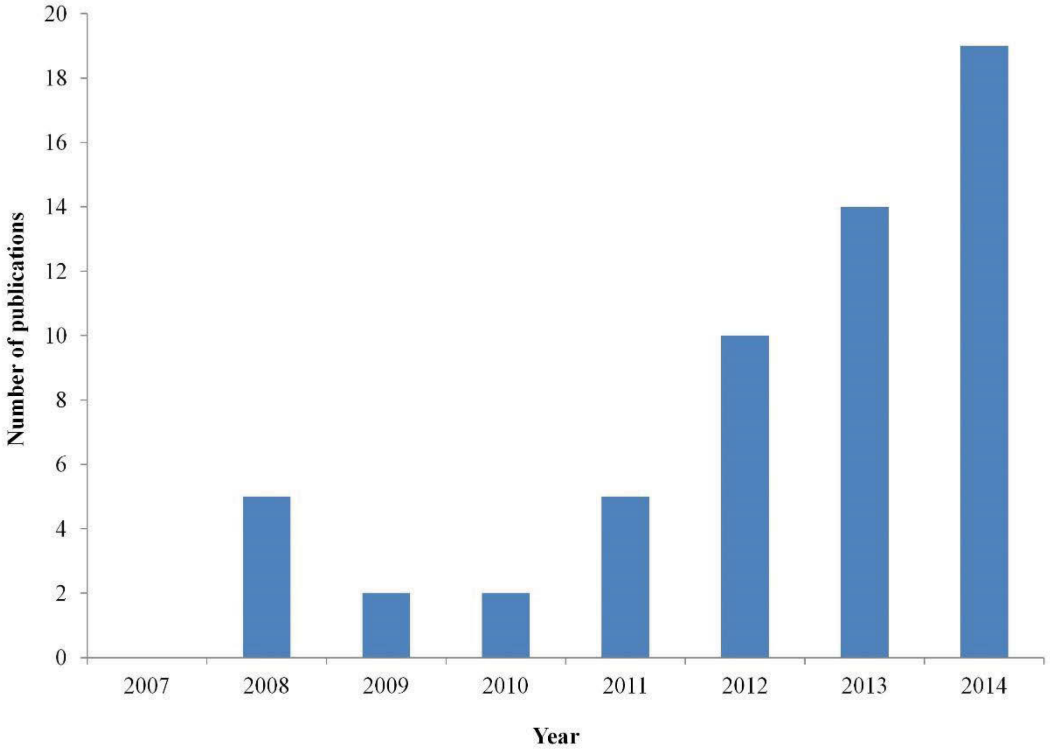


**Figure 1:** The increase in the number of sleep, athlete and recovery publications over the past eight years. The solid fill lines illustrate the amount of literature which appears following a Pub Med database search using the terms "sleep", "recovery" and "athlete" in all fields for each calendar year.

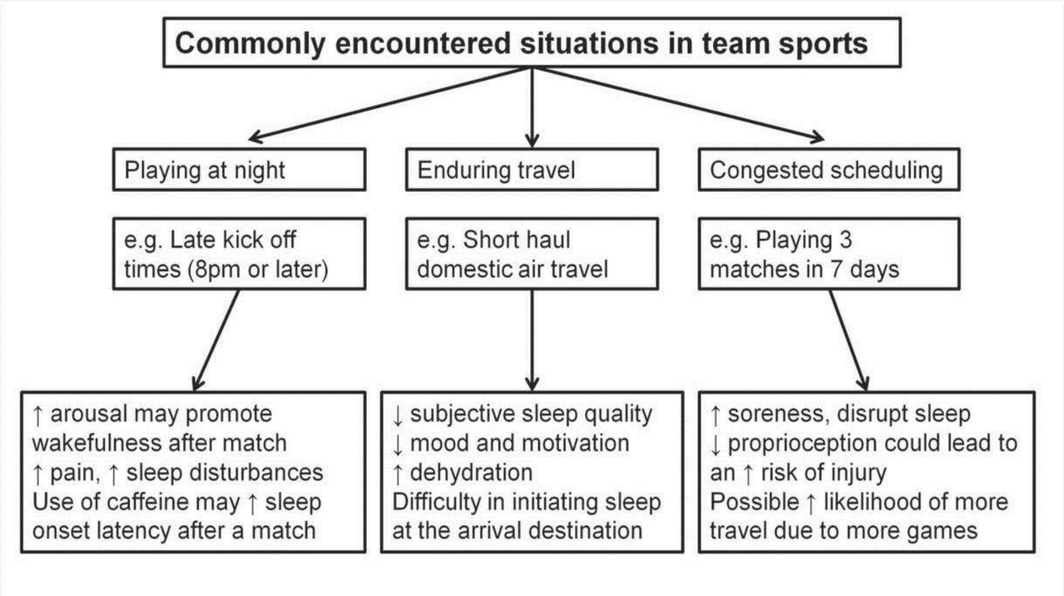


**Figure 2:** A schematic representation of the commonly encountered situations in team sports which may compromise sleep patterns and potentially recovery. Theoretical effects of these situations are also described; however it should be noted more research is required to confirm the majority of these effects.

**Table 1:** Practical sleep recommendations for players, coaches and practitioners.

| Issue | Response |
|---|---|
| Identify if sleep problems exist during normal scenarios within your athletic population. | One can do this by using subjective sleep diaries or wristwatch actimetry. Treat it in conjunction with a trained medical professional. Accommodating morning and evening types in team sports would appear particularly difficult, thus warranting clear communication between players, medical staff and coaches. |
| Late-night matches and congested schedules | Conduct correct sleep hygiene practice following competition. This includes no technology 30 min before bedtime, no TV or use of laptops in bed, dark, cool (but not cold) and quiet rooms (blinds closed). Set a regular sleep schedule where possible, and introduce relaxation and meditation techniques if necessary. These will presumably affect each athlete differently due to the intra-individual variability in sleep requirement. For further detail the reader is directed to Halson[5] and Malone.[49] |
| Short-haul domestic or international travel | When travelling, ensure adequate hydration and time meals appropriately (usually in sync with the arrival time zone), move around the transportation vessel where/when possible and synchronise light exposure to the arrival time zone. For detailed recommendations see Samuels.[33] |
| It is important for teams to be aware of the possible altered physiological load in next-day training sessions following sleep loss. | Given the association between sleep loss and injury, individualised training following periods of sleep loss would seem appropriate. In general, advise and remind athletes to achieve consistent and adequate sleep (7-10 h a night), especially after a match. |
| Daytime sleepiness | Napping appears beneficial for both repaying sleep debt and benefiting acute performance outcomes. However, be conscious of the effect of naps as they may also compromise recovery by interfering with subsequent sleep patterns |

# IMPAIRED SLEEP AND RECOVERY AFTER NIGHT MATCHES IN ELITE FOOTBALL PLAYERS

| | |
|---|---|
| Journal: | *Journal of Sports Sciences: Science and Medicine in Football* |
| Manuscript ID | RJSP-S-2015-0104.R2 |
| Manuscript Type: | Original Papers |
| Keywords: | soccer, circadian rhythms, performance, regeneration |
| Abstract: | Despite the perceived importance of sleep for elite footballers, descriptions of the duration and quality of sleep, especially following match play, are limited. Moreover, recovery responses following sleep loss remain unclear. Accordingly, the present study examined the subjective sleep and recovery responses of elite footballers across training days (TD) and both Day and Night matches (DM and NM). Sixteen top division European players from three clubs completed a subjective online questionnaire twice a day for 21 days during the season. Subjective recall of sleep variables (duration, onset latency, time of wake/sleep, wake episode duration), a range of perceptual variables related to recovery, mood, performance and internal training loads and non-exercise stressors were collected. Players reported significantly reduced sleep durations for NM compared to DM (- 157 min) and TD (- 181 min). In addition, sleep restfulness (SR; arbitrary scale 1=very restful, 5=not at all restful) and perceived recovery (PR; Acute Recovery and Stress Scale 0=not recovered at all, 6=fully recovered) were significantly poorer following NM than both TD (SR: +2.0, PR: -2.6), and DM (SR: +1.5; PR: -1.5). These results suggest that reduced sleep quantity and quality and reduced perceived recovery are mainly evident following night matches in elite players. |
| | |

**Article Type:** Original investigation

# IMPAIRED SLEEP AND RECOVERY AFTER NIGHT MATCHES IN ELITE FOOTBALL PLAYERS

---

**Running title:**

Sleep and recovery in footballers

---

**Keywords:**

Soccer, circadian rhythms, night, travel, regeneration, performance

---

**Document characteristics:**

Abstract: 200 words (limit 200)

Main text: 3839 words (limit 4000)

Tables: 2

Figures: 2

---

## Abstract

Despite the perceived importance of sleep for elite footballers, descriptions of the duration and quality of sleep, especially following match play, are limited. Moreover, recovery responses following sleep loss remain unclear. Accordingly, the present study examined the subjective sleep and recovery responses of elite footballers across training days (TD) and both Day and Night matches (DM and NM). Sixteen top division European players from three clubs completed a subjective online questionnaire twice a day for 21 days during the season. Subjective recall of sleep variables (duration, onset latency, time of wake/sleep, wake episode duration), a range of perceptual variables related to recovery, mood, performance and internal training loads and non-exercise stressors were collected. Players reported significantly reduced sleep durations for NM compared to DM (- 157 min) and TD (- 181 min). In addition, sleep restfulness (SR; arbitrary scale 1=very restful, 5=not at all restful) and perceived recovery (PR; Acute Recovery and Stress Scale 0=not recovered at all, 6=fully recovered) were significantly poorer following NM than both TD (SR: +2.0, PR: -2.6), and DM (SR: +1.5; PR: -1.5). These results suggest that reduced sleep quantity and quality and reduced perceived recovery are mainly evident following night matches in elite players.

## 1. INTRODUCTION

Self-reported sleep loss is suggested as a common occurrence prior to competition in elite athlete populations (Erlacher, Ehrlenspiel, Adegbesan, & Galal El-Din, 2011; Juliff, Halson, & Peiffer, 2014), which can result in a reduction in ensuing athletic performance outcomes (Edwards & Waterhouse, 2009; Jarraya, Jarraya, Chtourou, & Souissi, 2013; Reyner & Horne, 2013). However, despite these suggestions, there is limited evidence to highlight that team-sport athletes, -particularly elite footballers, experience sleep issues as part of their normative behaviour (Erlacher et al., 2011; Juliff et al., 2014). In addition, sleep behaviour following competitive match play remains unclear (Fowler, Duffield, & Vaile, 2014). This is concerning, given the proposed relationship between sleep loss and reduced recovery in team-sport athletes (Fullagar, Duffield, Skorski, Coutts, et al., 2015; Skein, Duffield, Minett, Snape, & Murphy, 2013). Furthermore, it is not known whether footballers' sleep quality and quantity differs following training days and match play. Therefore, further research investigating the behavioural sleeping patterns of elite footballers is warranted.

Sleep issues experienced by team-sport athletes are postulated to be predominately situational and sport-dependant, though explicit evidence is minimal (Juliff et al., 2014). For instance, on the night of an Australian football match sleep duration was significantly decreased to a similar degree whether home or away (by 68 and 64 min respectively (Fowler, Duffield & Vaile, 2014). Of the various team sports, association football is one which comprises numerous situations which may disrupt players' sleeping patterns; including periods of travel, congested fixture scheduling and training or playing at night (Fullagar, Duffield, Skorski, Coutts, et al., 2015). However, data to support these perceptions, especially with regards to training and playing at night, is unclear. For instance, whilst football players' sleep volume is reportedly reduced following a night match (Meyer, Wegmann, Poppendieck, & Fullagar, 2014; Nédélec et al., 2012), some have reported no effect of night matches (Roach et al., 2013) or early evening high-intensity training (Robey et al., 2013) on sleep duration and quality in elite junior players. Therefore, more research is required to confirm whether football players' sleep is hindered following night matches. Perhaps more importantly, whilst studies have investigated player sleeping patterns in comprising situations i.e. travel and night matches (Fullagar, Duffield, Skorski, White, et al., 2015), there is no study at present which has monitored *elite* footballers for more than an acute period (i.e. one week) during the regular season to give an accurate indication of a professional player's normal sleeping behaviour.

The lack of data surrounding sleep following match play is concerning, since these periods of sleep loss could potentially compromise the recovery process (Skein et al., 2013). Fowler et al. (2014) reported significant reductions in sleep duration and quality, along with an impaired stress-recovery balance, on the night of a match compared to the night prior for away matches in elite Australian footballers. Nonetheless, the evidence as to what are normal sleep and recovery responses within elite football is currently lacking. Accordingly, the purpose of the present study was to monitor the sleeping patterns of elite football players and to assess whether differences in sleep indices occurred in association with an altered perceptual recovery status. If sleep issues were present, we aimed to identify any potential factors within the professional sporting environment (e.g. stress, physical or psychological load) which contributed to these poor sleeping patterns, with a specific focus on the presentation of individual results.

## 2. METHODS

### Participants

Sixteen elite male football players participated in the present investigation (mean SD age 25.9 ± 7.5 y, body mass 74.8 ± 8.9 kg, height 179.5 ± 12.1 cm). The players were representatives of three UEFA© clubs within the top division in either Germany (Bundesliga) or the Netherlands (Eredivisie). Players were given information regarding the synopsis of the study and the associated risks, and if they wished to participate they provided written informed consent. The study was conducted in accordance with the Declaration of Helsinki and was approved by the institutional Human Research Ethics Committee (Saarland University).

### Study design

The present study was a descriptive, observational design. All players were familiarised with the study procedures prior to the collection of data, which was obtained over a 21 d period during either the second half of the 2013/2014 or the first half of the 2014/2015 season. Measures were obtained twice per day, whereby participants were asked to complete a sleep and sporting activity questionnaire (SosciSurvey™) in the morning after awakening, and at night prior to sleeping. This questionnaire was completed online, on the player's personal laptop or smart phone, and accessed through individual case-protected web URL links, ensuring complete confidentiality. Training schedules were set at the discretion of the team coaches and conditioning staff. Matches were scheduled by the respective external football organisations. Within this 21-d period, players did not complete the questionnaire on 'rest' days (e.g. days which they were away from the football club). Each player had approximately one designated rest day per week. Thus, players completed the questionnaire for 18 days/nights. At the end of the collection period, data sets which had an overall completion rate of 90% or greater were retained for analyses. These data sets were also required to include at least three matches for each player during this period (two day matches, one night match) where the player played at least 60 min of match play. Within these included data sets, days were categorised into 'training days' (day in which the player attended and participated in structured training), 'day matches' (matches which concluded before 6 pm) and 'night matches' (matches which kicked off after 6 pm; see Methods and Statistical Analysis) for final analyses. If a participant experienced a prolonged injury or illness during the data collection period (>1 weeks) they were also excluded from analyses. Furthermore, players whom were recovering from an injury incurred immediately prior to data collection were also excluded. From the 25 players originally recruited for the study, 16 were retained for final analyses. In total, 235 training days, 32 day matches and 16 night match responses were analysed.

### Study procedures

A subjective sleep questionnaire was used to assess players' sleep habits, perceptual fatigue and stress prior to and following training and matches. This questionnaire was previously created as part of the Regman™ recovery project, in which the authors' Institute is a co-partner. Although measures of sleep were subjective in nature, the sleep indices within the questionnaire have previously been validated against objective measures of actigraphy, with time in bed (ICC = 0.93 to 0.95) and total sleep time (ICC = 0.90 to 0.92) revealing strong agreement (Kölling, Endler, Ferrauti, Meyer, & Kellmann, 2015). This questionnaire (provided as Supplementary Material) also included an evaluation of the numerous variables within a professional football team environment (i.e. non-exercise stressors such as press conferences) which could potentially affect recovery following training or match play (Nédélec et al., 2013). The morning section was used to ascertain information about the previous night's sleep including questions relating to "restfulness" (sleep quality: 1 = very restful, 5 = not at all restful), "reasons for un-restfulness", details about sleep disturbances (if they were present), the duration of total sleep time and a short scale of general perceptual recovery (0 = not recovered at all, 6 = fully recovered; (Kölling et al., 2014)). Total sleep time was calculated as:

[(Δ of sleep duration between bedtime and awakening time) – duration of sleep onset latency – total wake episode duration]

E.g. [(23:15-07:15) – 15 min – 15 min] = 7 h 30 min of sleep.

Comparatively, the evening section asked closed-response questions such as how "relaxed" and "exhausted" the players felt, how they rated their "overall performance" for the day, whether they slept during the day (naps; this was calculated outside total sleep time at night), and then required them to provide open-response details of any "additional stress or non-exercise loads" they experienced that day. In addition, if participants played in a match, they provided details regarding kick-off time, personal playing time, sessional rating of perceived exertion (s-RPE = min played x RPE (Borg, 1998; Foster et al., 2001), match location (home or away), result (win, lose, draw), sleeping location (home, hotel, other) and travel duration from stadium to place of sleep (all closed response questions). When players trained, but didn't play, they provided s-RPE.

## Statistical Analyses

Data are presented as means ± standard deviations (SD) for bedtime, awakening time, sleep duration, sleep onset latency, wake episodes, wake episode duration, sleep restfulness and recovery. Means ± SD were also used to describe the internal load from both training and matches (min of activity x RPE) and the average non-exercise induced stress (scale 0-100). The percentage (%) of each answer for the closed response questions relating to “tenseness”, “exhaustion”, “general overall performance” was calculated. For comparative statistics, three different conditions were assessed: Training day (TD), day match (DM; matches which concluded before 6 pm) and night match (NM; matches which kicked off after 6 pm). Repeated measures analysis of variance (ANOVA) were calculated between conditions (TD vs. DM, DM vs. NM, NM vs. TD) for bedtime, awakening time, sleep duration, sleep onset latency, wake episodes, wake episode duration, sleep restfulness and recovery. When a significant main effect was found, a post hoc Bonferroni adjustment was used to assess pairwise comparisons of the estimated marginal means. Independent t-tests were utilized to analyze sleep duration differences between home and away locations for day and night matches (all home vs all away matches). Additional descriptive data that listed reasons for un-restfulness were used for the presentation of individual case reports. All statistical analyses were calculated using SPSS (v27, SPSS Inc., Chicago, IL, USA) with significance set at $P<0.05$. Furthermore, standardised effect size (Cohen’s *d*; ES) analyses were used to interpret the magnitude of the mean differences between conditions for all sleep and recovery parameters with $d < 0.20$ (trivial), $d = 0.20$ (small), $d = 0.50$ (medium), $d \geq 0.80$ (large) (Cohen, 1988).

## 3. RESULTS

### *Sleep variables*

All sleep variables are presented in Table 1, with mean and individual data for sleep duration for TD, DM and DM in Figure 1. Bedtime was significantly later for NM compared to both DM (+ 189 min; P<0.001, *d*=2.61) and TD (+ 248 min; *P* <0.001, *d* = 3.70) and for DM compared to TD (+ 59 min; *P* = 0.007, *d* = 1.95), whilst awakening time was significantly earlier for TD compared to both DM (- 45 min; *P* <0.001, *d* = 2.01) and NM (- 70 min; *P* <0.001, *d* = 2.45). Sleep onset latency was significantly greater for NM compared to TD (+ 10 min; *P* = 0.03, *d* = 1.60) but not different between DM and NM (*d* = 0.64) or TD and DM, despite a large ES being present (*P* = 0.42, *d* = 0.96). Sleep duration for NM was significantly less than DM (- 157 min; *P* <0.001, *d* = 3.71) and TD (- 181 min; *P* <0.001, *d* = 4.31), although there were no differences between DM and TD (*P* = 0.33, *d* = 0.60). No significant differences were evident between any condition for wake episodes (*P* >0.05). Sleep restfulness was significantly poorer following NM than both TD (*P* <0.001, *d* = 3.56) and DM (*P* = 0.007, *d* = 3.16).

