UNIVERSITY OF TECHNOLOGY SYDNEY

Physical Activity Demands of NBA Game Play

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Thesis submitted in fulfilment of the requirements for the degree of

Doctor of Philosophy

under the supervision of
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"There will come a time when you believe everything is finished.

That will be the beginning."

Louis L'Amour

CERTIFICATE OF ORIGINAL AUTHORSHIP

I, Keith D'Amelio, declare that this thesis, is submitted in fulfilment of the requirements for the award of doctor of philosophy, in the School of Sport, Exercise, and Rehabilitation / faculty of health at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise referenced or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

This document has not been submitted for qualifications at any other academic institution.

This research is supported by the Australian Government Research Training Program.

Signature: Production Note: Signature removed prior to publication.

Date: November 24th, **2020**

PREFACE

This thesis for the degree of Doctor of Philosophy is in the format of published or submitted manuscripts and abides by the 'Procedures for Presentation and Submission of Theses for Higher Degrees – University of Technology Sydney; Policies and Directions of the University'. All manuscripts included in this thesis are closely related in subject matter and form a cohesive research narrative.

Based on the research design and data collected by the candidate, four manuscripts have been submitted for publication. These papers are initially brought together by an Introduction, which provides background information, defines the research problem and the aim of each study. A literature review then follows to provide an overview of previous knowledge regarding physical and technical components of basketball game performance. The body of the research is presented in manuscript form (Chapter Three to Chapter Six), in a logical sequence following the development of research ideas in this thesis. Each manuscript outlines and discusses the individual methodology and the findings of each study separately. The general discussion chapter provides an interpretation of the collective findings, suggests practical recommendations and acknowledges the limitations from the series of investigations that comprise this thesis. Finally, the summary and recommendations chapter present the conclusions from each project and directions for future research to build on the findings of this thesis are suggested. The APA 6th reference style has been used throughout the document and the reference list is at the end of the thesis.

ACKNOWLEDGEMENTS

Professor Aaron Coutts, we certainly did not take the straightest road to the end – but we got here anyway. This journey is one that I know I will not fully realize and appreciate its impact on me for years to come. One thing I am well aware of already however, is that there is no one who's guidance and support I would have wanted more than yours. Thank you for everything

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I could not have done this without the patience, support, and encouragement of my family. Marcus & Christian, understand that this was as much for me as it was for you. You may face difficult and frustrating times in life, as I did thru this process. However, know that if you persevere and keep at it, anything is possible, and always remember….
… "Study as if you know nothing but work as if you can solve everything."
Also, now you can finally stop asking "When are you finished your stupid PhD???…."

To my wife Jaime, you are the most amazing woman in the world, and I am so fortunate to have you in my life. Thank you for your support in this and every other journey we have taken together in life so far. There are a lot more adventures ahead for us and regardless what they may be, if I am by your side – I know we'll be just fine.

LIST OF ARTICLES SUBMITTED FOR PUBLICATION

Due to confidentiality restrictions relating to the use of data obtained from contracted NBA players, the manuscripts included in this thesis cannot be submitted for publication. At the time of submission, the following manuscripts have been prepared with the intention to gain appropriate permissions for publication.

- **D'Amelio, K.**, Ward, P., Bilsborough, J., Coutts, A.J., (2018) Measurement accuracy of an optical tracking system for instantaneous velocity during basketball specific activity.
- **D'Amelio, K.**, Ward, P., Coutts, A.J. (2018) Quantifying the physical activity demands and game to game variation in NBA competition.
- **D'Amelio, K.**, Ward, P., Coutts, A.J. (2019). Forecasting physical output in NBA athletes using in-game optical tracking data.
- **D'Amelio, K.**, Ward, P., Coutts, A.J. (2019) The influence of physical activity on technical performance in the NBA.

ABSTRACT

Basketball is a physically demanding, high-intensity team sport that is one of the most popular sports in the world, played professionally in over 200 countries. The highest level of basketball competition is the National Basketball Association (NBA), the major professional basketball league in the United States of America. This thesis contains four independent studies which aim to provide a greater understanding of the physical activity profiles and investigate the factors that influence physical activity within NBA game play. Study One investigated the measurement accuracy of the optical tracking system used to quantify the physical activity during NBA competitions. These findings have implications for analysing measures of physical performance captured by optical tracking systems. The second study examined positional and temporal physical activity demands and their variation within NBA game play. These results provide a detailed description of the activity demands in NBA game play and additionally the results aid in assessing meaningful changes in activity measures. Study three assessed the ability to accurately forecast physical activity demands and to further investigate contextual factors that may influence the physical activity within game play. The results highlight the importance of understanding and considering contextual factors when planning training and analysing the physical activity profiles of NBA game play. Study Four investigated the relationship between measures of physical activity and technical game performance. The results demonstrate that whilst physical activity and technical performance are related, they have a complex relationship whereby increases in certain activity measures correspond with decreases in game performance. The collective findings in this thesis provide new detailed description of the game physical activity demands of elite basketball, with specific focus on the factors that influence game activity and also its subsequent relationship to game performance. The results of this thesis demonstrate that in-game physical activity is unique to the positional group and varies both within and between games. Furthermore, the influence of contextual factors such as, playing position, playing ability (All-Star), and altitude must be considered when interpreting game-based activity profiles from NBA players. While it is often assumed that increased game-based activity is related to improved technical performance, this thesis demonstrated that these two factors are not directly linked. Finally, while this thesis provides a step forward in understanding the physical demands of basketball at the highest level, a critical finding is

specific to the efficacy of the optical tracking system used by the NBA. This thesis questions the accuracy of an optical tracking system when quantifying discrete measures of physical activity demands in NBA games. Collectively, this thesis provides a comprehensive understanding of the physical activity demands found in the highest level of basketball competition.

Contents

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS AND ACRONYMS

AccT	- Total Accelerations
AccH	- High Accelerations
AIC	- Akaike Information Criterion
a.u/min	- Arbitrary units per minute
C	- Centre (playing position)
CI	- Confidence interval
cm	- centimetre (unit of length)
CV	- Coefficient of variation
ES	- Effect Size
F	- Forward (playing position)
G	- Guard (playing position)
GPS	- Global positioning system
HSE	- High Speed Efforts
HSR	- High Speed Running
Hz	- Hertz (unit of frequency)
kg	- kilogram
km	- kilometre
$km \cdot h^{-1}$	- kilometre per hour
LoA	- Limits of agreement
LPS	- Local Positioning system
m	- Meter
$m \cdot min^{-1}$	- Meters per minute
m/s^2	- meters per second (unit of speed)
NBA	- National Basketball Association
OTS	- Optical tracking system
P1	- Phase 1 (games 1-20)
P2	- Phase 2 (games 21-40)
P3	- Phase 3 (games 41-60)
P4	- Phase 4 (games 61-82)
Q1	- 1st Quarter
Q2	- 2nd Quarter

Q3	- 3rd Quarter
Q4	- 4th Quarter
s	- Second (unit of time)
TD	- Total distance
TEE	- Typical error of the estimate
TEM	- Typical error of the measurement
UWB	- Ultra wide band
y	- Year

LIST OF APPENDICES

CHAPTER ONE

INTRODUCTION

BACKGROUND

Basketball is an intermittent high-intensity court-based team sport requiring a wide range of physical capacities and well-developed technical skill. The highest-level basketball competition is the National Basketball Association, the major professional basketball league in the United States. Similar to other team sports, basketball game performance involves a dynamic interplay between physical, technical and tactical performance (Impellizzeri & Marcora, 2009). Practitioners working in basketball require valid and reliable physical and technical parameters to represent these different performance constructs.

The earliest investigations of activity profiles in basketball utilized manual-based distance measurement and customized electrical pursuit methods (Messersmith, 1944; Messersmith & Corey, 1931). More recent studies have used video-based time-motion analysis to assess the physical and technical requirements of game play (Klusemann, Pyne, Hopkins, & Drinkwater, 2013; McInnes, Carlson, Jones, & McKenna, 1995; Scanlan, Dascombe, Reaburn, & Dalbo, 2012; Scanlan, Tucker, et al., 2015). Time motion analysis utilizes video recordings to categorize player movement frequency, duration and intensity to describe the activity and skill requirements of sport (Ali & Farrally, 1991). Technological advances have led to an increase in the use of wearable micro-technologies in basketball to examine physical activity during training and within game play (Puente, Abian-Vicen, Areces, Lopez, & Del Coso, 2016; Schelling & Torres, 2016; Svilar, Casajus, & Jukic, 2019). Data gathered from these devices are now commonly used in applied basketball research studies (Fox, Scanlan, & Stanton, 2017). Since the 2013-2014 season, the NBA has utilized an optical tracking system to quantify measures of technical skill and physical activity. However, in contrast to other methods utilized in the quantification of activity demands in basketball, the validity and reliability of this optical tracking system has yet to be explored. Therefore, investigation of the measurement precision of the optical tracking system used in the NBA is required.

Similar to other court-based sports, basketball requires players to frequently accelerate, decelerate and change in direction at various intensities (Stojanovic et al., 2018). Early investigations of the activity demands in basketball have demonstrated that there are approximately 1000 different movements completed during high level matches (Ben

Abdelkrim, El Fazaa, El Ati, & Tabka, 2007; McInnes et al., 1995), with changes in movement intensity approximately every 1-3 s (Ben Abdelkrim et al., 2007; McInnes et al., 1995; Scanlan, Dascombe, & Reaburn, 2011). Some of the more commonly described activities include standing, walking, jogging, running, sprinting, jumping, back-pedalling, and side shuffling at varying intensities (McInnes et al., 1995). Previous research has reported semi-professional Australian basketball players spend ~30-42% of matches at low intensity ($\leq$3 m·s^{-1}), while only 2-5% was spent at high intensity (>7 m·s^{-1}) (Scanlan et al., 2011). Similarly, the mean frequency of high intensity running efforts (>7 m·s^{-1}) in elite junior level European players was 55 ± 11 per game, which was approximately 1 sprint every 39 s (Ben Abdelkrim et al., 2007). Whilst collectively these investigations of the activity demands in basketball competition have enhanced our understanding of the activity requirements of the sport, it is difficult to infer these results to NBA competitions due to the differences in playing levels, which has been shown to influence activity profiles (Ferioli et al., 2020; Scanlan et al., 2011; Scanlan, Tucker, et al., 2015). Recent investigations of the activity profiles in the NBA have demonstrated an average speed of ~ 6.4 km·h^{-1} (Sampaio et al., 2015) and covering ~ 4.49 km in total distance (Zhang et al., 2017). The primary focus of these investigations, however, has been technical skill and they have only used global measures of physical activity (i.e. average speed and total distance), which fail to describe the broader range of the activity profiles of NBA competitions previously described. For example, Caparros, Casals, Solana, and Pena (2018) examined more discrete measures of activity (i.e. accelerations, decelerations) of a single NBA team and reported similar average game speed to Sampaio et al. (2015) of ~6.7 km·h^{-1}. However, they reported an overall total distance of 2.57 km, which was lower than those reported by Zhang et al. (2017). Additionally, the average max speed in competition was 29.1 km·h^{-1} and the number of max accelerations and decelerations (>4 m·s^{-2}) were determined to be 0.7 and 0.3 per game respectively (Caparros et al., 2018). Whilst this investigation examined more discrete measures of activity, it is a single team case study and caution must be used when comparing the larger NBA population. These investigations provide a general overview of the activity demands the NBA, and it is difficult to directly compare findings of these studies as different playing levels, player tracking methods, general measures of activity and playing conditions have been employed. Therefore, information remains limited for the activity profiles in NBA competitions and further investigations are required to enhance our understanding of the demands of the NBA. Such information may be used to develop evidence-informed recommendations around athlete preparation and care (McLean, Strack, Russell, & Coutts, 2019).

In addition to the limited information regarding the physical activity profiles in NBA competition, no studies have examined the situational contextual factors (e.g. game location, game outcome, team ranking, playing skill, seasonal phase, and environment) which may influence these activity profiles during game play. It is important to account for the confounding effects of situational factors (e.g. game location, opposition strength and possession time), which may influence performance indicators during team sport match-play (Carling, 2013). Recent investigations of NBA game play have examined the influence of team strength (e.g. stronger vs. weaker) (Zhang et al., 2017) and playing skill (e.g. All-Star vs non-All-Star) (Sampaio et al., 2015). However, these investigations examined the influence of these situational factors on general measures of activity (i.e. average speed and total distances) and provide little insight into the discrete physical demands of the NBA. Other research examining sub-elite Australian professional basketball described the effect of game outcome on activity measures and demonstrated that both absolute and relative measures of accelerations and jumps were increased in losses (Scanlan et al., 2019). While interesting, the analysis is specific to one team (n = 5). However, these findings have limited transfer to the NBA due the level of competition investigated, and the low sample size used. Finally, such observational studies consist of serial measurements of individual players across the course of a season, which violates the assumption required for general linear models (Wilkerson, Gupta, Allen, Keith, & Colston, 2016). To date, no investigations into the influence of situational factors on discrete measures of physical activity in NBA competitions have been performed. Therefore, to enhance the current understanding of game performance in the NBA, additional research of the influence of situational effects on physical activity, using large game file samples and statistical methods that can account for dependent data are required.

RESEARCH QUESTION

Greater understanding of the physical activity demands of competition allows practitioners to better prepare athletes for the physical demands they will encounter.

There has been a recent increase in studies examining game performance in the NBA, these investigations however have primarily investigated general measures of physical activity (i.e. average speed and total distance) or technical performance. Additionally, there remains limited information about the influence of game related situational factors that may affect the activity demands. Moreover, many of the studies examining the activity demands in basketball competitions have been limited by small sample sizes or are case study in nature, were conducted in lower competition levels, or applied statistical techniques unable to account for the repeated measurements of the athletes over time. Therefore, the purpose of this thesis is to develop a greater understanding of the physical activity profiles and the contextual factors affecting these profiles within NBA game play.

RESEARCH OBJECTIVE

A series of applied research studies were conducted to enhance the understanding of physical activity profiles in NBA competitions. The first study examined the accuracy of an optical tracking system used to quantify physical activity in NBA game play. The second study examined the positional and temporal activity demands and the typical between-game variation of these activity demands during NBA competition. The third study further explored this concept by examining the independent effects of game-related situational factors on measures of physical activity and the ability to forecast activity demands to future NBA competitions. Study four investigated the influence of physical activity on a selected technical performance measure of game play. This thesis is comprised of league wide analysis over multiple seasons using data collected by the primary research team (studies two, three, and four) and an examination of the accuracy in the technology used to provide those measures to NBA teams and practitioners (study one).

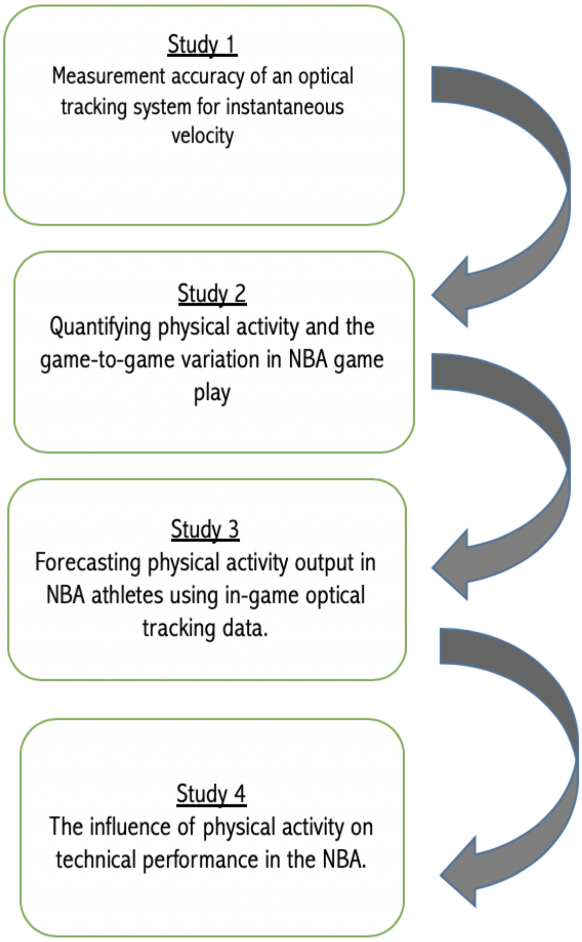

Figure 1.1. Research process linking the studies undertaken in this thesis.

STUDY 1 – MEASUREMENT PRECISION OF AN OPTICAL TRACKING SYSTEM FOR INSTANTANEOUS VELOCITY.

AIM:

The purpose of this study was to assess the measurement accuracy of instantaneous velocity in an optical tracking system.

SIGNIFICANCE:

The current accuracy of the optical tracking system used in the NBA is unknown, as a result, proper interpretation and application of this data is difficult. Therefore, the findings of this study will enhance the understanding of the measurement precision in an optical tracking system used to quantify physical activity demands in the NBA. These findings will aid practitioners of activity measures captured by an optical tracking system and allow for improved analysis of game related physical demands.

STUDY 2 – QUANTIFYING PHYSICAL ACTIVITY AND THE GAME-TO-GAME VARIATION IN NBA COMPETITION.

AIM:

The aims of this study were to: 1) determine the typical between match variability of physical activity between playing positions and 2) examine temporal variability of physical activity between playing quarters during NBA game play.

SIGNIFICANCE:

These findings will provide a greater understating of the positional and temporal physical activity demands, identify reliable physical activity measures, and assist in interpreting meaningful changes in activity profiles of NBA game play for analysis.

STUDY 3 – FORECASTING PHYSICAL ACTIVITY OF NBA ATHLETES USING IN-GAME OPTICAL TRACKING DATA.

AIM:

The aims of this study were to: 1) investigate the accuracy of forecasting physical activity demands in NBA game play and 2) examine the influence of game related situational factors on the physical activity in competition.

SIGNIFICANCE:

There remains limited information on the factors affecting physical activity in NBA competitions. Therefore, this information may provide greater insight into the factors affecting physical activity, and when accounting for these factors, provide the ability to forecast these demands. This insight may enhance practitioners ability to plan and develop training programs and implement appropriate recovery strategies. Additionally, greater forecasting precision will allow practitioners to understand expected training loads, increase player availability and enhance training practices.

STUDY 4 – THE INFLUENCE OF PHYSICAL ACTIVITY ON TECHNICAL PERFORMANCE IN NBA COMPETITION.

AIM:

The aim of this study was to examine the relationship between technical game performance and physical activity profiles.

SIGNIFICANCE:

Practitioners have often assumed a positive relationship between physical activity in game play and technical skill when evaluating individual player and team-based game performance. However, a limited number of investigations have examined the relationship between physical activity measures and technical skill performance. Greater understanding of this relationship may allow practitioners to identify key activity measures that have an influence on improved game performance. Additionally, this study will allow for an enhanced analysis of physical activity data as it relates technical skill, therefore allowing practitioners greater understanding and maximize the usage of game-based activity measures.

CHAPTER TWO

LITERATURE REVIEW

INTRODUCTION

Basketball is one of the most popular sports in the world with approximately 450 million registered participants across the globe (FIBA.com, 2015). It is played in over 200 countries around the world, with the leading professional competition, the National Basketball Association (NBA) based in North America. The NBA consists of 30 teams playing 82 regular season games over 25 weeks in 29 different cities. There are significant financial investments in the league with the average franchise worth ~1.1 billion USD (Forbes, 2015) and approximately $2.395 billion (USD) in salary being paid to the NBA players for the 2015-2016 season (Basketball-Reference.com, 2020). The average player salary for the 2019-2020 season was $7,700,000 dollars (USD). In 2020, the highest paid player received $37,500,000 as a playing contract (i.e. independent of endorsements), with more than 10 players making over $30,000,000. However, despite the global popularity and significant financial investment, relatively little is known about the physical requirements of these athletes during game play.

Basketball is an intermittent high intensity sport, that involves repeated bouts of intense actions consisting of sprinting, deceleration, changes in direction, shuffling and jumping while also including low level activities such as walking, jogging and recovery time (Ben Abdelkrim et al., 2007). Most previous studies investigating the game demands of basketball have investigated lower levels of play with small sample sizes (Matthew & Delextrat, 2009; McInnes et al., 1995; Montgomery, Pyne, & Minahan, 2010). Recently, to coincide with advances in technology, there has been an increased research investigating performance in the NBA (Franks, Miller, Bornn, & Goldsberry, 2015; Maheswaran, Chang, Henehan, & Denesis, 2012; Sampaio et al., 2015). Much of this recent research has focused on the technical and tactical aspects of the game, with little focus on the physical requirements of game play. To improve the understanding of match and training demands of elite level basketball further research is needed.

The purpose of this narrative review is to identify the current understanding of the physical activity demands of basketball games and the various contextual factors affecting these demands. This review examined methods currently used to understand the physical activity demands of basketball and assessed the positional and temporal requirements of game play. We also explored contextual factors related to game-based physical activity such as altitude, playing ability, game outcome, game location, phase of season, and team rank differential.

Relevant literature was obtained from an online search using the, PubMed, SportDiscus, and Google Scholar electronic databases. The following keywords were used in various combinations: ‘basketball’, ‘performance analysis’, ‘technical performance’, ‘physical performance’, ‘measurement validity’, ‘match demands’. Electronic database searching was supplemented by examining the reference lists of relevant articles. Match analysis studies examining professional, semi-professional and elite-junior basketball competitions were considered for review. Investigations of female basketball competition were excluded due to the differences in physical activities between genders (Scanlan et al., 2012). Additionally, investigations of the training demand of basketball were excluded. Due to the lack of literature available the search was widened to include relevant literature from other sports where appropriate.

METHODS FOR MEASURING PHYSICAL ACTIVITY IN TEAM SPORTS

Investigations into the activity demands of basketball date back to the early 1930’s using hand-based distance measurement and electrical pursuit tools (Messersmith, 1944; Messersmith & Corey, 1931). More recent investigations to assess activity demands in other team sports have utilized video-based time motion analysis (Ben Abdelkrim et al., 2007; Sirotic, Knowels, Catterick, & Coutts, 2011). This method consists of manually tracking an athlete’s movement from a digital recording. This technique has been used extensively in early basketball research to explore the physical activity demands (Ben Abdelkrim, Chaouachi, Chamari, Chtara, & Castagna, 2010; Klusemann et al., 2013; Scanlan et al., 2011; Scanlan, Tucker, et al., 2015). Whilst this has been shown to be a reliable method for performing time-motion analyses (Ben Abdelkrim et al., 2007; Duthie, Pyne, & Hooper, 2003; McInnes et al., 1995), the process is both time consuming and labour intensive (Edgecomb & Norton, 2006). Recently, there has been an increase in the use of micro-technologies in professional sports including, global positioning system (GPS), accelerometery-based, optical tracking system (OTS), and local position (LPS) system (Barris & Button, 2008; Fox et al., 2017; Scott, Scott, & Kelly, 2016;

Stojanovic et al., 2018). These systems are able to record time-motion profiles during team training and competitions without the time and labour of traditional time-motion analysis. Figure 2.1 shows the number of studies that have used the different time-motion analysis methods on basketball games. More recently, wearable microtechnology, and OTS have been used to quantify games demands (Montgomery et al., 2010; Pino-Ortega et al., 2019; Sampaio et al., 2015). The NBA has used an OTS to record both the physical and technical activity of game play since the 2013 season. In addition, the majority of NBA teams utilize some form of micro-technology to monitor the physical activity of their athletes in training. The time-motion profiles obtained from these devices are commonly used in basketball research studies (Sampaio et al., 2015; Schelling & Torres-Ronda, 2016; Stojanovic et al., 2018; Vazquez-Guerrero, Fernandez-Valdes, Goncalves, & Sampaio, 2019).

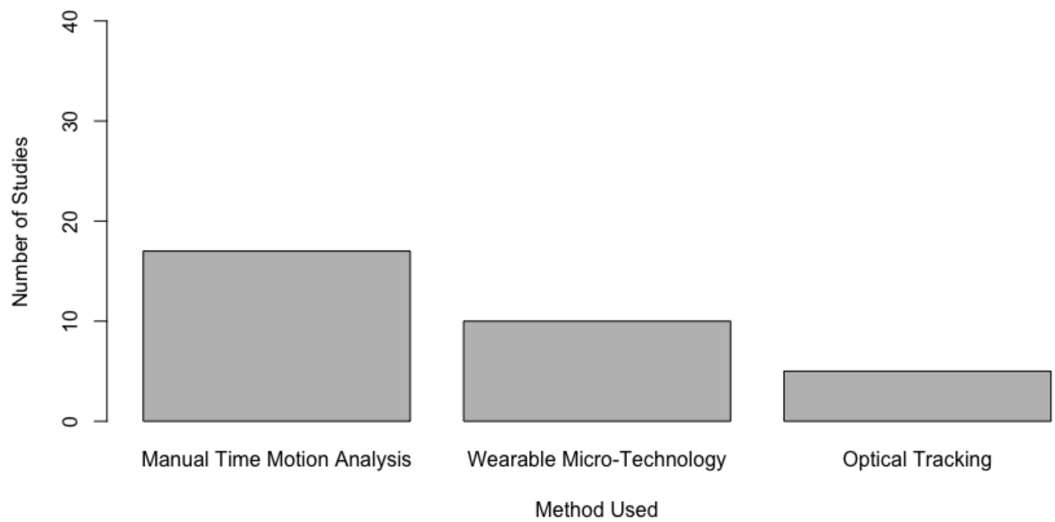

Figure 2.1. Methods used to quantify physical activity demands in basketball competition (n = 33) between 1931 and 2020.

