Physical and Technical Attributes of On-water Rowing Performance in Junior and Elite Rowers

By Natalie Legge

Thesis submitted in fulfilment of the requirements for
the degree of

Doctor of Philosophy

under the supervision of
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Certificate of Original Authorship

I, Natalie Legge, declare that this thesis is submitted in fulfilment of the requirements for the award of Doctor of Philosophy, in the Faculty of Health, School of Sport, Exercise, and Rehabilitation 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.

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Preface

This thesis, submitted for the degree of Doctor of Philosophy, is presented in accordance with the Procedures (Version 1.13) set out by the Graduate Research School, University of Technology Sydney.

The research design, data collection and analyses have resulted in five manuscripts published or submitted for publication in peer-reviewed journals. Chapter 1 provides an introduction with a background on rowing performance and literature relevant to this research, a statement of the research problem and the aims and objectives of each of the studies. The manuscripts of each study are subsequently presented as individual chapters (Chapters 2-6), beginning with a scoping review of the on-water rowing biomechanics literature. Each manuscript reviews the literature relevant to that study, outlines and discusses the individual methodology and presents the findings of that study. The studies are presented in an order reflecting a progression in understanding and development of the research topic as well as addressing the research questions. Chapter 7, the general discussion, provides an interpretation of the collective findings and practical applications from the studies conducted. Practical implications are provided for coaches, athletes, practitioners and researchers. Finally, Chapter 8 is a summary with recommendations and suggestions for future research based on the findings from the studies.

COVID-19 had a significant impact on the completion of this thesis leading to a 6-month extension and study modifications. In the plan presented at the Stage 1 Assessment, the Physical and Technical attributes study (Chapter 5) was a longitudinal study that involved a strength intervention with junior rowers to explore how improved maximal strength may lead to biomechanical changes and technique enhancement. Due to delays experienced during 2020 and then again in 2021, this study was modified to become a cross-sectional study. The intervention was removed to account for the extensive delays and also considering the risk of further lockdowns disrupting a planned data collection period of up to 12 weeks. Data collection was then completed in late 2022 and early 2023.

In contrast, the Coaches Perspectives study (Chapter 2) was scheduled to be run as face-to-face focus groups with coaches recruited from Sydney, NSW. Ethics was approved and recruitment was due to begin in early 2020. With the commencement of the first lockdown in March 2020, we sought ethics approval to move the focus groups to online interviews. This allowed easier access to coaches during a period where they had extra time during the lockdown to give an hour of their time and recruitment was expanded to nationwide with the online platform. This last-minute change due to COVID-19 led to a recruitment of a very high-calibre participant group within the National Rowing Coaching Network.

Acknowledgements

This project would not have happened without the help and support from many people, and I am very grateful for that. The length of the following list of acknowledgements reflects the support I have received during this time.

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Thank you to all the rowing coaches and athletes who participated in my study, including the coaches who took the time to discuss rowing with me during the 2020 covid lockdown and the coaches and athletes who made the time to travel to Penrith and Olympic Park to complete the testing days.

Thank you to Rowing Australia, the coaches, support staff and rowers. Erin McCleave and David Young, in particular, have been very generous in their support during my project, and I can’t thank them enough for that. To the national team coaches, particularly, Rhett and John, thanks for allowing me the time in your training programs to test your athletes, and to the support staff and coaches who helped with testing: Ellen, Hally, Rhett, Dave, Erin, Jan, Tristan and Phil.

To Alan Bennett, and Rowing NSW, thank you for allowing us access to the official regatta speed boats to support our on-water testing sessions. To Loreto Normanhurst and Sydney Rowing Club for the loan of rowing boats and oars to conduct the junior cohort testing. To the NSW Institute Sport (NSWIS) and the Australian Institute of Sport (AIS) for allowing us access to their training centres to conduct our land testing with the athletes and to NSWIS for access to their rowing biomechanics equipment.

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Lastly, to my family, in particular my partner Kirsten and my Mum, thank you for the continued support, I promise this is the last degree I will pursue. Thank you for all the times you have given me time to work on my PhD, whether it be for writing, spending long days at the regatta centre in Penrith or travelling for data collection opportunities. I am forever grateful.