****************INSERT TABLE 1****************

****************INSERT FIGURE 1****************

### *Subjective responses to exercise (training and matches)*

All subjective wellness responses for TD, DM and NM are presented in Table 2. Perceptual recovery the following morning for NM was significantly less than both TD (*P* <0.001, *d* = 3.09) and DM (*P* = 0.007, *d* = 1.78), whilst a large effect was present for TD compared to DM ($d$ = 1.31). Subjective exercise load was significantly greater for both DM and NM than TD (both $P$ <0.001; DM: $d$ = 4.04; NM: $d$ = 4.79), although there were no significant differences between DM and NM ($P$ = 0.42, $d$ = 0.74). Comparatively, players ranked perceptual performance similar across conditions (Table 2). There were no significant differences between sleep durations for matches played at home or away (home: 290 ± 73 min away: 316 ± 185 min $P$ = 0.95: two further players were excluded because they did not play both home and away). Players did not provide sufficient amount of details regarding sleeping location (home, hotel, other) and travel duration from stadium to place of sleep (these questions were optional), thus these analyses was abandoned.

****************INSERT TABLE 2****************

***Individual case reports***

As a practical example of the individualised nature of sleep responses, individual nightly sleep responses for four separate players (A-D), including duration and occurrences and reasons for ‘average-poor restfulness’, are presented in Figure 2. For instance, mean sleep duration for Player A was 476 ± 75 min (range 260-510 min) for TD, with the player reporting ‘average-poor restfulness’ on ten occasions all of which the reason was given due to ‘newborn children’.

****************INSERT FIGURE 2****************

## 4. DISCUSSION

The present investigation aimed to monitor the sleeping patterns of elite football players and to assess when reductions in sleep indices occurred; in addition to the perceptual recovery status. The main finding of this study was the significant reduction in sleep duration and later bedtime following NM compared to both TD and DM. Following these NM, there was also a significant reduction in perceived recovery compared to both DM and TD. Players subjectively reported several reasons for poor sleep such as children, nervousness, pain and adrenaline following a match. Overall, our results suggest that elite football players lose sleep and report reduced perceptual recovery following night match play; however players appear to report adequate sleep durations (i.e. 7-10 h; (National-Sleep-Foundation, 2013)) and qualities following training days and day matches.

Bedtime and total sleep duration were extended and reduced respectively following NM, supporting the idea that sleep indices are likely dependent on the situational demands and scheduling of the particular sport (Juliff et al., 2014; Sargent, Lastella, Halson, & Roach, 2014). These present observations of reduced sleep quantity in elite footballers are supported by objective evidence that elite rugby union players sleep less on game compared to non-game nights (Eagles, Mclellan, Hing, Carloss, & Lovell, 2014). Furthermore, professional Australian soccer players can lose 2-4 h of sleep following matches compared to non-match nights (Fowler et al., 2014) and a recent study states that 52.3% of elite (individual and team-sport) athletes subjectively report sleep disturbances following a late match or training session (Juliff et al., 2014). Comparatively, sleep duration on TD and following DM was within the presumed normal healthy range of 7-10 h in our study (National-Sleep-Foundation, 2013). Furthermore, match loads (calculated from s-RPE) were similar between DM and NM, and there were no significant differences between home and away matches. Thus, these data would suggest that there are particular nuances about a night match (compared to a day match) which cause this reduction in sleep duration outside reasons arising from the match/exercise itself. The most predictable reason for this would be the pure extension of a later bedtime caused by the timing of the match. The later bedtime, coupled with the environmental circumstance of a NM driving wakefulness over sleep at a time when the drive for sleep is normally stronger, likely explains the reduced sleep durations. Additionally, the evening exposure to light (depending on seasonal period) could also prolong sleep onset and reduce total sleep time (Malone, 2011). Another factor which is harder to control and report, but may play just as an important role, could be socialising (Fullagar, Duffield, Skorski, White, et al., 2015). Collectively, these data suggest that although 'normal' player sleep patterns may be sufficient, under specific circumstances (i.e. night matches) there are cases for reduced sleep durations in professional footballers.

Following a similar trend to sleep duration, there were also significant reductions in perceptual recovery following NM compared to TD and DM. Since no difference was evident for subjective exercise loads between DM and NM, it might be speculated this subsequent altered recovery state could be attributed to the reduction in sleep quantity. Indeed, sleep deprivation following exercise can lead to reductions in the recovery of psychological or perceptual performance (Fullagar, Duffield, Skorski, Coutts, et al., 2015; Skein et al., 2013). For instance, Fowler and colleagues (2014) reported significant reductions in sleep duration and quality in six professional footballers, along with an impaired stress-recovery balance, on the night of a match compared to the night prior for away matches. The present result of a reduction in perceptual recovery may represent concerns for the practitioner, especially since the competitive match load may suggest the homeostatic need for recovery sleep would be higher compared to rest days (Romyn, Robey, Dimmock, Halson, & Peeling, 2015); and this appears to not have been provided here. Although speculative, this could have important repercussions for players during subsequent training and competition where this reduction in wellbeing could unnecessarily add to an already suppressed overall psychological state. More research which focuses on the interaction between sleep loss and a suppressed psychological state is required, especially in elite footballers, and whether any subsequent associations affect the acute recovery-stress balance and ensuing performance.

Sleep is certainly an individual response, and grouping players may not capture the nuances of such individuality. Consequently we depict this in Figure 2, where four players mean sleep duration ranged from 460-581 min, with some players sleeping 2 h more than others on any given TD. Similarly, players' reasons for 'average - unrestfulness' varied with contrasting answers such as 'newborn children' (Player A) and 'urination' (Player B). Clearly in this context these two players will need contrasting approaches in order to address these issues. We believe this is a good example of how very simple data could potentially inform and change practice. Further analysis and presentation of individual cases within original scientific publications in the football science field is a proposal that is supported by coaches and practitioners. Indeed, quantifying, predicting and the overall understanding of the inter-individual differences in the magnitude of responses' to matches or training ("the individual response") is gaining considerable applied and scientific interest (Hecksteden, 2015). All players reported reductions in sleep duration following NM. Thus, an improvement in sleep indices through such measures as sleep hygiene protocols following night matches may seem advisable for these players. Indeed, sleep hygiene protocols have been shown improve sleep duration and perceived soreness in elite tennis players (Duffield, Murphy, Kellett, & Reid, 2014); however, evidence of their efficacy in football is lacking. Another possible management strategy would be to implement napping strategies to supplement sleep, repay sleep debt and possibly improve the subsequent performance (Waterhouse, Atkinson, Edwards, & Reilly, 2007).

Although the primary aim of the present investigation was to monitor the subjective sleeping patterns of elite football players, an additional focus was to identify factors within their environment which could possibly contribute to poor sleeping quality. Juliff et al. (2014) reported from a sample of 283 individual and team sport athletes the main reasons responsible for poor sleep were 'thoughts about the competition' and 'nervousness'. The players in our study also reported 'nervousness' as one of the most common problems for average-poor sleep restfulness during TD, along with 'unfamiliar sleeping environment' and 'urination'. For DM and NM, 'strenuous game', 'pain' and 'adrenaline after a game' were consistently present. Whilst the existing data set does not have the strength to determine whether a relationship (either correlation or causative) exists between these reasons for un-restfulness and various sleep indices, the description of these issues may provide important insight for practitioners or coaches. For instance, in Figure 2 it can be observed that Player A had higher mean sleep durations for TD (~8 h); however, there were some nights where he lost almost 4 h (lowest 4.3 h). This high variation was attributed to Player A's newborn children, with the player listing this ten times throughout the duration of the study. This provides a good practical example of additional issues which may not come under the realm of the 'normally' considered reasons for disturbances to sleep quality and duration.

One of the limitations of the present study was the use of a subjective measure (online survey) of sleep. Such a measure makes it difficult to estimate sleep quantity and quality compared to objective measurements, including actigraphy and the 'gold standard' polysomnography (PSG). Indeed, previous work has shown subjective measurements can be imprecise (Kawada, 2008) and can be influenced by mood, memory bias and personality characteristics (Jackowska, Dockray, Hendrickx, & Steptoe, 2011). However, it has been shown that respondents are capable of estimating total sleep duration with significant accuracy (Armitage, Trivedi, Hoffmann, & Rush, 1997). Furthermore, subjective measurements of sleep are preferred within these elite football environments as they are less invasive or burdening than actigraphy or PSG. The present study entailed a fairly short sampling period (21 d), though still longer than other reported actigraphy data. However, we acknowledge this makes it difficult to extrapolate our results, especially across different time points throughout a season. Furthermore, the sample size used in this study was low, limiting the significance of the results; however this is not uncommon in studies with professional players. Indeed, it should be acknowledged that all players were first division elite players, making these results very practically applicable to elite football. Finally, players were comprised from different teams and countries where situations relating to team environment (e.g. travel, style and intensity of training) can differ.

## **Conclusion**

The primary findings of this study were the significant reduction in sleep duration and later bedtime following NM compared to both TD and DM. Following NM, there was also a significant reduction in perceived recovery compared to both DM and TD. Players subjectively reported several reasons for poor sleep such as children, nervousness, and pain and adrenaline following a match. More research is required to objectively quantify and confirm that TD results in 'normal' sleep durations, similarly that this sleep volume is severely hampered following NM. In addition, the effect of reduced sleep duration and quality on the recovery of exercise performance following NM in elite players is warranted. The present findings suggest elite players lose significant amounts of sleep volume and quality following NM; however these variables appear within healthy ranges for TD and DM.

## **PERSPECTIVE**

Our results suggest that elite soccer players have normal sleep durations during training and match days; however, they lose sleep and report reduced perceptual recovery following night match play. Thus, suitable intervention strategies (e.g. sleep hygiene, napping the following day) following these night matches should be investigated forthwith to alleviate these issues. Practitioners should also be aware of the possible altered physiological load in subsequent training sessions following sleep loss. This is obviously dependant on numerous factors including scheduling, travel and team/coach preference. Furthermore, it is important to understand the intra-individual variability in sleep requirement and duration. Given some players will respond differently to sleep compromising situations, such as a NM, considering the monitoring of sleep for periods during the season and interpreting worthwhile changes in data on the individual level would appear the most beneficial practice for elite players.

## ACKNOWLEDGEMENTS

The authors would like to thank all the players for their time and participation. Much gratitude is also reserved for the coaches, fitness coaches and medical doctors for their assistance and enthusiasm towards the project. The authors would also like to thank Michael Kellmann and Michael Fuchs for their expertise and guidance during the construction phase of the questionnaire. Parts of the questionnaire were based upon the questionnaire developed as part of the RegMan—Optimization of Training and Competition: Management of Regeneration in Elite Sports project (IIA1-081901/12-16) which was initiated and funded by the German Federal Institute of Sport Science. The authors declare that there are no conflicts of interest.

## REFERENCES:

Armitage, R., Trivedi, M., Hoffmann, R., & Rush, A. J. (1997). Relationship between objective and subjective sleep measures in depressed patients and healthy controls. *Depression and Anxiety, 5*, 97-102. doi: 10.1002/(SICI)1520-6394(1997)5:2<97::AID-DA6>3.0.CO;2-2

Borg, G. (1998). *Borg's perceived exertion and pain scales* (Vol. viii). Champaign, IL, US: Human Kinetics.

Cohen, J. (1988). *Statistical Power Analysis for the Behavioral Sciences* (2nd ed ed.). Hillsdale: Lawrence Erlbaum.

Duffield, R., Murphy, A., Kellett, A., & Reid, M. (2014). Recovery from repeated on-court tennis sessions: combining cold-water immersion, compression, and sleep recovery interventions. *Int J Sports Physiol Perform, 9*(2), 273-282. doi: 10.1123/ijspp.2012-0359

Eagles, A., Mclellan, C., Hing, W., Carloss, N., & Lovell, D. (2014). Changes in sleep quantity and efficiency in professional rugby union players during home based training and match-play. *J Sports Med Phys Fitness, [Epub ahead of print]*. doi: Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/?term=Changes+in+sleep+quantity+and+efficiency+in+professional+rugby+union+players+during+home+based+training+and+match-play

Edwards, B. J., & Waterhouse, J. (2009). Effects of one night of partial sleep deprivation upon diurnal rhythms of accuracy and consistency in throwing darts. *Chronobiol Int, 26*(4), 756-768. doi: 10.1080/07420520902929037

Erlacher, D., Ehrlenspiel, F., Adegbesan, O. A., & Galal El-Din, H. (2011). Sleep habits in German athletes before important competitions or games. *J Sports Sci, 29*(8), 859-866. doi: 10.1080/02640414.2011.565782

Foster, C., Florhaug, J., Franklin, J., Gotschall, L., Hrovatin, L., Parker, S., . . . Dodge, C. (2001). A New Approach to Monitoring Exercise Training. *J Strength Cond Res, 15*(1), 109-115

Fowler, P., Duffield, R., & Vaile, J. (2014). Effects of domestic air travel on techincal and tactical performance and recovery in soccer. *Int J Sport Physiol Perform, 9*(3), 378-386. doi: 10.1123/IJSPP.2013-0484

Fullagar, H., Duffield, R., Skorski, S., Coutts, A., Julian, R., & Meyer, T. (2015). Sleep and Recovery in Team Sport: Current Sleep-related Issues Facing Professional Team-sport Athletes. *Int J Sport Physiol Perform, [Epub ahead of print]*

Fullagar, H., Duffield, R., Skorski, S., White, D., Bloomfield, J., Kölling, S., & Meyer, T. (2015). Sleep, Travel and Recovery Responses of National Footballers During and Following Long-Haul International Air Travel. *Int J Sports Physiol Perform, [Epub ahead of print]*. doi: Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/25946072

Jackowska, M., Dockray, S., Hendrickx, H., & Steptoe, A. (2011). Psychosocial factors and sleep efficiency: Discrepancies between subjective and objective evaluations of sleep. *Psychosomatic Med, 73*, 810-816. doi: 10.1097/PSY.0b013e3182359e77

Jarraya, S., Jarraya, M., Chtourou, H., & Souissi, N. (2013). Effect of time of day and partial sleep deprivation on the reaction time and the attentional capacities of the handball goalkeeper. *Biol Rhythm Res*, 1-9. doi: 10.1080/09291016.2013.787685

Juliff, L. E., Halson, S. L., & Peiffer, J. J. (2014). Understanding sleep disturbance in athletes prior to important competitions. *J Sci Med Sport, 18*(1), 13-18. doi: 10.1016/j.jsams.2014.02.007

Kawada, T. (2008). Agreement rates for sleep/wake judgments obtained via accelerometer and sleep diary: A comparison. *Behav Res Methods, 40*, 1026-1029. doi: 10.3758/BRM.40.4.1026

Kölling, S., Endler, S., Ferrauti, A., Meyer, T., & Kellmann, M. (2015). Comparing Subjective with Objective Sleep Parameters via Multi-Sensory Actigraphy in Physical Education Students. *Behav Sleep Med, [Epub ahead of print]*. doi: Retrieved from https://www.researchgate.net/publication/277268526_Comparing_Subjective _with_Objective_Sleep_Parameters_via_Multi-Sensory_Actigraphy_in_Physical_Education_Students

Kölling, S., Hitzschke, B., Holst, T., Ferrauti, A., Meyer, T., Pfeiffer, M., & Kellmann, M. (2014). Validity of the Acute Recovery and Stress Scale – Training monitoring of the German junior national field hockey team. *Int J Sports Sci Coach, (Epub ahead of print)*. doi: https://www.researchgate.net/publication/277269380_Validity_of_the_Acute_Recovery_and_Stress_Scale__Training_Monitoring_of_the_German_Junior_National_Field_Hockey_Team

Malone, S. K. (2011). Early to bed, early to rise?: An exploration of adolescent sleep hygiene practices. *J School Nursing, 27*(5), 348-354. doi: 10.1177/1059840511410434

Meyer, T., Wegmann, M., Poppendieck, W., & Fullagar, H. H. K. (2014). Regenerative interventions in professional football. *Sport Orthop Traumatol, 30*, 112-118. doi: Retrieved from http://www.sciencedirect.com/science/article/pii/S0949328X14000672

National-Sleep-Foundation. (2013). *Sleep in America poll: Exercise and sleep.* Retrieved from http://sleepfoundation.org/sites/default/files/RPT336%20Summary%20of%20Findings%2002%2020%202013.pdf

Nédélec, M., McCall, A., Carling, C., Legall, F., Berthoin, S., & Dupont, G. (2012). Recovery in Soccer: Part I. *Sports Med, 42*(12), 997-1015. doi: 10.2165/11635270-000000000-00000

Nédélec, M., McCall, A., Carling, C., Legall, F., Berthoin, S., & Dupont, G. (2013). Recovery in Soccer: Part II. *Sports Med, 43*(1), 9-22

Reyner, L. A., & Horne, J. A. (2013). Sleep restriction and serving accuracy in performance tennis players, and effects of caffeine. *Physiol Behav, 120*, 93-96. doi: 10.1016/j.physbeh.2013.07.002

Roach, G. D., Schmidt, W. F., Aughey, R. J., Bourdon, P. C., Soria, R., Claros, J. C. J., . . . Sargent, C. (2013). The sleep of elite athletes at sea level and high altitude: a comparison of sea-level natives and high-altitude natives (ISA3600). *Br J Sports Med, 47*, i114-i120. doi: 10.1136/bjsports-2013-092843

Robey, E., Dawson, B., Halson, S., Gregson, W., Goodman, C., & Eastwood, P. (2013). Sleep quantity and quality in elite youth soccer players: A pilot study. *Eur J Sport Sci*, 1-8. doi: 10.1080/17461391.2013.843024

Romyn, G., Robey, E., Dimmock, J., Halson, S., & Peeling, P. (2015). Sleep, anxiety and electronic device use by athletes in the training and competition environments. *Eur J Sport Sci, [Epub ahead of print]*

Sargent, C., Lastella, M., Halson, S., & Roach, G. (2014). The impact of training schedules on the sleep and fatigue of elite athletes. *Chronobiol Int, 31*(10), 1160-1168

Skein, Duffield, R., Minett, G., Snape, A., & Murphy, A. (2013). The effect of overnight sleep deprivation after competitive rugby league matches on postmatch physiological and perceptual recovery. *Int J Sport Physiol Perform, 8*, 556-564

Waterhouse, J., Atkinson, G., Edwards, B., & Reilly, T. (2007). The role of a short post-lunch nap in improving cognitive, motor, and sprint performance in participants with partial sleep deprivation. *J Sports Sci, 25*(14), 1557-1566

# **Supplementary Material**

## Morning Questionnaire

1. Which questionnaire do you want to fill out now?

Please select the appropriate questionnaire from:

Questionnaire "Morning"

Questionnaire "Evening"

2a. Good morning, how restful was your sleep?

Please tick:

1- 1= very
2- 2= pretty
3- 3= average
4- 4= hardly
5- 5= not at all

If players answer any of the bottom three answers they go to 2b.

2b. If your sleep wasn’t very restful, what was the reason?

Please tick the reasons. Multiple answers are possible!

unfamiliar sleeping environment

nervousness,

pain

Hunger / thirst

urination

jetlag

hotel bed

strenuous game

other

3. How long did it take for you to fall asleep after you turned off the lights and went to bed?

Although this is difficult to estimate, please try your best. Please indicate your approximate estimate of the duration in minutes (e.g. 15):

………………………………………………………………………………………

4a. Did you wake up at all during the night? This includes any interruptions to your sleep.