Given the widespread use of wearable micro-technology systems to quantify athlete activity in training and competition, several investigations have examined the validity and reliability of these systems. To date, the most commonly assessed wearable micro-technology has been GPS systems (Cummins, Orr, O'Connor, & West, 2013). Previous research has shown that a range of GPS devices provide acceptable validity and reliability for measuring movements over longer distances at low speeds (Jennings, Cormack, Coutts, Boyd, & Aughey, 2010; Waldron, Worsfold, Twist, & Lamb, 2011). Whilst some investigations have reported acceptable accuracy for assessing straight line acceleration and deceleration efforts, others have found that GPS measurements of high-speed movements and rapid changes of direction are highly variable and have questioned the precision of these measures (Buchheit, Al Haddad, et al., 2014; Rampinini et al., 2015; Varley, Fairweather, & Aughey, 2012). Caution, however, is required when discussing the reliability and validity of GPS systems as the device performance will vary according to manufacturer firmware, proprietary software and sampling frequency (Buchheit, Al Haddad, et al., 2014; Jennings et al., 2010). Unfortunately, GPS technology relies on satellites for positional information, making its use in basketball, which is played indoors, invalid.

More recent studies have examined the validity and reliability of more basketball relevant technologies including accelerometers, LPS and OTS (Boyd, Ball, & Aughey, 2011; Leser, Schleindlhuber, Lyons, & Baca, 2014; Linke, Link, & Lames, 2018; Roell, Roecker, Gehring, Mahler, & Gollhofer, 2018). Specifically, the validity of a trunk mounted accelerometery device has been examined and compared to a motion capture system (Wundersitz, Gastin, Robertson, Davey, & Netto, 2015). The trunk mounted accelerometer was found to have a peak acceleration mean bias of 0.03 ± 0.04g, 0.03 ± 0.13 g, 0.14 ± 0.28 g, and 0.11 ± 0.20 g for walk, jog, sprint and change of direction respectively (Wundersitz et al., 2015). Whilst researchers determined accelerometers to be acceptable to accurately measure movements in team sport, it is important to note that the researchers found that raw accelerometery data should be interpreted with caution and advocated the use of data filtering (Wundersitz et al., 2015). Additional research has examined the activity demands of basketball utilizing LPS (Bastida-Castillo et al., 2019; Leser et al., 2014; Pino-Ortega et al., 2019; Sampaio et al., 2016; Vazquez-Guerrero et al., 2019). Leser et al (2014) examined the accuracy of an Ultra-Wide band (UWB) system (e.g. LPS) with a mean sampling rate of 4.17 Hz, in measuring total distance covered when compared to hand measured distance. The LPS was found to have a systematic bias (Limits of Agreement (LoA): -3.91 – 3.91%), which was below their tolerance threshold of 10% (Leser et al., 2014). Additionally, whilst investigators determined court location (centre of court versus court boarder) did not influence the accuracy of the LPS, transponder positioning did affect the accuracy of the LPS. It was also reported that when transponders were located on the athletes head, there was lower error (LoA: -1.14 – 1.14%), compared to transponders placed on the athletes shoulder

(LoA: -8.87 – 8.87) (Leser et al., 2014). While this identified the accuracy of LPS in basketball, only total distance was examined making its application limited. Bastida-Castillo et al. (2019) conducted a more recent study on the accuracy and inter-unit reliability of an LPS, sampling at 18Hz, utilizing geographic information system (GIS) mapping. The mean absolute errors for the positional estimate accuracy of the UWB were reported as 5.2 cm (x-position) and 5.8 cm (y-position), which represent a percentage difference 0.97% and 0.94% respectively (Bastida-Castillo et al., 2019). Additionally, the inter-unit reliability was reported to have an intra-class correlation coefficient of 0.65 (x-position) and 0.88 (y-position) and had a typical error measurement (TEM) of 2% for both the X and Y position (Bastida-Castillo et al., 2019). Whilst this study builds on the knowledge of previous research and reports the accuracy and inter-unit reliability, results should be interpreted with caution as LPS may vary with different sampling rates and transponder placement. Additionally, although the accelerometery and LPS-based research has expanded our potential to investigate activity demands in basketball, we are unable to apply these results directly to NBA basketball as these systems are currently prohibited from use in NBA game play.

Investigations examining the measurement properties of OTS have demonstrated acceptable accuracy with global measures of physical activity, however accuracy is reduced with higher speed activities and athlete location (Barris & Button, 2008; Linke et al., 2018; Pers, Bon, Kovacic, Sibila, & Dezman, 2002). Early research into optical tracking systems, with a sampling rate of 25 Hz, demonstrated the effect of court location on the measurement error, Root Mean Squared Error (RMSE), in player position (0.28 m vs 0.64 m) , player velocity (2.00 $m \cdot s^{-1}$ vs 2.10 m s^{-1}) and distance covered (35 m vs 67.5 m) for centre court athlete position versus boundary position, respectively without the use of data smoothing when compared to a video-based biomechanical measurement system (APAS-99) (Pers et al., 2002). Moreover, the authors identified several potential sources of error in this method, including accurate camera placement and calibration, smoothing rate implemented, player congestion, and manual error (Pers et al., 2002). More recently, Linke et al. (2018) examined an optical tracking system and found RMSE percentages of 1.9%, 4.43%, and 2.79% in sport-specific course, shuttle run, and small-sided game measurement when examining total distance covered compared to a motion capture system. However, the RMSE percentage error increased across all testing conditions sport specific course (11.6% - 97.9%), shuttle runs (43.4% - 259.3%), and small-sided games (16.8% - 97.6%) for low, moderate, elevated, high and very high speeds respectively (Linke et al., 2018), demonstrating a similar finding to examinations of other tracking systems, where accuracy is reduced at higher speeds. However, these studies were not investigated specifically to basketball and may lack interpretability to the sport given differing technology. For example, Linke et al., (2018) examined the OTS outdoors while investigating soccer-based activities and whilst Pers et al., (2002) examined the OTS system on an indoor handball court, the system examined utilized only two cameras for object tracking. At the present time, the six-camera tracking system utilized by the NBA has yet to be investigated for its ability to identify game activities. As such, further examinations are required to assess optical tracking technology in basketball specific conditions such as instantaneous velocity, in indoor court conditions utilizing multi cameras. Improved understanding of the precision in the measurement systems used to quantify the physical activity demands of basketball will enhance practitioner's utilization of this data to make informed decisions about athlete preparation and training.

Taken collectively the methods used to quantify activity demands demonstrate acceptable levels of accuracy when examining more global activity measures, however this accuracy is reduced with increasing speeds, velocities, and changes in directions. Additionally, these studies highlight the influence of factors (e.g. device positioning, camera / transponder location, filtering method, sampling rate used, and athlete location) on system precision. Currently, however, no studies have examined the precision of the OTS used in NBA competition.

PHYSICAL ACTIVITY DEMANDS

POSITIONAL DEMANDS

Basketball is a physically demanding sport that requires players to a use variety of specific skills and locomotor activities, which can vary depending on the players positional role. There are five players on the court for each team, which can be broadly described in three general positions – Guards (point guards and shooting guard), Forwards (small forwards and power forward), and Centres. However, unlike many other professional sports there are different playing conditions in basketball game play between the various levels of play and competitions. For example, NBA games are comprised of four 12-minute quarters, with two minutes between quarters and a fifteen-minute half time (between quarters 2 and 3) intermission and utilizes a 24 s shot clock. In contrast, international FIBA (International Federation of Basketball) games (i.e. international competitions) are made up four 10-minute quarters, with two minutes between quarters and a fifteen-minute halftime. Similar to the NBA, FIBA now utilizes a 24 s shot clock, this however is a recent change from their previous regulations. The different rules and regulations across basketball leagues and competitions may limit the ability to have accurate comparisons across studies, even within the highest levels of competition.

Table 2.1 shows the studies that have investigated the physical activity demands of basketball competition. It has been shown that athletes in basketball travel ~5-6 km during 40 min games (Stojanovic et al., 2018), with an average game speed of ~6.4 $km \cdot h^{-1}$ have been reported in the NBA (Sampaio et al., 2015). However, the distances travelled, and game speeds have been shown to be influenced by playing position and level of play. For example, it has been shown with elite and sub-elite basketball competitions in Australia, that the athletes cover 6279 and 6208 m per game respectively, with elite front court athletes (i.e. Forwards and Centres) covering 6230 ± 26 m and elite back court players (i.e. Guards) covering 6390 ± 48 m (Scanlan, Tucker, et al., 2015). Earlier investigations described the changes in locomotor activities during game play (Ben Abdelkrim et al., 2007; McInnes et al., 1995; Scanlan et al., 2011). The activities described included – standing, walking, jogging, running, sprinting, jumping, backpedalling, and side-shuffling all performed at varying intensities. In elite Tunisian youth basketball games, 997 – 1105 changes in activities were reported, while there were 1911 – 2689 change in movements in both elite and sub-elite Australian men's basketball games (Ben Abdelkrim et al., 2007; Scanlan et al., 2011). Indeed, Scanlan et al. (2011) reported that, in Australian international elite competitions, changes in movement intensity occur approximately once every second. In contrast, other studies reported that basketball athletes change movement patterns every 2-3 s, on average, during game play (Ben Abdelkrim et al., 2007; McInnes et al., 1995). Despite these regular changes in activities in basketball, studies using TMA, have reported 30-42% of game time is spent at low intensity, 53-68% at moderate intensity, and 2-5% at high intensity (Ben Abdelkrim, Castagna, El Fazaa, & El Ati, 2010; Ben Abdelkrim et al., 2007; Scanlan et al., 2011). The mean frequency of high intensity running efforts in elite junior players, has been reported to be 55 ± 11 per game, which results in 1 sprint every 39 s, with Guards sprinting ~67/game, Forwards ~56/game and Centres ~43/game respectively (Ben Abdelkrim et al., 2007). Jumping has been shown in multiple studies to average 44-50 jumps per game (Ben Abdelkrim et al., 2007; McInnes et al., 1995; Montgomery et al., 2010). In contrast to previous research (Ben Abdelkrim et al., 2007; Pino-Ortega et al., 2019; Scanlan et al., 2011) demonstrated, in elite junior international competitions, Guards and Forwards completed greater total distance, recorded higher peak speeds, and peak accelerations than Centres. Additionally, no differences between playing positions were found in high intensity running, player load, and counts of accelerations and decelerations.

Table 2.1: Summary of published studies examining physical activity in basketball game play.

Author	Playing Level	Athletes (n)	Files (n)	Measurement Technique	Variables Investigated	Contextual Factors Examined	Study Purpose
Messersmith et al (1931)	NCAA	1	1	Hand measured distance (pursuit wheel); Hand TMA	Total distance	Playing period; Offensive and defensive distance covered	Investigate the total distance covered in NCAA game play
Fay et al (1931)	NCAA	3	3	Hand measured distance (pursuit wheel); Hand TMA	Total distance	Rule Change; Playing period; Offensive and defensive distance covered	Effect of rule change on activity demands
Messersmith et al (1939)	NCAA	3	3	Electrical pursuit device	Total distance	Offensive and defensive distance	Describe the competitive demands of Big Ten (NCAA) Basketball competitions
Messersmith et al (1944)	NCAA	200	200	Electrical pursuit device	Total distance	Playing position; Playing level; Rule change	Describe the competitive demands of basketball using a novel device for measuring activity
McInnes et al (1995)	International Elite	8	8	Video TMA; HR measurement	Speed-based movement types (stand/walk, jog, run, stride/sprint, low shuffle, med shuffle, high shuffle, jump); HR measures; Blood lactate		To classify and quantify the movement patterns and HR responses of basketball competition and to understand the relationship between the movement characteristics and physiological response.
Bishop et al (2006)	International Elite	6	30	Video TMA	Speed-based movement	Time on court	To examine the relationship between time on court and intensity of movement activity

Author	Playing Level	Athletes (n)	Files (n)	Measurement Technique	Variables Investigated	Contextual Factors Examined	Study Purpose
Sampaio et al. (2006)	NBA; International Elite	252	Not reported	Notational Analysis	Technical skill measures	Playing position; League	Positional differences in technical skills between professional leagues
Ben Abdelkrim et al (2007)	International Junior	28	185	Video TMA;	Speed-based distances	Playing position; Time-course changes	Quantify the movement demands of individual playing positions.
Ben Abdelkrim et al (2010)	International junior elite	18	18	Computerized TMA; HR; Blood lactate	Speed-based movement; HR; Blood lactate; physical capacity testing measures	Playing position; Playing period	Examine competition demands of elite junior players; Explore fatigue in basketball competition; and to examine the relationship between players physical capacity and game performance
Montgomery (2010)	International Junior	11	456 (33 competition records)	Triaxial accelerometer; Heart Rate		Practice drills, game play	Describe the physical and physiological activity of basketball games and practice
Sampaio (2010)	International Elite	198	5309	Notational Analysis (Publicly available data)	Technical skill measures	Period of season; team quality; playing time	Identify factors effecting seasonal differences of game related statistics
Scanlan (2011)	International Elite; Sub Elite	22 (10 Elite / 12 Sub elite)	56 (20 Elite / 36 Sub Elite)	Video TMA	Speed-based movements	Playing position; Playing level	Describe activity demands of competitions and compare activity profiles between playing standards
Hulka et al (2013)	International Junior	32	192	Video TMA; Heart rate	Total distance; Speed-based distances; HR measures	Playing position	Describe the external (total distance and speed-based measures) and internal (HR measures) loading measures of junior elite game play

Author	Playing Level	Athletes (n)	Files (n)	Measurement Technique	Variables Investigated	Contextual Factors Examined	Study Purpose
Klusemann et al (2013)	International Junior	8	Not reported	Video TMA; Heart rate	Speed-based movements; HR measures; Tactical measures	Competition type	Describe and compare the internal and external training loads during different competition types.
Leser et al (2014)	Junior	13	20	UWB positional tracking system; Hand measured distance	Total distance		To assess the accuracy of an Ultra-Wide band system
Scanlan et al (2015)	International Elite and Sub Elite	22 (10 Elite/ 12 sub elite)	56	Video-based TMA	Speed-based distances and movement frequencies	Playing Level; Temporal changes;	Describe and compare the activity demands and temporal differences between playing levels
Scanlan et al (2015)	International Elite	8	Not reported	Video-based TMA	Movement based counts; Speed-based movements and distances	Playing position	Describe activity demands during competition
Mateus et al (2015)	NBA	417	14150	OTS (open source); Notational analysis (Publicly available data)	Speed-based measures; Technical performance measures	Playing quarter; Game location; Game outcome	Quantify the variation of physical activity and technical performance between competitions
Sampaio et al (2015)	NBA	548	1230	OTS (open source)	Speed based distance; Technical skill measures	Playing Status (All-Star vs non-All-Star)	Investigate performance variables discriminating playing status and playing clusters
Sampaio et al (2016)	International Elite	20	104	LPS	Speed-based distances; Technical skill measures	Tactical strategy	Investigate the influence of tactical strategy on physical activity and technical actions.
Torres-Ronda et al (2016)	International Elite	14	98 (7 competitions – 7 HR records / 3 TMA records each player)	Video TMA; Heart Rate;	Heart Rate; Speed based distances / frequencies	Playing position	Investigate the cardiovascular workload and activity demands positional differences.

Author	Playing Level	Athletes (n)	Files (n)	Measurement Technique	Variables Investigated	Contextual Factors Examined	Study Purpose
Puente et al (2016)	International Elite	25	25	GPS; Triaxial accelerometer; Heart Rate	Speed-based distances; Player impacts; Acceleration / Deceleration counts; Heart Rate; Physical and physiological performance-based tests	Playing position	Investigate the physical and physiological competitive demands in basketball.
Zhang (2017)	NBA	354	12,724	OTS (open source)	Speed-based distances; Technical skill measures	Playing Position; Team Quality; Game Outcome; Game Location	Investigate the physical and technical demands and variation by playing position accounting for contextual factors
Mateus et al (2018)	NBA	Not reported	Not reported	OTS (open source); Notational analysis (publicly available data)	Speed-based distances; Technical skill measures		Identify different playing profiles in NBA playoffs and to describe differences in performance between games in NBA playoffs
Vazquez-Guerrero (2018)	International Elite	12	199	Triaxial Accelerometer	Acceleration / Deceleration measures; Acceleration training load	Playing position	Comparison of positional based external loading within basketball games.
Caparros (2018)	NBA	33	2613	OTS	Speed-based distances; Acceleration counts; Technical performance	Season; Phase of season; Age; Location; Result; Injury	Investigate sport injury related risk factors.

Author	Playing Level	Athletes (n)	Files (n)	Measurement Technique	Variables Investigated	Contextual Factors Examined	Study Purpose
Svilar et al (2019)	International Elite	16	385 (177 Official games / 208 Internal team scrimmages)	Tri-Axial accelerometer; Gyroscope; Magnetometer	Acceleration /Deceleration measures	Game type	Quantify and compare physical activity measures in different game types
Scanlan et al (2019)	International sub-elite	5	20 (10 regulation / 10 overtime games)	Tri-Axial accelerometer; Gyroscope; Magnetometer; Heart rate; Subjective rate of exertion	Acceleration / Deceleration measures; HR measures; sRPE	Playing position; Playing quarter;	Quantify and compare the internal and external workload measures of regular and overtime games. Examine temporal changes in workload in overtime compared to other playing periods
Vazquez-Guerrero (2019)	International Junior Elite	94	Not reported	UWB positional tracking system	Speed-based distances; Player Load	Playing Position; Playing quarter; Team strength	Identify the temporal changes in physical activity.
Pino-Ortega (2019)	International Junior Elite	94	Not reported	UWB positional tracking system	Speed-based distances; Acceleration measures; Player Load	Playing Position; Game Period; Team Quality; Game Congestion	Describe the activity intensity profile and understand the situational factors affecting physical activity
Feroli et al (2020)	International elite, sub-elite, and amateur	136	Not reported	Video TMA	Speed-based distances;	Playing Position; Playing level	Examine physical activity demands between playing levels and the game variation of activity measures.
Garcia et al (2020)	International sub-elite	13	708	UWB positional tracking system	Speed-based distances; Acceleration/Deceleration measures	Playing Position; Game period	Examine activity demands between playing positions and temporal changes

UWB – ultra wide band, OTS – optical tracking system, LPS – local positioning system, TMA – time motion analysis, HR – heart rate, NCAA – National Collegiate Athletics Association, NBA – National basketball Association

Despite the high requirement for brief but frequent intense actions, the cardiovascular demands of basketball are also considerable. Indeed, the mean heart rate during competition has been demonstrated to vary between 87-95% of maximum heart rate (McInnes et al., 1995; Montgomery et al., 2010; Rodriguez-Alonso, Fernandez-Garcia, Perez-Lanadluce, & Terrados, 2003), whilst the mean and peak heart rate were reported to be 83.9% / 95.6%, 80.1% / 93.7%, and 81.5% / 92.7 for Guards, Forwards and Centres, respectively (Vaquera et al., 2008). Collectively, these studies show the stochastic nature of basketball games and highlight that players are required to have well developed anaerobic and aerobic fitness characteristics to allow them to compete these competitive demands.

Many studies have assessed the effect of playing position in physical activity demands in lower levels of basketball competition (Ben Abdelkrim, Chaouachi, et al., 2010; Ben Abdelkrim et al., 2007; Scanlan et al., 2011). In general, it has been shown in competition that Guards (point guards and shooting guards) cover ~2315 m at ~85.5 $m \cdot min^{-1}$ and perform ~31.2 and ~1.2 accelerations and ~24.8 and ~4.5 decelerations at <3 $m \cdot s^{-1}$ and >3 $m \cdot s^{-1}$, respectively. Forwards (small forward and power forward), on average cover ~2049 m at ~86.8 $m \cdot min^{-1}$, and perform ~27.35 and ~1.1 accelerations and ~22.85 and ~3.35 decelerations at <3 $m \cdot s^{-1}$ and >3 $m \cdot s^{-1}$. Finally, Centres were observed to covered 1227 m at 76.6 $m \cdot min^{-1}$ and performed 28.3 and 1.5 accelerations and 23.4 and 3.7 decelerations. Whilst these previous investigations provide insight into the positional demands of basketball game play; it is difficult to infer the results to NBA competition due to the level of play and method used to quantify physical activity. Recent investigations into NBA competitions have examined positional differences, however they have focused on technical skill positional differences and have only described positional activity differences in regards to global physical activity measures and situational factors, such as team strength (Zhang et al., 2017) and variation by playing time (Sampaio et al., 2015). These investigations have enhanced the knowledge of global activity in the NBA; however, they have failed to provide a more detailed understanding of the positional differences in physical activity of NBA competitions.

Understanding the positional specific differences in basketball is important when developing training programs (Stojanovic et al., 2018). The positional activity demands of NBA basketball cannot be inferred from previous studies, as the level of play is substantially higher than that of these populations, which could affect the demands placed on the athletes. Additional research is therefore required to further understand the positional activity demands in NBA basketball game play.

TEMPORAL DEMANDS

Previous research in basketball has shown temporal changes in the physical activity demands during game play (Scanlan, Tucker, et al., 2015; Vazquez-Guerrero et al., 2019). These studies demonstrate that all measures of high intensity activities were reduced over the duration of the game, with both studies finding the largest differences between the first and fourth quarters (Mateus et al., 2015; Scanlan, Tucker, et al., 2015). Furthermore, the overall activity velocities decreased between playing quarters, with effect sizes ranging from 1.7–5.0 (large to very large), the largest differences being between the second and fourth quarters (Scanlan, Tucker, et al., 2015). Similar results were found in elite junior competitions, where relative running distance ($m \cdot min^{-1}$), high-intensity running (%), and player load (i.e. the sum of the accelerations across all axes of the internal tri-axial accelerometer during movement, a.u./min) were greatest in the first quarter and were reduced throughout the game (Pino-Ortega et al., 2019). In contrast to previous studies, Pino-Ortega et al. (2019) demonstrated in international junior elite players, the largest decreases in relative distance and high intensity running between the 1st and 2nd quarters, which was the only study to report this relationship in basketball. Whilst speculative, these decreases in activity profiles across basketball games may be influenced by game related contextual factors or sub-conscious pacing strategies by the athletes. Collectively, however, this research is challenging to interpret given the different tracking systems used between studies as well as their divergent findings. To truly investigate if these influences exist in top-level basketball, studies are required on the NBA competition.

While these investigations demonstrate the relationship between physical activity demands and temporal measures of game play, we currently do not understand the temporal changes of physical activity within NBA games. Indeed, to our best knowledge, no studies have described the temporal changes in activity demands in NBA competitions.

Therefore, further examination of the temporal changes of physical activity within NBA game play is required in order to provide greater insight into the competitive demands.

VARIATION IN PHYSICAL PERFORMANCE VARIABLES

Basketball is an intermittent high-intensity team sport and there is a dynamic interplay between athletes on the same team and with athletes on the opposing team. As a result, measures of physical activity can show large variations between games. Practitioners and coaches utilize the physical activity measures to understand a player's individual performance and assess changes to performance over time. Greater understanding of the variation of these activity measures will assist practitioners in identifying reliable measures of physical activity and enhance the interpretation of meaningful changes in these measures. Objective data from other teams sports have indicated that game to game variation in physical activity within individual players may be multi-factorial, and based on both internal factors (e.g. individual fitness status, motivation) and external factors (e.g. opposition strength, technical ability, tactical approach, game outcome, game location and environment) (Mohr, Krustrup, & Bangsbo, 2003; Mohr et al., 2010; Rampinini, Coutts, Castagna, Sassi, & Impellizzeri, 2007). Whilst there remains limited information about the physical activity variation in basketball, recent investigations in basketball have reported that global measures of physical activity such as absolute total distance and relative distance ($m \cdot min^{-1}$) are relatively stable activity measures, however higher-speed activities demonstrate greater variability between games (Ferioli et al., 2020). These results are consistent with studies in soccer (Gregson, Drust, Atkinson, & Salvo, 2010; Rampinini et al., 2007), Australian football (Kempton, Sullivan, Bilsborough, Cordy, & Coutts, 2015) and rugby union (McLaren, Weston, Smith, Cramb, & Portas, 2016). In addition to establishing the variation of specific physical performance measures, some studies have examined the factors that may influence the variation of these activity measures. Investigations of global measures of physical activity variation in the NBA and have reported that the magnitude of the variability between games may be influenced by playing position (Mateus et al., 2015; Zhang et al., 2017). Zhang et al (2017), demonstrated that Guards exhibited the least variability in both physical activity and technical performance measures when compared to Forwards and Centres. We speculate that this is a result of the positional roles and responsibilities in tactical strategies and game management. In contrast, Mateus et al (2015), demonstrated the variation was inversely related to playing time and that across all playing time categories (short, medium, and long) Guards and Centres had greater with-in playing positions variability for total distance and average speed than Forwards. Although these two studies have examined the variation of activity in the NBA, they primarily focused on technical measures of performance and examined more general measures of physical activity (e.g. average game speed and distance). Therefore, additional research investigating the variation of physical activity measures in the NBA is warranted.