List of Articles Submitted for Publication

Peer-reviewed Journal Publications:

Legge, N., Draper, C., Slattery, K., O'Meara, D., Watsford, M. On-water Rowing Biomechanical Assessment – A Systematic Scoping Review. *Sports Medicine - Open* **10**, 101(2024). https://doi.org/10.1186/s40798-024-00760-2

Legge, N., Watsford, M., O'Meara, D., Sharp, P., Slattery, K. M. (2023). "A feeling for run and rhythm": Coaches' perspectives of performance, talent, and progression in rowing. *Journal of Sports Sciences*, 41(10), pp.927-936. https://doi.org/10.1080/02640414.2023.2249752

Legge, N., Slattery, K. M., O'Meara, D., McCleave, E., Young, D., Crichton, S., Watsford, M. (2024). Physical and Technical attributes associated on-water rowing performance in Junior and Elite Rowers. *Journal of Sports Sciences*, 1-11. https://doi.org/10.1080/02640414.2024.2408521

Manuscripts Submitted for Publication:

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Manuscripts in Preparation for Publication:

Legge, N., Watsford, M., O'Meara, D., Slattery, K. M. (In Preparation). Movement Competency in Rowing – Current Opinion. *Sports Medicine.*

Abstract

Rowing performance research intends to provide coaches, support staff, applied researchers, and athletes with information that can improve our understanding of the attributes that contribute to success. The aim of this thesis was to explore the inter-relatedness of the physical and technical aspects of on-water rowing performance which optimise boat velocity. Establishing performance characteristics for elite and junior, male and female rowers contributes to improved understanding on aspects affecting the progression from junior to elite level rowing. In addition, the complex nature of rowing performance was explored. The extent of rowing biomechanics research specific to on-water rowing was unclear, prompting a scoping review in Chapter Two to establish the current state of evidence. The review highlights the lack of on-water research in comparison to ergometer-based research and the vast array of reported variables making systematic comparison and collation of data problematic.

Chapter Three presents coaches' perspectives on the physical and technical attributes pertinent to rowing performance. Research studies integrating physical and technical attributes to address performance outcomes were seemingly limited. Therefore, this study drew on the experiential knowledge of highly experienced rowing coaches to inform subsequent studies in this research project. A gap that was perceived by coaches was an inconsistent use of terminology creating a level of confusion around the differences between physiological capacity and physical competency for rowing. Thus, Chapter Four proposes and defines the concept of movement competency specific to rowing.

Chapter Five explores the integration of technical on-water rowing attributes with a comprehensive set of athlete physical attributes associated with rowing performance. Performance characteristics were established for each categorical group and the complex nature of sports performance was explored. Chapter Six utilises functional data analysis to enhance our understanding of elite rowing technique, focussing on the biomechanical patterns of force and acceleration in elite single scullers.

This research develops a greater understanding of how attributes of rowing performance are inter-related, and in general, how sports performance is dynamic and

complex in nature. A multiple methods research design included a practice-informed approach followed by novel exploratory studies to quantitatively understand the inter-relatedness of physical and technical characteristics. Male and female, junior and elite rowers are included as the research to-date tends to predominantly favour male participants, to address the need for gender specific guidelines (Johnston et al., 2018).

Higher order statistical modelling provides insights of the technical patterns and trends of elite single sculling which can be applied to junior rowers in the future. Understanding how the physical attributes of junior and elite rowers affect their technical on-water output can provide coaches, athletes and support staff with knowledge that can be integrated into the individual's daily training plan to support superior performance outcomes, minimise injury and retain participation in the sport.

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List of Abbreviations

AIS	Australian Institute of Sport
B	Junior males
CI	Confidence interval
cm	Centimetres
CM	Centre of mass
COREQ	Consolidated criteria for reporting qualitative studies
F	Female
FDA	Functional data analysis
FMS	Functional movement screen
G	Junior Girls
GPS	Global positioning system
Hz	Hertz
HW	Heavyweight
IMTP	Isometric mid-thigh pull
IMU	Inertial measurement unit
ISAK	International Society for the Advancement of Kinanthropometry
kg	Kilogram
LBP	Low back pain
LDA	Linear discriminant analysis
L/min	Litres per minute
LW	Lightweight
M	Male
m	Metre
$m.s^{-1}$	Metres per second
$m.s^{-2}$	Metres per second squared
$m.s^{-3}$	Metres per second cubed
N	Newtons
$N.kg^{-1}$	Newtons per kilogram
n	number
NCAS	National Coaching Accreditation Scheme