Please tick:

Yes

No

If players answer YES, they move onto 4b.

4b. How many times did you wake up and what was the total duration?

Please specify the frequency and approximate duration:

………………………………………………………………………

How often were you awake at night?

………………………………………………………………………

How long in total (time in minutes e.g. 25)?

………………………………………………………………………

5. When did you finally wake up?

Please enter the time (24 hr hour format e.g. 07:00):

………………………………………………………………………

6. When did you get out of bed?

Please enter the time (24 hr hour format e.g. 07:10):

………………………………………………………………………

7. Short scale for recovery. The following deals with your general recovery state. The rating “applies fully” symbolizes the highest ever reached recovery state.

General recovery state

(e.g. recovered, rested, physically relaxed)?

0 does not at all apply (not recovered at all)

1

2

3

4

5

6 applies fully (fully recovered)

## Evening Questionnaire

1. Which questionnaire do you want to fill out now?

Please select the appropriate questionnaire from:

Questionnaire "Morning"
Questionnaire "Evening"

2. Good evening, how tense do you feel right now?

Please tick:

tense
pretty tense
rather tense
rather relaxed
pretty relaxed
relaxed

3. How was your overall general performance today?

Please tick:
good
pretty good
rather good
rather poor
pretty bad
bad

4. Did you feel exhausted today?

Please tick:
no
a little
quite
very

5a. Did you sleep during the day today?

Please tick:

yes

no

If players answer YES, they move to 5b.

5b. How long and when did you sleep during the day?

Please indicate the length and the starting time of your nap:

.......................................................................................

Approximate duration in minutes (e.g. 45):

.......................................................................................

Start time (in 24 hr format e.g. 14:00):

........................................................................................

6a. Did you play a match today?

Please tick:

yes

no

If players answer yes, they proceed to answer 6b-6h. If no, proceed to 7.

6b. When did the match begin?

Please tick:

Start before 16:00 local time

Before 18:00 local time

18:00-19:30 local time

After 19:30 local time

6c. How long did you personally play for?

Please indicate the duration in minutes (e.g. 90):

6d. How physically exerting did you find the match?

Please enter your subjective assessment of the intensity of the game (CR -10 scale by Borg) :

0 rest
1 very easy
2 easy
3 moderately
4 somewhat hard
5 hard
6
7 very hard
8
9
10 extremely difficult (maximum)

6e. What was the result of the match (for your team)?

Please tick:

Win
Loss
Draw

6f. Where was the match played?

Please tick:
Home
Away

6h. Where are you sleeping tonight?

Please tick:
Home
Hotel
Other:

6h. How long was the trip from the stadium to your place of sleep?

Please indicate the approximate duration in minutes (e.g. 60):

Players who played a match skip to 8. Question 7 is designed for training days.

7. How long did your other sports activities last today (e.g. training, not including matches)?

Please indicate the approximate duration in minutes (e.g. 15):

8. How physically exerting did you feel about your sports activities today?

Please enter your subjective assessment of the intensity of the training day on (CR -10 scale by Borg):

0 rest

1 very easy

2 easy

3 moderate

4 somewhat hard

5 hard

6

7 very hard

8

9

10 extremely difficult (maximum)

9a. Did you use any recovery measures today (e.g. massage, cryotherapy, sauna, electrotherapy, compression garments, etc.)?

Please tick:

Yes

No

If players answer YES, move to 9b. if not, to 10.

9b. Which recovery measures did you use today and for how long?

Please tick the appropriate recovery measure (you can choose more than one) and enter the respective approximate duration in minutes (e.g. 15):

Active recovery in the swimming pool / hot tub

Acupuncture

Breathing techniques

Cool -down activities

Debriefing (Structured conversation with the trainer)

Self- massage (possibly with Foam Roller etc)

Ice bath (cold water bath)

Electrostimulation (EMS)

Cold chamber

Cold shower

Compression Clothing

Contrast shower (hot and cold alternately)

Massage by physio

Pharmacological actions

Meditation

Food supplements

Progressive Muscle Relaxation

Sauna

Stretching / stretching afterwards

Vibration, and vibration massage

Other:

Other:

Other:

10a. Did you experience any additional stress/loads today not associated with physical exercise (non-sporting strain: e.g. work commitments, testing, travel, sponsors appointment, personal, press conferences, etc.)?

Please tick:

Yes

No

If YES, players move to 10b. If not, move to 11.

10b. What additional stressors/loads did you experience today?

Please indicate the nature of the non-sporting strain.

Multiple answers are possible!

..................................................................................................

10c. How much stress did you feel due to these non-sporting loads?

Please move the slider to the appropriate position:

no stress .........................I.............................................................................maximum possible stress

11. When did you go to bed, or when will you go to bed?

Try to do your best to estimate

Please specify the exact time (in 24 hr format e.g. 22:15):

.........................................................................................................

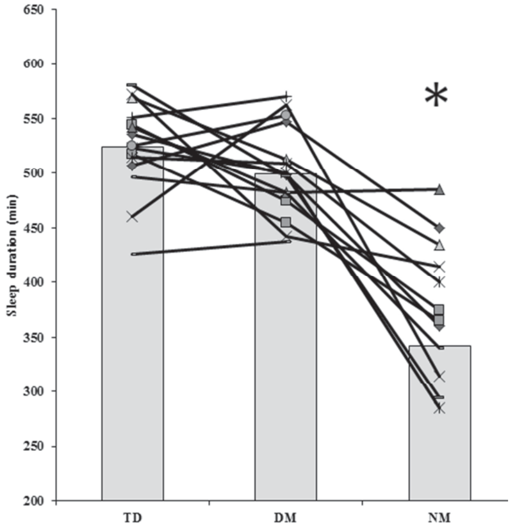


Figure 1: Mean (shaded bars) and individual cases (n=16) of sleep duration for a training day (TD), day match (DM) and a night match (NM). * Significant difference between NM and both TD and DM (P<0.05).
254x190mm (300 x 300 DPI)

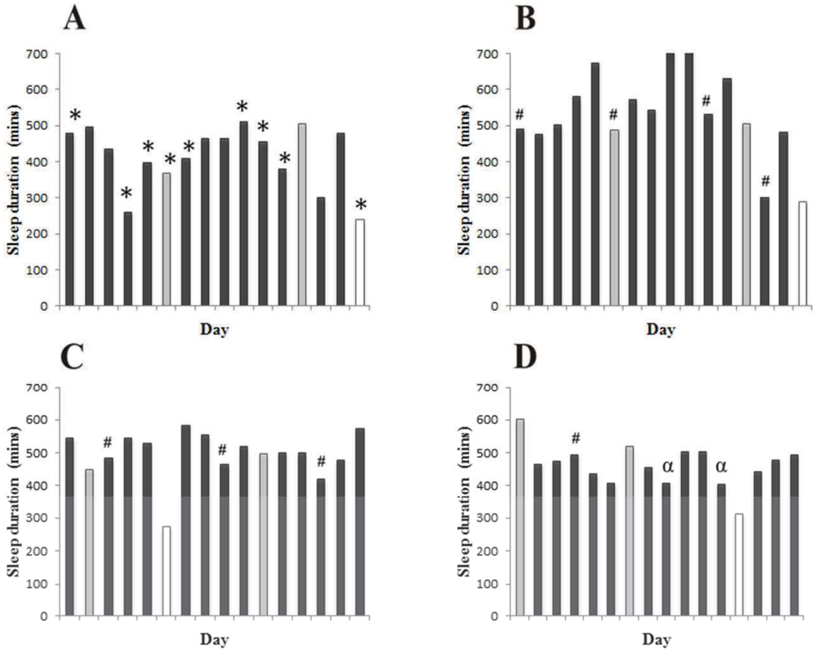


Figure 2: Examples of individual sleep duration responses (min) per night for four separate players (A-D) for the duration of the study. Abbreviations: Training Day in black bars; Day Match in light grey bars; Night Match in white bars.
* Indicates average-poor sleep restfulness with the reason provided being ‘newborn children’.
# Indicates average-poor sleep restfulness with the reason provided being ‘urination’.
ɑ Indicates average-poor sleep restfulness with the reason provided being ‘nervousness’.
254x190mm (300 x 300 DPI)

**Table 1: Subjective sleep responses following a normal training day (TD), day match (DM) and night match (NM) in elite soccer players collected over a 21-day period during the regular season.**

| n = 16 | TD | DM | NM |
|---|---|---|---|
| **Bedtime** | 23:19 ± 0:49 | 00:18 ± 1:24# | 03:27 ± 1:56* |
| **Awakening time** | 08:24 ± 1:07 | 09:09 ± 1:10# | 09:34 ± 0:47*** |
| **Sleep onset latency** | 16 ± 7 | 22 ± 13 | 26 ± 15*** |
| **Sleep duration** (h) | 8:44 ± 0:40 | 8:20 ± 0:41 | 5:43 ± 1:36* |
| **Wake episodes** (n) | 2.0 ± 1.2 | 2.8 ± 1.1 | 0 |
| **Total wake episode duration** (min) | 22.0 ± 39.1 | 11.4 ± 4.4 | N/A |
| **Sleep restfulness (1=very restful, 5=not at all restful)** | 1.8 ± 0.7 | 2.3 ± 0.8 | 3.8 ± 1.1* |
| **Number of players whom napped (at least once)** | 10** | 1 | 3 |
| **Average duration of naps (min)** | 57 ± 36 | 30 ± - | 77 ± 29 |

* Significant difference between NM and both DM and TD conditions (P<0.05)
** Significant difference between TD and both DM and NM conditions (P<0.05)
*** Significant difference between TD and NM condition (P<0.05)
# Significant difference between TD and DM condition (P<0.05)
NB: Napping data for TD was recorded during the day but *following* training, whereas napping data for DM and NM was recorded on the same day but *prior* to match play.

**Table 2: Subjective wellness responses for a normal training day (TD), day match (DM) and night match (NM) in elite soccer players collected over a 21-day period during the regular season. Means ± SD.**

| n= 16 | TD | DM | NM |
|---|---|---|---|
| *Tenseness (%)* | | | |
| 'tense' | 1 | 6 | 6 |
| 'pretty tense' | 8 | 16 | 38 |
| 'rather tense' | 7 | 31 | 6 |
| 'rather relaxed' | 22 | 16 | 6 |
| 'pretty relaxed' | 29 | 19 | 25 |
| 'relaxed' | 34 | 13 | 19 |
| *Performance (%)* | | | |
| 'good' | 27 | 22 | 25 |
| 'pretty good' | 34 | 38 | 44 |
| 'rather good' | 27 | 16 | 25 |
| 'rather bad' | 10 | 19 | 6 |
| 'rather bad' | 1 | 6 | 0 |
| 'bad' | 0 | 0 | 0 |
| *Exhaustion (%)* | | | |
| 'no, not at all' | 38 | 19 | 25 |
| 'a little' | 38 | 41 | 44 |
| 'quite' | 16 | 28 | 13 |
| 'yes, very, | 8 | 9 | 19 |
| *Recovery* (0=not recovered at all, 6=fully recovered) | 4.5 ± 0.7 | 3.4 ± 1.3 | 1.9 ± 1.1* |
| *Non-exercise induced stress* (*n* reported at least once; 0-100) | 5; 47 ± 30 | - | - |
| *Training Load* (AU) | 292 ± 195** | 659 ± 195 | 698 ± 254 |
| Listed reasons for sleep un-restfulness | Unfamiliar sleeping environment, nervousness, urination, children, wind, confrontation with coach, troubles with personal relationship | Children, urination, strenuous game | Adrenaline after the game, pain, strenuous game |

* Significant difference between NM and both DM and TD conditions (P<0.05)

** Significant difference between TD and both DM and NM conditions (P<0.05)

Abbreviations: AU: arbitrary units (Training Load (TL) = session rating of perceived exertion (s-RPE) x duration in min).

# Sleep, travel and recovery responses of national footballers during and following long-haul international air travel

| | |
|---|---|
| Journal: | *International Journal of Sports Physiology and Performance* |
| Manuscript ID: | IJSPP.2015-0012.R2 |
| Manuscript Type: | Original Investigation |
| Keywords: | soccer, fatigue, performance, regeneration, team sport |
| | |

| | |
|---|---|
| **Title:** | Sleep, travel and recovery responses of national footballers during and following long-haul international air travel |
| **Submission Type:** | Original investigation |

| | |
|---|---|
| **Authors:** | Hugh H.K. Fullagar[1],<br>Rob Duffield[2],<br>Sabrina Skorski[1],<br>David White[3],<br>Jonathan Bloomfield[4],<br>Sarah Kölling[5]<br>and Tim Meyer[1] |
| **Institutions:** | [1] Institute of Sport and Preventive Medicine, Saarland University, Germany<br>[2] Sport & Exercise Discipline Group, UTS: Health, University of Technology, Australia<br>[3] Irish Football Association, Belfast, Northern Ireland<br>[4] Support2Perform, Belfast, Northern Ireland<br>[5] Faculty of Sport Science, Ruhr-University Bochum, Bochum, Germany |
| **Corresponding author** | [1] Hugh Fullagar<br>Institute of Sport and Preventive Medicine, Saarland University,<br>GEB. B82<br>66123 Saarbrucken, Germany<br>Email: hughfullagar@uni-saarland.de<br>Phone: 0681-302 70400<br>Fax: 0681-302 4296 |

| | |
|---|---|
| **Running head:** | Travel, sleep and recovery in football |
| **Abstract word count:** | 250 |
| **Text only word count:** | 3876 |
| **Number of Figures:** | 3 |
| **Number of Tables:** | 3 |

## ABSTRACT

***Purpose:*** The present study examined the sleep, travel and recovery responses of elite footballers during and following long-haul international air travel, with a further description of these responses over the ensuing competitive tour (including two matches). ***Methods:*** In an observational design, 15 elite male football players undertook 18 h of predominately westward international air travel from the United Kingdom to South America (-4 h time-zone shift) for a 10-day tour. Objective sleep parameters, external and internal training loads, subjective player match performance, technical match data and perceptual jet-lag and recovery measures were collected. ***Results:*** Significant differences were evident between outbound travel and recovery night 1 (night of arrival; $P<0.001$) for sleep duration. Sleep efficiency was also significantly reduced during outbound travel compared to recovery nights 1 ($P=0.001$) and 2 ($P=0.004$). Furthermore, both match nights (5 and 10), showed significantly less sleep than non-match nights 2-4 and 7-9 (all $P<0.001$). No significant differences were evident between baseline and any time point for all perceptual measures of jet-lag and recovery ($P>0.05$); although large effects were evident for jet-lag on Day 2 (two days after arrival). ***Conclusions:*** Sleep duration is truncated during long-haul international travel with a 4 h time-zone delay, and following night matches in elite footballers. However this lost sleep appeared to have a limited effect on perceptual recovery, which may be explained by a westbound flight and a relatively small change in time-zones, in addition to the significant increase in sleep duration on the night of arrival following the long-haul flight.

**KEYWORDS:** Soccer, fatigue, match performance, regeneration, team sport

## Introduction

Sleep has been recognised by players, coaches and practitioners as critical to both optimal physiological and psychological recovery.[1,2] Unfortunately, professional footballers currently face numerous situations throughout a season where disrupted sleeping patterns can exist.[2] Such scenarios could include compromised recovery during and following short- and long-haul domestic or international travel, late-night matches and congested competition scheduling.[2,3] Of these, long-haul international air travel (LHIT) is a necessity for some national and club football teams who are required to play away matches in different continents due to international competitions. When LHIT is endured across multiple time-zones, numerous physiological variables are disrupted including the sleep-wake cycle,[4] body temperature and hormonal circadian rhythms.[5] Sleep is perhaps the more critical given sleep loss can affect athletic performance[6] and has been shown to reduce physiological and cognitive recovery in rugby-league footballers.[7] In addition, travelling across time zones can cause disruption to circadian rhythms and give rise to jet lag, further disrupting sleep and increasing residual fatigue – particularly in eastward compared to westward directions.[4] However, to date, the interaction between these aforementioned situational disturbances and objective measurements of sleep in team sports is relatively unknown. Given the upcoming 2016 Olympic Games in Brazil, further knowledge of the objective sleep and perceptual responses to LHIT in elite team-sport athletes would be welcomed to assist the planning of travel and training schedules.

Previous research has described the sleeping patterns of elite junior football players following LHIT.[8-10] For instance, Lastella et al[10] reported reductions in sleep duration (6.6±1.3 h per night compared to baseline 7.5±1.3 h) and quality immediately following travel from Sydney to Denver with an 8-h eastward time-zone change. However, Lastella et al[10] focused on the effects of altitude at the destination on ensuing sleep. Additionally, insights provided by Roach et al[8] and Sargent et al[9] into the influence of international travel on sleep are further compounded by the lack of sleep measurement during the flight, most likely due to understandable logistical issues.[8,9] Thus, further research is required to confirm the assumption that LHIT disrupts sleep, let alone aspects of team-sport performance. To date there is only one previous study that has attempted to investigate the effects of LHIT on sleep with relation to the physical and psychological demands of team sports. Fowler et al[11] reported 24 h simulated LHIT significantly reduced sleep quality and quantity in trained participants.[11] However, this study only focussed on the acute, 24 h post-travel recovery timeline.[11] Thus, recovery responses following this initial 24 h arrival period remain unclear, which is of particular relevance as matches are routinely conducted after this initial 24 h arrival period. Since sleep reportedly assists in memory consolidation, motor learning, cognitive growth and physical regeneration,[12] poor sleep during or following LHIT may limit athletes' post-exercise recovery timeline, which could also be especially pertinent to subsequent training sessions performed close to arrival. Therefore, further research is required to assess the sleep and recovery responses to LHIT in field-based team-sport settings.

Moreover, whilst there is evidence supporting the loss of sleep prior to competition in athletes,[13] research evaluating sleep following matches is lacking.[14] Considering that playing at night could promote arousal and prolong wakefulness,[2] playing at night might potentially cause sleep disturbances. Additionally, the physical demands of the actual game could inflict pain and increase perceived soreness and thus, combined with sleep disruption, may hinder physiological and/or psychological recovery.[7,12] Thus, there could be potential for players to sleep differently to those who do not play. Accordingly, the purpose of this study was to examine the sleep, travel and recovery responses of elite footballers during and following international air travel, with a further description of these responses on an ensuing competitive tour. Within this overall purpose, two secondary aims were investigated. Firstly, a comparison of sleep responses on outbound travel and recovery nights (nights following arrival), and secondly given this tour included two respective night matches we aimed to provide a comparison of sleep responses between players and non-players for both match nights and non-match nights.

## Methods

### *Subjects*

Fifteen elite male football players voluntarily agreed to participate in the investigation (mean±SD; age 25.5±4.9 y, body mass 74.3±7.3 kg and height 180.0±10.0 cm). The players were national representatives for their country with 5.1±4.8 y and 19.4±24.7 matches of playing experience. All players provided written informed consent prior to data collection. Participants were excluded if they experienced a prolonged injury or illness during the data collection period. One participant was excluded in accordance with these criteria. In addition, from an original pool of twenty-one players, all of whom partook in the study, a further five were excluded due to lack of complete data sets. Thus, data of fifteen participants were included for final analysis. This study was approved by the local Human Research Ethics Committee and conducted in accordance with the Declaration of Helsinki.