GAME RELATED CONTECXTUAL FACTORS

Playing level and Team Ranking

Recent studies have described the physical demands between different standards of basketball competition (Ferioli et al., 2020; Petway, Freitas, Calleja-Gonzalez, Medina Leal, & Alcaraz, 2020). Early research into playing level differences in both Tunisian and Australian elite and sub-elite junior competitions demonstrated (Ben Abdelkrim, Castagna, et al., 2010; Scanlan et al., 2011) that while there was no difference in total distance covered in game between elite and sub-elite, there were other physical activity demand differences. Most notably, these studies observed that elite competitions required greater intermittent physical activity demands and performed more total match movements when compared to sub-elite basketball competitions (Ben Abdelkrim, Castagna, et al., 2010; Scanlan et al., 2011). More recent research has examined the differences between athlete playing ability within the NBA, examining differences between All-Star and non-All-Star players (Sampaio et al., 2015) and strong and weak teams, with playoff teams classified as "strong teams" and non-playoff teams classified as "weak teams" (Zhang et al., 2017). It was demonstrated that stronger teams covered shorter distances (2.77 ± 0.18 km vs 2.81 ± 0.18 km, Effect Size (ES) = 0.21) and had lower average speed (4.15 ± 0.26 km·h^{-1} vs 4.20 ± 0.26 km·h^{-1}, ES = 0.20) than weaker teams (Zhang et al., 2017). Similar findings were also found when describing by playing position, with Guards and Forwards from stronger teams covering less total distance and running at lower speeds compared to their counterparts on weak teams. However, there were no differences found comparing Centres from strong or weak teams (Zhang et al., 2017). Researchers examining physical activity differences between player ability levels in the NBA (e.g. All-Star vs non-All-Star players) exhibited that, whilst total distance covered and average speed were not discriminating variables between these two groups, defensive velocity was lower in All-Star players when compared to non-All-Stars (5.87

± 0.26 vs 6.21 ± 0.32 km·h^{-1}) (Sampaio et al., 2015). It has been shown that in more global measures of physical activity (i.e. total distance covered and average speeds) there are trivial differences between playing abilities in the NBA. However, the more global measures of physical activity investigated in these studies may not provide sufficient detail of the more discrete activity differences between player ability and team strength. As a result, there remains limited information regarding the differences in physical activity between playing abilities within the NBA. Further research is therefore required to examine the relationship between measures of physical activity and team ranking and player ability within the NBA.

Game outcome

Whilst recent studies have compared physical activity profiles from teams of differing playing levels and abilities, other investigations have examined the influence of game result on physical activity profiles in basketball (Fernandez-Leo, Gomez-Carmona, Garcia-Rubio, & Ibanez, 2020; Fox, Stanton, Sargent, O'Grady, & Scanlan, 2019). Recent investigations in international sub-elite basketball athletes have demonstrated that external work load measures (e.g. PlayerLoad, impacts, steps, and jumps) were not influenced by the final quarter score or accumulated point difference (Fernandez-Leo et al., 2020). Though few studies have examined this relationship in basketball, these results have been reported to be have been reported to be in agreement with investigations in other sporting codes (Fox, Stanton, Sargent, O'grady, & Scanlan, 2019). For example, previous studies in both Australian Rules football (AFL) and soccer found that in less successful teams, there were increases in physical activity when trailing in competition (Di Salvo, Gregson, Atkinson, Tordoff, & Drust, 2009; Sullivan et al., 2014b). More specifically, Sullivan et al. (2014b) demonstrated that in AFL football, high speed running, and sprinting distances were increased during losing quarters. Similarly, in English Premier league soccer, there was a significant difference in the amount of high intensity activity between successful and less-successful teams, with less successful teams covering greater high speed running and sprinting distances (Di Salvo et al., 2009). While these studies demonstrate that specific measures of physical activity are influenced by game outcome in team sports, further research is required to examine this relationship in NBA basketball.

Game Location

In addition to research examining the physical activity and technical performance in basketball based on game outcome, recent studies have investigated the effect of game location on physical activity (Fernandez-Leo et al., 2020; Fox et al., 2019; Zhang et al., 2017). Early investigations examined the effect of game location on physical activity and demonstrated that there was no effect on total distance or average speed when comparing between away and home competitions (Zhang et al., 2017). Researchers also investigated the influence of game location on technical performance and demonstrated that when playing away there was a decrease in shooting percentage and defensive rebounds, as well as an increase in fouls committed (Sampaio & Janeira, 2017). In contrast, Zhang et al. (2017), examined game location on technical performance and found that fouls were the only technical variable shown to have greater variability when playing away. Whilst previous investigations have shown that certain technical performance variables are possibly affected due to game location, there remains limited information as to how game location influences physical activity profiles. Therefore, additional investigations are required to understand this relationship.

Seasonal Phase

The NBA regular season occurs over the course of 25 weeks (October – April), with several games played by each team each week. Due to the length of the season, it is possible that the phase of the season may influence activity profile of NBA players. Indeed, such observations have been made on other team-based sports that require prolonged, high-intensity, intermittent exercise and are play over extended seasons. Others have previously investigated the influence of seasonal phase on physical activity demands in team sports (Kempton et al., 2015; Rampinini et al., 2007). For example, researchers in Australian rules football (AFL) demonstrated that high speed running (3696 m (3552-3840 CI 95%) vs 3462 m (3336-3589 CI 95%), very high speed running (1145 m (1089 – 1200 CI 95%) v 1023 m (977 – 1070 CI 95%), sprint distance (459 m (427 – 490 CI 95%) vs 405 m (379 – 431 CI 95%), and sprint number (19.8 n (18.7 – 21.0 CI 95%) vs 17.9 n (16.9 – 18.9 CI 95%) were all increased at the end of the season when compared to the start respectively (Kempton et al., 2015). Similar results have been observed in Champions league football (soccer) players, as total distance (ES = 0.35), high intensity running (ES = 0.42), and very high intensity running (ES = 0.41) were greater at the end of the season compared to the start of the season (Rampinini et al., 2007). Investigations into this relationship collectively demonstrate that measures of physical activity are increased over the course of a competitive season. This is possibly due to improved player fitness and tactical strategies as well as seasonal rankings becoming more established. To date, however, the influence of the seasonal phase on physical activity has yet to be examined within the NBA.

Altitude

Previous research has shown that playing sport at high-altitude impairs aerobic-related physical activity outputs (Gore, McSharry, Hewitt, & Saunders, 2008). Investigations with highly-trained soccer athletes have demonstrated decreases in both total distance covered and high speed running distance in competitions played at altitude (3600 m) (Aughey et al., 2013). Comparing native altitude residents to non-altitude residents, researchers demonstrated that there were greater reductions in physical activity in non-altitude residents, who had a greater reduction in the peak 5-minute period for distance. Whilst this reduction was greater in the non-altitude residents, the relative reduction was similar for both groups (Aughey et al., 2013), therefore demonstrating that altitude induced reduction of physical activity is consistent regardless of a team's residence. Additionally, there was no effect on maximal accelerations between native and non-native teams when competing at altitude. Similar observations were made comparing elite Australian soccer players and Bolivian soccer players when competing at sea-level and at altitude (Buchheit et al., 2015), where the relative game intensities were reduced for both teams. These investigations help practitioners understand the potential effects of altitude on physical activity profiles, however they are case studies in nature. Unfortunately, however, these studies have focused on the relationship of altitude with physical activity and game performance in soccer, making comparisons to basketball competition difficult. Collectively these studies demonstrate that physical activity is reduced during competitions played at altitude. To our knowledge, no studies have examined the effect of altitude on physical activity in basketball. Therefore, given that the home stadiums of two NBA teams are situated at altitude (> 1200 m), further research is required to understand the effects of altitude on physical activity profiles in basketball.

The interconnection and influence of many situational factors found in team sport can have on the physical activity demands are presented in Figure 2.2. Collectively these studies demonstrate the influence of situational factors on the physical activity. Specifically, it has been shown that elite basketball competitions have a greater intermittent activity profiles than lower levels of competition. It is important to note that additionally, better teams tend to cover less total distance and have lower average speeds than weaker teams. Game outcome and game location were found to not influence physical activity measures. Though no studies have examined the effects of seasonal phase on activity demands in basketball, it has been demonstrated in other sports that activity measure increase over a competitive season. Moreover, the influence of altitude on activity demands has not been investigated in basketball, however in soccer, altitude has been demonstrated to reduce overall physical activity. Collectively these studies provide insight into the factors affecting physical activity in basketball and other team sports, however, there is limited information on how these factors affect activity demands in NBA game play.

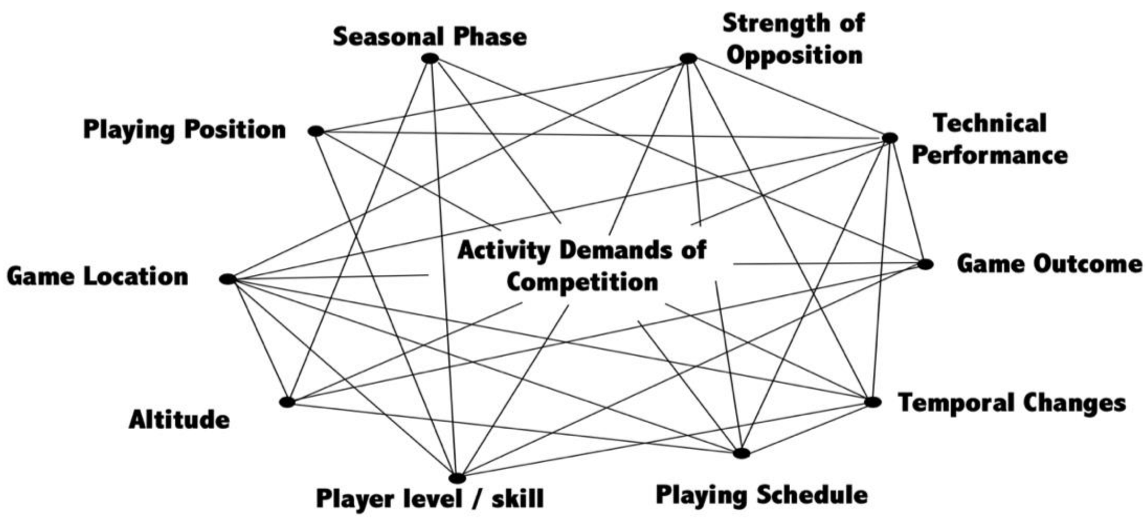

Figure 2.2. Conceptual model demonstrating the theoretical interactions between of various game contextual factors on activity demands in basketball.

TECHNICAL PERFORMANCE IN BASKETBALL

Technical skill (i.e. shooting percentage, free throw shooting percentage, rebounding) is an integral component of game play in team sports such as basketball. In recent years there have been several investigations into the technical performance in the NBA using optical tracking data and advanced statistical approaches (Chang et al., 2014; Goldsberry, 2012; Goldsberry & Weiss, 2013). These studies have provided greater understanding of specific aspects of technical performance that had previously been unable to quantify. For example, an investigation into a novel method to evaluate an NBA players shooting ability using visual and spatial analytics, described as range, determined that over the course of the 2006-2011 seasons, Steve Nash and Ray Allen (two All-Star players) had the best shooting range (i.e. percentage of scoring area a player averages more than one point per attempt) in the NBA at 31.6% and 30.1%, respectively) (Goldsberry, 2012). Additionally, other investigations have aimed to explore a greater range of technical skills in order to better understand technical game performance (Mateus et al., 2015; Sampaio et al., 2015; Zhang et al., 2017). These analyses provide insight into the technical requirements for the different positions and provide a detailed description of the various technical skills performed game play. For example, All-Star players were shown to outperform their non-All-Star counterparts in several technical performance variables specifically defensive rebounds, close touches, close points, pull-up points, and assists (Sampaio et al., 2015). Zhang et al. (2017) demonstrated that Centres and Forwards from stronger teams had greater success in made three-point shots, however they made less two-point shots than peers from weaker teams. In addition, researchers also determined Guards had the lowest variability amongst technical performance measures when compared to Forwards and Centres. These investigations utilized data obtained via a tracking system utilizing court location for a greater understanding of game statistics. However, whilst these investigations have enhanced our understanding of game performance in the NBA, they have focused on more discrete technical aspects of performance. For example, frequency counts of different technical skill activities offer one method of game performance analysis, however to provide a more sophisticated assessment of technical performance, others have attempted to develop a more holistic integrated performance measure by assigning subjective weighting – provided by an expert coach or analyst – to a range of important technical skill activities (Hollinger & Hollinger, 2005; Oliver, 2004). These analyses are useful for assessing individual player performance, independently of team performance, and may provide a more complete description of game performance due to their inclusion of multiple technical skill activities.

CONCLUSION

An increasing number of research studies have examined the physical, technical and tactical performance in basketball game play. This has been facilitated by the greater availability of micro-technologies such as wearable technologies including accelerometers and other wearable microsensors, or LPS and OTS to provide time-motion analysis of competition. The NBA utilizes an OTS and despite its league wide usage in quantifying physical and technical activities, the accuracy of this system has yet to be examined. Future investigations should therefore examine the accuracy of this system to allow teams, athletes and practitioners to assess this data with confidence. Moreover, while many studies now use general speed-based distances to describe the physical activity demands in the NBA, few studies have examined more discrete measures and activity requirements of game play that may provide a more detailed assessment of activity demands. Additionally, previous research in basketball and from other sport codes, has shown common physical activity measures vary between games, however, to date no studies have examined the variation of these measures within NBA competition. A greater understanding of the physical activity demands, and their variation may be useful in interpreting changes in performance for practitioners working in the NBA, allowing for enhanced game preparation and player care. In addition, further research is required to investigate situational factors that may affect physical activity and the variation in these measures of physical performance. Indeed, it is important to account for independent effects of contextual factors – such as game location, game outcome, seasonal phase, opposition strength, and altitude – which may influence performance during NBA game play. Lastly, an examination of the relationship between physical activity and technical performance may allow for an enhanced understanding of the interplay between these performance constructs as they relate to overall game performance and success. Despite research from other sports, reporting that technical and tactical skill may be more important determinants of game success than physical output, it is important to recognize that these are often related and should not be assessed in isolation.

CHAPTER THREE

MEASUREMENT PRECISION OF AN OPTICAL TRACKING SYSTEM FOR INSTANTANEOUS VELOCITY DURING BASKETBALL SPECIFIC ACTIVITIES

INTRODUCTION

Tracking systems that provide detailed information on athlete activity profile and technical involvements in competition are now common in most major professional sports. These systems provide information on players spatial positioning and can be used to assess athlete physical load (Carling, Bradley, McCall, & Dupont, 2016; Colby, Dawson, Heasman, Rogalski, & Gabbett, 2014) and provide data for tactical analysis (Bruce, 2016; Maheswaran et al., 2012; Sampaio et al., 2015). Such information can be used to inform athlete preparation, training strategies and to reduce injury risk (Aoki et al., 2016; Caparros et al., 2018; Ehrmann, Duncan, Sindhusake, Fanzen, & Greene, 2016; Vazquez-Guerrero, Suarez-Arrones, Gomes, & Rodas, 2018).

Many sports played outdoors have utilized wearable micro-technologies such as global position systems (GPS) to quantify player activity profile, however, this technology is unable to be used indoors due to the requirement for satellite availability (Roell et al., 2018). Therefore, alternate systems of player tracking that can be used indoors have been developed (Di Salvo, Collins, McNeill, & Cardinale, 2006; Harley, Lovell, Barnes, M.D., & Weston, 2011; Sampaio et al., 2015). For example, Optical tracking systems (OTS) (e.g., SportVU and SecondSpectrum) use fixed cameras and digital image recognition to track the spatiotemporal location of participants. These systems utilize athlete positional data to derive physical performance metrics (i.e. distance covered, running speed, accelerations, decelerations). Such data has been used to quantify the technical, tactical and physical demands of game play in the National Basketball Association (NBA) since 2013 (Caparros et al., 2018; Sampaio et al., 2015; Zhang et al., 2017). Despite measurement accuracy of optical systems being investigated in soccer (Buchheit, Allen, et al., 2014; Di Salvo et al., 2006; Harley et al., 2011; Randers et al., 2010), such analysis has yet been undertaken in basketball.

Determining the measurement accuracy of such athlete tracking systems is essential to allow confident interpretations of data both in the practical and research settings. Previous studies examining athlete tracking systems for team sports have assessed general indicators of activity such as total distance, distance in defined speed zones, number of accelerations / decelerations and peak speeds (Mateus et al., 2015). General descriptors of activity such as these are dependent on accurate measures of instantaneous velocity

(Luteberget, Spencer, & Gilgien, 2018; Varley et al., 2012). Therefore, determining the measurement accuracy of instantaneous velocity is critical for understanding the demands of indoor team sports, such as basketball. Accordingly, the aim of this study was to assess the validity an optical player tracking system for measuring instantaneous velocity during linear running on an indoor basketball court.

METHODS

PARTICIPANTS

Ten male recreational basketball subjects (age, 35.8 ± 7.3 years; body mass, 86.8 ± 12.9 kg; height, 181.7 ± 7.1 cm; mean ± standard deviation) volunteered to participate in this study. All participants received verbal and written information about the procedures of the study and gave signed consent to participate in the study. Informed consent and institutional ethics approval were obtained (HREC NO: ETH17-1847).

EXPERIMENTAL DESIGN

In order to determine the accuracy of the optical tracking system to measure instantaneous velocity, subjects were asked to perform 5 x 20 m linear sprints, with complete recovery between each repetition [approximately 5 minutes]. One trial for one participant was removed from analysis due to a recording error.

Testing was completed in a basketball arena (Cameron Indoor Stadium, Duke University, Durham, NC, USA), configured with an optical tracking system (SportVU). The arena was outfitted with 6 optical tracking cameras and were installed and configured as per manufacturer recommendations based on the specific venue. Instantaneous velocity was concurrently assessed using a Stalker Acceleration Testing System (ATS) II radar device (ATS Pro II version 5.020; Applied Concepts, Plano, TX, USA) and SportVU (STATS, Chicago, IL, USA) optical tracking system. Participants were instructed to run as fast as possible on a marked course, from a stationary standing starting position. The radar was positioned on a tripod 5 m behind the finish line of the sprint course [i.e. 25 m from the starting line] at the height of 1 m, approximate to the participants centre of mass. Radar data were sampled at 46.875 Hz and instantaneous velocity was determined following filtering in a proprietary software and exported to a Microsoft excel spreadsheet (version 16.18) for further analysis. Validity of radar to measure instantaneous velocity in linear sprinting has been previously determined in sprinting (r = 0.999) (Chelly & Denis, 2001; di Prampero et al., 2005).

The criterion measure of radar was compared to the optical tracking system, consisting of 6 fixed mounted cameras located above the playing court, each sampling at 25 Hz. Raw optical tracking data were filtered and processed by SecondSpectrum (SecondSpectrum, Los Angeles, USA). SecondSpectrum is the company that the NBA currently uses to manage and process the OTS data for game play.

STATISTICAL ANALYSIS

Prior to analysis, radar data were down sampled to 25 Hz to allow for a direct comparison to the OTS. Subsequently, dynamic time warping was used to align the start velocity curves between optical and radar data for each sprint effort. Such an approach has been previously used in human activity recognition research to match time series data (Muscillo, Conforto, Schmid, Caselli, & D'Alessio, 2007; Sempena, Maulidevi, & Aryan, 2011).

A K-means algorithm was applied to the instantaneous velocity data, seeded with four clusters, in order to create discrete velocity bands. A similar approach has been utilized in netball (Sweeting, Aughey, Cormack, & Morgan, 2017). K-means algorithm is an iterative method, which uses Euclidean distance, to create a user defined number of clusters of data within a given data set (Wu et al., 2007). The four clusters of instantaneous velocity were identified with centroids of 3.55, 12.08, 19.25, and 23.80 $km \cdot h^{-1}$, respectively (Figure 3.1) and were classified as "low", "medium", "high", and "maximal" velocity bands.

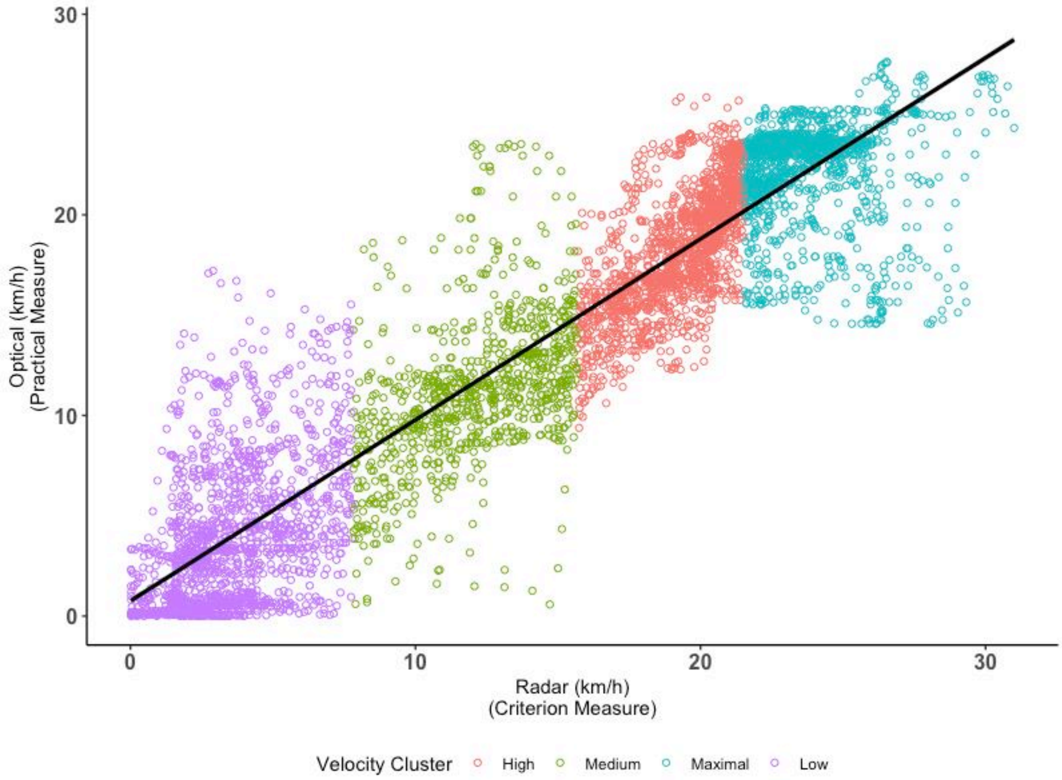

Figure 3.1: Instantaneous velocity by cluster (low, medium, high, and maximal). Black line is the line of equality and represents perfect agreement between the two systems within the respective cluster.

Accuracy of OTS instantaneous velocity for the pooled data and within each of the four velocity bands cluster Data were established through a linear regression model comparing the OTS (practical measure) to radar (criterion measure) (Bland & Altman, 1986). The agreement between radar and OTS was assessed via mean bias, standardized typical error of the estimate (standardized TEE). The association between the radar and the OTS measures were assessed using Pearson r (Hopkins, Marshall, Batterham, & Hanin, 2009).

Data are presented as mean and 95% confidence interval, unless otherwise stated. Standardized mean bias and standardized TEE were interpreted as: ≤0.02, trivial; >0.21-0.6, small; >0.61-1.2, moderate; >1.21-2.0, large; >2.1-4.0, very large; >4.1, extremely large (Hopkins et al., 2009). Pearson's correlation coefficient was interpreted as trivial (r < 0.1), small (r = 0.11 – 0.3), moderate (r = 0.31 – 0.5), large (r = 0.51 – 0.7), very large (r = 0.71 – 0.9), extremely large (r = 0.91 – .99), and perfect (r = 1.0) (Hopkins et al., 2009). All statistical analysis was performed in R statistical software (Version 3.5.2) (R Development Core Team, 2017).

RESULTS

Participants completed 49 total sprints with mean velocities of, 14.91 ± 8.22 and 14.21 ± 7.91 $km \cdot h^{-1}$, for our criterion and practical measures respectively. This provided 5299 instantaneous velocity samples. To examine narrower velocity bands we specified four clusters for analysis within the overall sample, low (range = 0.02-7.79 $km \cdot h^{-1}$: centroid = 3.55 $km \cdot h^{-1}$), medium (range = 7.82-15.66 $km \cdot h^{-1}$: centroid = 12.08 $km \cdot h^{-1}$), high (range = 15.68-21.52 $km \cdot h^{-1}$: centroid = 18.30 $km \cdot h^{-1}$), and maximal (range = 21.53-31.00 $km \cdot h^{-1}$: centroid = 22.31 $km \cdot h^{-1}$). Relationships between OTS and radar within each cluster are represented in Table 3.1. Overall, there was an extremely large correlation between OTS and radar (r = 0.93; 95% CI: 0.93, 0.93). However, when examined within velocity clusters the correlations dropped and ranged from trivial to large (Figure 3.2). Correlation between OTS and radar appeared to improve from low to high velocity bands, however, this relationship ranged from trivial to small in the maximal velocity band (r = 0.08; 95% CI: 0.02, 0.13). Additionally, in the maximal velocity band, the largest mean bias was expressed between the two systems with a moderate standardized TEE (TEE = 0.99; 95% CI: 0.96, 1.04).

Table 3.1. Comparison of instantaneous velocity between radar and optical tracking system (Mean ± SD).