NSO	National Sporting Organisation
NSWIS	New South Wales Institute of Sport
NZ	New Zealand
PRISMA-ScR	Preferred Reporting Items for Systematic Reviews & Meta-Analyses for Scoping Reviews
RAM	Mean to peak ratio of force
RFD	Rate of force development
ROM	Range of movement
SD	Standard deviation
SEE	Standard error of the estimate
SJ	Squat jump
spm	Strokes per minute
UK	United Kingdom
USA	United States of America
VO_2max	Maximal oxygen uptake
1x	Single scull
2x	Double scull
4x	Quadruple scull
2-	Coxless pair
4-	Coxless four
8+	Coxed eight
2D	Two-dimensional
^{o}	Degrees
^{o}C	Degrees Celsius
%	Percentage
< (≤)	Less than (or equal to)
> (≥)	Greater than (or equal to)

Chapter 1

Introduction

1.1 Background

Rowing is an international sport, popular across all ages and genders (Hume, 2017). The Olympic sport of rowing occurs on flat, enclosed waterways or purpose-built rowing courses. A standard rowing race is 2000 m and there are various boat categories that compete with the main two divisions being sculling and sweep rowing. In sculling the rower has two oars, one in each hand while in sweep rowing the rower has one oar, with both hands gripping the one handle (Volianitis et al., 2020). The typical race duration is 6-8 minutes, depending on the boat category. Sculling includes the single (1x), double (2x) and quadruple scull (4x) whilst sweep rowing includes the pair (2-), four (4-) and coxed eight (8+). The pair, four and quadruple scull can be coxless (-) or coxed (+) which refers to the addition of a coxswain to steer the boat and motivate the crew during the race (McArthur, 1997). A unique part of rowing is that it involves people moving in the direction opposite to where they are facing. The boat moves in the direction of the bow and the rower is sitting in the boat facing the stern (See Figure 1.1). This allows for an effective push-pull movement involving a full body motion with the primary objective to optimise boat velocity. Rowing is considered a technical sport as it involves coordinating movements of the whole body whilst managing the dynamics of the swinging oars, moving seat and unstable boat (Kleshnev, 2016).