### *Design*

This study had a descriptive-observational design. Data was obtained from all players over a 10-day period during a pre-FIFA™ World Cup friendlies 2014 trip to South America, which included a trip from Europe to South America and a similar return trip (Fig. 1). All players were familiarised with the experimental procedures prior to the commencement of the investigation. Data was collected from the players prior to the tour (baseline), during each flight (outbound and return travel) as well as during the 10-day tour (day 1-10). During this tour, two matches were played against Uruguay (day 5; 20:00 local time) and Chile (day 10; 20:40 local time). The outbound flight from London, United Kingdom (GMT+1 h) to Montevideo, Uruguay (GMT–3 h; an overall time-zone shift of 4 h) consisted of late-afternoon departure from London to Paris, France (eastbound travel; 1 h; 341 km travelled), a 3-h stopover in Paris then an evening departure from Paris to Montevideo for a final arrival at 10:00am (westbound travel; 14 h; 10931km). The return trip was from Santiago, Chile to London, United Kingdom, consisting of a late-afternoon departure from Santiago to Paris (15 h; 11627 km travelled), a 2-h stopover in Paris then a midday departure from Paris to London. The afternoon trip from Montevideo to Santiago on day 6 required a 2-h journey with no time-zone change. Modes of travel were in premium economy class, meaning players were restricted from lying in a pure supine position for all flights. During both flights players were left to their own travel routines and were not monitored. No sleep or travel recommendations were given to the players. Training schedules were continuously monitored and conducted at the discretion of coaches (days 1-4 and 8).

## *Methodology*

### *Sleep measures*

The assessment of sleep duration (total amount of sleep obtained; min), sleep onset latency (time at which bed was entered to when the individual first fell asleep; min), sleep efficiency (sleep time expressed as a % of time in bed), wake episodes and wake episode duration (min) were collected using wrist-watch actigraphy (Readiband™, Fatigue Science, Vancouver, Canada). Data were analysed using the manufacturer's software (Fatigue Avoidance Scheduling Tool™ software). The use of these actimetry measures is based upon a previously validated fatigue model[15] and have also been validated in flight crew and attendants during both work and rest patterns, making them suitable for sleep measurements on commercial aircraft[16]. In addition, within-industry tests revealed Readibands showed good agreement (93%) with polysomnographic measurements[15]. These actigraphs were utilised during outbound and return travel, and every night on the tour (worn continuously except during training and matches).

As with previous research,[17] logistical reasons prevented the allocation of wrist actigraphs until just prior to outbound travel. Accordingly, mean baseline sleep data was subjectively recorded over a three-day period prior to the outbound flight via the completion of an online sleep and sporting activity questionnaire (SosciSurvey©). The questionnaire was completed in the morning after awakening, and at night prior to sleeping. However, recent research suggests the majority of sleep parameters related to duration, latency and efficiency within this questionnaire correlate poorly with objective methods of actigraphy (ICC=0.22-0.70[18]). Consequently, sleep parameters during the tour were excluded from comparative analyses to baseline given such different methods of collection. Thus, baseline measures of sleep would be presented herewith purely to provide some descriptive context of pre-tour sleeping patterns.

### *Perceptual measures*

The Liverpool John Moore's Jet-lag Questionnaire (LJMJQ)[19] was completed both prior to boarding on the day of outbound travel (baseline) and before training (same time each day) on days 2, 4, 6 and 10. The questionnaire assessed participants' subjective ratings of jet-lag on a visual analogue scale (VAS) of 0 (no jet-lag) to 10 (very bad jet-lag), and sleep (latency, onset time, quality, wake time, inertia), function (fatigue, concentration, motivation, irritability), diet and bowel movement ratings on a VAS of -5 to +5, with 0 representing habitual ratings prior to travel. At the same time points, subjective mental, emotional, and physical well-being (total stress-recovery score) were assessed using the Recovery-Stress Questionnaire for Athletes (RESTQ-Sport)[20] and a Likert scale (1=very restful to 5=not at all restful) was used to assess sleep restfulness.

### *Training load and match performance*

For each training session mean total distance (m), high intensity running distance (>19.9 km/h), mean speed (m/min), mean heart rate (HR; beats per min) and time spent above 85% of $HR_{max}$ (min) were recorded using 10 Hz Global Positioning Satellite (GPS) devices (STATSports™ Viper, STATSports Technologies, Dundalk, Ireland) and Polar heart rate monitors. In addition, rating of perceived exertion (RPE) was collected approximately 30 min following each training session using Borg's CR-10 scale to calculate training load (session-RPE x min).[21] Additionally, subjective match performance for each player was assessed from the same member of coaching staff for both matches using a scale ranging from 0=very poor to 10=excellent. In addition, technical match data (possession percentage, passes attempted, passes completed, pass completion rates, and attacks in the final third) were collected and analysed using Prozone™ software for both matches (VideoPro, Amisco Sports Analysis Services).

### *Statistical Analysis*

Data are presented as means±SD. Recovery nights (those following outbound travel) were classified as nights 1-4. Non-match nights were classified as nights 2-4 and 7-9, whilst matches were played on nights 5 and 10. A one-way repeated measures ANOVA was used to compare differences between time points of the away trip including and following international travel (outbound travel, night 1-10, return travel) for all sleep parameters. A one-way repeated measures ANOVA was also used to compare differences in perceptual recovery and jet-lag parameters between baseline measures (pre-travel), and time points of the away trip including both directions of travel. Where significant effects were observed, a Scheffé post-hoc test was performed. $P<0.05$ was accepted as significance for statistical comparisons. Furthermore, standardised effect size (Cohen's *d*; ES) analyses were used to interpret the magnitude of the mean differences between pre- and post- outbound and return travel for sleep, jet-lag and recovery parameters with $d<0.20$ (trivial), $d=0.20$ (small), $d=0.50$ (medium), $d=0.80$ (large)[22]; NB: only large ES reported for sleep parameters). ES analyses were also used to assess pre- and post-match differences for objective sleep indices for both players (played more than 60 min in each game) and non-players.

## Results

### *Sleep measures*

A summary of variables related to sleep quantity and quality is presented in Table 1. In addition, individual subject cases for sleep duration are illustrated in Fig. 2.

*The effect of travel on sleep parameters*

Significant differences were evident between outbound travel and night 1 ($P<0.001$; $d=1.86$) for sleep duration, with large ES evident on nights 2-4 ($d=1.20$-$1.41$). Significant differences were evident for sleep efficiency between outbound travel and recovery nights 1 ($P=0.001$; $d=1.05$) and 2 ($P=0.004$; $d=1.00$). There were no significant differences between outbound travel and recovery nights (1-4 all $P>0.05$) for either sleep onset latency or wake episodes, nor were any large ES present. Large ES were present between outbound travel and recovery night 2 ($d=0.90$), and 3 ($d=0.80$) for wake episode duration. Significant differences were also evident between the return flight and the preceding nights 7 ($P<0.001$; $d=1.54$), 8 ($P=0.002$; $d=1.35$) and 9 ($P=0.01$; $d=1.30$) for sleep duration. In addition, significant differences were present between return travel and nights 7 *(P*=0.03; *d*=0.92) for sleep efficiency, with large ES also present on night 9 *(d*=0.86).

*The effect of match play on sleep parameters*

Match 1 (night 5) showed significantly less sleep than non-match nights 2-4 (all *P*<0.001; *d*=1.79-2.00) and 7-9 (all *P*<0.001; *d*=1.95-2.18). Match 2 (night 10) also showed significantly less sleep than non-match nights 2-4 (all *P*<0.001; *d*=1.46-1.60) and 7-9 (all *P*<0.001; *d*=1.56-1.72). No significant differences were evident for sleep onset latency (*P*=0.75), although large ES were present between Match 2 and non-match night 8 (*d*=1.20). Match 1 showed large ES with non-match nights 7 (*d*=0.93) and 9 (*d*=0.85) for sleep efficiency, although no significant differences or large ES were present between Match 2 and non-match nights 2-4 or 7-9. A significant difference was present for wake episodes between both match nights (5 and 10) and non-match night 3 (*P*=0.02; *d*=1.78 and *P*=0.007; *d*=2.08, respectively). Large ES were also present between Match 1 and non-match nights 2-4 (*d*=1.17-1.78) and non-match night 8 (*d*=0.86). No significant differences were evident for wake episode duration for all comparisons, although large ES were also evident between Match 2 and non-match night 3 and 4 (*d*=0.80 and *d*=1.02, respectively).

Participants mainly napped on three specific days: day of arrival (Day 1; number of nappers=6, mean start time: 14:27±1:29, mean end time: 15:32±1:19, mean duration: 65±15 min), day of match 1 (Day 5; n=7; 14:54±1:28; 16:34±1:06; 100±35 min) and day of match 2 (Day 10; n=11; 14:53±0:14; 16:30±0:32; 91±38 min). Outside of these days no more than two participants each day napped during the daylight hours.

*Players vs. non-players*

As presented in Table 2, small ES were found for the within-player change in sleep duration when comparing players to non-players for match 1 (*d*=0.25). This was determined as the relative change following a match compared to the individual mean of the previous three nights. For the second match, non-players presented overall poorer absolute means and within-player changes, including sleep duration and efficiency (Table 2). For the first match, five starters played the full game and a further four played at least 80 min (overall starting mean 87 min). In the second match five starters played the full game, with a further three playing at least 80 min (mean 85 min).

***Perceptual measures***

There were no significant differences between baseline and any day of the tour for any perceptual measure (*P*>0.05; Fig. 3). However, large ES were evident for jet-lag on day 2 (*d*=1.47; two days after outbound travel) and moderate (*d*=0.76 on day 6. Moderate ES were present for sleep restfulness on day 6 following match 1 (*d*=0.52).

### ***Training load and match performance***

The physical performance data for the five training sessions are presented in Table 3. The results of both matches were similar (0-1 in match 1 and 0-2 in match 2), along with coaches' ratings of player performance (match 1=7.5±1.0, match 2=7.4±0.9). Match technical data included 46% and 32% possession, 451 and 175 passes attempted, 368 and 122 passes completed (pass completion rates of 82% and 70%), and 44 and 21 attacks in the final third of the pitch, per game in match 1 and 2 respectively.

## **Discussion**

This study describes the sleep, travel and recovery responses of professional footballers during and following LHIT from the United Kingdom to South America, including a comparison of sleep responses during travel and nights following arrival, and a comparison of sleep responses between players and non-players for both match nights and non-match nights. The main finding was the truncated sleep durations during outbound and return travel. That said, a 'rebound' effect (significant increase in sleep duration) was evident on the first night of arrival. Furthermore, both match nights (5 and 10) showed significantly less sleep than non-match nights 2-4 and 7-9. Interestingly, there were no significant differences in perceptual recovery between baseline and any day of the tour, nor were players any worse in sleep than non-players. Thus, it would appear further analysis of the relationship between the nuances of sleep loss and recovery in elite football players is required to confirm sleep loss impedes athletic recovery.

Sleep duration is reported to be reduced during simulated LHIT,[11] and following actual transmeridian travel.[10] Although we were unable to provide direct comparisons of sleep parameters to baseline in the present study, the mean of 5.5 and 5.7 h during outbound and return travel respectively is both far below the recommended 7-9 h for healthy adults[23] and the mean 8.5 h players subjectively reported prior to travel. Moreover, mean sleep efficiency during outbound travel was approximately 20% worse than average values for young adults who sleep for 8 h a night (~90% with polsomnography)[24], indicating poor sleep quality. Previous research suggests this poor duration and quality of sleep during travel could be due to hydration or cabin air pressure.[4] Additionally, the non-supine position experienced in economy class may have hindered melatonin secretion thus perhaps preventing the inducement of sleep[25]. Within the present study, noise within the cabin, comfort and the extensive travel schedule and timing of meals may also have played a role. Notwithstanding, there was a significant increase in players' sleep durations on the first night of arrival. This acute increase in sleep duration on night 1, followed by some stability on nights 2-4, suggests alterations to the sleep-wake cycle due to travel. The 4 h time zone shift is likely to have had only minor effects compared to more extensive time-zone shifts (i.e. 8-10 h).[4] In addition, it is suggested that body clocks are better adept at extending the day, and thus westbound flights such as the one experienced in this study are more likely to elicit reduced severity of jet lag symptoms (such as reduced sleep) than eastward travel.[4] Alternatively, the significantly greater sleep duration observed on the night following travel may be explained by an increased homeostatic pressure (drive) for sleep caused by the poor sleep incurred during outbound travel.[26]

Although perceptual jet-lag was present during the early stages of the trip, all other parameters relating to the LJMJQ, perceived recovery and sleep restfulness were relatively unchanged. These results may be explained by a westbound flight and a relatively small change in time zones, in addition to the substantial increase in sleep following the long-haul flight.[4] The finding of no effect on perceptual recovery could also possibly be explained by the elite playing experience of the current players, who are accustomed to constant travel and competition. Alternatively, athletes may have intentionally not reported concerns through fears of not being chosen to play.[27] Nonetheless, these results were somewhat surprising given reductions in subjective sleep quality and perceptual responses have been previously reported in athletes immediately following LHIT.[5] The presence of perceived jet lag on day 2 was anticipated, with the players' adjusting to the new light-dark cycle following travel. However, the dissipation of this effect by day 4 suggests that the timing of arrival five days prior to the first match was sufficient to alleviate symptoms of jet-lag fatigue. This sufficient re-adjustment may have been important given the effect circadian readjustment can have on athletic performance.[17]

In addition, sleep duration was significantly less on both match nights than non-match nights 2-4 and 7-9. These reductions were likely due to excess arousal, post-match commitments (i.e. press-conferences) and socialising.[2] These observations of altered sleep in our investigation are supported by evidence of post-competitive sleep disturbance in professional Australian soccer players[14] and elite individual and team-sport athletes.[13] It should be acknowledged that in our study the nights of matches were not controlled, thus a range of social-related factors were not controlled which may have contributed to the poor sleep. Notwithstanding, a 'rebound' effect was again evident in the majority of nights following match one (7-9) during which sleep duration was significantly greater. Thus, from a volume perspective, there appeared to be no *ongoing* concerns for the players in terms of sleep quantity for match preparation (for either match 1 or 2). However, sleep efficiency, and thus perhaps quality, saw limited improvement. Of further concern, a significant reduction in sleep duration occurred following match 2 and during return travel compared to the preceding nights 7 to 9. Given the congested scheduling of club fixtures following international matches,[3] this return journey represents perhaps the most demanding context for sleep loss in elite football players.

Interestingly, sleep parameters did not differ extensively between players and non-players following either match. It is perhaps indicative that it is not so much the act of playing that retards sleep duration and impairs quality, as has been previously hypothesised based on increased arousal at onset of sleep.[28] Indeed, the effect of exercising at night versus not is presently unclear. Some report no significant sleep changes following evening exercise,[29] whilst others have shown that judo competitors performing maximal aerobic exercise in the evening experienced greater elevated sleep-onset latency and awakenings.[30] Since non-players reported poorer aspects of sleep for the second match it is likely poor sleep induced from later bedtimes (due to the timing of the match and post-match functions) can be further attenuated from other sources (e.g. socialising, psychological reasons).

### *Limitations*

Given the ecological nature of data collection, certain limitations should be acknowledged. Unfortunately, due to players being located in different countries it was not logistically possible to obtain objective sleep and/or performance data prior to departure. Hence, a subjective online survey of sleep was used to collect baseline measures of sleep. This method makes it difficult to estimate sleep quantity and quality due to mood, memory bias and personality characteristics.[31] Although it has also been shown that respondents are capable of accurately estimating total sleep duration,[32] the overall poor agreement between objective and subjective measures[18] forced an exclusion of sleep parameters from baseline comparisons. Thus, this weakens inferences about the explicit effect of travel. In addition, the lack of a sleep diary filled out during the trip (especially during both directions of air travel, where subjects were sitting down for extended periods), limits the comprehensiveness, and perhaps accuracy, of sleep measurements. The lack of standardisation of numerous variables, perhaps most notably the lack of control for activities conducted post-match (i.e. socialising), weakens the internal validity of the effect of various influences on sleep. However, since those factors are usually not controlled for in real matches, external validity of our results is high. The low frequency of jet-lag data collection could also possibly have hindered perceptions of jet-lag.[33] In addition, having a stand-alone question(s) related to perceived soreness or muscle pain, outside that of the RESTQ-Sport, may have allowed for a greater derivation of factors associated with poor sleep after a match. Finally, no physiological measures of circadian rhythms were able to be collected to confirm whether or not circadian rhythms were disrupted. Indeed, it is difficult to differentiate between the effects from a time-zone shift and that of long-haul travelling in its own right.

## Practical Applications

- Sleep duration is poor during LHIT and following match play in elite footballers. Practitioners should be aware this may have repercussions for subsequent training sessions if performed closely after arrival or following matches.
- Despite this hindrance to sleep, international travel of more than 12 h (mostly westbound) together with a time-zone shift of 4 h, appears to have a limited effect on the perceptual recovery of elite footballers.

## Conclusion

LHIT results in worsened sleep durations in elite footballers than the recommended values for healthy adults. However this poor sleep appeared to have a limited effect on perceptual recovery, leaving the relationship between sleep loss and recovery ambiguous. These results suggest although sleep is initially poor during long-haul travel with a 4-h time-zone delay, a strong ‘rebound’ effect (significantly increased sleep duration) occurs upon arrival for the following night(s). Furthermore, sleep duration was significantly less on both match nights than non-match nights in elite footballers. Interestingly, there were no longitudinal perceptual recovery concerns for either playing or non-playing representatives outside that of early effects on jet-lag, and moderate effects on sleep restfulness following match 1. However, the hindrance to sleep during travel and following match play would suggest the future analysis of interventions which could potentially improve sleep parameters in these scenarios (e.g. the use of sleep hygiene protocols) is required, if not at least from a health perspective. In addition, further research into the relationship between sleep loss and recovery (i.e. physiological) of footballers is required to confirm the popular belief that sleep loss impedes athletic recovery.

## Acknowledgements

No funding was provided which contributed to the development of this manuscript. The authors report no conflicts of interest. The authors deeply appreciate the time and participation given by the players. Many thanks are also directed towards the coaches and fitness/medical staff for their assistance and enthusiasm towards the project. The authors gratefully acknowledge Support2Perform for providing equipment support (Readibands$^{TM}$), Patrick Dippel for the kind provision of Prozone$^{TM}$ match data reports, and Peter Fowler and Anne Hecksteden for their helpful insight and valuable critique of the manuscript. The authors also thank Michael Kellmann and Michael Fuchs for their contribution and assistance with the subjective online questionnaire.

## REFERENCES:

1. Halson SL. Nutrition, sleep and recovery. *Eur J Sport Sci.* 2008;8(2):119-126.
2. Meyer T, Wegmann M, Poppendieck W, et al. Regenerative interventions in professional football. *Sport Orthop Traumatol.* 2014;30:112-118.
3. Nédélec M, McCall A, Carling C, et al. Recovery in soccer: Part II-recovery strategies. *Sports Med.* 2013;43(1):9-22.
4. Reilly T. How can travelling athletes deal with jet-lag? *Kinesiology.* 2009;41:128-135.
5. Waterhouse J. Identifying some determinants of "jet lag" and its symptoms: a study of athletes and other travellers. *Br J Sports Med.* 2002;36(1):54-60.
6. Fullagar HHK, Skorski S, Duffield R, et al. Sleep and athletic performance: The effects of sleep loss on exercise performance, and physiological and cognitive responses to exercise. *Sports Med.* 2014:[Epub ahead of print].
7. Skein M, Duffield R, Minett G, et al. The effect of overnight sleep deprivation after competitive rugby league matches on postmatch physiological and perceptual recovery. *Int J Sport Physiol Perform.* 2013;8:556-564.
8. Roach GD, Schmidt WF, Aughey RJ, et al. The sleep of elite athletes at sea level and high altitude: a comparison of sea-level natives and high-altitude natives (ISA3600). *Br J Sports Med.* 2013;47:i114-i120.
9. Sargent C, Schmidt WF, Aughey RJ, et al. The impact of altitude on the sleep of young elite soccer players (ISA3600). *Br J Sports Med.* 2013;47(Sup. 1):i86-i92.
10. Lastella M, Roach G, Halson SL, et al. The effects of transmeridian travel and altitude on sleep: preparation for football competition. *J Sports Sci Med.* 2014;13:718-720
11. Fowler P, Duffield R, Vaile J. Effects of simulated domestic and international air travel on sleep,

performance and recovery. *Scand J Med Sci Sports.* 2014;[Epub ahead of print].