Cluster	Velocity ($km \cdot h^{-1}$) Optical	Velocity ($km \cdot h^{-1}$) Radar	Mean Bias ($km \cdot h^{-1}$) Optical – Radar (CI 95%)	Standardized Mean Bias (CI 95%)	Standardized TEE (CI 95%)	Pearson r
Low	3.95 (± 3.60)	3.55 (± 1.92)	0.40 (-6.02, 6.82)	0.21 (-0.002, 0.42)	0.90 (0.87, 0.94)	0.43 (0.38, 0.47)
Medium	11.23 (± 3.90)	12.08 (± 2.31)	-0.85 (-7.60, 5.85)	-0.37 (-0.60, -0.14)	0.88 (0.84, 0.93)	0.47 (0.42, 0.52)
High	18.30 (± 3.03)	19.25 (± 1.60)	-0.96 (-5.40, 3.50)	-0.60 (-0.71, -0.58)	0.73 (0.71, 0.76)	0.68 (0.65, 0.71)
Maximal	22.31 (± 2.50)	23.80 (±1.81)	-1.50 (-7.25, 4.30)	-0.83 (-1.02, -0.71)	0.99 (0.96, 1.04)	0.08 (0.02, 0.13)
All Samples	14.21 (± 7.95)	14.91 (± 8.22)	-0.70 (-6.66, 5.30)	-0.99 (-0.21, -0.003)	0.37 (0.36, 0.38)	0.93 (0.93, 0.93)

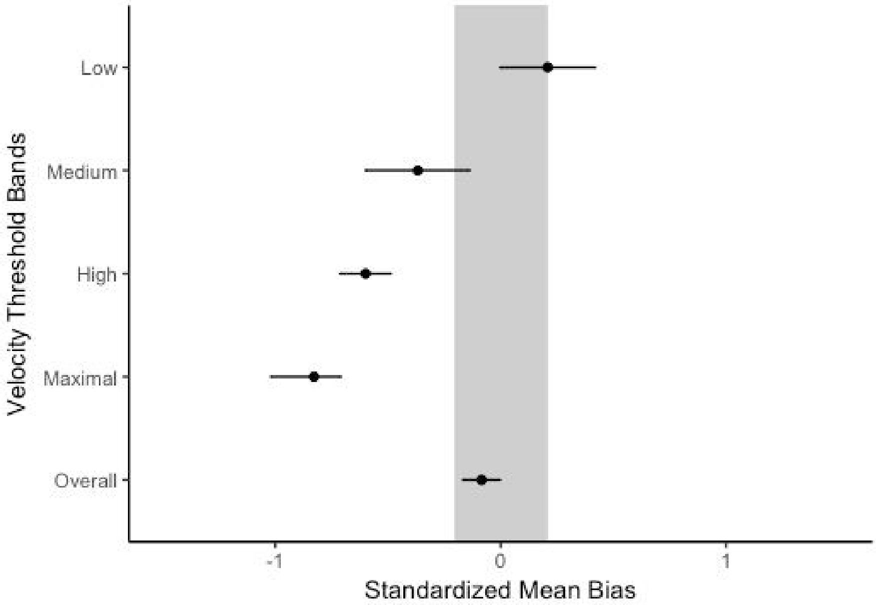

Figure 3.2: Standardized Mean Bias with velocity band (km·h^{-1}).

Low Velocity Band (0.02-7.8 km·h^{-1}: centroid = 3.55 km·h^{-1}); Medium Velocity Band (7.8-15.6 km·h^{-1}: centroid = 12.08 km·h^{-1}); High Velocity Band (15.6-21.5 km·h^{-1}: centroid = 18.3 km·h^{-1}); Maximal Velocity Band (21.5-31.0 km·h^{-1}: centroid = 22.31 km·h^{-1})

DISCUSSION

The present study was the first to investigate the accuracy of the OTS used in the NBA for assessing instantaneous velocity. The main finding was that mean bias between systems increased as instantaneous velocity increased. Overall OTS underestimated instantaneous velocity within the medium, high, and maximal clusters, while overestimating velocity in the low cluster. The standardized TEE was higher within the low and maximal velocity cluster, with lower TEE exhibited in the medium and high velocity cluster. Although there was an extremely large correlation between the two systems across the entire sample of instantaneous velocity data, within discrete and narrower velocity ranges correlations were smaller and ranged from moderate to large between the low, medium, and high velocity cluster, with a trivial correlation displayed in the maximal velocity cluster.

The results showed that the optical tracking system underestimated the instantaneous velocity overall by 0.7 km·h^{-1} (95% CI, -6.66-5.30). This underestimation increased from a 0.85 to 1.50 km·h^{-1}with an increase in velocity. In the low velocity cluster, however, optical tracking system overestimated velocity by 0.4 km·h^{-1} (95% CI -6.02-6.82). Moreover, the 95% LOA remained wide in all clusters, demonstrating a lack of accuracy with the OTS in all velocity clusters. The standardized TEE was small 0.37 (95% CI, 0.36-0.38) when the Data were assessed across the entire sample. However, the standardized TEE was large when assessed within discrete velocity ranges, ranging from 0.73 (95% CI, 0.71-0.76; High), 0.88 ((95%, 0.84-0.93; Medium), 0.90 (95% CI, 0.87-0.94; Low) to 0.99 (95% CI, 0.96-1.04; Maximal), respectively. These differences were reduced as velocity increased, with the exception of the maximal velocity cluster. While not directly comparable, the current findings are similar to those of Rampinini et al. (2015), who reported that GPS underestimated velocity when compared to radar with an increasing bias as velocity increased. In contrast, Linke et al. (2018) showed increasing error between OTS and an infrared camera based motion capture system as velocity increased. Based on the current findings, caution should be used by the practitioner when using the OTS for assessing instantaneous velocity across narrow activity bands.

Overall, the optical tracking system showed a very high correlation (Hopkins, 2002), (r = 0.93 (0.93, 0.93), compared to our criterion measure of radar, when calculated using the entire velocity range. When examined in the different velocity clusters, however, the association between the OTS and radar decreased and appears velocity dependent as the correlation was lowest, 0.08 (95% CI: 0.02, 0.13) in the maximal velocity cluster. Direct comparison of the current findings to other research is not possible, as no other studies have compared this OTS to radar in order to assess instantaneous velocity. However, we are able to compare our results to other studies that have investigated the validity of instantaneous velocity using athlete tracking systems such as GPS (Varley et al., 2012) and OTS (Linke et al., 2018). Varley et al. (2012) demonstrated a decrease in correlation between GPS and criterion measures of laser during straight line running as velocity increased. These findings differ compared to ours as we observed an increasing correlation between OTS and radar, until the maximal velocity band was reached. A possible reason for the lack of agreement may be differences in sampling rates between OTS (25 Hz) and the GPS units (10 Hz) used by, to different sprint start mechanics (static start vs. flying start) Varley et al. (2012). Similar to findings by Linke et al. (2018) the current study demonstrated an increase in error as velocity increased.

This is the first study to examine the validity of optical tracking system for measuring instantaneous velocity indoors, however, it is not without limitations. Direct comparison to other studies is difficult due to differing criterion measures (Linke et al., 2018), technology assessed (Luteberget et al., 2018), and activities performed (Varley et al., 2012). In addition, we cannot exclude that the synchronization and data filtering methods influenced the magnitude of these differences, but it is unlikely that the large confidence intervals (i.e. low agreement) may be explained by approximations due to synchronization and data filtering. This study was limited in its specificity to basketball movement demands as athletes frequently change direction during competition (Scanlan et al., 2011), whereas only linear running was assessed, which is probably a less challenging condition for the optical system. Future research should investigate the validity of optical tracking technology for measuring velocity during non-linear movements. Future studies should also seek to establish the measurement reliability of the OTS, given its daily use during competition in professional sport since even if not accurate their reliability may be acceptable to track changes over time. Accordingly, the between-venue reliability of this OTS should be investigated across the 29 NBA arenas, where competition is played. Previously reported research examining OTS and linear position system (LPS) have shown increasing measurement error on the edge of the playing court (Luteberget et al., 2018; Pers et al., 2002). It is important to note that in the current study, sprint trials occurred close to the sideline. It is not known if the OTS exhibits similar error to that of LPS based on movement activity location relative to the court. Therefore, this potential limitation should be investigated in future research to ensure that practitioners can confidently interpret game data.

CONCLUSION

As an aggregate measure of velocity, the OTS appears to have greater validity than when used across discrete velocity clusters. This is due in part to larger error observed in the low and maximal ranges. Accordingly, practitioners can use this data as a global proxy for game loads, which may be useful in directing training and recovery strategies between games. Moreover, such data should be evaluated for its utility in identifying difference between positional groups during games and within varying game contexts.

Based on the current findings, the OTS is not appropriate due to low accuracy for assessing instantaneous velocity within discrete activity bands at individual level. However, the accuracy of OTS may be adequate when used to derive averaged measures at group level. As a consequence, this optical system seems to be of limited usefulness for individual training monitoring but it may be acceptable for defining the activity profile in basketball games and training as long as the velocity derived data are examined at group level (e.g. team or playing positions level) and as average of speed bands.

CHAPTER FOUR

QUANTIFYING THE PHYSICAL ACTIVITY DEMANDS AND THE GAME TO GAME VARIATION IN NBA COMPETITION

INTRODUCTION

Basketball is one of the most popular global sports, with 450 million participants and being played professionally in over 200 countries (FIBA.com, 2015). The National Basketball Association (NBA) is the highest level of basketball competition in the world, consisting of 30 teams, each playing 82 regular season games over 25 weeks across 29 different cities within the United States. Despite the NBA being the highest level of basketball competition, very little is known about the physical game demands of the athletes competing in this league (McLean et al., 2019).

Previous research describing the training and competition demands of basketball has focused on the lower levels of competition (i.e. youth, amateur or semi-professional) (Ben Abdelkrim et al., 2007; Montgomery et al., 2010), or professional leagues in Europe and Australia (Ben Abdelkrim, Chaouachi, et al., 2010; Klusemann et al., 2013; Puente et al., 2016; Scanlan et al., 2011; Schelling & Torres, 2016; Torres-Ronda, Ric, Llabres-Torres, de Las Heras, & Schelling, 2016). From a positional standpoint, this research showed that Guards reached higher speeds (24.0 - 1.6 $km \cdot h^{-1}$), and produced higher counts of accelerations and decelerations (8.0 - 2.0 /min) than Forwards or Centres, respectively (Puente et al., 2016). Collectively, these studies demonstrated that in higher-level competitions the physical performance demands placed on players is increased when compared to lower level competitions (Ben Abdelkrim, Castagna, et al., 2010; Scanlan, Dascombe, Kidcaff, Peucker, & Dalbo, 2015; Scanlan et al., 2011). Despite being the highest level of competition, it is not clear whether these findings would still hold when evaluating the physical demands within the NBA.

Recent research has described the technical and physical performance demands in the NBA using the in game optical tracking system data which has been collected since 2013 (Caparros et al., 2018; Maheswaran et al., 2012; Mateus et al., 2015; Sampaio et al., 2015). These studies have investigated novel approaches to exploring in game tactical behaviour between higher and lower performing NBA players and demonstrated that all players had better technical performance (i.e. skilled performance within 12 ft (~3 m) of the basket) when closer to the offensive basket, no differences however, were observed in the physical activity requirements (e.g. distance covered and average speed) between higher and lower performing players (Sampaio et al., 2015). This could be due to the limited physical metrics examined in this study and the sensitivity of those metrics to differentiate higher and lower performing players. Unfortunately however, these studies have only provided limited insight into the demands of the NBA as they have described the global technical data (e.g. shot location and frequency, rebound distribution) and general physical activity demands (i.e. total distance and mean speed) (Sampaio et al., 2015) or have been limited to case studies of a single team (Caparros et al., 2018). Despite the league wide application of this data, there remains a poor understanding of the physical activity demands in the NBA and how they vary across positions, playing periods, and games.

In addition to the limited data on the physical activity demands of NBA competitions, there is a poor understanding of the game variation in these measures. The game to game variation of physical activity measures has been demonstrated in other sports including rugby, Australian rules football, and soccer there remains limited data on the variation found in basketball. A recent investigation into the physical activity variation in NBA game play demonstrated that the game to game variability of global measures of physical activity (i.e. average distance and average speed) was low across playing positions. The game to game variation, however, was related to playing time, with an increase in variation as playing time was reduced (Zhang et al., 2017). Whilst this investigation examines the game to game variation in NBA game play, it is explored gross measures of physical activity and it is difficult to derive a complete understanding of the variation of physical activity found in NBA competition.

Therefore, the aim of the study is to provide a detailed description of the physical performance demands of the NBA. Specifically, this study aims to investigate the differences in physical performance demands across playing positions, the temporal changes in activity profiles within games, and the variability of these measures between games. This information will enable practitioners to identify reliable physical performance measures to monitor and interpret meaningful changes in performance of athletes competing in the NBA.

METHODS

Design

This study retrospectively examined game captured data at each NBA stadium using an optical tracking system (OTS), which consists of six cameras fixed above the playing surface, each sampling at 25 Hz. Following each game, OTS Data were processed by SecondSpectrum (SecondSpectrum, Los Angeles, USA), the official company the NBA uses to manage and process the OTS data for match play. The Data were then exported by members of the research team to a Microsoft excel spreadsheet for further analysis (Microsoft, Redmond, USA). The variables used to investigate physical activity included total distance (m), high intensity running (>14.4 $km \cdot h^{-1}$), count of high intensity running efforts (effort performed >14.4 $km \cdot h^{-1}$), count of total accelerations, and count of high accelerations (>3.5 $m \cdot s^{-2}$). Each variable was examined on both an absolute and a relative per minute basis. These variables were selected as they are similar to those used in previous research in basketball (Puente et al., 2016; Sampaio et al., 2015) and are consistent with the game variables provided to practitioners working within NBA teams. Despite some limitations, the OTS has recently been shown to be a valid measure for assessing running velocity in the aggregate, absent of discrete velocity bands (D'Amelio, Ward, Bilsborough, & Coutts, 2018).

Participants

An inclusion criterion was established whereby athletes who participated in a minimum of two games per season and played in 17.5 minutes of the total game, which represented the 25th percentile of total minutes played across the player population within the complete data set, were retained for analysis. Five hundred and four professional basketball players (age: 26.7 ± 2.0 y) competing in regular season matches over the course of two seasons (2015-2016 and 2016-2017) met these criteria and were included in this study. This resulted in 39,962 total game observations. To examine the physical performance differences by positions, athletes were categorized into three positional groups, Guard (n = 201), Forward (n = 221), and Centre (n = 100), as identified by the NBA. Additionally, to examine the physical demands by playing quarter an inclusion criterion was established whereby athletes who competed in a minimum of two games per season and played in 4.77, 5.45, 4.99, and 4.95 minutes respectively for playing quarters 1-4, which corresponded to the 25th percentile of minutes played for each of the playing quarters were retained for analysis. A total of 135,806 observations (Q1 = 33,705, Q2 = 35,365, Q3 = 33,137, Q4 = 33,599) met these criteria and were included in the analysis. Institutional ethics approval has been obtained (HREC NO: ETH17-1847).

Statistical analysis

Visual plots of the data were used to confirm a normal distribution for the six physical activity variables, which are presented as mean and standard deviation, unless otherwise noted. Within athlete game-to-game variation was determined for each physical performance variable by calculating the standard deviation for each group of repeated performance for each athlete and dividing by the corresponding mean value for that individual (Hopkins et al., 2009). The between match coefficient of variation (CV%) were calculated by dividing the standard deviation of repeated performance data by the corresponding mean value for each athlete. A one-way ANOVA was used to compare differences in physical performance variables across playing positions and game quarters. When significant main effects were observed, Tukey post hoc test was applied. Standardized effect sizes (ES) were interpreted as <0.2, small; >0.2–0.8, moderate; >0.8-1.3 large; >1.3, very large (Cohen, 1988). Statistical significance was set at an alpha level of 0.05. All statistical analysis was performed in R statistical software (Version 1.1.383) (R Development Core Team, 2017).

RESULTS

The mean absolute total distance (TD), high speed running (HSR), high speed efforts (HSE), and total accelerations ($Accel_T$) and high accelerations ($Accel_H$) were 3103 ± 1044 m, 694 ±255 m, 78 ± 29, and 188 ± 64, 18.9 ± 9.8 respectively. When HSR, HSE, $Accel_T$, and $Accel_H$ were expressed per minute these measures were 24 ± 6 $m \cdot min^{-1}$, 2.8 ± 0.6, 22 ± 10, and 7.0 ± 0.8 respectively. The current data showed that Guards and Forwards had greater minutes played when compared to Centres (Guard = 29 ± 5, Forward = 29 ± 5, Centre = 27 ± 5). Table 4.1 shows the physical performance demands for each playing position. Post hoc analysis revealed differences in total distance across positions were moderate in their effect (ES = 0.20 – 0.49), with Guards covering the greatest distance in games. Forwards covered greater distance at high speed than compared to Centres and Guards in absolute and relative terms, however the differences ranged from small to moderate (ES = 0.15 - 0.48). Guards completed a moderately greater number of high intensity efforts, both in absolute (ES = 0.26 – 0.85) and relative (ES = 0.33 - 0.74) terms than did forwards and Centres. Guards performed a greater number of $Accel_T$ (ES = 0.34 – 0.67) and there were moderate to very larges differences in the number of $Accel_H$ (ES = 0.7 – 1.6) when compared to Forwards and Centres.

Table 4.1. Physical activity requirements according to playing position. Mean (± SD)

Physical Activity	Centres	Forwards	Guards
Total Distance (m)	2884 ± 492 [bc]	3138 ± 545 [a]	3246 ± 545 [a]
Total Distance ($m \cdot min^{-1}$)	106 ± 5 [bc]	109 ± 5 [a]	109 ± 5 [a]
High Speed Running (m)	678 ± 149 [b]	744 ± 161 [ac]	698 ± 133 [b]
High Speed Running ($m \cdot min^{-1}$)	23.3 ± 5.3	26.1 ± 5 [c]	23.8 ± 4.1 [b]
Total Accelerations (n)	185 ± 32 [bc]	196 ± 33 [ac]	206 ± 34 [ab]
Total Accelerations (n/min	6.84 ± 0.73	6.79 ± 0.62 [c]	7.00 ± 0.67 [b]
High Accelerations (n)	16 ± 6 [bc]	20 ± 5 [ac]	25 ± 5 [ab]
High Accelerations / min	0.60 ± 0.24 [bc]	0.70 ± 0.21 [ac]	0.85 ± 0.18 [ab]
High Speed Efforts (n)	75 ± 15 [bc]	83 ± 17 [ac]	87 ± 15 [ab]
High Speed Efforts /min	3.40 ± 0.67 [bc]	3.60 ± 0.63 [ac]	3.84 ± 0.57 [ab]
Minutes (n)	27 ± 5 [bc]	29 ± 5 [a]	29 ± 5 [a]

Centres (100 players, n = 7292); Forwards (221 players, n = 17,8467); Guards (183 players, n = 14,824)

[a] Significantly ($p < 0.05$) different than Centres; [b] Significantly ($p < 0.05$) different than Forwards; [c] Significantly ($p < 0.05$) different than Guards.

Game-to-game variation by playing position is shown in Table 4.2. Guards exhibited the most game variability when compared to Forwards and Centres on both absolute and relative terms. Centres however, exhibited the greatest variation in HSE on a per minute basis (ES = 0.32 – 0.45) and $Accel_H$, both absolute (ES = 0.32 – 0.66) and relative (ES = 0.54 – 1.0) when compared to Forwards and Guards, respectively.

Table 4.2. Game to game variation of physical activity variables by playing position.

Physical Activity	Centres CV % [±SD] (range)	Forwards CV % [±SD] (range)	Guards CV % [±SD] (range)
Total Distance (m)	19 ± 4 (9 – 31)	20 ± 5 (4 – 42)	21 ± 5 (4 – 39)
Total Distance /min	4 ± 1 (2 – 5)	4 ± 1 (1 – 6)	4 ± 1 (1 – 5)
High Speed Running (m)	22 ± 4 [bc] (12 – 39)	23 ± 5 [a] (9 – 40)	24 ± 5 [a] (11 – 37)
High Speed Running /min	16 ± 4 (3 – 25)	15 ± 3 (6 – 30)	16 ± 3 (6 – 30)
Total Accelerations (n)	20 ± 4 [bc] (6 – 28)	21 ± 4 [a] (6 – 44)	22 ± 5 [ab] (6 – 41)
Total Accelerations /min	8 ± 2 [b] (4 – 12)	8 ± 2 [a] (1 – 12)	8 ± 2 (4 – 14)
High Accelerations (n)	37 ± 9 [bc] (13 -67)	34 ± 7 [ac] (10 – 71)	32 ± 6 [ab] (16 – 50)
High Accelerations / min	34 ± 1 [bc] (15 – 75)	29 ± 9 [ac] (0 – 100)	25 ± 6 [ab] (1 – 46)
High Speed Efforts (n)	21 ± 5 [bc] (3 – 33)	23 ± 5 [a] (7 – 42)	23 ± 4 [a] (10 – 35)
High Speed Efforts /min	14 ± 3 [bc] (9 – 29)	13 ± 3 [a] (5 – 22)	13 ± 2 [a] (6 – 21)
Minutes (n)	20 ± 4 [c] (8 – 29)	21 ± 5 (5 – 43)	21 ± 5 [a] (2 – 40)

[a] Significantly ($p < 0.05$) different than Centres, [b] Significantly ($p < 0.05$) different than Forwards, [c] Significantly ($p < 0.05$) different than Guards.

Table 4.3 shows the physical performance demands by game quarter. Differences between playing quarters were observed across all absolute physical performance measures. The magnitude of such differences, however, ranged from small to moderate effect (ES = 0.02 – 0.55). When examined on a relative basis the differences in demands between playing quarters were larger. The first and fourth quarters showed the greatest differences with effect sizes ranging from 1.0 – 1.28 for HSE/min, HSR/min and TD/ min respectively. $Accel_T$ and $Accel_H$ conversely, showed greater differences in absolute terms between the first and fourth quarters than with relative terms, however these differences were remained small with ES 0.54 and 0.45.

Table 4.3. Physical activity demands in each playing quarter.

Physical Activity	1st Quarter	2nd Quarter	3rd Quarter	4th Quarter
Total Distance (m)	923 ± 173 [d]	905 ± 96 [d]	919 ± 155 [d]	964 ± 117 [ab]
Total Distance ($m \cdot min^{-1}$)	112 ± 5.5 [bcd]	110 ± 5.6 [acd]	108 ± 5.2 [abd]	105 ± 5.3 [abc]
High Speed Running (m)	226 ± 53 [cd]	220 ± 44 [cd]	208 ± 45 [ab]	202 ± 47 [ab]
High Speed Running /min	28 ± 5.6 [cd]	27 ± 5.3 [cd]	25 ± 5 [abd]	22 ± 4.8 [abc]
Total Accelerations (n)	57 ± 9.8 [d]	58 ± 6.8 [d]	58 ± 9.4 [d]	62 ± 8.9 [abc]
Total Accelerations /min	6.9 ± 0.72 [cd]	7.1 ± 0.69 [cd]	6.8 ± 0.72 [ab]	6.7 ± 0.66 [ab]
High Accelerations (n)	5.9 ± 1.9 [bd]	6.4 ± 2 [ad]	6.1 ± 2 [d]	6.8 ± 2.3 [abc]
High Accelerations / min	0.73 ± 0.26 [b]	0.78 ± 0.25 [acd]	0.72 ± 0.24 [b]	0.74 ± 0.23 [b]
High Speed Efforts (n)	25.6 ± 5.4 [cd]	25.1 ± 4.3 [c]	24 ± 4.7 [ab]	24.3 ± 4.9 [a]
High Speed Efforts /min	3.14 ± 0.49 [bcd]	3.06 ± 0.48 [acd]	2.84 ± 0.46 [abd]	2.66 ± 0.46 [abc]

1st Quarter (n = 33,705); 2nd Quarter (n = 35,365); 3rd Quarter (n = 33,137); 4th Quarter (n = 33,599).

[a] Significantly ($p < 0.05$) different than first quarter; [b] Significantly ($p < 0.05$) different than second quarter; [c] Significantly ($p < 0.05$) different than third quarter; [d] Significantly ($p < 0.05$) different than fourth quarter.

Game variation by playing quarter, Table 4.4, shows that that the largest variation occurs in the fourth quarter in both absolute and relative measures. When comparing the fourth and first quarter on an absolute basis, TD, HSR, $Accel_T$, and HSE had large ES, (1.0, 1.0, 1.2, 1.1) respectively. When examined on a relative basis ES were reduced, however the largest differences remained between the fourth and first quarters.

Table 4.4. Game to game variation in physical activity measures by playing quarter.

Physical Activity	1st Quarter CV % [±SD] (range)	2nd Quarter CV % [±SD] (range)	3rd Quarter CV % [±SD] (range)	4th Quarter CV % [±SD] (range)
Total Distance (m)	23 ± 6 [cd] (4 – 44)	23 ± 5 [cd] (2 – 41)	24 ± 6 [abd] (5 – 43)	30 ± 6 [abc] (4 – 540
Total Distance /min	5 ± 1 [bcd] (1 – 11)	6 ± 1 [ad] (0 – 10)	6 ± 1 [ad] (1 – 10)	6 ± 1 [abc] (1 – 10)
High Speed Running (m)	30 ± 6 [cd] (8 – 48)	31 ± 6 [cd] (5 – 42)	32 ± 6 [abd] (12 – 58)	37 ± 7 [abc] (6 – 64)
High Speed Running /min	21 ± 5 [cd] (2 – 41)	22 ± 5 [cd] (6 – 41)	23 ± 5 [abd] (4 – 46)	25 ± 5 [abc] (7 – 48)
Total Accelerations (n)	24 ± 6 [cd] (5 – 48)	25 ± 4 [cd] (12 – 44)	26 ± 6 [abd] (7 – 45)	31 ± 6 [abc] (5 – 57)
Total Accelerations /min	12 ± 2 [cd] (1 – 21)	12 ± 2 [cd] (2 – 18)	12 ± 3 [ab] (4 – 32)	13 ± 2 [ab] (1 – 22)
High Accelerations (n)	50 ± 13 [d] (11 – 200)	50 ± 12 [d] (15 – 124)	51 ± 12 [d] (16 – 146)	54 ± 12 [abc] (6 -141)
High Accelerations / min	48 ± 15 (11 – 200)	46 ± 15 (0 – 200)	48 ± 15 (11 – 200)	47 ± 15 (0 – 200)
High Speed Efforts (n)	29 ± 6 (7 – 48)	29 ± 5 (9 – 51)	31 ± 6 (4 – 53)	35 ± 6 (4 – 64)
High Speed Efforts /min	18 ± 4 [cd] (0 – 37)	19 ± 4 [cd] (3 – 35)	20 ± 4 [abd] (6 – 39)	21 ± 4 [abc] (3 – 46)

1st Quarter (n =33,705); 2nd Quarter (n = 35,365); 3rd Quarter (n = 33,137); 4th Quarter (n =33,599).