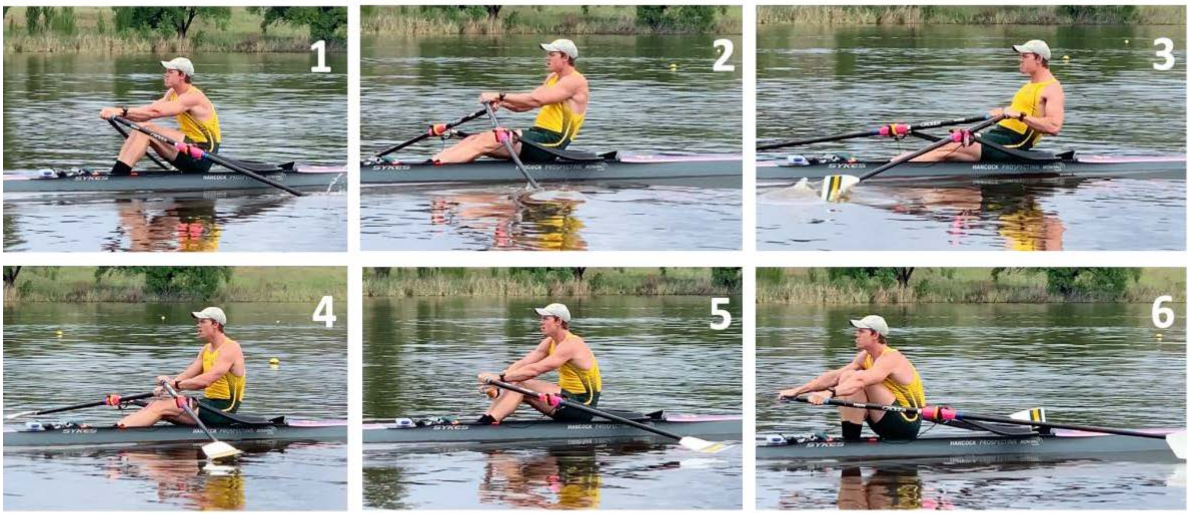


Figure 1.1: Phases of the Rowing Stroke Cycle

The rowing stroke is divided into two phases: the drive and the recovery. The drive phase (Images 1-3, Figure 1.1) begins at the catch (Image 6, Figure 1.1) when the blade enters the water and ends when the blade is released from the water at the finish (Image 3, Figure 1.1). The recovery phase is therefore the movement from the finish back to the next catch (Images 3-6, Figure 1.1), during which the blade is not in the water. Propulsive forces and drag forces (air and water resistance) directly interact to influence boat velocity (Warmenhoven et al., 2018b). Drag is a combination of hydrodynamic and aerodynamic resistance contributing 87% and 13% respectively (Kleshnev, 2016). Maximal propulsive force is generated through the mechanical work in the drive phase, whilst skilled rowers carry the oars above the water during the recovery phase to minimise drag forces contributing to the rower-boat-oar system.

Competitive rowing involves physical, technical, psychological, and tactical components that all contribute to successful performance. Similar to many other sports, rowing performance has progressively become faster over the last century, athletes have become taller and stronger, and training load has increased (Seiler, 2006). Development in boat and oar design to reduce drag and increase blade efficiency alongside improvements in rowing technique have also contributed to faster rowing results (Affeld et al., 1993). In turn, improved patterns of force application combined with reduced roll, pitch and yaw have resulted from this enhanced rowing technique. Based on these examples, it is clear that the sport of rowing has significantly progressed in terms of physical and technical aspects. Yet, the literature is limited when it comes to on-water rowing performance, specifically, understanding how the physical attributes of the rower impact the technical on-water performance. Interestingly, coaches' perspectives can provide a rich source of highly relevant information, which can contribute to the understanding of a currently limited topic. This insight can inform upon sports science concepts that are difficult to establish through objective experimental assessment (Shanteau et al., 2002). Coaches' knowledge gained through years of experience evolving and refining training for junior rowers to become successful elite athletes has the potential to provide important contextual information for how quantitative evidence is integrated for superior performance outcomes (Burnie et al., 2018).

The physical attributes of the rower have an impact on the technical output in the boat. For example, anthropometric measures such as height, arm span and leg length dictate the stroke length and mechanics of the levers of the body during the rowing cycle.

Accordingly, these attributes have a large influence on the rower's ability to generate force production (Akça, 2014). Rowing involves a whole-body motion to execute the rowing stroke correctly. Approximately 70% of a rower's muscle mass is recruited during the rowing stroke, contributing to the propulsive force on the boat (Steinacker, 1993). This significant recruitment of muscle mass highlights the important contribution of strength to rowing performance. Understanding the components of performance and how they interact helps to inform the physical preparation and technical aspects of training. Moreover, understanding and assessing changes in technique is vital for optimising rowing performance, while poor execution of technique is thought to be a major cause of chronic rowing injury (Buckeridge et al., 2012). Despite awareness of these aspects of rowing performance, further investigation is needed to better understand the integration of the physical and technical attributes for optimising on-water rowing performance.

1.2 Physiological and physical attributes of rowers

On-water rowing performance requires a well-developed aerobic and anaerobic capacity (Sebastia-Amat et al., 2020). Anaerobic capacity in a 2000 m rowing race is important during the initial start and final sprint to the finish line, accounting for 20-30% of the energy requirements, with aerobic capacity accounting for the other 70-80% (Treff et al., 2021). Rowers have shown extraordinary measurements when assessed for aerobic metabolism, specifically the maximal oxygen uptake or VO_2max. Oxygen uptake in heavyweight elite female and male rowers exceeds 4.0 L/min and 6.0 L/min, respectively (Klusiewicz et al., 2014). Further, rowers generate an average force per stroke of 686-882 N for the duration of a 2000 m rowing race (McNeely et al., 2005) and work at approximately 40% of peak rowing strength for the duration of a 2000 m rowing race (McNeely et al., 2005). Therefore, in addition to elevated aerobic demands, muscular strength is also an important physical capacity for rowers. Accordingly, a strong relationship has been established between rowing-specific strength tests and 2000 m ergometer rowing time, further highlighting muscular strength as an important characteristic of rowing performance (Sebastia-Amat et al., 2020).