12. Samuels C. Sleep, recovery, and performance: The new frontier in high-performance athletics. *Neurol Clin.* 2008;26(1):169-180.
13. Juliff LE, Halson SL, Peiffer JJ. Understanding sleep disturbance in athletes prior to important competitions. *J Sci Med Sport.* 2014:[Epub ahead of print].
14. Fowler P, Duffield R, Vaile J. Effects of domestic air travel on techincal and tactical performance and recovery in soccer. *Int J Sport Physiol Perform.* 2014;9(3):378-86.
15. Russell CA, Caldwell JA, Arand DL, et al. Controlling fatigue risk with the Fatigue Science ReadiBand actigraph and associated sleep/wake classification algorithms: use case and validation. *IEEE Eng Med Biol Mag.* 2011.
16. Roma P, Hursh SR, Mead A, et al. *Flight attendant work/rest Patterns, alertness, and performance assessment: field validation of biomathematical fatigue modeling.* Washington, DC: Office of Aerospace Medicine;2012.
17. Reilly T, Atkinson G, Budgett R. Effect of low-dose temazepam on physiological variables and performance tests following a westerly flight across five time-zones. *Int J Sports Med.* 2001;22:166-174.
18. Kölling S, Endler S, Ferrauti A, et al. Comparing subjective with objective sleep parameters via multi-sensory actigraphy in German Physical Education students. *Behavioral Sleep Medicine.* 2015;(in press).
19. Leatherwood W, Dragoo J. Effect of airline travel on performance: a review of the literature. *Br J Sports Med.* 2013;47:561-567.
20. Kellmann M, Kallus KW. *The recovery-stress questionnaire for athletes: user manual.* Champaign, IL: Human Kinetics; 2001.
21. Foster C, Florhaug J, Franklin J, et al. A New Approach to Monitoring Exercise Training. *J Strength Cond Res.* 2001;15(1):109-115.
22. Cohen J. *Statistical Power Analysis for the Behavioral Sciences.* 2nd ed. Hillsdale: Lawrence Erlbaum; 1988.
23. Sleep in America poll: Exercise and sleep. National Sleep Foundation. 2013; http://sleepfoundation.org/sites/default/files/RPT336%20Summary%20of%20Findings%2002%2020%202013.pdf. Accessed 20 August, 2014.
24. Ohayon M, Carskadon M, Guilleminault C, et al. Metaanalysis of quantitative sleep parameters from childhood to old age in healthy individuals: Developing

normative sleep values across the human lifespan. *Sleep.* 2004;27:1255–1273.

25. Cajochen C, Krauchi K, Wirz-Justice A. Role of melatonin in the regulation of human circadian rhythms and sleep. *Journal of Neuroendocrinology.* 2003;15:432–437.
26. Sargent C, Darwent D, Ferguson SA, et al. Sleep restriction masks the influence of the circadian process on sleep propensity. *Chronobiol Int.* 2012;29(5):565-571.
27. Kölling S, Hitzschke B, Holst T, et al. Validity of the Acute Recovery and Stress Scale – Training monitoring of the German junior national field hockey team. *Int J Sports Sci Coach.* 2014;(in press).
28. Porter JM, Horne JA. Exercise and sleep behaviour - a questionnaire approach. *Ergonomics.* 1981;24:511-521.
29. Myllymaki T, Kyröläinen H, Savolainen K, et al. Effects of vigorous late-night exercise on sleep quality and cardiac autonomic activity. *J Sleep Res.* 2011;20(1):146–153.
30. Souissi N, Chtourou H, Aloui A, et al. Effects of time-of-day and-partial sleep deprivation on short term maximal performances of judo compeitiors. *J Strength Cond Res.* 2013;27(9):2473-2480.
31. Jackowska M, Dockray S, Hendrickx H, et al. Psychosocial factors and sleep efficiency: Discrepancies between subjective and objective evaluations of sleep. *Psychosomatic Med.* 2011;73:810-816.
32. Armitage R, Trivedi M, Hoffmann R, et al. Relationship between objective and subjective sleep measures in depressed patients and healthy controls. *Depression and Anxiety.* 1997;5:97-102.
33. Waterhouse J, Edwards B, Nevill AM, et al. Do subjective symptoms predict our perception of jet-lag? *Ergonomics.* 2000;43(10):1514-1527.

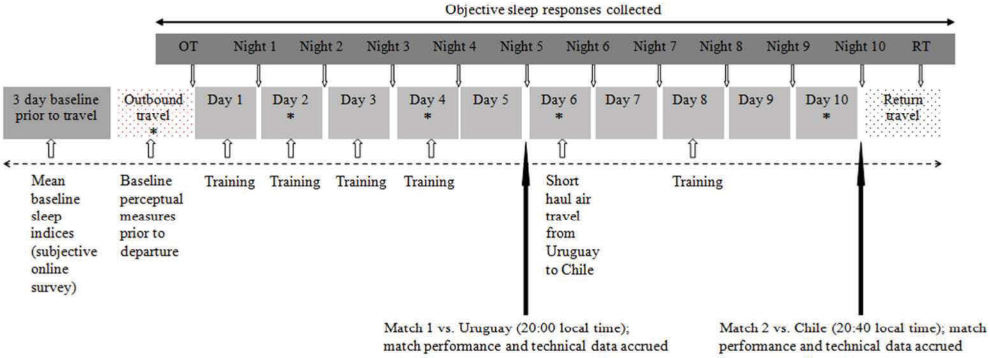
## FIGURE CAPTIONS

**Figure 1:** Schematic representation of the study design. * represents when perceptual measures (Liverpool John Moores Jetlag Questionnaire, REST-Q-19 for Sport and sleep restfulness) were collected prior to training. During training, external (Global positioning systems) and internal load (ratings of perceived exertion, heart rate) monitoring were collected. OTN: Outbound travel night; RTN: Return travel night.

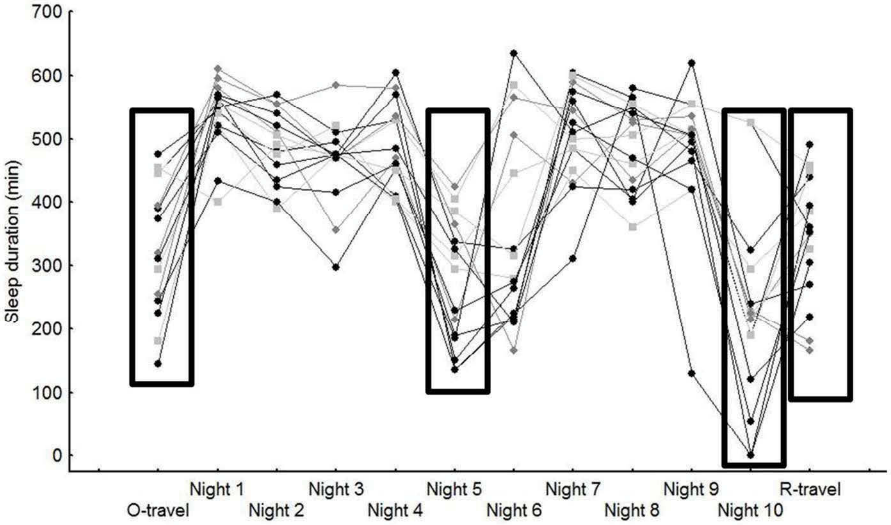
**Figure 2:** All fifteen subjects' sleep durations (minutes) for baseline, outbound travel (O-travel), each night on the trip (Night 1-10) and return travel (R-travel). The thick black boxes

signify nights of long-haul travel (both directions) and night matches (Night 5 and 10).

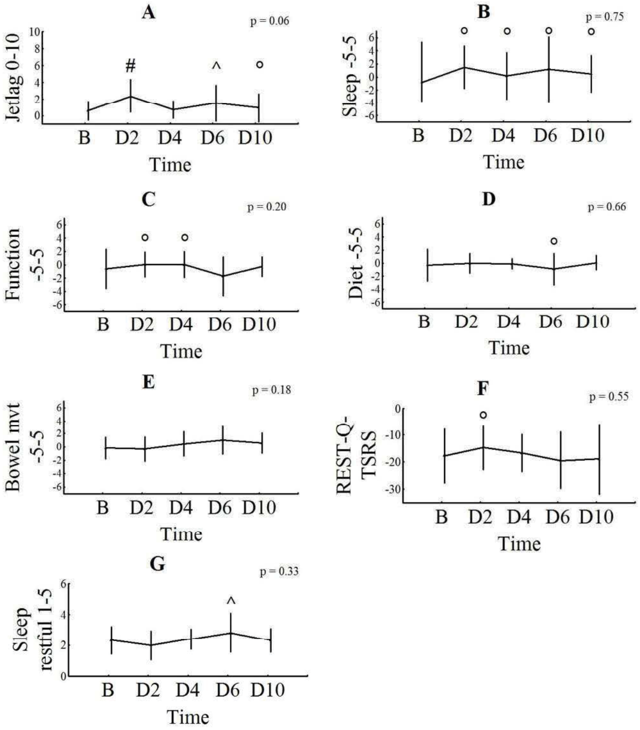
**Figure 3:** Mean ± standard deviation of Liverpool John Moores questionnaire (Jet-lag (A), Sleep (B), Function (C), Diet (D), Bowel mvt (movement (E)), RESTQ-Sport (RESTQ total stress recovery score (REST-Q-TSRS); F) and a Likert scale (1-5) for sleep restfulness (G). ° represents a small effect size (*d* = 0.20-0.49) compared to baseline, ^ represents a moderate effect size (*d* = 0.50-0.79), # represents a large effect size (*d* >0.80). B: Baseline; D2: day 2, and so forth.



Schematic representation of the study design. * represents when perceptual measures (Liverpool John Moores Jetlag Questionnaire, REST-Q-19 for Sport and sleep restfulness) were collected prior to training. During training, external (Global positioning systems) and internal load (ratings of perceived exertion, heart rate) monitoring were collected. OTN: Outbound travel night; RTN: Return travel night.
254x190mm (300 x 300 DPI)



All fifteen subjects' sleep durations (minutes) for baseline, outbound travel (O-travel), each night on the trip (Night 1-10) and return travel (R-travel). The thick black boxes signify nights of long-haul travel (both directions) and night matches (Night 5 and 10).
254x190mm (300 x 300 DPI)



Mean ± standard deviation of Liverpool John Moores questionnaire (Jet-lag (A), Sleep (B), Function (C), Diet (D), Bowel mvt (movement (E)), RESTQ-Sport (RESTQ total stress recovery score (REST-Q-TSRS); F) and a Likert scale (1-5) for sleep restfulness (G). ° represents a small effect size (d = 0.20-0.49) compared to baseline, ^ represents a moderate effect size (d = 0.50-0.79), # represents a large effect size (d >0.80). B: Baseline; D2: day 2, and so forth.
254x190mm (300 x 300 DPI)

**Table 1: Sleep responses prior to, during and following a return long-haul flight from United Kindgom to South America. Means ± SD.**

| n = 15 | Baseline (survey) | Out flight | Night 1 | Night 2 | Night 3 | Night 4 | Night 5 (Match 1) | Night 6 | Night 7 | Night 8 | Night 9 | Night 10 (Match 2) | Return flight |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Sleep duration** (min) | 512 ± 71 | 330 ± 105* | 537 ± 56 | 487 ± 56 | 464 ± 67 | 486 ± 68 | 272 ± 101** | 348 ± 155 | 506 ± 80 | 486 ± 69 | 481 ± 109 | 223 ± 155** | 343 ±100*** |
| **Mean bed time** | 23:15 | 22:17 | 22:33 | 23:02 | 23:30 | 23:46 | 04:58$^{\wedge e}$ | 02:06 | 00:37 | 01:06 | 00:25 | 05:20$^{\wedge e}$ | 19:54$^{c,d}$ |
| **Mean wake time** | 09:22 | 05:45 | 08:30 | 07:58 | 08:32 | 08:41 | 10:28 | 10:56 | 09:49 | 09:47 | 09:34 | 10:37 | 02:55*** |
| **Sleep onset latency** (min) | 20.0 ± 16.7 | 25.9 ± 31.5 | 23.7 ± 26.6 | 19.1 ± 18.5 | 17.7 ±9.9 | 20.6 ± 13.8 | 22.6 ± 29.8 | 20.9 ± 17.9 | 24.1 ± 21.6 | 33.0 ± 31.5 | 22.5 ± 11.1 | 15.8 ± 13.5 | 28.6 ± 26.3 |
| **Sleep efficiency** (%) | 91.6 ± 3.7 | 68.4 ± 15.3$^{*a}$ | 85.4 ± 7.2 | 84.5 ±9.6 | 81.0 ± 9.6 | 81.2 ± 7.9 | 78.1 ± 9.7 | 77.0 ± 11.2 | 87.7 ± 5.1 | 85.1 ± 6.1 | 86.8 ± 6.2 | 71.4 ± 30.0 | 75.2 ± 12.8$^{c}$ |
| **Wake episodes** (n) | 1.0 ± 0.9 | 5.3 ± 2.1 | 4.6 ± 2.7 | 5.2 ± 3.2 | 6.7 ± 2.5 | 6.0 ± 3.3 | 2.4 ± 2.3$^{b}$ | 3.9 ± 2.8 | 4.1 ± 2.5 | 4.5 ± 2.4 | 4.1 ± 2.3 | 2.1 ± 2.1$^{c}$ | 4.1 ± 3.4 |
| **Wake episode duration** (min) | 4.4 ± 4.2 | 17.3 ± 8.3 | 10.9 ±4.6 | 9.34 ± 4.2 | 10.23 ± 6.1 | 11.4 ±4.8 | 12.4 ± 7.7 | 9.9 ± 5.1 | 8.9 ± 6.9 | 6.9 ± 2.4 | 11.9 ±10.6 | 6.0 ± 5.0 | 15.8 ± 16.0 |

Significantly different to: * night 1 only ($P<0.05$); ** to non-match nights 2-4 and 7-9 ($P<0.05$); *** to non-match nights7-9 ($P<0.05$) only; $^{\wedge}$to non-match nights 2-4 ($P<0.05$) only; $^{a}$to non-match night 2 only ($P<0.05$); $^{b}$to non-match night 3 only ($P<0.05$); $^{c}$ to non-match night 7 only ($P<0.05$); $^{d}$ to non-match night 8 only ($P<0.05$); $^{e}$ to non-match night 9 only ($P<0.05$); NB: Baseline sleep responses were collected via a subjective online survey whilst all other responses were collected via objective actimetry. Average bed and wake times from outbound through to return flight are in accordance with the arrival time zone in South America. Mean bedtime and wake time from baseline values are in accordance with local time zones where the players resided prior to departure.

**Table 2: Objective sleep patterns in playing (n=7) vs. non-playing (n=8) footballers following the matches. Means ± SD, effect sizes in parentheses (*d*) for raw values and bold for delta change.**

| **Sleep parameters** | **Group** | **3N Pre-Match 1** | **Match 1** | **Δ change** | ***d* for Δ change** | **3N Pre-Match 2** | **Match 2** | **Δ change** | ***d* for Δ change** |
|---|---|---|---|---|---|---|---|---|---|
| **Sleep duration** (min) | P | 496±51 | 265±107 (*d* =4.02) | -231.1±129.4 | ***d* = 0.25** | 501±49 | 264±175 (*d* =4.12) | -237.3±187.9 | ***d* = -0.27** |
| | NP | 461±47 | 271±97 (*d* =3.72) | -190.4±82.6 | | 481±41 | 217±142 (*d* =5.02) | -264.6±137.2 | |
| **Sleep onset latency** (min) | P | 21.6±9.7 | 18.3±23.7 (*d* =-0.31) | -3.3±26.8 | ***d* = -0.35** | 25.6±11.1 | 17.2±14.4 (*d* =-0.76) | -8.3±19.0 | ***d* = 0.06** |
| | NP | 18.7±8.0 | 26.8±32.7(*d* =0.91) | 7.2±34.7 | | 24.3±10.3 | 17.2±14.1 (*d* =-0.80) | -7.1±17.8 | |
| **Sleep efficiency** (%) | P | 82.9±8.2 | 79.9±12. (*d* =0.33) | -3.1±8.7 | ***d* = -0.28** | 86.8±4.5 | 82.9±9.7 (*d* =0.42) | -3.9±8.7 | ***d* = -2.11** |
| | NP | 81.7±7.3 | 72.4±12.0 (*d* =1.09) | -9.4±9.7 | | 85.0±5.5 | 64.3±36.8(*d* =2.52) | -20.7±37.6 | |
| **Wake episodes** (n) | P | 6.0±2.4 | 1.3±1.1 (*d* =-1.73) | -4.7±2.3 | ***d* = -0.29** | 4.1±1.0 | 1.7±1.6 (*d* =-0.87) | -2.4±2.1 | ***d* = -0.36** |
| | NP | 6.3±2.7 | 3.4±2.7 (*d* =-0.97) | -2.9±4.0 | | 4.7±2.3 | 2.3±2.3 (*d* =-0.80) | -2.4±3.7 | |
| **WED** (min) | P | 10.1±4.1 | 9.8±9.2 (*d* =-0.08) | -0.4±10.5 | ***d* = -0.16** | 9.8±5.2 | 6.6±5.8 (*d* =-0.70) | -3.2±6.3 | ***d* = 0.01** |
| | NP | 10.1±3.8 | 13.2±7.5 (*d* =0.73) | 3.1±7.2 | | 8.8±3.5 | 5.8±3.9 (*d* =-0.70) | -2.9±4.0 | |

Abbreviations: P, Players; NP, Non-players; Δ, delta change; 3N, 3 night mean prior to match; WED, wake episode duration.

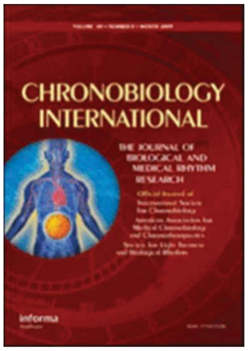
*d* <0.20 trivial, *d*=0.2 (small), *d*=0.5 (medium), *d*=0.8 (large).

NB: Within-group effect sizes (d) compare the mean of the previous three nights to match nights. Additionally, effect sizes were also used to compare between-groups delta changes of players vs. non players.