[a] Significantly ($p < 0.05$) different than first quarter; [b] Significantly ($p < 0.05$) different than second quarter;

[c] Significantly ($p < 0.05$) different than third quarter; [d] Significantly ($p < 0.05$) different than fourth quarter.

DISCUSSION

This is the first paper to provide a detailed examination of the in-game physical performance demands of NBA players. The aim of this study was to describe the physical demands from a positional and temporal perspective on both absolute and relative terms. Additionally, we examined the game variability of these physical demands between playing positions and game play quarters. The main findings of this study were that there were physical performance differences between positions, with Guards and Centres having the largest positional differences. In addition, there were temporal changes between playing quarters, with the first and fourth quarters having the largest differences. The between game variability analysis showed that the fourth quarter to have the greatest variability in physical performance of the four playing quarters. The findings of this study may assist practitioners in identifying quantifiable training targets that can best prepare athletes for NBA match-play based on their positional requirements.

We observed positional differences in the physical performance demands during game play which is similar to previous studies in basketball (Ben Abdelkrim et al., 2007; Scanlan et al., 2011; Scanlan et al., 2012; Vazquez-Guerrero et al., 2018), and other team sports including soccer (Carling et al., 2016; Gregson et al., 2010), Australian-Football (Kempton et al., 2015), and rugby (Sirotic et al., 2011). Specifically, Guards covered greater TD and completed a greater number of HSE, both in absolute and relative terms when compared to Centres and Forwards, which is consistent with earlier research in basketball (Ben Abdelkrim et al., 2007). However, in contrast to earlier research (Vazquez-Guerrero et al., 2018) our data showed that Centres completed the least amount of $Accel_H$, both in absolute and relative measures. This could be due to a relatively small sample size (n = 12), the differing competition levels, and/or the technology used in previous research. The current study showed Guards performed more $Accel_T$ and $Accel_H$ in game play compared to Centres and Forwards. These results are consistent with the general technical and tactical roles and responsibilities of these positions within NBA competition. Centres typically play closer to the basket and therefore cover a smaller area on both offense and defence. In contrast, a Guard's typical role within a team is to set up the offensive strategy and attack the basket while on offense and conversely on defence must cover their positional counterpart who run similar patterns.

We observed that the game-to-game variation of physical performance demands by playing positions, total distance was the most stable of the physical performance measures and that the variability increased as speed increased. These findings are in agreement with similar studies from different team sports (Al Haddad, Mendez-Villanueva, Torreno, Munguia-Izquierdo, & Suarez-Arrones, 2018; Carling et al., 2016; Gregson et al., 2010;

Kempton et al., 2015). When examined on an absolute basis our results demonstrate greater game-to-game variation than those found in other sports in terms in both total distance and higher intensity activities. This is potentially due to the sample size of the current data set and the wide range of playing time by each athlete. However, when calculated for relative time on court, our results are consistent with those found in other sports for both total distance and higher speed and intensity activities.

The present results show that for absolute values, guards showed the most variation in total distance when compared to Forwards and Centres. However, when analysed relative to time, the game to game variation of Guards was reduced and became similar to other the other positions. The exception to this was in regard to high intensity activities where Centres exhibited the greatest variation in both absolute and relative measures in the number of $Accel_H$, as well as having higher game variation in HSE/min than Forwards and Guards. There is limited research on the game variation of physical performance by position within basketball competitions, thus making any direct comparisons to other basketball research difficult. These results are consistent with the more variable tactical nature of the Centre position in the NBA based on game strategy and opposition, where the Centre is often tasked with protecting the basket defensively and to strategically create space for offensive opportunities.

We observed differences in physical performance measures between quarters. The differences in the absolute values ranged from small to moderate, however, when examined relative to playing time these differences became more evident. Specifically, the current data showed the first quarter has differences in physical performance measures compared to the fourth quarter, with effect sizes ranging from small to large. These results are similar to previous basketball research (Scanlan, Tucker, et al., 2015), which also showed the largest differences in physical activity coming between the first and fourth quarters. The overall reduction in the intensity of physical activities across playing quarters could be multifactorial and be due not only to player fatigue but also tactical decisions and game state (e.g., point differential, offensive pacing, player substitutions, foul strategies) (Sullivan et al., 2014b). In general, our results are similar to previous research in basketball (Scanlan, Tucker, et al., 2015), and other team sports such as soccer (Carling et al., 2016) and rugby (Kempton, Sirotic, & Coutts, 2014), which showed the intensity of activities decreased throughout the match. However, in contrast to Scanlan, Tucker, et al. (2015), who showed that all high intensity measures decreased during competition, our findings demonstrated in absolute terms $Accel_T$ and $Accel_H$ increased over the duration of games and remained somewhat stable over the game relative to time on court. Whilst these measures have a moderate effect size in absolute terms, 0.54 and 0.45 respectively, we speculate however that the increases in $Accel_T$ and $Accel_H$ may be due to potential game outcome and the resulting shift in tactical strategy, which has been demonstrated in other sports (Sullivan et al., 2014b). Further investigation into situational and individual game related contextual factors may provide insight as to cause of these changes in activities.

The current study shows the greatest variation of physical activity measures occurs in the fourth quarter both in absolute (% CV 30-54) and relative (% CV 6-47) terms. Greater variation in the fourth quarter could be due to several factors such as game strategy, match outcome, player substitutions, and sub-conscious pacing strategies. There is limited research regarding the temporal variation of physical performance measure in the sport of basketball, thus making comparison to previous sport related research difficult. Results from the current study are consistent with previous research from other sports (Al Haddad et al., 2018; Carling et al., 2016) and showed an increase in the variation of these physical performance measures across the game.

CONCLUSION

This is the first study to demonstrate that physical demands vary both amongst position groups and within games in the NBA. The results demonstrate that unique positional activity profiles exist in the NBA. Specifically, Guards performed more acceleration and higher intensity efforts than forwards and Centres, while forwards cover greater distances at high speed. Guards demonstrated the most variability for all physical performance metrics within position, with the exception of $Accel_H$, where Centres have the most game-to-game variation. Investigating our data relative to playing quarters, our results demonstrate that the first quarter has the least amount of physical performance variation, while the fourth quarter produces the greatest amount of variation. When examined on a relative basis the variation between playing quarters was reduced, however the fourth quarter remained the most variable. Collectively, the current findings demonstrate that overall activity profiles are reduced across games and physical activity is more variable in the last quarter. These findings have important implications for interpreting changes of the in-game activity profile of individual players, as well for examining temporal changes in game performance. While this study has provided detailed assessment of physical activity in the NBA, physical activity in team sports is complex and a greater understanding of the factors that influence these activities is required. Therefore, future research should investigate factors that impact these physical performance measures and how technical performance in game is related to physical performance.

PRACTICAL APPLICATIONS

- This study has provided researchers and practitioners working in the NBA greater understanding to the activity demands of NBA competitions. This may allow for the implementation of enhanced training strategies and recovery interventions specific to the demands these athletes face in game play.
- Additionally, this study has demonstrated the game-to-game variation of the physical activity in NBA competitions. This will allow for practitioners working in the NBA to identify meaningful changes in player activity profiles to provide enhance preparation and athlete care.

CHAPTER FIVE

FORECASTING PHYSICAL ACTIVITY DEMANDS IN NBA ATHLETES USING IN-GAME OPTICAL TRACKING DATA

INTRODUCTION

Advances in athlete tracking technology now permit many physical, technical and tactical aspects of performance in team sports such as basketball to be quantified. The systematic use of these data has been used to provide insights into how these variables underpin performance in these sports (Mateus et al., 2015; Sampaio et al., 2015). These data can also be used to better understand the workloads encountered by athletes in training and competition (Pino-Ortega et al., 2019; Schelling & Torres-Ronda, 2016; Vazquez-Guerrero et al., 2018). Typical movement demands of match play including time and distances spent in speed zones, total distances, peak speeds and accelerations / decelerations are used to inform training prescription and athlete training management. These data can be directed towards the accumulated physical demands arising from an entire session, or acutely focussed on a single game with even more targeted analyses of the shorter, most intense periods of play during a game.

The National Basketball Association (NBA) has utilized an optical tracking system (OTS) since 2013 to quantify physical, technical and tactical aspects of game play. The most common application of these data in published studies has been in the investigation and description of the technical and tactical aspects of competition (Franks et al., 2015; Mateus et al., 2018). This has led to a greater understanding of player spatio-temporal positioning (Goldsberry, 2012) and skill involvements (Chang et al., 2014). For example, several studies have used these data to create shot equity and rebounding models which can be used to inform on tactical strategies (Franks et al., 2015; Goldsberry & Weiss, 2013; Maheswaran et al., 2012). Surprisingly however, there are few investigations into the physical activity demands of NBA players. Recent studies of NBA game play have shown that the average distances covered in both offensive and defensive play is 0.64 and 0.48 km respectively (Sampaio et al., 2015) and demonstrating performance differences between playing positions (Mateus et al., 2015). Other research have shown that physical output, in particular higher intensity activities, vary between positions and playing periods during Australian state league basketball play (Scanlan et al., 2011; Scanlan, Tucker, et al., 2015), with Guards performing greater amount of higher speed activities relative to

Forwards and Centres and a temporal reduction in higher intensity activities as games progress. This information provides general insights into the physical requirements of basketball, however, there are many contextual factors such as travel, environmental factors, and game-related factors (i.e. score, location. opponent etc.) have not been fully investigated and their potential influence on physical activity in the NBA remains unknown. Many of these factors have been shown to influence to understand the physical activity demands of other court and field-based sports (Kempton & Coutts, 2016; Ryan, Coutts, Hocking, & Kempton, 2016; Sullivan et al., 2014a) and it is reasonable to expect that these may influence the demands of the NBA game play.

In the NBA, teams often undertake trans-continental travel across several time zones and varying environmental conditions (i.e. temperature and altitude) within short periods. In some cases, the travel may result in jetlag or travel-related fatigue which can impact on performance (Roy & Forest, 2018). Two locations in the NBA are located at significant altitude difference (i.e. Denver and Salt Lake City), 1609 m and 1300 m respectively, compared to the other 26 NBA franchise home courts. In addition to travel and environmental factors, the quality of opposing players and teams varies across the league, this is represented by weekly team power ranking scores (i.e. ESPN power ranking) and All-Star playing status (i.e. NBA All-Star player selection). Finally, the competitiveness of game play [i.e. game score or outcome] may also affect the physical activity profile of the players. These contextual factors are thought to influence the game, yet their influence on the physical activity profiles of players is not known. Understanding how these factors may influence the physical activity profiles can be used to better understand player workload and assist in the planning and management of training and competition for individual players. Understanding the collective impact of contextual factors on the physical activity profiles of individual NBA players can be used to model future loads. At the present however, no studies have attempted to develop a model to forecast future physical loads with adequate precision to make confident decisions on players future training or game loads. Such information may be useful for practitioners to develop individual athlete management plans.

The influence of the contextual factors that affect NBA game physical activity are presently not well understood. Given the likely complex interplay between these factors and their subsequent influence on physical performance, studies are required to examine these factors in more detail. Additionally, the ability of practitioners to model likely future game physical activity demands is limited at present. Therefore, the main purpose of the present study was to describe the impact of both individual and external contextual factors on game physical activity profiles. A second purpose of the current study was to determine, if accounting for these factors, a model could accurately forecast measures of physical activity in NBA game play.

METHODS

An inclusion criterion was established whereby athletes who participated in a minimum of two games in a season and played at least 8.5 minutes of the total game, which represented the 25th percentile of total minutes played, were retained for analysis to examine the physical activity demands of complete games. 426 professional basketball players (age: 26.7 ± 2.0 y) competing in regular season games over two NBA seasons met these criteria and were included in the analysis. This resulted in 46,030 total game observations. Institutional ethics approval was provided (HREC NO: ETH17-1847).

Player time-motion Data were collected using an optical tracking system (OTS) during two complete seasons (2015/2016 and 2016/2017). The OTS system consists of six cameras fixed above the playing surface at each stadium, each sampling players x-y position at 25 Hz. Upon the completion of each game, OTS raw Data were processed using bespoke algorithms (SecondSpectrum, Los Angeles, USA). The resultant Data were exported by a member of the research team to a Microsoft excel spreadsheet for further analysis (Microsoft, Redmond, USA). Physical activity measures reported in this study include total distance (m), high speed running (>14.4 $km \cdot h^{-1}$), count of high-speed running efforts (effort performed >14.4 $km \cdot h^{-1}$), count of total accelerations, and count of high accelerations (>3.5 $m \cdot s^{-2}$). Each game physical activity variable was examined on absolute basis accounting for time on court. The physical activity variables used in this study were selected as they are similar to previous basketball research (Puente et al., 2016; Sampaio et al., 2015) and are consistent with the variables provided to practitioners working within NBA teams.

Independent variables consisted of player position (Forward (F), Guard (G) and Centre (C)), season phase (P1, games 1-20; P2, games 21-40; P3, games 41-60; P4, games 61-82), player All-Star Status (i.e. selected in the annual NBA All Star Game) for the respective season (Yes or No), game outcome (Win or Loss), whether the game was at higher altitude (Yes, Denver and Salt Lake City; No, all other locations), game location (home or away), and team ranking differential (ESPN weekly power ranking). Weekly team power ranking Data were obtained from the ESPN website (www.espn.com/nba/powerrankings) for each week of the two corresponding seasons. The ESPN weekly power rankings are determined by voting of more than 40 ESPN NBA reporters, insiders and editors. The team ranking differential was calculated as the difference in weekly team rankings between teams for the week each respective game was played. The team with the higher rank for each game was given a positive rank differential score and the lower team a negative rank differential score.

Statistical Analysis

A data set of 46,030 individual game observations was used. A multi-level mixed model was constructed, model selection was based on the Akaike Information Criterion (AIC). A stepwise AIC approach was used to iteratively fit the multi-level mixed model that best described the variation of physical activity (Table 5.1). Dependent variables included total distance, high speed running, accelerations (total), accelerations (high), and high-speed efforts derived from optical tracking system A separate model was built for each dependent variable. Independent variables consisted of player position (C, F, G), seasonal phase (P1, P2, P3, P4), player All-Star status for the respective season (Yes or No), game outcome (Win or Loss), whether the game was played at altitude (Yes or No), game location (home or away), and team ranking differential (season power ranking difference). A separate model was built for each dependent variable. The model intercept was allowed to deviate from the mean based on the random effects specified in the model for team. The model slope and intercept were allowed to deviate from the mean based on the random effects specified in the model for minutes played (slope) and player (intercept) and nested within team. This allowed us to account for individual player time on court. A forecasting model was built as data were randomly separated into a training set consisting of 80% of the available data (training model) and an out-of-sample set consisting of the remaining 20% (test model). The training model was built using a multi-level mixed model. Model selection was based on the Akaike Information Criterion (AIC). Model accuracy was represented as the root mean squared error (RMSE) on the out-of-sample testing set for each model. The effect of each model coefficient was quantified using an effect size calculated as the beta coefficient divided by the sum of the between and residual random effect standard deviation. Effect sizes were interpreted as <0.1, trivial; >0.1-0.3, small; >0.30-0.5, moderate; >0.5-0.7, large; >0.7-0.9, very large; >0.9-0.99, almost perfect; 1.0, perfect (Hopkins et al., 2009). All statistical analysis was performed in R statistical software (Version 1.1.383) (R Development Core Team, 2017).

Table 5.1. Covariates included in model specification.

Level		Factors	Type	Classification
Level 3	*Cluster of Clusters (random factor)*	Team	Continuous	Team 1-30
Level 2	*Cluster of Units (random factor)*	Player		
	Covariate	Minutes Played	Continuous	
Level 1	*Unit of Analysis*	Individual match sample		
	Dependent Variable	Total Distance (Model 1)	Continuous	($m \cdot min^{-1}$)
		High Speed Running distance (Model 2)	Continuous	HSR ($m \cdot min^{-1}$)
		Total Accelerations (Model 3)	Continuous	Number (n/min)
		High Accelerations (Model 4)	Continuous	Number (n/min)
		High Speed Efforts (Model 5)	Continuous	Number (n/min)
	Covariates	Position	Dummy Variable	Guard, Forward, Centre
		Seasonal Phase	Dummy Variable	P1, P2, P3, P4
		Game Location	Dummy Variable	Home, Away
		Altitude	Dummy Variable	Yes, No
		Game Outcome	Dummy Variable	Win, Loss
		Rank Difference	Continuous	Weekly Power Ranking
		Playing Ability (All-Star)	Dummy Variable	Yes, No

RESULTS

A multi-level mixed model construction used a stepwise AIC approach and was optimized by removing location as an independent variable. Level one covariate position, both guard and forward, demonstrated an increase in the amount of high intensity activities performed in game, these ranged from trivial to large (Tables 5.2 – 5.6) There was a moderate reduction in high speed running, high-speed efforts, and total accelerations for matches played at higher altitude, while only a trivial reduction for total distance and total accelerations. Player All-Star status had a trivial to small reduction in overall physical activity profile, with All-Star players covering more high speed running than non-All-Stars. There was a trivial to moderate reduction in the overall physical activity as the season progressed, with phase 4 having the greatest reductions in physical activities. In contrast, outcome and team rank differential had a trivial effect across all physical activity measures.

Table 5.2. Influence of contextual factors on total distance.

	Total distance (Model 1)				
	Coefficient	**95% CI**	**df**	**t Value**	**Effect Size**
Fixed Effects					
Intercept (m)***	1218.3	1099.6, 1334.2	195.70	126.4	
Position [Forward] **	25.84	6.8, 44.9	388.80	2.70	0.023
Position [Guard]***	46.75	27.7, 65.8	389.20	4.90	0.041
All-Star [Y] **	-18.01	-29.2, -6.7	24720.0	-3.20	0.020
Altitude [Higher] ***	-63.40	-68.8, -57.9	35690.0	-22.70	0.100
Outcome [Win]	-2.10	-4.6, 0.4	36050.0	-1.70	0.002
Season Phase [P2] ***	-23.40	-26.7, -20.1	36090.0	-13.80	0.021
Season Phase [P3] ***	-19.91	-23.3, -16.6	36140.0	-11.64	0.020
Season Phase [P4] ***	-36.40	-39.7, -33.1	36210.0	-21.60	0.032
Rank Differential***	-0.22	-0.3, -0.1	34660.0	-3.52	

Season Phase [2] – games 21-40; Season Phase [3] – games 41-60; Season Phase [4] – 61-82

** Significant ($p < 0.05$), *** Significant ($p < 0.001$)

Table 5.3. Influence of contextual factors on high speed running.

	High Speed Running (Model 2)				
	Coefficient	**95% CI**	**df**	**t Value**	**Effect Size**
Fixed Effects					
Intercept (m)***	300.3	273.54, 311.10	156.6	31.4	
Position [Forward]	-7.50	-21.84, 12.97	387.1	-0.82	0.04
Position [Guard]**	-27.70	-41.43, -6.60	388.8	-3.10	0.13
All-Star [Y]	-4.32	-11.95, 6.81	34340	-0.81	0.02
Altitude [Higher]***	-58.20	-63.10, -53.92	36280	-22.20	0.30
Outcome [Win]***	-7.61	-9.80, -5.70	36350	-6.44	0.04
Season Phase [2]***	-33.40	-36.10, -30.53	36350	-21.02	0.20
Season Phase [3]***	-36.03	-38.41, -32.81	36360	-22.51	0.20
Season Phase [4]***	-55.60	-57.64, -52.12	36420	-35.20	0.30
Rank Differential***	-0.50	-0.60, -0.38	35990	-8.31	

Season Phase [2] – games 21-40; Season Phase [3] – games 41-60; Season Phase [4] – 61-82

** Significant ($p < 0.05$), *** Significant ($p < 0.001$)

Table 5.4. The influence of contextual factors on total accelerations.

	Total Accelerations (Model 3)				
	Coefficient	95% CI	df	t Value	Effect Size
Fixed Effects					
Intercept (n)***	52.62	46.92, 56.50	232.3	52.4	
Position [Forward]	-1.32	-3.02, 0.94	351.1	-1.3	0.03
Position [Guard	-0.30	-2.32, 1.74	356.7	-0.3	0.01
All-Star [Y]***	-4.82	-6.12, -3.50	24140	-6.41	0.12
Altitude [Higher]***	-5.86	-6.40, -5.14	34350	-15.70	0.14
Outcome [Win]***	-0.74	-1.02, -0.42	36160	-4.40	0.10
Season Phase [2]***	-5.20	-5.60, -4.83	36130	22.83	0.13
Season Phase [3]***	-7.10	-7.43, -6.62	36080	-31.02	0.20
Season Phase [4]***	-10.30	-10.80, 9.83	35990	45.72	0.25
Rank Differential	0.01	0.001, 0.030	29920	1.5	

Season Phase [2] – games 21-40; Season Phase [3] – games 41-60; Season Phase [4] – 61-82

** Significant ($p < 0.05$), *** Significant ($p < 0.001$)

Table 5.5. The influence of contextual factors on high accelerations.

	High Accelerations (Model 4)				
	Coefficient	95% CI	df	t Value	Effect Size
Fixed Effects					
Intercept (n)***	4.13	3.30, 6.45	1060	14.83	
Position [Forward]*	-0.74	-0.80, 0.69	8713	-2.40	0.131
Position [Guard]**	-1.00	-2.10, 0.93	8816.0	-3.20	0.200
All-Star [Y]**	-0.80	-1.10, -0.10	30590	-2.82	0.142
Altitude [Higher]***	-1.80	-2.10, -1.59	24190	-12.70	0.320
Outcome [Win]	-0.02	-0.10, 0.12	36300	-0.30	0.003
Season Phase [2]***	-1.70	-1.82, -1.50	36330	-19.60	0.301
Season Phase [3]***	-2.10	-2.29, -1.90	36340	-24.43	0.400
Season Phase [4]***	-3.04	-3.20, -2.80	36300	-36.51	0.520
Rank Differential***	0.02	0.017, 0.024	12100	5.50	

Season Phase [2] – games 21-40; Season Phase [3] – games 41-60; Season Phase [4] – 61-82

* Significant ($p < 0.01$), ** Significant ($p < 0.05$), *** Significant ($p < 0.001$)

Table 5.6. The influence of contextual factors on high speed efforts.

	High Speed Efforts (Model 5)				
	Coefficient	**95% CI**	**df**	**t Value**	**Effect Size**
Fixed Effects					
Intercept (n/min)***	30.2	26.81, 33.60	161.8	37.1	
Position [Forward]	-0.32	-1.90, 1.23	360.3	-0.41	0.01
Position [Guard]	0.61	-1.00, 2.20	364.4	0.8	0.03
All-Star [Y]	0.20	-0.90, 1.20	24180	0.3	0.01
Altitude [Higher]***	-6.02	-6.52, -5.52	35700	-23.55	0.30
Outcome [Win]***	-0.94	-1.20, -0.72	36110	-8.20	0.04
Season Phase [2]***	-3.00	-3.31, -2.70	36140	-19.40	0.13
Season Phase [3]***	-3.50	-3.81, -3.20	36150	-22.44	0.20
Season Phase [4]***	-5.20	-5.50, -4.90	36160	-33.54	0.23
Rank Differential**	-0.02	-0.03, -0.01	34530	-3.20	

Season Phase [2] – games 21-40; Season Phase [3] – games 41-60; Season Phase [4] – 61-82

** Significant ($p < 0.05$), *** Significant ($p < 0.001$)

The forecasting model was tested on a hold-out set comparing actual with modelled data. Table 5.7 shows the root-mean squared error (RMSE), correlation, and coefficient of variation (CV) between the actual and modelled data.

Table 5.7. Root Mean Squared Error (RMSE), correlation, and coefficient of variation (CV%), of forecasted compared to actual physical activity.

Variable	**Root Mean Squared Error (RMSE)**	**Pearson's Correlation (R^2)**	**Coefficient of Variation (CV %)**
Distance (m)	112.6	0.99	9
High Speed Running (m)	106.1	0.91	35
High Speed Efforts (n)	10.33	0.93	34
Total Accelerations (n)	15.01	0.97	28
High Accelerations (n)	5.5	0.85	133

DISCUSSION

This study investigated factors that influence physical activity profiles during NBA games and using such information, constructed a forecasting model to predict the physical activity demands of game play. The main findings were that contextual factors of playing position, All-Star status, playing at higher altitude, seasonal phase, and team rank differential were observed to lead to meaningful changes in physical activity profiles of NBA game play. Additionally, we examined the accuracy of forecasting physical activity measures from the model developed from the training data set, on a holdout set and found that our model performed well in accurately forecasting the physical activity of NBA game play, in particular with regards to total distance. These finding have practical implications for developing evidence-based workload management strategies for NBA players.

In agreement with previous studies (Ben Abdelkrim, Chaouachi, et al., 2010; Mateus et al., 2015; Scanlan et al., 2011) the present results demonstrated that playing position influences physical activity profiles in basketball, with greater locomotor requirements for guards than forwards and guards. These differences are likely consequences of the tactical role and physical attributes of the players in each of these positions. Most notably guards had higher overall acceleration profiles, potentially due to their role in accelerating through the court in running offensive strategies as well as their defending their respective counterparts when in defence. Guards typically have greater ball-handling responsibilities, are a more focal point of the offense and have a greater defensive role. As a result, guards have an increased necessity to accelerate quickly to create space during offensive play and reduce any open space of their opponent whilst playing defence. In contrast, the Centres tactical role is often to remain in the middle of the court and have limited movements further from the basket in order to protect the rim. Although these findings are consistent with previous studies (D'Amelio, Ward, & Coutts, 2019; Mateus et al., 2015; Vazquez-Guerrero et al., 2019) the present study demonstrated that playing position had the largest effect on physical activity than other contextual factors investigated. Accordingly, playing position should be a primary consideration in workload management strategies.