The physical attributes of the rower, distinct to the physiological capacity, for the purposes of this research project, is defined as the ability to move through the rowing stroke with the required mobility and stability and associated muscular strength and endurance to execute and coordinate an effective transfer of force and resultant boat speed. Rowing is a complex, repetitive movement that involves sequential flexion and extension of the legs, trunk and arms (Thornton et al., 2017). The motion and position of the spine, pelvis and hips are an area of focus, due to low back pain (LBP) being the most prevalent injury in rowers (Alijanpour et al., 2021; Thornton et al., 2017; Trease et al., 2020). During the drive phase, coordination is primarily driven from the hip joint in all three planes of motion which corresponds to the legs and trunk providing 80% of the propulsive force (Kleshnev, 1998; Zainuddin et al., 2019). Knee and ankle joint movements are relevant in two dimensions, the sagittal and frontal planes, and sagittal and transverse planes respectively. The application of the force on the foot stretcher has an association with the position of the pelvis. With an anterior pelvic tilt, greater forces result (Buckeridge et al., 2015a). In contrast, posterior pelvic tilt has been shown to increase lumbar flexion and knee flexion with excessive lumbar flexion related to an increased risk of lumbar spine injury (Nugent et al., 2021). Although there is no clear consensus on the ideal biomechanics to reduce or prevent injury (Nugent et al., 2021), greater hip flexion is suggested to prevent posterior pelvic tilt and excessive lumbar flexion particularly at the catch position. The relevance of how these parameters affect the force transfer to the oar are not known. Collectively, these findings suggest a connection between the physical attributes including the mobility and stability of the rowing athlete and how it effects the execution of an effective rowing stroke. Coaches, athletes, and support staff could benefit from guidelines on the physical attribute requirements for rowing when planning and evaluating training and performance, and this may lead to superior outcomes.

1.3 Biomechanical factors associated with rowing performance

The connection between technique and physical attributes is critical for optimal rowing performance. Furthermore, poor technique can lead to increased risk of injury which can be detrimental to performance (Buckeridge et al., 2015a; Murphy, 2009). Rowing biomechanics research has attempted to identify characteristics of successful rowing technique and highlight the fundamental rowing performance indicators. The main performance indicator of rowing is race time over 2000m. Consequently, boat velocity and propulsive force are also closely associated with performance (Baudouin & Hawkins, 2002; B. Smith & W. Hopkins, 2012; Smith & Loschner, 2002; Soper & Hume, 2004). The catch angle, stroke length, and the application of force to the oar are critical variables as they directly influence propulsive work (Warmenhoven et al., 2018b). Further analysis has identified specific features of the propulsive force during the drive phase such as a higher rate of force development, larger mean to peak force ratios and the occurrence of an earlier peak force in elite scullers compared to sub-elite scullers (Holt et al., 2020; Smith & Draper, 2006). Furthermore, smoother force curve profiles (see Figure 1.2) are suggested to reduce within stroke velocity fluctuations and boat drag. The mean to peak force ratio provides a measure for this degree of smoothness (Holt et al., 2020). There are two main points of force generation in rowing. Firstly, the gate force is where the oar sits in the gate or swivel and force is generated on the oar and transferred to the gate and subsequently the boat. Secondly force is generated by the feet pressing against the foot plate, this is referred to as the stretcher force and directly interacts with the gate force to produce a net applied boat force (Draper, 2005). Similarly, features of the boat acceleration have been identified and related to improved performance outcomes. These measures are frequently used to provide feedback on technique by coaches but are not as prevalent in the literature (Holt et al., 2021). A greater understanding of specific boat acceleration features that relate to successful rowing performance are needed with the potential to make connections to technical coaching strategies that target these parameters.