**Table 3: Training Load from Global Positioning Satellite (GPS), Heart Rate (HR) and Rating of Perceived Exertion (RPE) data of professional footballers during the trip. Means ± SD.**

| Physical performance data | **Day 1** | **Day 2** | **Day 3** | **Day 4** | **Day 8** | **Overall mean** |
|---|---|---|---|---|---|---|
| Total distance ran (m) | 4354 ±498 | 6438 ±353 | 4472 ±195 | 4147 ±406 | 6233 ±354 | 5129 ±1110 |
| Mean speed (m/min) | 68±4 | 73±4 | 71±3 | 67±6 | 68±4 | 69±2 |
| High intensity running distance (m) | 72.0±44.1 | 92.9±57.6 | 45.9±29.3 | 162.7±81.1 | 136.0±57.3 | 101.9±47.4 |
| Mean HR (bpm) | 147±12 | 149±14 | 148±14 | 135±14 | 139±11 | 144±6 |
| Time above 85% of $HR_{max}$(min) | 13.4±11.7 | 22.2±20.1 | 24.9±11.2 | 12.0±8.5 | 21.3±13.1 | 18.8±5.7 |
| Training load (AU) | 289±82 | 487±72 | 363±69 | 318±84 | 503±74 | 392±76 |

Abbreviations: AU: arbitrary units (s-RPE: session rating of perceived exertion x duration in min)



# The effect of an acute sleep hygiene strategy following a late-night soccer match on recovery of players

| | |
|---|---|
| Journal: | *Chronobiology International* |
| Manuscript ID | LCBI-2015-0134.R2 |
| Manuscript Type: | Original Reports |
| Date Submitted by the Author: | n/a |
| Complete List of Authors: | Fullagar, Hugh; Saarland University, Institute of Sports and Preventive Medicine<br>Skorski, Sabrina; Saarland University, Institute of Sports and Preventive Medicine<br>Duffield, Rob; University of Technology Sydney, Sport & Exercise Discipline Group, UTS: Health<br>Meyer, Tim; Saarland University, Institute of Sports and Preventive Medicine |
| Keywords: | sleep quality, regeneration, exercise, team sports , football |
| | |

# The effect of an acute sleep hygiene strategy following a late-night soccer match on recovery of players

HUGH H.K. FULLAGAR[1,2], SABRINA SKORSKI[1,3], ROB DUFFIELD[2] and TIM MEYER[1],

[1]*Institute of Sport and Preventive Medicine, Saarland University, Germany*

[2]*Sport & Exercise Discipline Group, UTS: Health, University of Technology Sydney, Australia*

[3]*Research Institute for Sport and Exercise (UC-RISE), Faculty of Health, University of Canberra.*

Corresponding author:
Hugh Fullagar
Institute of Sport and Preventive Medicine, Saarland University, GEB. B82
66123 Saarbrucken, Germany
Email: hugh.fullagar@uni-saarland.de
Phone: 0681-302 70400 Fax: 0681-302 4296

**Running title: Sleep hygiene, night soccer matches & recovery**

**KEYWORDS:** Sleep quality, regeneration, exercise, team sports and football.

*Conflicts of interest and sources of funding: No funding was provided which contributed to the development of this manuscript. The authors declare that there are no conflicts of interest. Ethical approval was endorsed by the local ethics committee.*

## Abstract

Elite soccer players are at risk of reduced recovery following periods of sleep disruption, particularly following late-night matches. It remains unknown whether improving sleep quality or quantity in such scenarios can improve post-match recovery. Therefore, the aim of this study was to investigate the effect of an acute sleep hygiene strategy (SHS) on physical and perceptual recovery of players following a late-night soccer match. In a randomised cross-over design, two highly-trained amateur teams (20 players) played two late-night (20:45) friendly matches against each other seven days apart. Players completed a SHS after the match or proceeded with their normal post-game routine (NSHS). Over the ensuing 48 h, objective sleep parameters (sleep duration, onset latency, efficiency, wake episodes), countermovement jump (CMJ; height, force production), YoYo Intermittent Recovery test (YYIR2; distance, maximum heart rate, lactate), venous blood (creatine kinase, urea and *c*-reactive protein) and perceived recovery and stress markers were collected. Sleep duration was significantly greater in SHS compared to NSHS on match night (P=0.002, *d*=1.50), with NSHS significantly less than baseline (P<0.001, *d*=1.95). Significant greater wake episodes occurred on match night for SHS (P=0.04, *d*=1.01), without significant differences between- or within-conditions for sleep onset latency (P=0.12), efficiency (P=0.39) or wake episode duration (P=0.07). No significant differences were observed between conditions for any physical performance or venous blood marker (all P>0.05); although maximum heart rate during the YYIR2 was significantly higher in NSHS than SHS at 36 h post-match (P=0.01; *d*=0.81). There were no significant differences between conditions for perceptual 'overall recovery' (P=0.47) or 'overall stress' (P=0.17). Overall, an acute SHS improved sleep quantity following a late-night soccer match; albeit without any improvement in physical performance, perceptual recovery or blood-borne markers of muscle damage and inflammation.

## Introduction

In professional soccer it is important to achieve an adequate balance between the stress of training/games and recovery to ensure optimal physical preparation, particularly during the competitive season (Nédélec, McCall et al., 2013; Meyer, Wegmann et al., 2014). Though matches are expected to cause increased strain on players, factors that prolong or result in inadequate post-match recovery can potentially induce greater symptoms of fatigue and reduced performance (Nédélec, McCall et al., 2013). Sleep is often postulated as an essential component of recovery (Halson, 2008; Samuels, 2008), and given the regularity of late-night matches, is particularly applicable to elite soccer players (Nédélec, McCall et al., 2013; Meyer, Wegmann et al., 2014; Fullagar, 2015). However, despite the widely held assumption that sleep aids the recovery process, to date there is limited evidence to support the notion that the improvement of sleep indices (e.g. sleep duration and/or quality) can aid the recovery of physical or perceptual function in athletes, let alone soccer players. This is most likely due to the complexity of sleep function, contrasting sporting environments and the variability in the individual requirements for sleep (Fullagar, Skorski et al., 2015). Accordingly, the interaction between the improvement of sleep quality/quantity and recovery in soccer, especially following late-night matches, is an issue that remains to be fully addressed.

Although limited evidence supports elite soccer players as healthy sleepers in ‘normal’ situations i.e. rest days and training (Meyer, Wegmann et al., 2014; Fullagar, 2015), there are instances whereby sleep may be disrupted. For example, regular early training session start times (06:00) can lead to desynchronization during off days in athletes i.e. in swimmers (Sargent, Halson et al., 2014), although such evidence in association in soccer players is lacking. It is generally accepted that elite players are sensitive to disruptions to their natural sleep environment (Drust, Waterhouse et al., 2005; Nédélec, McCall et al., 2013; Fullagar, Duffield et al., 2015). For example, late-night matches are often scheduled during periods of congested fixtures (i.e. multiple games in seven days, such as UEFA Champions League and national team matches). These later kick-off times (20:45) invariably result in late-night finishes to matches and in turn, players reporting a loss of sleep compared to normal (Meyer, Wegmann et al., 2014). This reduction in sleep quantity and quality, particularly when training or travel demands are fixed the next day, is proposed to result in inadequate physical and perceptual recovery (Nédélec, McCall et al., 2013; Skein, Duffield et al., 2013).

The effects of sleep disturbance encountered after night soccer matches may be long-lasting and thus altering the sleep in the ensuing days after the match. Despite the lack of explicit evidence in footballers, it is known that reductions in non-rapid eye movement (NREM) sleep can disrupt energy conservation and nervous system recuperation (Stickgold, 2005). Furthermore, reductions in rapid eye movement (REM) sleep can affect periodic brain activation, localized recuperative processes and emotional regulation (Stickgold, 2005; Vyazovskiy & Delogu, 2014). However, it remains unknown whether an improvement in sleep duration or quality can improve the rate of perceived or physical recovery following compromised sleep (i.e. late-night matches). Even then, recovery may incorporate numerous dimensions, including: physical performance (e.g. countermovement jump), physiological (e.g. blood-borne damage markers) and perceptual (wellness/mood) (Rattray et al., 2015). Thus, with players at risk of hindered recovery following sleep disrupted periods, further research is required to examine the relationship between sleep as a post-match intervention and the recovery of physical performance, physiological state and perceptual wellness (Rattray, Argus et al., 2015).

To help counter situations of compromised sleep, the use of sleep hygiene strategies (SHS) has recently been proposed for athletes (Halson, 2014; Fullagar, Duffield et al., 2015; Fullagar, Skorski et al., 2015). SHS were first introduced by medical physicians in an attempt to provide recommendations for patients with sleep disorders i.e. insomnia; (Hauri, 1977). In general, these strategies are aimed at avoiding behaviour that might compromise normal sleep or at supporting/initiating the behaviour that promotes good sleep (Nédélec, McCall et al., 2013). For example, various techniques including turning off all technological devices at least 30 min before bedtime, abstinence from watching TV/using laptops while in bed, creating cool, dark quiet rooms and wearing eye masks have been proposed (Malone, 2011). SHS have been shown to improve sleep quality and onset latency in university students and reduced sleep irregularity in adolescents (Stepanski & Wyatt, 2003). Further, SHS often represent ongoing habits that promote improved sleep behaviours. However, from a football perspective, little is known about either the chronic or acute effects of SHS and post-exercise recovery as related to performance.

Given the absence of evidence, it could be hypothesised that increasing sleep duration/quality may alleviate the decrements in physiological and cognitive performance caused by sleep loss. For instance, sleep extension has been shown to improve vigour, mood and athletic performance; including sprint speed, basketball shooting accuracy and reaction time (Mah, Mah et al., 2011). Further preliminary evidence indicates adhering to some of the previous SHS recommendations improves sleep quantity, resulting in a reduction in perceived soreness and fatigue in tennis players (Duffield, Murphy et al., 2014). However, given the regularity of late-night matches and the proposed benefits of sleep, the effects of SHS on performance recovery following late-night soccer matches remain unknown. Accordingly, the aim of this study was to investigate the effect of an acute sleep hygiene strategy on physical, physiological and psychological recovery of soccer players following a late-night match.

## Materials and methods

### Subjects:

Twenty highly-trained amateur soccer players volunteered to participate in the study, providing written and verbal informed consent following full disclosure of all procedures. Additionally, participants underwent a medical check-up consisting of medical history, physical examination, 12-lead resting electrocardiogram and blood pressure measurement. Participants were also screened with a medical questionnaire (local institute Erholungs-Beanspruchungs-Fragebogen), and if necessary, excluded if they had past sleep related disorders, or were currently on medications possibly affecting sleep. All players were deemed eligible following this process and thus partook in the investigation. This study abided with the Declaration of Helsinki and was approved by the local Human Research Ethics Committee.

### Experimental design

In a randomised cross-over design, two semi-professional teams (5th and 6th division of the German Football Federation) played two (friendly) matches against each other during the mid-season preparation period of the German 2014/15 soccer year. Matches were separated by seven days and played on the same ground at the same late-night kick-off time of 20:45 (to simulate kick-off time in the UEFA Champions League or national team home games). Both matches were officiated by a German Football Federation accredited referee and followed official FIFA™ rules and regulations. The same players played during both games, with all players playing at least 70 min in each match (excluding goalkeepers). Following each match, players completed two days of structured testing and training. Specifically, testing times and procedures were standardised by the researchers each morning, while each training session was set at the discretion of the coaches but replicated for volume and intensity on both weeks. Consuming alcohol/caffeine was prevented over the duration of the testing periods. To retain inclusion for data analysis, all data points were required from for all measurement variables (unless otherwise stated).

In a randomised order (both within- and between-teams), players then either completed a SHS after the match or proceeded with their normal post-game routine without any assistance or recommendations for sleep (NSHS). The SHS group proceeded to their bedrooms at 23:45 in preparation for sleep. The SHS included ensuring players were in bed rooms as soon as possible with lights dimmed, and provided (optionally) with ear plugs and eye-masks in cool temperature rooms (~17°C). Further, no technological or light stimulation was allowed ~15-30 min prior to bedtime. To ensure this mobile phones and TV remotes were collected for the night. Finally, lights were turned off at 00:00 which was deemed the earliest manageable bedtime given the end of the match. In contrast, players in the control condition (NSHS) were permitted to undertake normal activities (but onsite under the supervision of the research team within the common room at the training centre) following each match. These players remained awake until they were allowed to go to bed at 02:00 am. The time was chosen both because of previous anecdotal reports and researcher experience of players' usual bedtime at this time following night matches (Meyer, Wegmann et al., 2014; Fullagar, 2015). The NSHS group was allowed to use their mobile phones/TV as they saw fit. All protocols were adhered to and the research team monitored all rooms until bedtime (including personally turning off the lights at bedtime). All players from both conditions were woken by the research team at 07:30 the next morning in preparation for breakfast and measurements.

### Experimental procedures

All players were familiarised with procedures and measures in the two weeks prior to commencement. Players resided at the onsite Olympic Training Centre for the night of and the night following each match. During both the control and intervention phase, players slept in the same bedding conditions in single beds, double rooms and paired with the same player over both conditions, whilst they provided their own pillows from home for comfort. The match itself was played at a local stadium of a semi-professional team on an artificial turf surface, 5 min drive from the training centre. Environmental conditions were similar during both matches (range 2-6°C, floodlights emitting light in accordance with official German FA sub-elite division requirements i.e. at least 200 lux) and 74-82% relative humidity)). Players finished playing both games at ~ 22:30, commenced a standardised light active recovery and stretching session while listening to their respective coaches (22:30-22:40), and showered at approximately 22:40-23:00, before returning directly to the training centre and commencing dinner at ~ 23:10. On the day of and for the two days following the match, players were provided meals. Meals were offered in a buffet form and although not identical, consisted of similar nutritional content of a serving of meat (chicken), vegetables (potatoes and mixed green salad) and pasta/rice. Moreover, players took photographs on mobile phones of their meals each week to attempt to match portioning over both conditions. Players' personal liquid intake immediately post-match was not controlled; although the consumption of protein or recovery shakes, caffeine or alcohol was prevented and intake was similarly asked to be replicated over the span of the study.

### Measurements:

#### *Sleep measures*

Each of the three days prior to each game (mean baseline), the night of (match night) and the night following (match night + 1), objective (SenseWear actigraphy; BodyMedia, Pittsburgh, Pennsylvania) and subjective sleep data (subjective sleep diary) were collected. All data points were required for data to be retained (six players excluded for either lack of baseline measure or equipment failure; 14 players included for final analyses). Objective data was downloaded via relevant software and generated using manufacturers' algorithms (SenseWear 7.0 Professional, BodyMedia, Pittsburgh, Pennsylvania). Objective measures included sleep duration, time in bed, sleep onset latency, sleep efficiency, wake episodes (including wake episode duration). It is recognised polysomnography (PSG) is the most accurate method to quantify sleep, however given the field-based nature of this study, actigraphy was used in this investigation. Subjective measures included perceived sleep restfulness (very restful, pretty restful, average, hardly restful and not at all restful) and general recovery state upon waking (Likert scale 0 (not at all recovered) to 6 (absolutely recovered)) (Kölling, Hitzschke et al., 2014). Players refrained from napping on the day following the match but were allowed to engage in napping activity on the second day following the match. In addition, sleep chronotype was evaluated using the Morningness-Eveningness Questionnaire (MEQ) (Horne & Ostberg, 1976) to determine if sleep chronotype influenced sleep variables. This questionnaire uses 19 questions regarding to sleep behaviour, with a cumulative score used to categorise individuals as 'morning' types (scores 59-86), 'evening' types (14-41) and neither types ('intermediate'; 42-58) (Horne & Ostberg, 1976; Lastella, Roach et al., 2011).

### *Match and training measures*

External (global positioning systems [GPS]) and internal (heart rate [HR]) load markers, along with rating of perceived exertion (RPE; CR-10 scale) (Borg, 1998) to calculate training load (session-RPE x min) (Foster, Florhaug et al., 2001), were collected following each match. In addition, load responses to one standardised training session the day following the match (16:00: ~19 h post-match; Match+ 1 PM) and two sessions two days after the match (10:30; ~37.5 h post-match; Match+2 AM and 16:00: ~ 43 h post-match; Match+2 PM) were collected. Whilst each training session was composed separately by the respective team coaches, they were replicated for drill type and duration and basic skill composition across both weeks. Players also completed a short 'recovery run' on the morning after the match (~ 13 h post-match); however load responses to this run were not collected. Rather than scheduled for research *per se*, these sessions were requested by the teams to form part of their mid-season preparation phase. GPS variables included total distance (m), mean speed (m/min), peak speed (m/s), high intensity running distance (distance (m) covered above each player's previously determined speed at individual anaerobic threshold (Stegmann, Kindermann et al., 1981)), mean HR (bpm) and number of very high intensity bouts (defined as the number of bouts performed above 19.8 km/h for more than 1 s (Carling, Bloomfield et al., 2008)). During both training and match play players wore localised 2-Hz GPS systems (Adidas miCoach elite©, Adidas©, Nurumberg, Germany) on the back between scapulae within a customised undergarment (Adidas Climalite©). Adidas miCoach accelerometers have been previously validated for distance covered, although given the recent developments in the miCoach product further research into the validation of the GPS system is required (Porta, Acosta et al., 2012). In addition, HR monitors were positioned within the customised undergarment allowing for the collection of average and peak HR data. Data was retained from players who completed at least five of the six available sessions (13 players retained for analyses). All data was extracted using the miCoach© software, processed in MatLab™ (where raw data was derived from the miCoach© system and analysed for each individual player by a trained analyst) and stored in Microsoft Excel 2007™.

### ***Recovery measures***

*Recovery of exercise performance*

Counter movement jump's (CMJ) were performed three days prior to the first match week (baseline) and 12 h and 36 h post-match to determine jump height (cm) and force production (N). CMJ were performed using a calibrated force platform (Quattro Jump, Type 9290AD, Kistler Instrument AG, Winterthur, Switzerland; sampling rate 500 Hz) and analysed using professional motion analysis software (Contemplas Bewegungs analyse, Contemplas Gmbh, Kempten, Germany). Jump height was determined as the height of centre of mass displacement, calculated from the recorded force and body mass. The CMJ began from an upright position, making a downward movement to a knee angle of approximately 90° and simultaneously beginning to push-off, whilst hands were placed upon hips. Thirty s of rest was allowed between 5 trials of each test, the maximum being used in subsequent analyses. A standardised 10-min warm-up preceded the jumps.

The YoYo Intermittent recovery test level two (YYIR2; (Bangsbo, Iaia et al., 2008)) was performed indoors on a hard wooden floor (basketball court). The test was performed immediately after the CMJ and consisted of repeated 2x20-m runs at a progressively increased speed controlled by audio beeps from a laptop and speakers (Bangsbo, Iaia et al., 2008). When a player had failed twice to reach the finish line in time, the distance covered was recorded as the test result. In addition, maximum HR (Polar RS 400, Polar Electro, Kempele, Finnland) and RPE (Borg, 1998) were also recorded. Capillary whole blood samples from the ear were also collected prior to the test, immediately after finishing the test and 1, 3 and 5 min post to determine maximum lactate concentration to ensure comparable exhaustion in both conditions (18 players included for final analyses).

*Physiological recovery responses to training*

In addition to baseline measures (3 d prior to first match week, NB: performed only once), prior to both afternoon training sessions (18 h and 42 h post-match, respectively) all subjects completed a submaximal interval-based running test (Heart Rate Interval Monitoring System (HIMS) (Lamberts & Lambert, 2009). These tests were performed under similar environmental conditions on the artificial turf where training and match play took place. The full protocol for the HIMS is available elsewhere (Lamberts & Lambert, 2009); however, it comprises 4x2-min stages (S1, S2, S3 and S4) repeated 2x20-m runs with increasing speeds from 8.4, 9.6, 10.8, and 12.0 km/h, respectively as controlled by audio signals. After each 2-min stage, players rest and stand upright for 1 min. After the final stage (S4) there is a 2-min recovery period. Mean HR (derived from the HR monitors within the Adidas© vests and miCoach© system) for each exercise stage and each recovery period was calculated from the last final 15 s of each period to produce a final value of absolute decrease in HR during recovery (HRR) and recovery HR expressed as a percentage of the mean HR during the last minute of the stage (HRr%) for each stage (Lamberts & Lambert, 2009).