We observed a reduction in overall game speed and higher intensity activities with exposure to altitude, which is in agreement with other studies from soccer (Buchheit et al., 2015; Williams & Walters, 2011). Specifically, the present results showed that altitude had a trivial effect on total distance (ES = 0.10), but moderate effects on higher intensity activities such as high-speed running (ES = 0.30), high accelerations (ES = 0.32) and high-speed efforts (0.30). It is well established that the ability to complete high-intensity power output is reduced with acute exposure to hypoxia (~3000 m) due to increased reliance on anaerobic energy provision (Balsom, Gaitanos, Kekblom, & Sjodin, 1994). Our results agree with studies in youth soccer that reported decreased match activity profiles at altitude, with a greater effect of hypoxia on higher intensity activities (Aughey et al., 2013). Indeed, both the present and previous studies demonstrated that the effect of altitude was greater in higher intensity game activities (Aughey et al., 2013). It has been suggested that these changes in higher intensity activities at higher altitudes are due to altered pacing strategies as a means to protect the ability to complete very high intensity efforts such as accelerations. We observed that while high acceleration counts were influenced by altitude, the influence on the total number accelerations was smaller. This suggests that the players were able to accelerate regularly but their ability to accelerate at very high levels was reduced in hypoxia. While speculative, plausible reasons for the differences between these studies are in the obvious differences in comparison of basketball to soccer (i.e. less available court space). It is also possible that the increased sample size and the measurement system used in these studies may explain these differences. Future investigations are required to elucidate the exact mechanisms behind these observations.

A further novel finding of the present study was that All-Star status (i.e. increased player ability) influenced physical activity profiles, with greater activity profile in the All-Star group for all activity measures. These results are in part contrast to Sampaio et al. (2015), who reported significantly lower defensive speeds in All-Star players. Notably, in both the present and previous study, the All-Star players spent more time on court, however, only the present study statistically adjusted for these differences. A new finding from the present study was that when accounting for time on court, the All-Star players completed greater total distance and more high-speed efforts, although the observed effect was only small. This slightly increased activity profile in the All-Stars is likely explained by the increased importance and focus on these players (i.e. they are more likely to be involved in the play) as they are often central to team success. Although these differences are small, they may have a cumulative effect over the 82-game regular season and therefore should be understood in the athlete workload strategies. This may be further exacerbated by the requirements of these plays to participate in All-Star game duties, national team representation and playoffs.

The present results demonstrated trivial increases in distance travelled as the season progressed, but a reduction in acceleration demands. Collectively, this shows a temporal increase in lower intensity activities of game play but with a concomitant reduction in higher intensity activities during the season. Although speculative, we suggest that these small adjustments in the high speed and high energetic tasks could be due to tactical alterations as a result of greater team cohesion, or as a result of cumulative fatigue from the training and games and travel requirements of the competing on the NBA. Since this is the first study to examine the temporal changes in game activity in the NBA over a season, we are unable to make any direct comparison to other basketball studies. Nonetheless, our results agree in part with studies from professional Australian football and Italian soccer that showed an increase in total distance as the season progressed (Kempton et al., 2015; Rampinini et al., 2007). Notably, however in contrast to the present results, both these previous studies also reported temporal increases higher intensity activities. Despite the obvious differences physical and tactical differences between basketball and these sports, a notable difference is in the total number of games, the game density and the travel requirements of NBA players. It has been previously suggested that frequent air travel may cause a delay in recovery between games – through altered hydration status, nutritional behaviours, and sleep (Leatherwood & Dragoo, 2013). Collectively, these changes may manifest in a reduction of physical activity within in the NBA. Additionally, periods of increased game congestion have been shown to alter physical activity profiles in basketball (Ibanez, Garcia, Feu, Lorenzo, & Sampaio, 2009). Elucidation of the exact mechanisms that underpin these changes in activity is difficult; however, practitioners may still use this information to guide their training and recovery activities to optimize player health.

In the present study, game location (i.e. home or away) did not affect the activity profiles in the NBA. The present observations are in contrast to earlier research in other sporting codes that have shown differences in technical and physical measures based on competing home or away (Kempton & Coutts, 2016; Lago-Peñas & Lago-Ballesteros, 2011; Ribeiro, Mukherjee, & Zeng, 2016). While not directly comparable to the current study, home-court advantage has been investigated in multiple sports and is often shown to be an advantage in relation to points scored, where crowd support, arena familiarity and other factors may have a greater effect. The present results show that this home court advantage may not influence physical activity profile. Moreover, we observed that game outcome did not influence physical activity profiles. However, we did observe significant but trivial effect of opposing team rank difference on physical activity variables. Specifically, the present model shows that for an increase in team ranking of one position (i.e. playing the team 1 rank above), players have an increase of less than 1-m in overall distance travelled and a 0.03 increase in high accelerations per game. These changes support studies from other sport showing that higher ranked teams have lower activity profiles (Di Salvo et al., 2009; Rampinini et al., 2007), however, the practical implications are likely inconsequential. Collectively, these observations suggest that game location, outcome and team rank differential have little influence on activity profiles.

The present study utilized a novel approach to examine physical activity by developing a forecast model to estimate physical activity of future NBA games. The results demonstrate moderate to strong relationships between the actual and expected measures ($r = 0.85 – 0.99$). The model for estimating total distance was the most accurate variable in our forecasting model, with an RMSE of 112.5. In contrast, the correlation between modelled and actual high accelerations was shown to have a strong correlation (r = 0.85), however, this variable had the largest RMSE and CV of activity measures examined. It is well reported that higher intensity activities have greater variations (Gregson et al., 2010; Kempton et al., 2015), likely due to measurement precision (D'Amelio et al., 2018; Linke et al., 2018). These results demonstrate that the forecasting models can be used to estimate the expected physical activity within an NBA game with moderate accuracy. These findings may allow practitioners a greater understanding of the physical activity demands players may undergo in upcoming games and thus allow for adjustment of training demands leading into games expected to have a higher level of physical demands.

Despite this being the first study to examine the influence of contextual factors on physical activity in the NBA and develop a practical forecasting approach of physical activity demands, this study is not without its limitations. One limitation of the current study is the measurement precision of the OTS used to quantify the physical activity profiles within the NBA. Whilst this system has been shown to have strong accuracy for mean speed, this system had poor measurement precision at higher speeds (D'Amelio et al., 2018). This might explain why total distance had the lowest error in our model and additionally the higher error found in the variables of higher intensities, such as high accelerations. Other limitations are that other potentially important contextual variables were not directly assessed in the current study. For example, factors such as congested fixture schedule, differences in game density and effects of travel demands may influence game activity profiles. Other factors such as the specific nature of training loads, pre-game activities and individual player fitness characteristics and experience could also be influential. It was not possible to account for these variables, given that this data is not currently provided by the clubs and future studies should investigate these issues. Despite these limitations, the present findings remain novel and have practical applications for improved statistical forecasting, training load management and athlete care of NBA players.

CONCLUSION

This is the first study to examine the influence of game-related contextual factors on physical activity profiles of NBA players. The results demonstrate that while certain game related factors do effect physical output, their effect remains trivial in many cases, with few variables providing small to moderate effects. Specific findings of this study are that physical activity profiles reduce as the season progresses, are lower when playing at altitude, but are slightly higher for all star players. The forecasting results from our model suggest the ability to accurately forecast future NBA game activity demands can be done with high accuracy. Accuracy in the forecasting model was reduced with higher intensity activities, however these activities were also shown to have the greatest variability. Nonetheless, there may be some practical benefit in using the current model to estimate future playing loads to assist in objective training load planning. However, to improve athlete care, additional studies are required to assess the specific training load demands on player health and wellness in the NBA. Future investigations should examine the relationship of physical activity and technical performance. Furthermore, identification of the influence of contextual factors on physical activity, leaves the question of how these factors may influence technical performance. Therefore, examination of the influence of game related situational factors on technical performance is warranted.

PRACTICAL IMPLICATIONS

- This study demonstrates the ability to accurately forecast future game physical activity demands. This may allow practitioners to optimize training and recovery strategies when accounting for possible increases in activity of pending competitions.
- The topic of player rest has been a matter of increased concern on the team and league level, the use of a forecasting model may allow for a more objective approach to resting players during the regular season.
- The identification of game related situational and individual contextual factors may allow for practitioners to better manage training loads and implement recovery strategies specific to the athletes needs and demands. Additionally, greater understanding of the influence on these factors on physical activity

profiles may allow coaches to optimize in game management and player substitution patterns.

CHAPTER SIX

THE INFLUENCE OF PHYSICAL ACTIVITY ON TECHNICAL PERFORMANCE IN NBA GAME PLAY

INTRODUCTION

Basketball is a sport that requires a combination of physical, technical and tactical skills for success (Ben Abdelkrim et al., 2007; Sampaio et al., 2015). Early research in basketball has focused on understanding the physical performance demands of the sport, investigating the influence of factors such as playing level and playing position on these demands (Ben Abdelkrim, Chaouachi, et al., 2010; Scanlan et al., 2011; Scanlan, Tucker, et al., 2015; Stojanovic et al., 2018). In addition to these studies on physical activity, there have been several examinations of the technical performance of basketball players (Sampaio, Janeira, Ibáñez, & Lorenzo, 2006; Sampaio et al., 2015). These studies, however, have examined these components of performance in isolation. The relationship between the physical and technical performance in team-based sports has been suggested as having an important role in overall game performance and therefore should not be examined in isolation when analysing game performance (Impellizzeri & Marcora, 2009). Recent research in team sports such as soccer, rugby, and Australian rules football has investigated the relationship between physical and technical variables and game performance (Carling, 2013; Kempton & Coutts, 2016; Kempton, Sirotic, Cameron, & Coutts, 2013; Sullivan et al., 2014b). Recent investigations in basketball have aimed to examine the relationship between physical activity, physical characteristics and technical aspects of game play (Sampaio et al., 2016; Teramoto, Cross, Rieger, Maak, & Willick, 2018). While these studies have expanded the current understanding of basketball game play and the relationship between the physical and technical, they are limited to focusing on isolated aspects of physical performance or have been performed on lower quality of basketball than that of the NBA.

Presently, the relationship between physical activity and technical performance within NBA game play is not well understood. Moreover, it is not known how game based contextual factors influence player performance. Improved understanding of the influence and relationship of physical activity to game performance is important to enhance practitioner's interpretation of game analysis and preparing athletes for NBA competition. Therefore, the objective of this study was to investigate the impact of physical activity has on game performance and factors related to game performance.

METHODS

To examine the physical activity of complete games, an inclusion criterion was established and athletes who participated in a minimum of 8.5 minutes of the total game, which represents the 25th percentile of total minutes played, were retained for analysis. 426 professional basketball players (age: 26.7 ± 2.0 y) competing in regular season games over during two NBA seasons met this criterion and were included in the analysis. This resulted in 46,030 total game observations. Institutional ethics approval was provided (HREC NO: ETH17-1847).

This study retrospectively examined physical activity data captured at each NBA stadium using an optical tracking system (OTS). The optical tracking system consists of six cameras fixed above the playing surface, each sampling at 25 Hz. The optical tracking system used in the current investigation has recently been shown to be a valid measure for assessing physical activity demands in wide velocity bands (D'Amelio et al., 2018). Following each match, optical tracking Data were processed by SecondSpectrum (SecondSpectrum, Los Angeles, USA), the official company the NBA uses to manage and process the optical tracking data for match play. The Data were then exported to a Microsoft excel spreadsheet for further analysis (Microsoft, Redmond, USA). To asses technical performance, the game score (GmSc) metric was used. GmSc is a publicly available measure of individual player game performance, intended to give a complete perspective on a player's statistical performance within a game (www.basketball-reference.com) (Hollinger & Hollinger, 2005). The scale for GmSc is similar to that of points total points scored (40 is an outstanding performance and a score of 10 being is an average performance).

The GmSc formula is:

$$GmSc = PTS + 0.4 * FG - 0.7 * FGA - 0.4*(FTA - FT) + 0.7 * ORB + 0.3 * DRB + STL + 0.7 * AST + 0.7 * BLK - 0.4 * PF – TOV$$

PTS = Points; FG = Field Goals; FGA = Field Goal Attempts; ORB = Offensive Rebounds; DRB = Defensive Rebounds; STL = Steals; AST = Assists; BLK = Blocks; PF = Personal Fouls; TOV = Turnovers

The independent variables examined for this study consisted of the physical activity measures, total distance (m), high speed running (>14.4 $km \cdot h^{-1}$), count of high-speed running efforts (effort performed >14.4 $km \cdot h^{-1}$), count of total accelerations, and count of high accelerations (>3.5 $m \cdot s^{-2}$). The GmSc metric was chosen as an overall metric for player performance as it is a popular publicly available measure of technical performance with-in the NBA that accounts for both offensive and defensive statistical measures. Independent physical activity variables were selected as they are similar to those used in previous research in basketball (Caparros et al., 2018; Sampaio et al., 2015) and are consistent with the activity variables provided by the NBA to practitioners working within NBA teams.

Statistical Analysis

A data set 46,030 game observations from the 2015/16 and 2016/17 NBA seasons were used for this study. Previous research has demonstrated playing positions have different game based physical activity profiles (Ben Abdelkrim et al., 2007; D'Amelio et al., 2019; Scanlan et al., 2011). Therefore, a separate linear mixed model was created for each playing position to investigate if physical activity measures contribute differently to game performance based on playing position. To determine the optimal model for each playing position a stepwise AIC approach was used to iteratively fit a multi-level mixed model that best described the variation of GmSc (Table 6.1). Physical output independent variables included were total distance, high speed running, high speed efforts, total accelerations, and high accelerations. The model intercept was allowed to deviate from the mean based on the random effects specified in the model for team.

Additionally, the model slope and intercept were allowed to deviate from the mean based on the random effects specified in the model for minutes played (slope) and player (intercept), nested within team. This allowed us to account for an individual players' time on court.

Additionally, a model was built to examine the influence of contextual factors on GmSc (Table 6.2). The Independent variables consisted of player position (Guard, Forward, Centre), seasonal phase (P1, P2, P3, P4), player All-Star status for the respective season (Yes or No), game outcome (W or L), whether the game was played at altitude (Yes [Denver, Utah] or No [all other arenas]), game location (home or away), and team ranking differential (weekly power ranking difference). In the positional model, GmSc and physical activity measures were grand-mean cantered. The effect of each model coefficient was quantified by calculating the beta coefficient divided by the sum of the between and residual random effect standard deviation. Effect sizes were interpreted as <0.1, trivial; 0.1-0.3, small; 0.31-0.5, moderate; 0.51-0.7, large; 0.71-0.9, very large; 0.91-0.99, almost perfect; 1.0, perfect. All statistical analysis was performed in R statistical software (Version 1.1.383) (R Development Core Team, 2017)

Table 6.1. Game Score (GmSc) positional model specification.

Level		Factors	Type	Classification
Level 3	Cluster of Clusters (random factors)	Team	Continuous	Team 1-30
Level 2	Cluster of Units (random factor)	Player		
	Covariate	Minutes Played	Continuous	
Level 1	Unit of Analysis	Individual match sample	Continuous	
	Dependent Variable	GmSc	Continuous	Game Score Rating (#)
	Covariates	Total Distance	Continuous	Distance (m)[a]
		High Speed Running Distance	Continuous	Distance (m)[a]
		High Speed Efforts	Continuous	Count (#)[a]
		Total Accelerations	Continuous	Count (#)[b]
		High Accelerations	Continuous	Count (#)[c]

[a] Included in all Positional Models (Guard, Forward, and Centre); [b] Included in Guard and Centre Models; [c] Included in Guard and Forward Models.

Table 6.2 Game Score (GmSc) situational and individual contextual factor model specification.

Level		Factors	Type	Classification
Level 3	Cluster of Clusters (random factor)	Team	Continuous	Team 1-30
Level 2	Cluster of Units (random factor)	Player		
	Covariate	Minutes Played	Continuous	
Level 1	Unit of Analysis	Individual match sample		
	Dependent Variable	GmSc	Continuous	Game Score Rating (#)
	Covariates	Position	Dummy variable	Guard, Forward, Centre
		All-Star	Dummy variable	Yes, No
		Altitude	Dummy variable	Yes (Denver, Utah), No (All other team arenas)
		Game outcome	Dummy variable	Win, Loss
		Time of Season	Dummy variable	Phase 1, Phase 2, Phase 3, Phase 4
		Rank Differential	Continuous	Weekly rank difference between competing teams

RESULTS

The mixed model built to examine the influence of physical activity on GmSc was optimized by the removal of independent variables high accelerations, in the Centre position model and total accelerations in the forward position model. The model for the guard position included all of the physical activity independent variables. Level one covariate, total distance, demonstrated a very large effect across all playing positions (Table 6.3). High speed running had a significant negative influence on GmSc in all positions, however the effect ranged from small to large across the position groups. For the Centre position model, we observed that all physical activity variables investigated had a significant effect on GmSc (Table 6.3). These results however ranged from small to very large.

In the contextual model, all factors examined were found to significantly influence GmSc, however these effects ranged from trivial to moderate (Table 6.4). Altitude was found to have a moderate negative influence on GmSc, while All-Star player status had a moderately positive effect on GmSc. In contrast, seasonal phase had a significant but trivial effect influence on GmSc.

Table 6.3. Game Score – Position Models (Guard n = 19278, Forward n = 18453, Centre n = 8299).

Variable	**Coefficient**	**Confidence Interval**	**Degrees of Freedom**	**T Value**	**Effect Size**
Fixed Effects					
Guard Intercept (GmSc)	8.3	7.93, 8.60	198.6	51.52	
Distance (m)***	0.004	0.003, 0.005	3264	19.82	1.1
High Speed Running (m)***	-0.004	-0.005, -0.003	14970	-6.10	0.3
High Speed Efforts (n)	-0.001	-0.015, 0.012	18560	-0.22	0.01
Total Accelerations (n)	-0.002	-0.008, 0.004	18110	-0.62	0.03
High Accelerations (n)***	0.04	0.024, 0.054	18890	5.11	0.06
Forward Intercept (GmSc)	7.7	7.34, 8.03	111.1	43.53	
Distance (m)***	0.004	0.0036, 0.0042	686.2	28.31	1.10
High Speed Running (m) ***	-0.003	-0.0045, -0.0021	17420	-5.60	0.23
High Speed Efforts (n)	0.01	-0.0034, 0.023	18370	1.50	0.10
High Accelerations (n)**	0.02	0.0070, 0.0350	17660	2.96	0.06
Centre Intercept (GmSc)	8.9	8.50, 9.32	66.65	41.02	
Distance (m) ***	0.005	0.0046, 0.006	989.7	17.61	2.9
High Speed Running (m)***	-0.006	-0.008, -0.004	6708	-6.61	0.7
High Speed Efforts (n)***	-0.044	0.024, 0.064	8035	4.30	0.3
Total Accelerations (n)***	-0.014	-0.022, -0.006	7094	3.50	0.2

** Significant ($p < 0.05$), *** Significant ($p < 0.001$)

Table 6.4. The influence of contextual factors on Game Score.

Variable	Coefficient	Confidence Interval	Degrees of Freedom	T-Value	Effect Size
Fixed Effects					
Intercept (GmSc)	3.2	2.70, 3.70	221.7	-34.7	
Position [Forward]***	-1.2	-1.51, -0.09	274.8	-7.5	0.20
Position [Guard]***	-1.4	-1.71, -1.10	288	-8.7	0.21
All-Star [Y]***	2.5	2.10, 2.90	16060	12.1	0.31
Altitude [Y]*	-2.7	-0.50, -0.06	22110	-2.5	0.34
Outcome [Win]***	1.8	1.73, 1.92	45310	36.5	0.23
Season Phase [2]**	0.2	0.07, 0.33	45410	3.0	0.03
Season Phase [3]***	0.4	0.30, 0.60	45230	6.4	0.04
Season Phase [4]***	0.6	0.45, 0.71	45160	8.7	0.06
Rank Differential**	-0.008	-0.01, -0.003	9313	-3.2	0.30

GmSc – Game Score Metric; Season Phase [2] – Games 21-40; Season Phase [3] -Games 41-60; Season Phase [4] – Games 61-82

* Significant ($p < 0.01$), ** Significant ($p < 0.05$), *** Significant ($p < 0.001$)

DISCUSSION

The current study investigated the influence of physical activity on game performance, quantified by the GmSc metric for three general playing positions (Guard, Forward, and Centres) in the NBA. In addition, a second model was developed to examine the influence of contextual factors (playing position, all star status, altitude, game outcome, seasonal phase, and rank differential) on technical performance. The main findings were that physical activity was related to technical performance and this differed between playing positions. In addition, the present study identified that some contextual factors - altitude and All-Star status – influenced technical performance.

The current results demonstrated the greatest physical activity influence on GmSc came from total distance. This finding was consistent amongst all playing positions. Total distance is the most general of the activity measures investigated, as this includes movements across all speeds. A possible explanation for this finding is that in order to accumulate GmSc points, a player needs to be on the court, and if a player is on the court, they are also accumulating distance. Examining the relationship between physical activity and technical performance of the three main playing positions, the present study found that each playing position displayed their own activity profiles. Specifically, for the guard position, all physical activity measures investigated for this study were included to best describe the relationship between technical performance and physical activity. The relationship between technical performance and the physical activity profiles for Forwards and Centres, however, did not include total accelerations and high accelerations respectively. These results are consistent with previous research into the positional physical activity profiles (Ben Abdelkrim, Chaouachi, et al., 2010; D'Amelio et al., 2019; Scanlan et al., 2011) and in-line with the general tactical and technical requirements of these positions (Sampaio et al., 2006). In general, Guards have the most varied tactical demands among playing positions and therefor are required to perform a greater variety of physical activities within a game. Previous research in the NBA has shown that Guards cover the greatest distance as well as perform a greater number of high intensity efforts in competition when compared to Centres and Forwards (D'Amelio et al., 2019). A Guard's primary responsibility is initiating a team's offensive strategy and distributing the ball to create offensive opportunities. This typically results in a greater number of assists and points scored for Guards when compared to other playing positions. On defence, Guards will most often defend players who have similar roles in their respective team's offense. Due to these technical roles and requirements, Guards will typically have a greater overall physical activity profile than other positions. In the current study, high speed running distance was found to have a moderate negative effect on GmSc for Guards. We speculate that this is the result of teams perform a greater amount of high speed running and increase physical activity while trailing in order to reduce the scoring deficit. This is similar to previous research in other sports (Sullivan et al., 2014b), which demonstrated an increase in high speed running when their team was trailing. Alternatively, Guards are the primary ball handler and involved in initiating the offense, the influence of high speed running on technical performance is possibly related to an increase offensive pace (number of offensive possessions per game). Increasing offensive pace would require an increase in the number of fast break-based possessions, causing the Guard position to push the ball up the floor more often, resulting in the Guard position performing a greater amount of high-speed running. This may result in an increase in scoring and assist opportunities, which would result in a higher GmSc, however there is also greater risk of increased turnovers and missed field goals, which would result in a reduction of GmSc.

Forwards have wide ranging technical abilities and demands, and their responsibilities are directly related to the team's tactical strategy. Indeed, some teams can have a more Guard focused approach while others have a more dominant player at the Forward position and will then adopt their team strategy to reflect that players abilities. While the Forwards team role and responsibilities may vary, overall this position demonstrated the least amount of total accelerations when accounting for playing time (D'Amelio et al., 2019). This is seemingly in agreement with the exclusion of total accelerations in the optimized model for the Forward position in the current study. An increase in high speed running distance corresponded with a reduction in GmSc for Forwards, the effect however was small. As speculated with Guards, the reason for this is potentially related to Forwards possibly running at higher speeds while trailing in an attempt to reduce the score deficit. Another potential explanation of this relationship may be due to an increase in high speed activities may lead to greater fatigue which may lead to an increase in technical errors.

Each of the physical activity variables investigated for the Centre position, with the exception of total distance, had a negative relationship to GmSc, with effects ranging from small to very large. This may indicate that the measures used to quantify physical performance do not appropriately relate to the physical demands of the game and /or specific positional roles. In general, Centres protect the basket on the defensive end and operate close to the basket while on the offense. However, as stated earlier regarding Forwards, the technical and tactical roles and responsibilities of the Centre position are highly dependent on team strategy and team structure. As described, the Centres role is different from that of a Forward or Guard and often is much more physical, due to their responsibilities and positioning on the court (i.e. nearer the basket). This is a limitation of the current study as the data source used for physical activity quantification within the NBA, may not adequately capture this activity and may only represent the locomotor activity. Therefore, it does not capture the totality of physical demands on the Centre position. Previous research regarding positional physical activity differences, demonstrated that the Centre position had the least amount of high accelerations when compared to Guards and Forwards (D'Amelio et al., 2019). It was also shown that the Centres had the largest between game variability for high accelerations than did Forwards and Guards (D'Amelio et al., 2019). This is a possible explanation as to why the Centre model was optimized by excluding high accelerations.