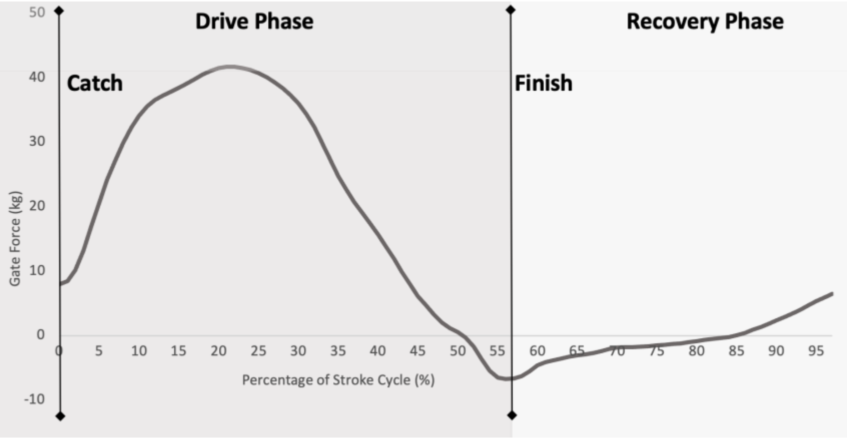


Figure 1.2: Typical gate force-time profile per stroke

Discrete metrics have commonly been reported in rowing biomechanics, however, individual movement signature profiles with unique characteristics require deeper analysis to understand and interpret the continuous time series data. More recently, functional data analysis (FDA) has been employed to better understand the temporal patterns of rowing force profiles (Warmenhoven, 2017a; Warmenhoven et al., 2017b). FDA is a suite of statistical techniques that are suitable for higher dimensional datasets such as curves and waveforms in biomechanics (Ramsay & Silverman, 2005). FDA techniques used more recently in rowing have proved useful for exploring the associations between rowing signatures and performance (Warmenhoven, 2017a; Warmenhoven et al., 2018d). However, further research and on-water testing can develop understanding beyond gate force profiles to include foot-stretcher force, boat velocity and boat acceleration for a novel and comprehensive biomechanical assessment of on-water rowing performance.

Kinematic studies in rowing often investigate body position and motion during the rowing stroke in relation to injury risk or incidence (Buckeridge et al., 2012; Nugent et al., 2021; Trompeter et al., 2021). Kinetics and kinematics are both areas of biomechanics. Kinematics is the division that measures the human motion without considering the forces that produce the motion. Whereas kinetics involves the relationship of the forces and how it changes the body movement. Performance and injury are closely related when considering the kinematics as injury regularly involves loss of training time and altered biomechanics. Accordingly, it is important to incorporate the kinematics of the rower’s movement when assessing technique for performance. Inaccurate sequencing of the body segments can negatively impact the force transfer from the foot stretcher through to the oar handle and blade in the water, reducing overall boat velocity (Buckeridge et al., 2015a). Kinematic studies of the rowing stroke have been primarily limited to ergometer studies in the laboratory using motion capture systems (Buckeridge et al., 2012; Cerne et al., 2013; B. Smith & W. Hopkins, 2012). The instrumentation required to assess joint angles and body movements has been non-existent for the on-water rowing environment, therefore the rowing ergometer in the laboratory has been the preferred modality. On-water rowing studies have attempted to use digital video analysis to assess the coordination of the legs, trunk and arms during the rowing stroke (Lamb, 1989). However, this requires time intensive analysis to assess the video frame by frame and can involve an inherent amount of perspective error (Soper et al., 2004; Weise, 1997). Inertial sensors are emerging devices in this area and may provide an avenue for on-water kinematic assessment in the near future (Worsey et al., 2019) as described herein.

1.4 Technology, Instrumentation and On-water Rowing Testing

Rowing instrumentation has evolved to allow more accessible and manageable systems of on-water analysis of boat velocity, acceleration, athlete force, power, stroke length, and body segment motion. Real-time feedback systems are becoming more common, particularly with the enhanced availability of smart devices containing triaxial accelerometers, gyroscopes & magnetometers. The advancement of mobile applications to collect and display rowing data in the boat has strongly advanced the accessibility and understanding of biomechanical parameters to the everyday social and competitive rower. Coaches traditionally critique, evaluate and educate their athletes by using the art and skill of the “coaches’ eye” (Jokuschies et al., 2017). However, with the availability of commercial measurement systems, coaches are increasingly incorporating the use of objective data to assist their coaching strategies and to assess the efficiency of the rower’s technique (Sieghartsleitner et al., 2019; Soper & Hume, 2004).

The Peach PowerLine Rowing Instrumentation system (PowerLine^{TM}) is a commercially available on-water rowing system. It is comprised of an instrumented footplate, oarlocks and boat motion sensors that measure foot stretcher forces, gate forces, gate oar angles, boat velocity and boat acceleration, at a sampling rate of 50Hz. Data from PowerLine^{TM} can be interpreted by the coach to assist with evaluating technique and performance of an individual rower or a whole crew. The ability to synchronise video with the force curve provides a visual cue to the interpretation of data, offering an important tool for coaches and athletes when trying to understand the impact of technical changes in daily training environment.