*Blood-borne markers of muscle damage and inflammation*

Venous blood samples were obtained at 2 h prior to each match (venous blood baseline) and 10 h, 20 h, 34 h and 44 h post-match from the antecubital vein by standard protocol, following 5 min of seated rest. Serum tubes were  centrifuged at 4000 revolutions per minute for five min, aliquoted, then measured for c-reactive protein (CRP), creatine kinase (CK) and urea (U) using a Unicel DxC600 synchronised clinical system (Beckmann Coulter GmbH, Krefeld, Germany). Remaining serum samples were then stored frozen at -20°C until analysis. Blood count was determined automatically by an ACT 5 Diff AL (Beckmann Coulter GmbH, Krefeld, Germany). Given the high physical demands and noted skeletal muscle damage following matches, these parameters were chosen as representative markers of recovery due to their known response to exercise-induced stress and their prevalent use in the fatigue and recovery literature (Nédélec, McCall et al., 2013). For all blood recovery parameters, all data points were required for data to be retained (20 players included for final analyses).

### *Psychological recovery*

Players completed a perceptual fatigue and recovery questionnaire (Short version of the Acute Recovery and Stress Questionnaire; SRSS (Kölling, Hitzschke et al., 2014)) at baseline (2 h prior to each match), the morning after the match (12 h post) and after each training session (24 h post, 36 h post and 48 h post). The SRSS consists of eight adjectives describing physical, emotional, mental, and overall aspects of recovery and stress (recovery: 'Physical Performance Capability', 'Mental Performance Capability', 'Emotional Balance', 'Overall Recovery' and stress: 'Muscular Stress', 'Lack of Activation, 'Emotional Imbalance', and 'Overall Stress' (Kölling, Hitzschke et al., 2014). These items were assessed with a seven-point Likert-type scale ranging from 0 (not at all) to 6 (absolutely) and are designed to be analysed and interpreted separately. Items 'overall recovery' and 'overall stress' are reported herein. In addition, morning subjective measures (diary completed upon waking) including perceived sleep restfulness and general recovery state, as mentioned previously were collected (14 players included for final analyses).

## Statistical Analysis

Data are presented as means±SD. A two-way repeated measures ANOVA (time x condition) was used to compare differences between all time-points for both conditions (SHS and NSHS) for sleep parameters and all recovery markers (physical, physiological responses to training, blood-borne and psychological). A two-way repeated measures ANOVA was also used to compare differences between time points for both conditions (SHS and NSHS) for all physical and perceptual training variables. Where significant effects were observed, a Scheffé post-hoc test was performed. Independent *t*-tests were used to i) determine differences between matches for all physical and perceptual match variables and ii) determine differences between sleep chronotypes for all measures of sleep variables. Dependant t-tests were used to determine whether an order effect was observed from the first to the second weekend. $P<0.05$ for the α-error was accepted as significance for all statistical comparisons. All statistical procedures were performed using the statistical package Statistica© Version 7 (StatSoft Inc©, Tulsa, OK). Furthermore, standardised effect size (Cohen's d; ES) analyses were used to interpret the magnitude of the mean differences between conditions for all sleep and recovery parameters with $d<0.20$ (trivial), $d=0.20$-$0.49$ (small), $d=0.50$-$0.79$ (medium), $d\geq0.80$ (large) (Cohen, 1988). Due to the multitude of analyses only large ES are reported herein.

## **Results**

### ***Sleep measures***

All sleep variables for both conditions are presented in Table 1. Individual cases for sleep duration are additionally illustrated in Figure 1. No significant differences were evident between any baseline measures prior to both conditions (all $P>0.05$). Sleep duration was significantly reduced on match night from baseline in the NSHS condition ($P<0.001$, $d=1.95$) but not in the SHS condition ($d=0.73$). On match night, sleep duration was significantly greater in SHS compared to NSHS ($P=0.002$, $d=1.50$), whilst there were also significant within-condition differences apparent for NSHS between match night and match night +1 ($P<0.001$, $d=2.22$). Large ES were also present in the SHS condition where sleep duration improved on match night + 1 compared to match night ($d=0.82$). A significant difference was evident between conditions for wake episodes on match night, with more wake episodes present for SHS (P=0.04, *d*=1.01). There were no significant differences between- or within-conditions for sleep onset latency (P=0.12), sleep efficiency (P=0.39) or wake episode duration (P=0.07); although large ES were evident between conditions for wake episode duration (longer in the SHS condition; *d*=0.90). Mean MEQ score was 49 ± 6 (range: 36-58). Four participants were classified as 'evening types' (14-41) and the remaining 16 as 'neither' types (42-58); thus the analysis of the difference between 'evening' and 'morning' chronotypes was abandoned. There was a significant order effect present on the second weekend compared to the first for both sleep onset latency and sleep efficiency (improvement; P<0.05); however no other order effects were present for any other match, training or recovery measure.

### *Match and training measures*

There were no significant differences between matches for either condition for any match-based physical or perceptual variable, or any physical performance or perceptual response data from training sessions performed following the match between either condition (all P>0.05; Table 2).

### *Recovery measures*

#### *Recovery of exercise performance*

Mean and individual recovery responses of the primary exercise performance parameters for both conditions at 12 h post following the late-night match are presented in Figure 2. There were no significant differences between conditions for CMJ height (P=0.53) or force production (P=0.49) at either 12 h post or 36 h post; although, CMJ height was significantly less at 12 h post in the NSHS condition compared to baseline (P=0.04; *d*=0.81). Within conditions, CMJ height was significantly greater 12 h post than 36 h post for SHS (P=0.03; *d*=0.22). There were no significant differences between conditions for YYIR2 distance (P=0.50), RPE (P=0.70) or maximal lactate (P=0.75) for 12 h post or 36 h post; although, there were significant reductions in YYIR2 distance in the NSHS condition (P=0.04; *d*=0.51) at 12 h post and in the SHS condition 12 h post (P=0.01; *d*=0.71) and 36 h post (P=0.01; *d*=0.69) compared to baseline. No significant between-condition differences were evident for max HR during the YYIR2 at 12 h post (P=0.71); however max HR was significantly higher in NSHS than SHS at 36 h post (P=0.01; *d*=0.69).

### *Physiological recovery responses to training (HIMS)*

Physiological HR responses to the HIMS are presented in Table 3. There were no significant differences in HRR recovery or HRr% between conditions at any stage for either training session performed at 18 h and 42 h post-match respectively (all P>0.05).

### *Blood-based variables*

No significant differences were evident between conditions for any blood parameter at any time point (P>0.05; Table 3). The only large ES present between conditions was for CK at baseline (*d*=1.29).

### *Psychological recovery*

Mean 'overall recovery' and 'overall stress' SRSS scores are presented in Figure 3. Following the late-night match 'overall recovery' showed no significant differences between SHS and NSHS (P=0.53), nor were there any significant differences between conditions for 'overall stress' (P=0.94). There were no significant differences between conditions (all P>0.05) for recovery state upon waking in the morning following the match (SHS: 2.7 ± 0.9;

NSHS: 2.8 ± 0.7) or for the percentage of answers for restfulness (sleep quality) for SHS (very restful: 0%, pretty restful: 24%, average 57%, hardly restful: 14% and not all restful: 5%) compared to NSHS (very restful: 0%, pretty restful: 19%, average 52%, hardly restful: 17% and not all restful: 12%).

## Discussion

The present study investigated the effect of an acute SHS on the recovery of players following a late-night soccer match. The SHS increased sleep duration compared to NSHS, despite significantly more wake episodes and large ES to suggest longer wake episode durations. Regardless, players subjectively reported no difference in sleep quality between conditions. Overall, no significant improvements in perceived stress and recovery, the recovery of exercise performance, or blood-borne markers of damage and inflammation were present. SHS appeared to have no effect on overall training loads, with players covering similar distances and intensities during the standardised training sessions following both conditions on the two days following the match. The present findings suggest soccer players may consider acute SHS strategies where possible following a late-night match to ensure sufficient volume of sleep; however there appears to be no additional benefit for the recovery of performance.

The effect of SHS on sleep quality and quantity has previously been studied in certain populations, with SHS shown to improve sleep quality and onset latency in university students (Stepanski & Wyatt, 2003). Comparatively, the effect of SHS in normal sleepers is equivocal (Stepanski & Wyatt, 2003). Interestingly, there is limited data from athletes, with little known about the interaction between SHS and sleep, let alone ensuing improved recovery (Halson, 2014). Recently, Duffield and Murphy et al. (2014) investigated the effect of a SHS (21:00 bed time; low-light (8 ± 5 lux), cool (19 ± 2°C) environment, no technology 30 min prior to bedtime)) on sleep duration/quality and recovery of elite tennis players following simulated match play. SHS was shown to improve sleep quantity (increased time in bed and min asleep; (Duffield, Murphy et al., 2014)), which is comparable to the present study, with SHS significantly improving sleep duration. Such findings are likely given the enforced earlier bedtime as part of the SHS and were a primary aim of the SHS strategy. Consequently, players were in bed as soon as possible to maximise exposure to sleeping environments and then assisted them within this environment. Although speculative, it is also possible the removal of technology prior to bedtime aided the subsequent improvement in sleep duration, especially given the enforced earlier bed time. For example, bright light emitted from portable technological devices may suppress melatonin and disrupt ensuing subsequent sleeping quantity and quality although this is debated (Lewczuk, Redlarski et al., 2014) – and is currently unsubstantiated here. Regardless of the mechanisms responsible, given elite soccer players report large reductions in sleep quantity following night matches (Meyer et al., 2014), this improvement in sleep duration in our study is ~~a~~ both a novel and practical outcome for soccer players.

Despite the increased sleep duration with SHS, significantly greater wake episodes and a trend towards increased wake episode duration (38.9 ± 27.5 v 20.0 ± 18.1 for SHS and NSHS) and sleep onset latency (21.1 ± 16.9 min v 8.8 ± 7.1 min for SHS and NSHS) existed. The inverse responses of these sleep variables is likely due to the context of the players attempting sleep. Specifically, the homeostatic drive for sleep in the NSHS condition, given the prolonged duration of wakefulness, likely resulted in faster sleep onset times and reduced awakening (Vyazovskiy & Delogu, 2014). Conversely, in the SHS condition, players were likely to still be highly aroused when attempting to fall asleep following the night match;

hence resulting in longer sleep onset latency (Vyazovsky and Delogu, 2014). That is, enforcing an earlier bedtime may have led to a delayed sleep onset as this went against players' current preparedness for sleep, and consequentially a low sleep propensity. In one sense, this likely further justifies the need to use behavioural interventions to aid sleep at a time where players may still be reluctant to attempt sleep, thereby by providing conditions which are conducive to assisting the drive for sleep to override the drive for wakefulness. That said, it should be noted that other reasons for the inverse response of sleep variables could also include the unfamiliar sleeping environment of the training centre or the evening exposure to light (Malone, 2011), even though these factors were standardised. Thus, whilst sleep duration can be extended in a SHS following a late-night match it should be acknowledged that players may face difficulties initiating sleep when enforced with earlier bed times post-match.

The acute SHS showed limited to no effect on markers of physical recovery. These results concur with previous research which has investigated the effect of sleep on recovery-post exercise (Duffield, Murphy et al., 2014), and are not unexpected considering a meta-analysis revealed that psychological mood and fatigue states are more affected by sleep deprivation than both cognitive and motor performance (Pilcher & Huffcutt, 1996; Rattray, Argus et al., 2015). It should be noted that some physiological effects were present, with maximum HR significantly higher during the YYIR2 in the NSHS condition 36 h post-match. This could suggest that SHS may reduce the sympathetic capacity during intermittent-sprint performance; although a lack of an effect 12 h post likely limits such an assumption. Similarly, whilst the reduction in CMJ height from 12 h post to 36 h post in SHS could lead to the postulation of SHS enhancing training output (and thus leading to increased fatigue and a reduction in lower body power), the lack of any differences between conditions for any training variable likely negates such theories. Taken collectively, outside these findings the majority of effects on the recovery of exercise performance and physiological recovery were non-existent. Further explanation could include the restricted napping in the 24 h post-match could hinder improvements in the 24-48 h post-match recovery via prevention of the 'repayment' of any sleep debt due to the late-night finish. Indeed, the timing, duration and performance benefits of napping have been well documented (Waterhouse, Atkinson et al., 2007). However, it should be noted that naps were avoided in the day following the match in our study to ensure that any effects on recovery were a result of the SHS rather than naps. Besides, the lack of naps wouldn't explain the lack of an effect on performance in the morning following the match.

The SHS also showed no effect on blood-borne markers of recovery and inflammation. Although the physical demands of the match and subsequent training sessions led to an increase in inflammatory markers in this study (e.g. CK), the observed increase sleep duration was not sufficient to alter these responses. This is in line with our previous knowledge of sleep deprivation studies where nights of complete sleep loss (e.g. 0 h), rather than partial sleep deprivation (e.g. 3-5 h) and a night of normal sleep (~8 h), are more likely to affect measures of post-exercise recovery (Skein, Duffield et al., 2013). Therefore, it may be speculated that a larger sleep difference between conditions during the night (from both a duration and quality perspective) is required to affect the majority of physical and physiological measures of recovery.

Similar to the lack of an improvement in performance recovery there were no significant improvements in measures of psychological stress and recovery in the sleep hygiene condition. These findings differ with previous results from the aforementioned work by

Duffield et al. (2014) with large effect sizes evident for perceived soreness and feelings of fatigue the following morning after the sleep hygiene intervention in their study. Indeed, our results are surprising given almost all forms of extensive sleep deprivation result in increased negative psychological mood states (e.g. fatigue, loss of vigour, sleepiness, and confusion (Pilcher & Huffcutt, 1996)), It has been shown that sleep disturbances lead to feelings of waking unrefreshed and greater perceptual fatigue (Koutedakis, Budgett et al., 1990). It would appear a greater sleep differential between conditions is required to improve perceptual recovery and stress. It should be further noted that the effect of the SHS was also only acutely assessed in the present study (i.e. after one late-night soccer match). Elite soccer players who regularly play late-night matches may consequently enjoy greater benefit from the SHS if such strategies were applied regularly throughout the season, i.e. after each night soccer match.

Given this was a field-based study there are certain limitations that need to be acknowledged. Firstly, it is assumed late-night matches cause reductions in recovery, though the evidence to highlight this point seems lacking in the research literature. From an equipment perspective, the 'gold standard' of sleep quantity and quality monitoring is recognised as via PSG (Halson, 2008; Halson, 2014). Without the use of this technique in this investigation, we recognise the limitations of interpreting sleep data from actigraphy; however, for primarily ~~for~~ logistical reasons the use of PSG was not possible. Moreover, both actigraphy and subjective reports have been shown to not significantly differ to PSG data for total sleep time and sleep efficiency (Kushida, Chang et al., 2001). Secondly, the two matches played were 'friendly' fixtures. This limits the applicability of our results to actual matches, where numerous other extraneous disruptions to sleep can exist; including, post-match interviews, press conferences, anxiety and social/club demands (Fullagar, Duffield et al., 2015).

However, by excluding such factors and attempting to control others (i.e. timing of the match, time of sleep, time of wake, sleeping conditions) our results possess some internal validity for a field-based study. Floodlights in our study were likely less than the lux emitted at professional stadiums (i.e. up to 2000 lux), possibly limiting the inference to professional players. Although post-match nutrition was comprised of similar nutritional content, nutrition was not individually monitored (e.g. weighing of meals and detailed ingredients). Given some nutritional compounds are known to affect sleep responses (i.e. protein and sleep onset) and that sleep deprivation can induce a preference for high-caloric foods, it is noted as a limitation that we did not quantify the change in nutritional behaviour in the current study (Halson, 2014)). Nonetheless, every attempt in a field setting was made to match meals over both weeks, similar type of meals were served and photos of portions were recorded to attempt to match nutritional intake over both conditions. It could be argued that the primary component of our intervention was the pure extension of sleeping hours. However, from our perspective the enforced bedtime is *part* of an 'acute sleep hygiene strategy', but in recognizing this, we are attempting to make it easier with other factors i.e. no technology. Finally, due to the nature of the strategy imposed, blinding for the SHS intervention was not possible.

In summary, an acute SHS increased sleep duration compared to a NSHS following a late-night soccer match; although there were significantly more wake episodes in the SHS and players reported similar sleep qualities between conditions. The SHS did not improve measures of psychological stress and recovery, or the recovery of exercise performance. Furthermore, there were no significant differences between conditions for blood-borne markers of muscle damage and inflammation or physiological responses to training (HIMS). More research is required to assess whether a larger sleep differential (e.g. longer duration and higher quality sleep in the SHS condition) is required to affect the physical and physiological markers measured in this study. In addition, the effect of SHS on recovery in real-world elite environments requires further investigation, especially over the course of a season. For instance, there would be an increased likelihood for potential benefits if sleep behaviour was modified for more than an acute period. Taken collectively, the present findings suggest soccer players might consider SHS strategies where possible following a late-night match to promote restorative sleep; however there appears to be no additional benefit for the recovery of acute performance or perceptual recovery outcomes.

## Declaration of interest

There are no conflicts of interest. H.F is supported by a scholarship funded by the German Academic Exchange Centre (DAAD). Funding for the study was provided by a FIFA João Havelange Scholarship$^{©}$.

## Acknowledgments

The authors would also like to extend their gratitude to all players and staff from both participating teams, the Saarland Football Federation and local Olympic Training Centre, the University of Canberra (UC-RISE) for the lending of equipment and finally to all undergraduate and post-graduate students who assisted with data collection.

## References

Bangsbo J, Iaia M, Krustrup P. (2008). The Yo-Yo Intermittent Recovery Test A Useful Tool for Evaluation of Physical Performance in Intermittent Sports. *Sports Med*. 38:37-51.

Borg G. (1998). *Borg's perceived exertion and pain scales*. Champaign, IL, US: Human Kinetics.

Carling C, Bloomfield J, Nelsen L, Reilly T. (2008). The role of motion analysis in elite soccer: Contemporary performance measurement techniques and work rate data. *Sports Med*. 38:839-862.

Cohen J. (1988). *Statistical Power Analysis for the Behavioral Sciences*. Hillsdale: Lawrence Erlbaum.

Drust B, Waterhouse J, Atkinson G, Edwards B, Reilly T. (2005). Circadian rhythms in sports performance: an update. *Chronobiol Int*. 22:21-40.

Duffield R, Murphy A, Kellett A, Reid M. (2014). Recovery from repeated on-court tennis sessions; combining cold water immersion, compression and sleep recovery interventions. *Int J Sport Physiol Perform*. 9:273-282.

Foster C, Florhaug J, Franklin J, Gotschall L, Hrovatin L, Parker S, Doleshal P, Dodge C. (2001). A New Approach to Monitoring Exercise Training. *J Strength Cond Res*. 15:109-115.

Fullagar H. (2015). Late-Night Matches for Professional Soccer Players: Should we be Concerned about Sleep and Recovery? *Int J Sports Exerc Med*. 1:002e:1.

Fullagar H, Duffield R, Skorski S, Coutts A, Julian R, Meyer T. (2015). Sleep and Recovery in Team Sport: Current Sleep-related Issues Facing Professional Team-sport Athletes. *Int J Sport Physiol Perform*. [Epub ahead of print].

Fullagar H, Skorski S, Duffield R, Hammes D, Coutts AJ, Meyer T. (2015). Sleep and athletic performance: The effects of sleep loss on exercise performance, and physiological and cognitive responses to exercise. *Sports Med*.45(42):161-186.

Halson S. (2014). Sleep in elite athletes and nutritional interventions to enhance sleep. *Sports Med*. 44:S13-23.

Halson SL. (2008). Nutrition, sleep and recovery. *Eur J Sport Sci*. 8:119-126.

Hauri P. (1977). *Current concepts: the sleep disorders.* : Kalamazoo: The Upjohn Company.