In addition to the influence of physical activity on GmSc, the current study examined contextual factors that may influence technical performance. The current results show that altitude and All-Star player status had the greatest effect on GmSc. Whilst there have been no previous studies that have examined the acute effect of playing basketball at altitude on physical activity and performance, it is well established that hypoxia can reduce work capacity through lower relative and absolute and relative aerobic contribution to energy provision primarily mediated through reduced blood oxygen saturation (Deb et al., 2018). The current results are consistent with previous research from soccer that demonstrated playing at altitude reduces technical performance and physical activity. Our results show that All-Star playing status was found to have a moderate positive effect on GmSc. This is a somewhat intuitive finding, as All-Star players are typically the most talented players on each team and team strategies are often built around these players. This results in All-Star players having greater tactical impact and increased statistical measures than non-All-Stars. These findings are consistent with previous research displaying that All-Star players have differing technical performance profiles that non- All-Star players (Sampaio et al., 2015). These findings have practical implications for understanding the role of physical activities and the influencing factors within NBA game performance.

CONCLUSION

The present results demonstrate that there is a relationship between technical performance and physical activity, however this relationship varies by playing position. Our findings suggest the physical activity profile of a player alone may not explain technical performance, and other contextual factors may need to be considered when assessing game-based performance. However, understanding the role of physical activity measures in game performance are nonetheless important for practitioners in order to provide optimal care and physical preparation for their athletes. Future research should examine the effect of these physical activity measures for players with and without the ball and also examine how tactical strategies may influence the physical activity within the NBA.

PRACTICAL IMPLICATIONS

- The identification of unique positional activity profiles related to technical game performance may allow for practitioners to construct positional specific training protocols to optimize technical performance.
- This study demonstrates positional specific activity demands related to technical performance, as a result, coaches may utilize this data to refine and optimize strategic in game management
- Physical activity should not be utilized by coaches or practitioners as surrogate measures of basketball game performance. We recommend that a holistic and integrated assessment of physical, technical, tactical and psychological factors be considered when making such judgements about player game performance. This will allow for greater clarity for coaches and practitioners to identify, understand and develop appropriate strategies for basketball performance enhancement.

CHAPTER SEVEN

GENERAL DISCUSSION

MAIN FINDINGS

Although the physical activity demands of basketball competition were first investigated in 1930, the physical activity demands of contemporary NBA game play are largely unknown. Therefore, a series of four applied research studies were conducted to provide a greater understanding of the measurement of the physical activity demands of NBA, with specific focus on the influence of situational and game-related factors that may influence these demands. Study one examined the accuracy of the optical tracking system used to quantify activity demands in the NBA. Study two quantified the physical activity demands of the NBA players describing the demands according to playing position, temporal changes within games, and assessed the between-game variation of these activity characteristics. Study three modelled the independent effects of game-related and situation-related factors on these measures of physical activity and then tested the ability of this model to forecast the expected physical activity demands on future game play. Finally, Study four explored the relationship between physical activity and technical game performance.

ACCURACY OF AN OPTICAL TRACKING SYSTEM

The NBA implemented an OTS to quantify the physical activity demands of game play in 2013. Despite the widespread use of this system by the NBA, the media and each of its franchises, the accuracy of this system has not been examined. Therefore, the first study in this thesis examined the accuracy of this OTS to quantify instantaneous velocity during linear sprinting under controlled a setting. Instantaneous velocity was chosen as our standardized measure as according to first principles, if instantaneous velocity was found to be precise, then measures derived from instantaneous velocity will also be valid. This was the first study to examine the accuracy of the OTS used to quantify physical activity in the NBA. The results of Study one demonstrated that OTS provided accurate measures of mean speed when taken in larger epochs of time, but the accuracy of the instantaneous velocity at specific timepoints was imprecise. Moreover, when the Data were assessed in velocity bands, the narrower bands were less accurate than the broad velocity bands. Finally, the precision of the OTS was demonstrated to be less precise at both the low and maximal ends of the velocity spectrum. The underestimation of instantaneous velocity was consistent across the full velocity range and within each discrete velocity band, with the exception of the lowest velocity band, where the OTS, was shown to overestimate instantaneous velocity. These results demonstrate that whilst the OTS may be adequate for assessing velocity across a full velocity range and averaged measures at the group level, caution should be used for assessing instantaneous velocity within discrete velocity ranges at the individual level. Understanding the precision of the OTS used in the NBA, allowed for the identification of physical activity measures that are both useful and sensitive for understanding training load in NBA game play.

PHYSICAL ACTIVITY DEMANDS AND GAME-TO-GAME VARIATION IN NBA COMPETITION

Previous studies of the movement demand in NBA competitions have examined general activity measures such as total distance and average speed. These activity measures do not encapsulate all of the physical demands encountered during NBA game play. Nor is there an understanding of the variance of these measure between games. Additionally, these studies have failed to describe physical activity demands relative to playing position or the temporal changes in these demands between playing quarters. Therefore, study two described the physical activity in contemporary NBA game play, examining more discrete measures of activity (e.g. high-speed running, high speed efforts, accelerations, and high accelerations) for the different positional groups. Additionally, we examined changes in temporal activity throughout games, and the game to game variation of these activity measures. Study two is the first study to demonstrate differences in activity profiles between playing positions and also highlight the temporal changes in activity measures of NBA competitions. Additionally, we determined the variation of physical activity measures of NBA game play. Study two describes the physical activity demands found in NBA competitions and expands our knowledge in understanding of these demands by playing positions, playing quarter, and the variation of these activity measures. After first identifying meaningful activity measures and their sensitivity and describing match play in the first two studies, we then further examined the physical activity demands of NBA competition by investigating the game related situational factors (i.e. game outcome, game location, seasonal phase, altitude, and playing status) that may affect these activity measures.

FORECASTING PHYSCIAL ACTIVITY AND SITUATIONAL FACTORS AFFECTING ACTIVITY.

A limitation of previous research into the activity demands in the NBA was a failure to account for the many situational and game-related factors influencing physical activity such as player position, opposition strength, game location, game outcome, altitude, seasonal phase, and playing ability. In addition, the ability to accurately forecast expected physical demands would be of importance to the practitioner yet has not been examined in basketball research. Accordingly, study three examined the accuracy of a forecasting model to estimate physical activity of future NBA games and the influence of game related situational factors on the physical activity demands. The results showed that game related factors including playing position, altitude, seasonal phase, and playing ability affect measures of physical activity during NBA game play (ES = 0.20 - 0.52). Conversely, some game and situation related factors including match outcome, opposition strength and location had trivial effects (ES = 0.0 – 0.10) on physical activity profiles. This may allow coaches and practitioners greater understanding and clarity interpreting meaningful changes in activity profiles and in overall preparation strategies. Study three is the first study to demonstrate the use of a model to forecast physical activity demands in the NBA with the final model showing moderate to strong accuracy. The results of study three also showed that forecasting models may be used to estimate expected physical activity in NBA game play. These results highlighted the importance of understanding and considering contextual factors when analysing game activity profiles.

THE INFLUENCE OF PHYSCIAL ACTIVITY ON TECHNICAL GAME PERFORMANCE

Despite research from other sporting codes that have examined the physical, technical and tactical relationships of gameplay, relatively few studies have examined this relationship in NBA competitions. Therefore, study four aimed to investigate this relationship by developing a model to examine the influence of physical activity on technical performance in NBA game play. The main findings of this study showed that there was a relationship between physical activity profile and technical performance, and this varied between each playing position. The largest influence of physical activity on technical performance came from total distance, this finding was consistent across all playing positions. To accumulate distance, a player must be on the court playing, additionally in order to perform technically a player must be on the court. Therefore, this relationship can be interpreted as, general participation in game play is related to technical performance. However, this study also demonstrated certain measures of increased physical activity such as high-speed running and were negatively associated with technical game performance. Whilst, study four demonstrated the influence of game related situational factors such as playing position, playing ability (All-Star), and altitude on technical game performance, when interpreted collectively, the results of study four suggest that physical activity measures (e.g. high speed efforts, total accelerations, high accelerations) have a limited influence on technical performance and should not be assessed as surrogates to overall game performance. Additionally, the results from study four, highlight limitations in activity demand quantification, as current activity measures may not be adequate to accurately measure the complete positional demands of NBA competitions (i.e. jumping and physical impacts). Therefore, future investigations should examine relevant and specific positional activity measures and their relationship to technical performance. Study four demonstrates the unique specific positional activity profiles and game related situational actors to technical performance. These findings have practical implications for practitioners by enhancing the understanding of relevant positional demands in game play and then may allow for improved athlete workload management in the NBA.

LIMITATIONS

Although this thesis makes a scientific contribution to the knowledge of the competitive demands of the NBA, there are limitations resulting from the applied nature of the research studies that must be acknowledged. Firstly, in study one the OTS system was assessed in linear acceleration only, this was due in part to data loss and the OTS data provider. As study one was performed to the best of our ability using the data provided, we aimed to assess the OTS system and the data provided to NBA teams throughout the thesis with this known limitation. Additionally, the data used for study one was collected at a single basketball arena where the optical tracking system was employed. Due to the nature of the optical system and the placement of cameras above the court, it is possible that the results from this study are applicable to this specific area. Regular season NBA competitions take place across 29 areas of varying size and dimensions. As a result, it is possible that the optical tracking system in each area may have differing levels of accuracy. Therefore, it is recommended the measurement precision be examined at each

NBA arena and particularly in varying areas on the court, which have been previously shown to present larger errors (Luteberget et al., 2018). Additionally, a limitation in study one is that while the precision was examined the measurement reliability was not assessed. It is recommended that future investigations examine the reliability of optical tracking system.

Permission was granted to use specific activity measures for studies two, three, and four by an NBA team and the optical tracking company based on available data provided by the tracking system. These, however, may not be the most applicable measures to quantify physical activity in NBA game play. For example, this data set lacked the ability to track measures of jumping, which is a key activity in basketball (Narazaki, Berg, Stergiou, & Chen, 2009; Scanlan et al., 2011) and therefore a potential key measure of activity in NBA game play is not measured. Quantification of other activities such as measures of deceleration and the directionality of movement may also be relevant areas of investigation. Further investigations identifying additional measures of activity in NBA competition is therefore required. Study three utilized The ESPN Power Ranking metric as the measure of team strength. Power Rank is a composite metric that takes into account several different team-based measures and is widely used by media and NBA franchises as an indicator of team success, however this is a subjective commercial statistic and has not been investigated regarding its validity as a representative measure of team success. Finally, Study 4 utilized the GmSc metric, a publicly available holistic statistical measure of individual player game performance, that uses multiple statistical measures of technical performance. The formula is made public and has appeared in published books and online websites, however a more rigorous evaluation of the weighting coefficients applied to the variables within GmSc is warranted.

CONTRIBUTION OF THESIS

The series of research studies included in this thesis have identified several important aspects that should be considered when analysing game activity profiles in the NBA. The thesis included the first study to assess the accuracy of the measurement system used to quantify physical activity in the NBA. This enabled the identification of physical activity that are both meaningful and sensitive for understanding physical activity in NBA competition. This understanding of physical activity measures of game play in the NBA allowed this thesis to examine the game related situational factors that affect physical activity. A novel model was then applied, in order to assess the ability to accurately forecast physical activity of NBA competitions. Lastly, this thesis described the relationship between physical activity and technical performance in NBA game play.

Collectively, this thesis has provided greater insight into the role of physical activity tracking and its contribution to understanding game-based training load on players and their performance. This information can be applied to improve athlete health care and preparation in the NBA. For example, practitioners are now able to assess meaningful measures of physical activity and the understand the noise in these activity measures. Additionally, this thesis has identified some important limitations in current understanding of the physical activity demands in NBA basketball. Whilst these limitations are not unique for applied game analysis research projects and do not diminish the contribution of the individual studies contained within this thesis, it is important to consider the results of this research in light of these constraints. In the following chapter, a summary of recommendations for future investigative studies to expand on current the body of work presented in this thesis and continued development of understanding of performance in basketball is presented.

PRACTICAL APPLICATIONS

This thesis is one of the first comprehensive examinations of NBA game play. The studies contained in this thesis have provided practical recommendations regarding the analysis of physical activity, the situational and individual contextual factors affecting physical activity, provided a forecasting model for physical activity, and examined its relationship to technical performance:

- The OTS used in the NBA was demonstrated to provide adequate accuracy across a wide velocity range, however, the precision was significantly reduced when examined in more discrete velocity ranges, specifically in the low and maximal velocity ranges. Therefore, researchers and practitioners should understand and account for these limitations and the error found in this data when analysing and assessing activity profiles in NBA competitions.

- Limitations in the OTS were highlighted in this thesis which will aid in the direction of future investigations into the OTS system used in the NBA. Additionally, during the development of this thesis, the NBA and NBPA agreed to new collective bargaining agreement. This agreement included the implementation of a joint wearable technology committee to examine technologies used in the NBA, with the intent to identify valid and reliable technologies for league, team, and player use. As a result of the investigations in this thesis, I have been selected to participate in this committee and aid in this process.

- The identification of unique in game physical activity profiles, based on playing position, will allow practitioners to develop positional specific training protocols to enhance athlete preparation. Additionally, greater understanding of the training loads encountered in competition will aid practitioners in developing and implementing appropriate recovery. Furthermore, with this data, practitioners may be able to design more appropriate and representative return to play protocols for athletes recovering from injury. Researchers and practitioners may also utilize the insights provided in this thesis to interpret meaningful changes in game-based activity profiles.

- This thesis demonstrates temporal changes in physical activity measures over the duration of NBA games, with most activity measures reducing across playing quarters. Coaching staffs may utilize this information to enhance game management and tactical strategies. Additionally, practitioners may use this information to examine the effectiveness of training programs at both the team and individual player level.

- Game related situational and individual contextual factors such as playing position, altitude, seasonal phase and playing skill (All-Star) were demonstrated to impact physical activity profiles in game play. This is important for practitioners to consider when interpreting and analysing physical activity profiles.

- This thesis developed a model that accurately forecasted physical activity in future NBA competitions. Practitioners may implement these findings to optimize training and recovery strategies when accounting for projected activity demands. This may also allow for a more objective approach in teams player resting strategies during the regular season. Moreover, coaches may use this data to adjust practice and game strategies, as well as in game player management.

- Successful game performance in the NBA is not linked to increased measures of physical activity. Therefore, game based physical activity should not be used by coaches or practitioners as an independent measure of technical game performance. Additionally, coaches and practitioners may now have a greater understanding of the factors related to overall game performance, which may result in greater specificity in the planning of training demands and competition preparation.

CHAPTER EIGHT

SUMMARY AND RECOMMENDATIONS

SUMMARY

This thesis contains four original research studies (Chapters Three to Six) that examine multiple aspects of the physical activity demands found in NBA competition. The first study examined the accuracy of an optical tracking system to measure instantaneous velocity in basketball related movements in a controlled environment. The second study examined the positional and temporal physical activity demands of NBA game play and their game to game variation. Study three further explored this concept by examining the independent effects of a variety of game related situational factors on measures of physical activity. Additionally, study three investigated the ability to forecast the physical activity demands of future NBA competitions. Study four examined the influence of physical activity on technical game performance. A summary of the main findings from each study is presented in Table 8.1.

Table 8.1. Summary of studies included in this thesis.

Chapter	Study Title	Athletes	Files	Variables	Findings
3	Measurement accuracy of an optical tracking system for assessing instantaneous velocity	10	345	Instantaneous velocity	OTS demonstrated reasonable accuracy when examined across wide velocity ranges. When assessed in narrow velocity bands the measurement precision was significantly reduced. The precision increased as velocity increased, however at the maximal velocity band the measurement error of the OTS was greatest. In general, OTS overestimated velocity when compared to a radar, this was demonstrated across all velocity ranges except the lowest velocity band.
4	Quantifying the physical activity demands and game to game variation in NBA competition.		39,962	Speed based distances and accelerometry measures. Playing position and playing quarter	Positional specific physical activity profiles were found in NBA competitions. Guards had the greatest game variation of physical activity. Additionally, there were temporal differences of physical activity across game duration with the greatest differences being demonstrated between the 1st and 4th quarters. The 4th quarter demonstrated the greatest variation in physical activity measures
5	Forecasting physical output of NBA athletes using in-game optical tracking data.	426	46,030	Speed based distances and accelerometry measures. Game related factors (e.g. game location, game outcome, seasonal phase, opposition strength, playing status (All-Star), and altitude)	The ability to forecast physical activity in future NBA competitions was demonstrated with moderate to high levels of accuracy. Game related situational factors (e.g. playing status (All-Star), altitude, and seasonal phase) were demonstrated to affect physical activity measures in NBA competitions.
6	The influence of physical activity on technical performance in the NBA	426	46,030	Speed based distances and accelerometry measures. Game related factors (e.g. game location, game outcome, seasonal phase, opposition strength, playing status (All-Star), and altitude). Individual player game rating (e.g. GmSc)	Physical activity was shown to have little to no influence on overall technical performance. The exception was the total distance metric, which did show a positive relationship with technical performance. Additionally, each playing positions was shown to have unique activity profiles related to technical performance.

OTS: Optical tracking system; GmSc: Game Score Metric

FUTURE DIRECTIONS

This thesis has developed a framework for understanding the physical activity demands and the game related factors that influence these demands in the NBA. Additionally, this thesis has examined the accuracy of the measurement system used to quantify these activity demands and explored the ability to forecast activity demands in future NBA competitions. To expand on the findings presented in this thesis, it is recommended that further research investigates the following areas:

- Since this thesis began, the NBA now utilizes a different optical tracking system. To the best our knowledge the validity of the current system has yet to be investigated. Therefore, the measurement error in the current system used in game play, remains unknown and direct comparison to study one of this thesis results may not be applicable. Therefore, further investigation into the accuracy of the current system is warranted.

- To date, the reliability of the optical tracking system used in the NBA has not been assessed. Examinations into the reliability of the optical tracking system used in the NBA would allow practitioners to have a complete understanding of the optical tracking systems limitations. Additionally, regular season competitions in the NBA are played across 29 arenas, which all possess different architectural design and layout. For this reason, it is also recommended that future investigations assess the accuracy and reliability of the optical tracking system in each NBA playing arena.

- Currently physical activity in competition and in training are captured with different measurement systems, as wearable micro technology is not allowed in NBA game play. The NBA and NBPA (NBA Players Association), as part of the new collective bargaining agreement, have established a wearable technology committee in order to investigate wearable micro technology to be worn in game play. Future research should examine physical activity of competitions and training using integrated measures. This would allow for enhanced understanding of the relationship between training and competitions. Additionally, this would provide a more complete understanding of the training load demands NBA players face and allow greater athlete preparation and care.

- The ability to forecast physical activity was demonstrated in Chapter 5 of this thesis. Future research, however, should examine forecasting models and include the physical activity demands found in training to provide a more robust model of future game physical activity.

- To date no study has examined the relationship between individual physical characteristics and game related fatigue during NBA competition. Identifying certain physical characteristics (as measured by specific relevant performance-based tests) that may attenuate fatigue-related reductions in physical activity in NBA game play has important implications for the development and preparation of NBA players.

- Future research should continue to examine positional relevant activity measures found in NBA game play, such as jumping and physical contact. Current activity measures fail to account for the unique demands of each playing position. Greater understanding of these positional specific measures will allow for enhanced specificity of training and athlete preparation

- Investigations into the influence of playing group on physical activity should be further developed. The influence of starters vs non-starters and line up entropy on activity measures is important to understand and may have applications for training as well in game technical strategies.

- Due to the extensive travel demands of the NBA, future research should investigate the effect of different recovery strategies on subsequent game physical activity and performance.

- Chapter 6 demonstrated the unique physical activity profiles related to each playing position and technical performance. Future research should therefore investigate the relevant technical measures of positional performance. This may allow for enhanced understanding and assessment of overall player performance. Additionally, future research should assess the validity of overall team strength measures and rankings.

REFERENCES

REFERENCES

Al Haddad, H., Mendez-Villanueva, A., Torreno, N., Munguia-Izquierdo, D., & Suarez-Arrones, L. (2018). Variability of GPS-derived running performance during official matches in elite professional soccer players. *The Journal of Sports Medicine and Physical Fitness 58*(10), 1439-1445. doi:10.23736/S0022-4707.17.07500-4

Ali, A., & Farrally, M. (1991). A computer-video aided time motion analysis technique for match analysis. *Journal of Sports Medicine and Physical Fitness, 31*(1), 82-88.

Aoki, M. S., Torres Ronda, L., Marcelino, P. R., Drago, G., Carling, C., Bradley, P. S., & Moreira, A. (2016). Monitoring training loads in professional basketball players engaged in a periodized training programme. *Journal of Strength and Conditioning Research*. doi:10.1519/JSC.0000000000001507

Aughey, R., Hammond, K., Varley, M., Schmidt, W., Bourdon, P., Buchheit, M., . . . Gore, C. (2013). Soccer activity profile of altitude versus sea-level natives during acclimatisation to 3600 m (ISA3600). *British Journal of Sports Medicine, 47 Suppl 1*, i107-113. doi:10.1136/bjsports-2013-092776

Balsom, P., Gaitanos, G., Kekblom, B., & Sjodin, B. (1994). Reduced oxygen availability during high intensity intermittent exercise impairs performance. *Acta Physiologica Scandinavia, 152*, 279-285.

Barris, S., & Button, C. (2008). A Review of Vision-Based Motion Analysis in Sport. *Journal of Sports Medicine, 38*(12), 1025-1043.

Bastida-Castillo, A., Gómez-Carmona, C., De la Cruz-Sánchez, E., Reche-Royo, X., Ibáñez, S., & Pino Ortega, J. (2019). Accuracy and inter-unit reliability of ultra-wide-band tracking system in indoor exercise. *Applied Sciences, 9*(5). doi:10.3390/app9050939

Ben Abdelkrim, N., Castagna, C., El Fazaa, S., & El Ati, J. (2010). The effect of players standard and tactical strategy on game demands in men's basketball *Journal of Strength and Conditioning Research, 24*(10), 2652-2662.

Ben Abdelkrim, N., Chaouachi, A., Chamari, K., Chtara, M., & Castagna, C. (2010). Positional role and competitive-level differences in elite-level men's basketball players. *Journal of Strength and Conditioning Research, 24*(5), 1346-1355.

Ben Abdelkrim, N., El Fazaa, S., El Ati, J., & Tabka, Z. (2007). Time-motion analysis and physiological data of elite under-19-year-old basketball players during competition. *British Journal of Sports Medicine, 41*(2), 69-75. doi:10.1136/bjsm.2006.032318

Bland, J. M., & Altman, D. G. (1986). Statistical method for assessing agreement betweeen two methods of clinical measurement. *Lancet, 327*(8476), 307-310.

Boyd, L., Ball, K., & Aughey, R. (2011). The reliability of minimaxx accelerometers for measuring physical activity in australian football. *International Journal of Sports Physiology and Performance*, 311-321.

Bruce, S. (2016). A scaleable framework for NBA player and team comparisons using player tracking data. *Journal of Sports Analytics, 2*(2), 107-119.

Buchheit, M., Al Haddad, H., Simpson, B., Palazzi, D., Bourdon, P., Di Salvo, V., & Mendez-Villanueva, A. (2014). Monitoring accelerations with GPS in football: time to slow down? *International Journal of Sports Physiology and Performance, 9*(3), 442-445. doi:10.1123/ijspp.2013-0187

Buchheit, M., Allen, A., Poon, T. K., Modonutti, M., Gregson, W., & Di Salvo, V. (2014). Integrating different tracking systems in football: multiple camera semi-automatic

system, local position measurement and GPS technologies. *Journal of Sports Sciences, 32*(20), 1844-1857. doi:10.1080/02640414.2014.942687
Buchheit, M., Hammond, K., Bourdon, P., Simpson, B., Garvican-Lewis, L., Schmid, W., . . . Aughey, R. J. (2015). Relative match intensities at high altitude in highly-trained young soccer players (isa3600). *Journal of Sports Science and Medicine, 14*, 98-102.
Caparros, T., Casals, M., Solana, A., & Pena, J. (2018). Low external workloads are related to higher injury risk in professional male basketball games. *Journal of Sports Science and Medicine, 17*, 289-297.
Carling, C. (2013). Interpreting physical performance in professional soccer match-play: should we be more pragmatic in our approach? *Sports Med, 43*(8), 655-663. doi:10.1007/s40279-013-0055-8
Carling, C., Bradley, P., McCall, A., & Dupont, G. (2016). Match-to-match variability in high-speed running activity in a professional soccer team. *Journal of Sports Sciences, 34*(24), 2215-2223. doi:10.1080/02640414.2016.1176228
Chang, Y., R., M., Su, J., Kwok, S., Levy, T., Wexler, A., & Squire, K. (2014). *Quantifying Shot Quality in the NBA*. Paper presented at the MIT Sloan Sports Analytics Conference, Boston, MA.
Chelly, S. M., & Denis, C. (2001). Leg power and hopping stiffness- relationship with sprint running performance. *Medicine and Science in Sports and Exercise, 33*(2), 326-333.
Cohen, J. (1988). *Statistical Power Analysis for the Behavioral Sciences*. Hillsdale, NJ: Lawrence Erlbaum Associates.
Colby, M. J., Dawson, B., Heasman, J., Rogalski, B., & Gabbett, T. J. (2014). Accelerometer and GPS-Derived Running Loads and Injury Risk in Elite Australian Footballers. *Journal of Strength and Conditioning Research, 28*(8), 2244-2252. doi:10.1519/jsc.0000000000000362
Cummins, C., Orr, R., O'Connor, H., & West, C. (2013). Global positioning systems (GPS) and microtechnology sensors in team sports: a systematic review. *Journal of Sports Medicine, 43*(10), 1025-1042. doi:10.1007/s40279-013-0069-2
D'Amelio, K., Ward, P., Bilsborough, J., & Coutts, A. (2018). *Measurement accuracy of an optical tracking system for instantaneous velocity*. University of Technology, Sydney.
D'Amelio, K., Ward, P., & Coutts, A. (2019). *Quantifying the physical performance demand and game to game variation within the NBA*
Deb, S. K., Brown, D. R., Gough, L. A., McLellan, C. P., Swinton, P. A., Andy Sparks, S., & McNaughton, L. R. (2018). Quantifying the effects of acute hypoxic exposure on exercise performance and capacity: A systematic review and meta-regression. *Eur J Sport Sci, 18*(2), 243-256. doi:10.1080/17461391.2017.1410233
di Prampero, P., Fusi, S., Sepulcri, L., Morin, J., Belli, A., & Antonutto, G. (2005). Sprint running: a new energetic approach. *The Journal of Experimental Biology, 208*(Pt 14), 2809-2816. doi:10.1242/jeb.01700
Di Salvo, V., Collins, A., McNeill, B., & Cardinale, M. (2006). Validation of Prozone ®: A new video-based performance analysis system. *International journal of performance analysis in sport, 6*(1), 108-119. doi:10.1080/24748668.2006.11868359
Di Salvo, V., Gregson, W., Atkinson, G., Tordoff, P., & Drust, B. (2009). Analysis of high intensity activity in Premier League soccer. *International Journal of Sports Medicine, 30*(3), 205-212. doi:10.1055/s-0028-1105950
Duthie, G., Pyne, D., & Hooper, S. (2003). The reliability of video-based time motion analysis. *Journal of Human Movement Studies, 44*(3), 259-272.