Rowing races can be a dynamic and evolving situation with environmental influences providing additional challenges, that requires the rower to be adaptable and flexible in their approach to competition. For example, tailwind versus headwind conditions can substantially change race duration, varying race times from 2 to 3 minutes over the 2000 m distance (B. Smith & W. Hopkins, 2012). Similarly, environmental challenges also exist during on-water assessment of rowing technique. The aquatic environment is unstable and minor changes in wind and temperature can potentially account for differences in technical parameters being measured (Binnie et al., 2023). Thus, a considerable amount of rowing research continues to be completed in a controlled laboratory setting using rowing ergometers (Gorman et al., 2021; B. Smith & W. Hopkins, 2012; Veličkaitė, 2021). Interestingly, it is well accepted in the literature that there are significant biomechanical differences between on-water rowing and ergometer rowing (Lamb, 1989) primarily due to the stationary position of the ergometer and the handle attached to a centrally located chain versus the dynamic movement of the rowing boat with a mobile point of support (see Figure 1.3). Previous research has shown that the forces at the handle are up to 30-40% higher on the ergometer compared to on-water (Kleshnev, 2005). Whereas maximal handle speed is up to 20% higher on-water than when using an ergometer (Kleshnev, 2005). However, it is essential that research reflects performance conditions and the objective data available for coaches is accurate, reliable, and easily accessible. On-water rowing involves a myriad of variables that are important considerations when assessing rowing performance. Specifically, technique, skill, and balance are required to manage the unstable boat, coordination of two oars and the skilful execution of the oars entering and exiting the water efficiently (Legge et al., 2023). Additional rowing research is needed in the on-water environment to provide an ecologically valid appraisal, with the outcomes particularly applicable for coaches, sports scientists and athletes (Yusof et al., 2020).

Figure 1.3: Rowing ergometer and on-water single sculling comparison

1.5 Summary

The physiology of rowing is complex as it involves contributions from each of the energy systems of the body and tends to favour larger individuals with long arms and legs that allow for a longer stroke length (Volianitis et al., 2020). In addition, the seated aspect of rowing is advantageous for larger people, since metabolic capacity increases with body mass and their body weight is supported by the boat. Rowing performance is physically a combination of muscular endurance and muscular strength, given rowers work at approximately 40% of peak rowing strength for the duration of a 2000 m rowing race (McNeely et al., 2005). Elite athletes tend to possess superior strength capabilities than their sub-elite counterparts (Sebastia-Amat et al., 2020), however, improvements in strength have not been associated with corresponding on-water rowing performance metrics such as rate of force development and time to positive acceleration (Holt et al., 2021).

Performance in any sport follows a typical although varied pathway from a novice learning a new skill through to an elite athlete, who can be considered an expert in their chosen sport. The transition from junior to elite level is complex and diverse with individual variability (Gulbin et al., 2013), however it is important to consider and evaluate all attributes of performance at both the elite and junior levels. The provision of a discrete and detailed set of performance characteristics associated with successful rowing can help establish expectations for prospective elite athletes. Moreover, this information can inform the development pathway of junior athletes by highlighting specific performance indicators shown to be related to successful rowing performance at the junior and elite level. Furthermore, the research to-date tends to predominantly favour male participants, highlighting the need for gender specific guidelines (Johnston et al., 2018). Analysis of the physiology and biomechanics of rowing is extensive in the literature (Veličkaitė, 2021; Yusof et al., 2020), however, it is clear that a greater understanding is required about the associations between certain physical and technical attributes of on-water rowing to optimise boat velocity and rowing performance.

1.6 Statement of the Problem

There is limited peer-reviewed literature involving on-water rowing research to inform training and technique for superior performance outcomes. Caution is warranted when interpreting ergometer-related research if the desired outcome is executing superior on-water rowing technique and performance. There are environmental and logistical challenges associated with on-water testing, however, establishing recommendations and specific methodological considerations could assist with the management and monitoring during testing to standardise results. To differentiate the physical from the physiological attributes for rowing performance, distinguishable terms and clear definitions are required. The complexity of performance generates problems to ascertain training priorities and escalates the limited understanding on how the physical and technical attributes are integrated for superior rowing performance outcomes. Finally, there is limited established knowledge on the physical attributes required to execute effective rowing technique.