Horne J, Ostberg O. (1976). A self-assessment questionnaire to determine morningness-eveningness in human circadian rhythms. *Int J Chronobiol*. 4:97-110.

Kölling S, Hitzschke B, Holst T, Ferrauti A, Meyer T, Pfeiffer M, Kellmann M. (2014). Validity of the Acute Recovery and Stress Scale – Training monitoring of the German junior national field hockey team. *Int J Sports Sci Coach*. (in press).

Koutedakis Y, Budgett R, Faulmann L. (1990). Rest in underperforming elite competitors. *Br J Sports Med*. 24:248-252.

Kushida C, Chang A, Gadkary C, Guilleminault C, Carrillo O, Dement W. (2001). Comparison of actigraphic, polysomnographic, and subjective assessment of sleep parameters in sleep-disordered patients. *Sleep Med*. 2:389-396.

Lamberts RP, Lambert MI. (2009). Day to day variation in heart rate at different levels of submaximal exertion: implications for monitoring training. *J Strength Cond Res*. 23:1005-1010.

Lastella M, Roach G, Teng E, Mattey E, Halson S, Sargent C. (2011). Sleeping to a schedule: Does chronotype play a part? In Kennedy G, Sargent C (Eds). *Little clock, big clock: Molecular to physiological clocks*. Melbourne: Australasian Chronobiology Society, pp. 01-04.

Lewczuk B, Redlarski G, Zak A, Ziółkowska N, Przybylska-Gornowicz B, Krawczuk M. (2014). Influence of electric, magnetic, and electromagnetic fields on the circadian system: current stage of knowledge. *Biomed Res Int*. 2014:169459.

Mah CD, Mah KE, Kezirian EJ, Dement WC. (2011). The effects of sleep extension on the athletic performance of collegiate basketball players. *Sleep*. 34:943–950.

Malone SK. (2011). Early to bed, early to rise?: An exploration of adolescent sleep hygiene practices. *J School Nursing*. 27:348-354.

Meyer T, Wegmann M, Poppendieck W, Fullagar HHK. (2014). Regenerative interventions in professional football. *Sport Orthop Traumatol*. 30:112-118.

Nédélec M, McCall A, Carling C, Legall F, Berthoin S, Dupont G. (2013). Recovery in soccer: Part II-recovery strategies. *Sports Med*. 43:9-22.

Pilcher J, Huffcutt A. (1996). Effects of sleep deprivation on performance: a meta-analysis. *Sleep*. 19:318–326.

Porta J, Acosta D, Lehker A, Miller S, Tomaka J, King G. (2012). Validating the Adidas miCoach for estimating pace, distance, and energy expenditure during outdoor over-ground exercise accelerometer. In Lyons S, Navalta J (Eds). *International Journal of Exercise Science: Conference Proceedings*.

Rattray B, Argus C, Martin K, Northey J, Driller M. (2015). Is it time to turn our attention toward central mechanisms for post-exertional recovery strategies and performance? *Front Physiol*. 17:79.

Samuels C. (2008). Sleep, recovery, and performance: The new frontier in high-performance athletics. *Neurol Clin*. 26:169-180.

Sargent C, Halson S, Roach G. (2014). Early-morning training severely restricts the amount of sleep obtained by elite swimmers. *Eur J Sport Sci*. 14:S310-S315.

Skein, Duffield R, Minett G, Snape A, Murphy A. (2013). The effect of overnight sleep deprivation after competitive rugby league matches on postmatch physiological and perceptual recovery. *Int J Sport Physiol Perform*. 8:556-564.

Stegmann H, Kindermann W, Schnabel A. (1981). Lactate kinetics and individual anaerobic threshold. *Int J Sports Med*. 2:160-165.

Stepanski E, Wyatt J. (2003). Use of sleep hygiene in the treatment of insomnia. *Sleep Med Rev*. 7:215-225.

Stickgold R. (2005). Sleep-dependent memory consolidation. *Nature*. 437:1272-1278.

Vyazovskiy V, Delogu A. (2014). NREM and REM Sleep: Complementary roles in recovery after wakefulness. *The Neuroscientist*. [Epub ahead of print].

Waterhouse J, Atkinson G, Edwards B, Reilly T. (2007). The role of a short post-lunch nap in improving cognitive, motor, and sprint performance in participants with partial sleep deprivation. *J Sports Sci*. 25:1557-1566.

## Figure captions

**Figure 1:** Individual cases (n=14) of sleep duration for either a non-sleep hygiene strategy (A) or a sleep hygiene strategy (B) following a late-night soccer match. B: baseline; MN: match night; MN + 1: match night plus 1. * Significant difference between conditions (P<0.05). # Significant difference within conditions (P<0.05). Shaded bars represent condition. Horizontal black connected lines represent individual sleep responses.

**Figure 2:** Mean and individual recovery of exercise performance parameters in response to a either a non-sleep hygiene strategy (NSHS) or a sleep hygiene strategy (SHS) 12 h post following a late-night soccer match. A: Counter movement jump height (CMJ; cm), B: Countermovement jump force production (N); C: YoYo Intermittent recovery level two performance (YYIR2; distance in m), D: YoYo Intermittent recovery level two (YYIR2; max heart rate, beats per minute). Shaded bars represent condition. Horizontal connected lines represent individual recovery responses.

**Figure 3:** Subjective recovery and stress questionnaire responses ("Overall recovery and stress"; 0 (not at all) to 6 (absolutely) (Kölling et al. 2014)) at baseline (prior to the match), the morning after the match (12 h post-match) and after each training session (24 h, 36 h and 48 h post).

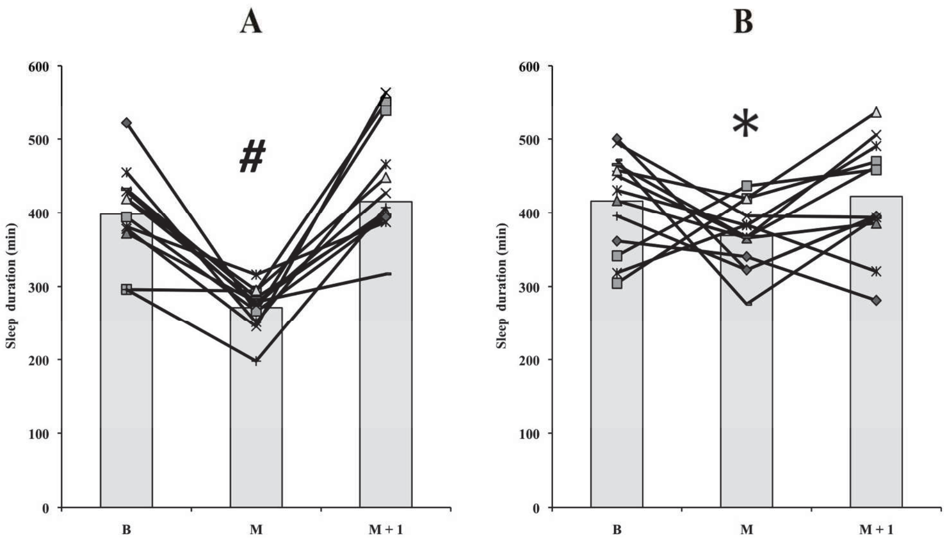


Figure 1: Individual cases (n=14) of sleep duration for either a non-sleep hygiene strategy (A) or a sleep hygiene strategy (B) following a late-night soccer match. B: baseline; MN: match night; MN + 1: match night plus 1. * Significant difference between conditions (P<0.05). # Significant difference within conditions (P<0.05). Shaded bars represent condition. Horizontal black connected lines represent individual sleep responses.
254x190mm (300 x 300 DPI)

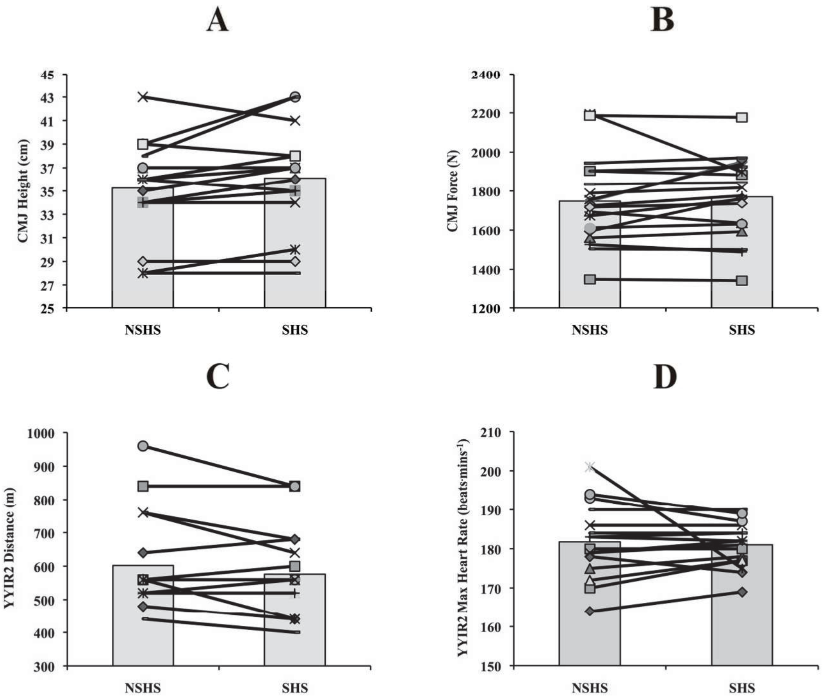


Figure 2: Mean and individual recovery of exercise performance parameters in response to a either a non-sleep hygiene strategy (NSHS) or a sleep hygiene strategy (SHS) 12 h post following a late-night soccer match. A: Counter movement jump height (CMJ; cm), B: Countermovement jump force production (N); C: YoYo Intermittent recovery level two performance (YYIR2; distance in m), D: YoYo Intermittent recovery level two (YYIR2; max heart rate, beats per minute). Shaded bars represent condition. Horizontal connected lines represent individual recovery responses.
254x190mm (300 x 300 DPI)

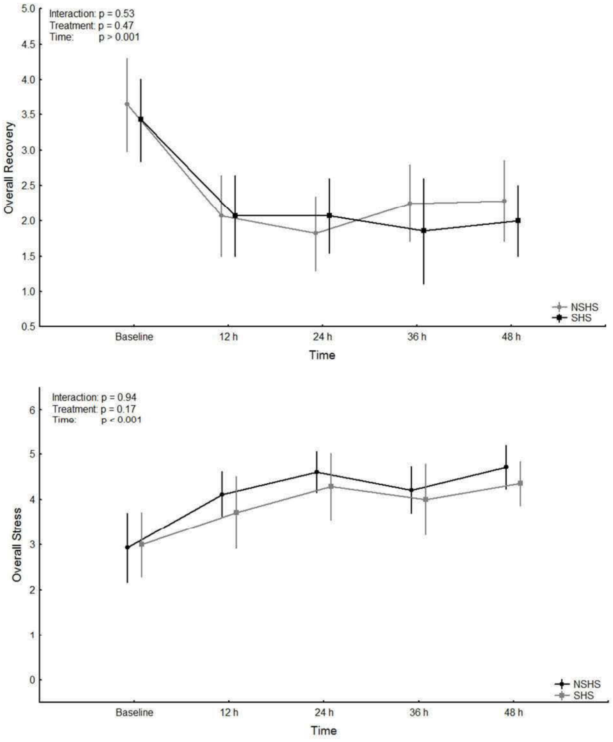


Figure 3: Subjective recovery and stress questionnaire responses ("Overall recovery and stress"; 0 (not at all) to 6 (absolutely) (Kölling et al. 2014)) at baseline (prior to the match), the morning after the match (12 h post-match) and after each training session (24 h, 36 h and 48 h post).
254x190mm (300 x 300 DPI)

**Table 1: Sleep variables prior to, and in response to, either a sleep hygiene strategy condition (SHS) or a control condition (non-sleep hygiene; NSHS) following a late night match in soccer players.**

| | SHS | | | NSHS | | |
|---|---|---|---|---|---|---|
| **n = 14** | **Baseline** | **Match night** | **Match night+1** | **Baseline** | **Match night** | **Match night+1** |
| **Sleep duration** (h) | 6:54 ± 1:06 | 6:09 ± 0:43$^{*}$ | 7:00 ± 1:10 | 6:38 ± 1:01 | 4:30 ± 0:27$^{\#}$ | 6:54 ± 1:56 |
| **Sleep onset latency** (min) | 12.6 ± 11.6 | 21.1 ± 16.9 | 9.8 ± 15.3 | 15.2 ± 14.8 | 8.8 ± 7.1 | 10.1 ± 19.4 |
| **Sleep efficiency** (%) | 89.2 ± 4.0 | 84.6 ± 9.0$^{‡}$ | 91.2 ± 4.1$^{\wedge}$ | 89.0 ± 4.0 | 87.6 ± 8.3 | 87.6 ± 14.5 |
| **Wake episodes** (n) | 9.8 ± 4.4 | 12.1 ± 6.9$^{*}$ | 9.6 ± 4.3 | 8.7 ± 3.9 | 7.5 ± 4.1 | 11.2 ± 5.7$^{‡}$ |
| **Total wake episode duration** (min) | 29.6 ± 17.0 | 38.9 ± 27.5$^{\wedge}$ | 25.2 ± 14.7 | 31.0 ± 19.8 | 20.0 ± 18.1 | 32.9 ± 21.5 |
| **Time asleep** | 00:22±0:46 | 00:21±0:29$^{*}$ | 23:56±1:10 | 00:12±1:06 | 02:25±0:09$^{\#}$ | 23:40±1:58 |
| **Time awake** | 07:52±1:14 | 07:07±0:32 | 07:20±0:07 | 07:43±1:47 | 07:18±0:09 | 07:21±0:15 |
| **Number of players whom napped** | 3 | - | 2 | 5 | - | 2 |
| **Average duration of naps (min)** | 56±21 | - | 66±19 | 42±34 | - | 81±2 |

* Significant difference between conditions (P<0.05), # Significant difference within conditions (P<0.05)

^ Large effect size (d ≥ 0.80) between conditions, ‡ Large effect size (d ≥ 0.80) within conditions

NB: Naps are categorised into: during days at 'baseline', the day following 'match night' and the day following 'match night + 1'.

**Table 2: A description of external and internal load from Global Positioning Satellite (GPS), Heart Rate (HR) and Rating of Perceived Exertion (RPE) data of soccer players to a late-night match and ensuing training sessions. Means ± SD.**

| | SHS | | | | NSHS | | | |
|---|---|---|---|---|---|---|---|---|
| **n = 13** | **Match** | **Match+1: PM** | **Match+2: AM** | **Match+2: PM** | **Match** | **Match+1: PM** | **Match+2: AM** | **Match+2: PM** |
| Total distance (m) | 9796±1720 | 3764±462 | 2536±846 | 3496±1067 | 9361±1575 | 3732±358 | 2701±857 | 3422±924 |
| Mean speed (m/min) | 118±7 | 82±7 | 55±13 | 75±13 | 122±13 | 80±7 | 53±12 | 72±13 |
| Peak speed (m/s) | 7.6±1.2 | 6.1±0.5 | 5.4±1.0 | 5.8±0.8 | 7.7±1.1 | 6.1±0.6 | 5.7±0.9 | 6.1±0.8 |
| High intensity distance (m) | 2401±953 | 559±140 | 212±213 | 372±292 | 2168±921 | 576±177 | 241±173 | 358±277 |
| Mean HR (bpm) | 161±11 | 140±7 | 119±13 | 136±10 | 160±10 | 139±9 | 121±11 | 136±12 |
| Peak HR (bpm) | 185±13 | 174±9 | 165±8 | 175±10 | 187±14 | 173±11 | 168±12 | 175±10 |
| Very high intensity bouts (n) | 27±8 | 2±1 | 2±3 | 2±2 | 23±11 | 2±2 | 2±2 | 2±3 |
| Training load (au) | 450±162 | 361±108 | 227±84 | 365±139 | 522±180 | 377±93 | 206±84 | 317±124 |

* Significant difference between conditions (P<0.05). Abbreviations: AU: arbitrary units (Training Load (TL) = session rating of perceived exertion (s-RPE) x duration in min). High intensity running distance is expressed as the distance covered above each players previously calculated speed at individual anaerobic threshold. Very high intensity bouts are representative of the number of bouts performed over the training session above 19.8 km/h for more than 1 sec.

**Table 3: Recovery of soccer players following a late-night match with either a sleep hygiene strategy (SHS) or control condition (non-sleep hygiene; NSHS).**

| | SHS | | | | | NSHS | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Blood variables** | **B** | **10 h** | **20 h** | **34 h** | **44 h** | **B** | **10 h** | **20 h** | **34 h** | **44 h** |
| Creatine kinase (mg/ml) | 586 ± 991 | 813 ± 792$^{\#}$ | 1305 ± 986$^{\#}$ | 926 ± 720$^{\#}$ | 1035 ± 772$^{\#}$ | 322 ± 189 | 668 ± 344 | 1193 ± 743$^{\#}$ | 795 ± 494 | 934 ± 581$^{\#}$ |
| Urea (mg/dl) | 41.5 ± 9.0 | 46.6 ± 10.0 | 51.2 ± 10.0$^{\#}$ | 43.0 ± 10.7 | 52.6 ± 10.8$^{\#}$ | 40.4 ± 8.7 | 47.7 ± 9.5 | 51.7 ± 8.6$^{\#}$ | 44.4 ± 9.3 | 54.2 ± 13.9$^{\#}$ |
| CRP (mg/dl) | 1.1 ± 1.6 | 1.5 ± 1.3 | 2.0 ± 1.5 | 1.9 ± 1.7 | 1.4 ± 1.5 | 0.7 ± 0.7 | 1.0 ± 0.6 | 1.9 ± 2.0 | 2.1 ± 3.3 | 2.0 ± 3.8 |

| **Responses to HIMS** | **B** | **18 h post SHS** | **42 h post SHS** | **18 h post NSHS** | **42 h post NSHS** |
|---|---|---|---|---|---|
| HRR S1 | 52 ± 12 | 58 ± 12 | 56 ± 12 | 54 ± 10 | 55 ± 12 |
| HRr% after S1 | 61 ± 10 | 58± 8 | 59 ± 9 | 59 ± 9 | 59 ± 9 |
| HRR S2 | 57 ± 16 | 61 ± 11 | 60 ± 12 | 58 ± 12 | 55 ± 10 |
| HRr% after S2 | 62 ± 11 | 59 ± 7 | 59 ± 9 | 60 ± 9 | 62 ± 7 |
| HRR S3 | 55 ± 15 | 61 ± 12 | 61 ± 14 | 58 ± 10 | 56 ± 13 |
| HRr% after S3 | 66 ± 10 | 62 ± 7 | 61 ± 8 | 63 ± 7 | 63 ± 8 |
| HRR S4 1 min P | 65 ± 18 | 56 ± 11 | 56 ± 16 | 58 ± 12 | 60 ± 15 |
| HRr% after S4 1 min P | 63 ± 10 | 66 ± 6 | 67 ± 9 | 65 ± 5 | 64 ± 8 |
| HRR S4 2 min P | 83 ± 15 | 77 ± 14 | 79 ± 18 | 77 ± 9 | 77 ± 13 |
| HRr% after S4 2 min P | 53 ± 8 | 54 ± 7 | 52 ± 10 | 54 ± 6 | 53 ± 7 |

* Significant difference between conditions; # Significant difference within conditions compared to the baseline. Abbreviations: B, Baseline; HIMS, Heart Rate Interval Monitoring System; HR, heart rate; HRR, absolute decrease in heart rate during recovery (bpm); HRr%, recovery heart rate expressed as a per cent of the mean heart rate during the last minute of the stage; P, post; S, stage.