Edgecomb, S., & Norton, K. (2006). Comparison of global positioning and computer-based tracking systems for measuring player movement distance during Australian football. *Journal of Science and Medicine in Sport, 9*(1-2), 25-32. doi:10.1016/j.jsams.2006.01.003

Ehrmann, F., Duncan, C., Sindhusake, D., Fanzen, W., & Greene, D. (2016). GPS and injury prevention in professional soccer. *Journal of Strength and Conditioning Research, 30*(2), 360-367.

Ferioli, D., Schelling, X., Bosio, A., La Torre, A., Rucco, D., & Rampinini, E. (2020). Match activities in basketball games: comparison between different competitive levels. *Journal of Strength and Conditioning Research, 34*(1).

Fernandez-Leo, A., Gomez-Carmona, C., Garcia-Rubio, J., & Ibanez, S. J. (2020). Influence of contextual variables on physical and technical performance in male amateur basketball: A case study. *International Journal of Environmental Research and Public Health 17*(4). doi:10.3390/ijerph17041193

Fox, J., Scanlan, A., & Stanton, R. (2017). A review of player monitoring approaches in basketball: Current trends and future directions. *Journal of Strength and Conditioning Research*. doi:10.1519/JSC.0000000000001964

Fox, J., Stanton, R., Sargent, C., O'Grady, C., & Scanlan, A. (2019). The impact of contextual factors on game demands in starting, semi-professional, male basketball players. *International Journal of Sports and Performance, 1-7*. Retrieved from https://doi.org/10.1123/ijspp.2019-0203

Franks, A., Miller, A., Bornn, L., & Goldsberry, K. (2015). Characterizing the spatial structure of defensive skill in professional basketball. *The Annals of Applied Statistics, 9*(1), 94-121. doi:10.1214/14-aoas799

Goldsberry, K. (2012). *CourtVision: New Visual and Spatial Analytics for the NBA*. Paper presented at the MIT Sloan Sports Analytics Conference Boston, MA.

Goldsberry, K., & Weiss, E. (2013). *The Dwight effect: A new ensemble of interior defense analytics for the NBA*. Paper presented at the MIT Sloan Sports Analytics Conference Boston, MA.

Gore, C., McSharry, P., Hewitt, A., & Saunders, P. (2008). Preparation for football competition at moderate to high altitude. *Scandanavian Journal of Medicine and Science in Sports, 18 Suppl 1*, 85-95. doi:10.1111/j.1600-0838.2008.00836.x

Gregson, W., Drust, B., Atkinson, G., & Salvo, V. D. (2010). Match-to-match variability of high-speed activities in premier league soccer. *International Journal of Sports Medicine, 31*(4), 237-242. doi:10.1055/s-0030-1247546

Harley, J. A., Lovell, R. J., Barnes, C. A., M.D., P., & Weston, M. (2011). The interchangeability of global positioning system and semiautomated video-based performance data during elite soccer match play. *Journal of Strength and Conditioning Research, 25*(8), 2334-2336.

Hollinger, J., & Hollinger, J. (2005). *Pro Basketball Forecast, 2005-2006*: Potomac Books.

Hopkins, W. G. (2002). *A scale of magnitudes for effect statistics*. Retrieved from http://www.sportsci.org/resources/stats/index.html

Hopkins, W. G., Marshall, S. W., Batterham, A. M., & Hanin, J. (2009). Progressive statistics for studies in sports medicine and exercise science. *Medicine and Science in Sports and Exercise, 41*(1), 3-12.

Ibanez, S., Garcia, J., Feu, S., Lorenzo, A., & Sampaio, J. (2009). Effects of consecutive basketball games on the game-related statistics that discriminate winner and losing teams. *Journal of Sports Science and Medicine, 8*, 458-462.

Impellizzeri, F., & Marcora, S. (2009). Test validation in sport physiology: Lessons learned from clinimetrics. *International Journal of Sports Physiology and Performance, 4*, 269-277.

Jennings, D., Cormack, S., Coutts, A., Boyd, L., & Aughey, R. (2010). The validity and reliability of GPS units for measuring distance in team sport specific running patterns. *International Journal of Sports Physiology and Performance, 5*(3), 328-341. doi:10.1123/ijspp.5.3.328

Kempton, T., & Coutts, A. (2016). Factors affecting exercise intensity in professional rugby league match-play. *Journal of Science and Medicine in Sport, 19*(6), 504-508. doi:10.1016/j.jsams.2015.06.008

Kempton, T., Sirotic, A., Cameron, M., & Coutts, A. (2013). Match-related fatigue reduces physical and technical performance during elite rugby league match-play: a case study. *Journal of Sports Sciences, 31*(16), 1770-1780. doi:10.1080/02640414.2013.803583

Kempton, T., Sirotic, A., & Coutts, A. (2014). An integrated analysis of match-related fatigue in professional rugby league. *Journal of Sports Sciences, 33*(1), 39-47. doi:10.1080/02640414.2014.921832

Kempton, T., Sullivan, C., Bilsborough, J., Cordy, J., & Coutts, A. (2015). Match-to-match variation in physical activity and technical skill measures in professional Australian Football. *Journal of Science and Medicine in Sport, 18*(1), 109-113. doi:10.1016/j.jsams.2013.12.006

Klusemann, M., Pyne, D., Hopkins, W., & Drinkwater, E. (2013). Activity profiles and demands of seasonal and tournament basketball competition. *International Journal of Sports Physiology and Performance, 8*, 623-629.

Lago-Peñas, C., & Lago-Ballesteros, J. (2011). Game location and team quality effects on performance profiles in professional soccer. *Journal of Sports Science and Medicine, 10*, 465-471.

Leatherwood, W., & Dragoo, J. (2013). Effect of airline travel on performance: a review of the literature. *British Journal of Sports Medicine, 47*(9), 561-567. doi:10.1136/bjsports-2012-091449

Leser, R., Schleindlhuber, A., Lyons, K., & Baca, A. (2014). Accuracy of an UWB-based position tracking system used for time-motion analyses in game sports. *European Journal of Sport Science, 14*(7), 635-642. doi:10.1080/17461391.2014.884167

Linke, D., Link, D., & Lames, M. (2018). Validation of electronic performance and tracking systems EPTS under field conditions. *PLoS One, 13*(7), e0199519. doi:10.1371/journal.pone.0199519

Luteberget, L., Spencer, M., & Gilgien, M. (2018). Validity of the catapult clearsky t6 local positioning system for team sports specific drills, in indoor conditions. *Frontiers in Physiology, 9*, 115. doi:10.3389/fphys.2018.00115

Maheswaran, R., Chang, Y., Henehan, A., & Denesis, S. (2012). *Deconstructing the rebound with optical tracking data*. Paper presented at the MIT Sloan Sports Analytics Conference, Boston, MA.

Mateus, N., Goncalves, B., Abade, E., Leite, N., Gomez, A., & Sampaio, J. (2018). Exploring game performance in NBA playoffs. *Kinesiology, 50*.

Mateus, N., Goncalves, B., Abade, E., Liu, H., Torres Ronda, L., Leite, N., & Sampaio, J. (2015). Game to game variability of technical and physical performance in NBA players. *International journal of performance analysis in sport, 15*(1), 764-776.

Matthew, D., & Delextrat, A. (2009). Heart rate, blood lactate concentration, and time-motion analysis of female basketball players during competition. *Journal of Sports Sciences, 27*(8), 813-821. doi:10.1080/02640410902926420

McInnes, S., Carlson, J., Jones, C., & McKenna, M. (1995). The physiological load imposed on basketball players during competition. *Journal of Sports Sciences, 13*(5), 387-397. doi:10.1080/02640419508732254

McLaren, S. J., Weston, M., Smith, A., Cramb, R., & Portas, M. D. (2016). Variability of physical performance and player match loads in professional rugby union. *J Sci Med Sport, 19*(6), 493-497. doi:10.1016/j.jsams.2015.05.010

McLean, B., Strack, D., Russell, J., & Coutts, A. (2019). Quantifying physical demands in the national basketball association-challenges around developing best-practice models for athlete care and performance. *International Journal of Sports Physiology and Performance, 14*(4), 414-420. doi:10.1123/ijspp.2018-0384

Messersmith, L. (1944). A study of the distance travelled by basketball players. *Research Quarterly. American Association for Health, Physical Education and Recreation, 15*(1), 29-37. doi:10.1080/10671188.1944.10624811

Messersmith, L., & Corey, S. (1931). The distance traversed by a basketball player. *Research Quarterly. American Association for Health, Physical Education and Recreation, 2*(2), 57-60. doi:10.1080/23267402.1931.10625026

Mohr, M., Krustrup, P., & Bangsbo, J. (2003). Match performance of high-standard soccer players with special reference to development of fatigue. *Journal of Sports Sciences, 21*(7), 519-528. doi:10.1080/0264041031000071182

Mohr, M., Mujika, I., Santisteban, J., Randers, M., Bischoff, R., Solano, R., . . . Krustrup, P. (2010). Examination of fatigue development in elite soccer in a hot environment: A multi-experimental approach. *Scandanavian Journal of Medicine and Science in Sports, 20 Suppl 3*, 125-132. doi:10.1111/j.1600-0838.2010.01217.x

Montgomery, P., Pyne, D., & Minahan, C. (2010). The physical and physiological demands of basketball training and competition. *International Journal of Sports Physiology and Performance, 5*, 75-86.

Muscillo, R., Conforto, S., Schmid, M., Caselli, P., & D'Alessio, T. (2007). *Classification of motor activities through derivative dynamic time warping applied on accelerometer data.* Paper presented at the International Conference of the IEEE EMBS, Lyon, France.

Narazaki, K., Berg, K., Stergiou, N., & Chen, B. (2009). Physiological demands of competitive basketball. *Scandanavian Journal of Medicine and Science in Sports, 19*(3), 425-432. doi:10.1111/j.1600-0838.2008.00789.x

Oliver, D. (2004). *Basketball on Paper: Rules and tools for performance analysis*: Potomac Books.

Pers, J., Bon, M., Kovacic, S., Sibila, M., & Dezman, B. (2002). Observation and analysis of large-scale human motion. *Human Movement Science, 21*, 295-311.

Petway, A. J., Freitas, T. T., Calleja-Gonzalez, J., Medina Leal, D., & Alcaraz, P. E. (2020). Training load and match-play demands in basketball based on competition level: A systematic review. *PLoS One, 15*(3), e0229212. doi:10.1371/journal.pone.0229212

Pino-Ortega, J., Rojas-Valverde, D., Gomez-Carmona, C., Bastida-Castillo, A., Hernandez-Belmonte, A., Garcia-Rubio, J., . . . Ibanez, S. J. (2019). Impact of contextual factors on external load during a congested-fixture tournament in elite U'18 basketball players. *Frontiers in Physiology, 10*, 1100. doi:10.3389/fpsyg.2019.01100

Puente, C., Abian-Vicen, J., Areces, F., Lopez, R., & Del Coso, J. (2016). Physical and physiological demands of experienced male basketball players during a competitive game. *Journal of Strength and Conditioning Research*. doi:10.1519/JSC.0000000000001577

R Development Core Team. (2017). R: A language and environment for statisical computing. Vienna, Austria: R Foundation for Statistical Computing Retrieved from http://www.R-project.org

Rampinini, E., Alberti, G., Fiorenza, M., Riggio, M., Sassi, R., Borges, T. O., & Coutts, A. J. (2015). Accuracy of GPS devices for measuring high-intensity running in field-based team sports. *International Journal of Sports Medicine, 36*(1), 49-53. doi:10.1055/s-0034-1385866

Rampinini, E., Coutts, A., Castagna, C., Sassi, R., & Impellizzeri, F. (2007). Variation in Top Level Soccer Match Performance. *International Journal of Sports Medicine, 28*(12), 1018-1024. doi:10.1055/s-2007-965158

Randers, M. B., Mujika, I., Hewitt, A., Santisteban, J., Bischoff, R., Solano, R., . . . Mohr, M. (2010). Application of four different football match analysis systems: a comparative study. *Journal of Sports Sciences, 28*(2), 171-182. doi:10.1080/02640410903428525

Ribeiro, H., Mukherjee, S., & Zeng, X. (2016). The advantage of playing home in NBA: Microscopic, team-specific and evolving features. *PLoS One, 11*(3), e0152440. doi:10.1371/journal.pone.0152440

Rodriguez-Alonso, M., Fernandez-Garcia, B., Perez-Lanadluce, J., & Terrados, N. (2003). Blood lactate and heart rate during national and international women's basketball. *Journal of Sports Medicine and Physical Fitness, 43*(4), 432-436.

Roell, M., Roecker, K., Gehring, D., Mahler, H., & Gollhofer, A. (2018). Player Monitoring in Indoor Team Sports: Concurrent Validity of Inertial Measurement Units to Quantify Average and Peak Acceleration Values. *Frontiers in Physiology, 9*, 141. doi:10.3389/fphys.2018.00141

Roy, J., & Forest, G. (2018). Greater circadian disadvantage during evening games for the National Basketball Association (NBA), National Hockey League (NHL) and National Football League (NFL) teams travelling westward. *Journal of Sleep Research 27*(1), 86-89. doi:10.1111/jsr.12565

Ryan, S., Coutts, A., Hocking, J., & Kempton, T. (2016). Factors affecting matching running performance in profession Australian football *International Journal of Sports Physiology and Performance*, In press.

Sampaio, J., & Janeira, M. (2017). Statistical analyses of basketball team performance: Understanding teams' wins and losses according to a different index of ball possessions. *International journal of performance analysis in sport, 3*(1), 40-49. doi:10.1080/24748668.2003.11868273

Sampaio, J., Janeira, M., Ibáñez, S., & Lorenzo, A. (2006). Discriminant analysis of game-related statistics between basketball guards, forwards and centres in three professional leagues. *European Journal of Sport Science, 6*(3), 173-178. doi:10.1080/17461390600676200

Sampaio, J., Leser, R., Baca, A., Calleja-Gonzalez, J., Coutinho, D., Gonçalves, B., & Leite, N. (2016). Defensive pressure affects basketball technical actions but not the time-motion variables. *Journal of Sport and Health Science, 5*(3), 375-380. doi:10.1016/j.jshs.2015.01.011

Sampaio, J., McGarry, T., Calleja-Gonzalez, J., Jimenez Saiz, S., Schelling, X., & Balciunas, M. (2015). Exploring game performance in the National Basketball Association using player tracking data. *PLoS One, 10*(7), e0132894. doi:10.1371/journal.pone.0132894

Scanlan, A., Dascombe, B., Kidcaff, A., Peucker, J., & Dalbo, V. (2015). Gender-specific activity demands experienced during semiprofessional basketball game play. *International Journal of Sports Physiology and Performance, 10*(5), 618-625. doi:10.1123/ijspp.2014-0407

Scanlan, A., Dascombe, B., & Reaburn, P. (2011). A comparison of the activity demands of elite and sub-elite Australian men's basketball competition. *Journal of Sports Sciences, 29*(11), 1153-1160. doi:10.1080/02640414.2011.582509

Scanlan, A., Dascombe, B., Reaburn, P., & Dalbo, V. (2012). The physiological and activity demands experienced by Australian female basketball players during competition. *Journal of Science and Medicine in Sport, 15*(4), 341-347. doi:10.1016/j.jsams.2011.12.008

Scanlan, A., Stanton, R., Sargent, C., O'Grady, C., Lastella, M., & Fox, J. (2019). Working overtime: The effects of overtime periods on game demands in basketball players. *International Journal of Sports Physiology and Performance*, 1-7. doi:10.1123/ijspp.2018-0906

Scanlan, A., Tucker, P., Dascombe, B., Berkelmans, D., Hiskens, M., & Dalbo, V. (2015). Fluctuations in activity demands across game quarters in professional and semiprofessional male basketball. *Journal of Strength and Conditioning Research, 29*(11), 3006-3015.

Schelling, X., & Torres, L. (2016). Accelerometer load profiles for basketball-specific drills in elite players. *Journal of Sports Science and Medicine, 15*, 585-591.

Schelling, X., & Torres-Ronda, L. (2016). Accelerometer load profiles for basketball specific drills in elite players. *Journal of Sports Science and Medicine*.

Scott, M., Scott, T. J., & Kelly, V. (2016). The validity and reliability of global positioning in team sport: a brief review. *Journal of Strength and Conditioning Research, 30*(5), 1470-1490.

Sempena, A., Maulidevi, N. U., & Aryan, P. R. (2011). *Human action recognition using dynamic time warping*. Paper presented at the International Conference on Electrical Engineering and Informatics, Bandung, Indonesia.

Sirotic, A. C., Knowels, H., Catterick, C., & Coutts, A. J. (2011). Positional match demands of professional rugby league competition. *Journal of Strength and Conditioning Research, 25*(11), 3076-3087.

Stojanovic, E., Stojiljkovic, N., Scanlan, A., Dalbo, V., Berkelmans, D., & Milanovic, Z. (2018). The activity demands and physiological responses encountered during basketball match-play: A systematic review. *Sports Medicine, 48*(1), 111-135. doi:10.1007/s40279-017-0794-z

Sullivan, C., Bilsborough, J., Cianciosi, M., Hocking, J., Cordy, J., & Coutts, A. (2014a). Factors affecting match performance in professional Australian football. *International Journal of Sports Physiology and Performance, 9*(3), 561-566. doi:10.1123/ijspp.2013-0183

Sullivan, C., Bilsborough, J., Cianciosi, M., Hocking, J., Cordy, J., & Coutts, A. (2014b). Match score affects activity profile and skill performance in professional Australian Football players. *Journal of Science and Medicine in Sport, 17*(3), 326-331. doi:10.1016/j.jsams.2013.05.001

Svilar, L., Casajus, J., & Jukic, I. (2019). Comparison of 5v5 training games and match-play using microsensor technology in elite basketball. *Journal of Strength and Conditioning Research, 33*(7).

Sweeting, A. J., Aughey, R. J., Cormack, S. J., & Morgan, S. (2017). Discovering frequently recurring movement sequences in team-sport athlete spatiotemporal data. *Journal of Sports Sciences, 35*(24), 2439-2445. doi:10.1080/02640414.2016.1273536

Teramoto, M., Cross, C., Rieger, R., Maak, T., & Willick, S. (2018). Predictive validity of national basketball association draft combine on future performance. *Journal of Strength and Conditioning Research, 32*(2), 396-408. doi:10.1519/JSC.0000000000001798

Torres-Ronda, L., Ric, A., Llabres-Torres, I., de Las Heras, B., & Schelling, I. D. A. X. (2016). Position-dependent cardiovascular response and time-motion analysis during training drills and friendly matches in elite male basketball players.

Journal of Strength and Conditioning Research, 30(1), 60-70. doi:10.1519/JSC.0000000000001043

Vaquera, A., Refoyo, I., Villa, J. G., Calleja, J., Rodriguez-Marroyo, J. A., Garcia-Lopez, J., & Sampedro, J. (2008). Heart rate response to game play in professional basketball players. *Journal of Human Sport and Exercise, 3*(1), 1-9.

Varley, M. C., Fairweather, I. H., & Aughey, R. J. (2012). Validity and reliability of GPS for measuring instantaneous velocity during acceleration, deceleration, and constant motion. *Journal of Sports Sciences, 30*(2), 121-127. doi:10.1080/02640414.2011.627941

Vazquez-Guerrero, J., Fernandez-Valdes, B., Goncalves, B., & Sampaio, J. (2019). Changes in locomotor ratio during basketball game quarters from elite under-18 teams. *Frontiers in Physiology, 10*, 2163. doi:10.3389/fpsyg.2019.02163

Vazquez-Guerrero, J., Suarez-Arrones, L., Gomes, D., & Rodas, G. (2018). Comparing external total load, acceleration and deceleration outputs in elite basketball players across positions during match play. *Kinesiology, 50*(2).

Waldron, M., Worsfold, P., Twist, C., & Lamb, K. (2011). Concurrent validity and test-retest reliability of a global positioning system (GPS) and timing gates to assess sprint performance variables. *Journal of Sports Sciences, 29*(15), 1613-1619. doi:10.1080/02640414.2011.608703

Wilkerson, G., Gupta, A., Allen, J., Keith, C. M., & Colston, M. (2016). Utilization of practice session average inertial load to quantify college football injury risk. *Journal of Strength and Conditioning Research, 30*(9), 2369-2374.

Williams, T., & Walters, C. (2011). *The effects of altitude on soccer match outcomes.* Paper presented at the MIT Sloan Sports Analytics Conference, Boston, MA.

Wu, X., Kumar, V., Ross Quinlan, J., Ghosh, J., Yang, Q., Motoda, H., . . . Steinberg, D. (2007). Top 10 algorithms in data mining. *Knowledge and Information Systems, 14*(1), 1-37. doi:10.1007/s10115-007-0114-2

Wundersitz, D., Gastin, P., Robertson, S., Davey, P., & Netto, K. (2015). Validation of a trunk-mounted accelerometer to measure peak impacts during team sport movements. *International Journal of Sports Medicine, 36*(9), 742-746. doi:10.1055/s-0035-1547265

Zhang, S., Lorenzo, A., Gómez, M., Liu, H., Gonçalves, B., & Sampaio, J. (2017). Players' technical and physical performance profiles and game-to-game variation in NBA. *International journal of performance analysis in sport, 17*(4), 466-483. doi:10.1080/24748668.2017.1352432

APPENDICES

APPENDIX A: UNIVERSITY ETHICS APPROVAL

Dear Applicant

Thank you for your response to the Committee's comments for your project titled "The validity of the SportVU optical tracking camera system in quantifying physical demands of professional basketball and its relationship to accelerometer based micro-technology". Your response satisfactorily addresses the concerns and questions raised by the Committee who agreed that the application now meets the requirements of the NHMRC National Statement on Ethical Conduct in Human Research (2007). I am pleased to inform you that ethics approval is now granted.

Your approval number is UTS HREC REF NO. ETH16-1046.

Approval will be for a period of five (5) years from the date of this correspondence subject to the provision of annual reports. Your approval number must be included in all participant material and advertisements. Any advertisements on the UTS Staff Connect without an approval number will be removed.

Please note that the ethical conduct of research is an on-going process. The National Statement on Ethical Conduct in Research Involving Humans requires us to obtain a report about the progress of the research, and in particular about any changes to the research which may have ethical implications. This report form must be completed at least annually, and at the end of the project (if it takes more than a year). The Ethics Secretariat will contact you when it is time to complete your first report.

I also refer you to the AVCC guidelines relating to the storage of data, which require that data be kept for a minimum of 5 years after publication of research. However, in NSW, longer retention requirements are required for research on human subjects with potential long-term effects, research with long-term environmental effects, or research considered of national or international significance, importance, or controversy. If the data from this research project falls into one of these categories, contact University Records for advice on long-term retention.

You should consider this your official letter of approval. If you require a hardcopy, please contact Research.Ethics@uts.edu.au.

If you have any queries about your ethics approval or require any amendments to your research in the future, please do not hesitate to contact Research.Ethics@uts.edu.au.

Yours sincerely,

Associate Professor Beata Bajorek

Chairperson

UTS Human Research Ethics Committee

C/- Research & Innovation Office

University of Technology, Sydney

Dear Applicant,

The faculty has considered your Nil/Negligible Risk Declaration Form for your project titled, “Match to Match variation and the factors affecting match performance measures in professional basketball.” and agree your research does not require review from the UTS Human Research Ethics Committee. Please keep a copy of your Declaration from on file to show you have considered risk.

For tracking purposes, you have been provided with an ethics application number which is UTS HREC ETH17-1847.

I also refer you to the AVCC guidelines relating to the storage of data, which require that data be kept for a minimum of 5 years after publication of research. However, in NSW, longer retention requirements are required for research on human subjects with potential long-term effects, research with long-term environmental effects, or research considered of national or international significance, importance, or controversy. If the data from this research project falls into one of these categories, contact University Records for advice on long-term retention.

You should consider this your official letter of noting.

You should consider this your official letter of approval. If you require a hardcopy, please contact Research.Ethics@uts.edu.au.

If you have any queries about your ethics approval or require any amendments to your research in the future, please do not hesitate to contact Research.Ethics@uts.edu.au.

Yours sincerely,

Associate Professor Beata Bajorek

Chairperson

UTS Human Research Ethics Committee

C/- Research & Innovation Office

University of Technology, Sydney