Context of the Thesis

This thesis was completed in collaboration with the NSW Institute of Sport and Rowing Australia. Dr Damien O'Meara, an NSWIS applied sports biomechanist and member of the project team was integral to the conceptual development of the project and provided current knowledge and advice through his work with NSWIS rowing coaches and athletes. These established relationships facilitated the project and formed the basis for the junior rower recruitment through Sydney rowing clubs and schools. Rowing Australia is the national sporting organisation (NSO) for the sport of rowing in Australia with seven state-based organisations operating at a local level. They provide support and conduct rowing activities for schools, clubs, and the high-performance pathway as well as providing an education pathway for coaches through the national coaching accreditation scheme (NCAS). The extensive support from Rowing Australia provided access to the national coaches' network for the qualitative study on coaches' perspectives. In addition, the Men's and Women's National Training Centres and respective coaches and athletes permitted the project access into their daily training environment to conduct our extensive land and on-water testing for the cross-sectional study on performance characteristics in junior and elite rowers. Australia has an extensive history of success in rowing at World Championships and Olympic Games. Therefore, this sample of participants was of high ecological validity and the elite group were considered world class according to the McKay (2022) classification framework.

The concept for this project was to explore the development pathway for rowing from a junior to elite level. The junior cohort was representative of athletes under 19 years of age whilst the under 23 years of age cohort was excluded. This was due to the overlap that often occurs between the under 23 cohort and the elite international level rowers. The development pathway is not a linear process, therefore some athletes reach the elite level earlier than others and this would have led to indistinctive cohorts. The purpose was to compare junior and elite rowers, specifically exploring their physical attributes and on-water rowing technique. A multiple methods research design included a practice-informed approach followed by novel exploratory studies to quantitatively understand the interrelatedness of physical and technical characteristics in junior and elite rowers. Higher order statistical modelling provided insights of the technical patterns and trends of elite single sculling which can be applied to junior rowers in the future

Myself as the Researcher

I was introduced to the sport of rowing myself when I tested into a talent identification program at a local rowing club as a teenager. The testing battery and talent identification program resembled the system set up by Peter Shakespeare at the AIS during the 1980s and 1990s in Canberra (Poke, 2006). I accelerated through a learn to row program and gained national under 23 team selection within three years. However, I come to this research as a sport scientist, chiropractor, rowing coach and academic with a continued interest in rowing technique, injury and performance. Current perspectives on developing young athletes and nurturing talent are vastly different from the systems that were in place thirty years ago and the coaches' perspectives in this project further informed these concepts.

As the researcher, I approached the project as a critical realist, understanding and recognising that whilst an objective reality exists, my experiences and interpretations of reality provide a basis for knowledge (Archer et al., 2013). My previous experience in the sport of rowing as an athlete, sport scientist and coach may have an influence on my interpretation of the results. However, an important aspect of my involvement in this project has been to maintain objectivity throughout the research process (Levitt et al., 2022; Wa-Mbaleka, 2020). Furthermore, my experience and knowledge in the sport was of benefit as it allowed me to quickly develop a good rapport with the coaches and athletes during recruitment and throughout the project. I leveraged my position and experience in the sport to establish connections with rowing administrators, managers, coaches and former work colleagues to generate interest in the project. The rowing community is small relative to other sports, so I was able to draw on those relationships. Through the knowledge I have gained by completing this thesis, I hope to continue my involvement within the rowing community and contribute to the ongoing improvement of training applications in the development pathway.

1.7 Thesis Aims and Questions

Thesis Overview

This thesis addresses the need for additional on-water rowing research and to explore and integrate physical and technical aspects of rowing performance to gain a more comprehensive understanding of on-water rowing performance in junior and elite level athletes of both sexes. The research methodology was approached from a critical realist standpoint, recognising that whilst an objective reality exists people’s experiences and interpretations of reality provide a basis for knowledge (Archer et al., 2013). This method assumes that knowledge is both intuitive and empirical (Wiltshire, 2018). Accordingly, a multiple methods approach utilising both qualitative and quantitative data was employed to gain insights into a research topic that was seemingly limited. An overview of the studies and inter-related relevance to each other and the overall aims of the thesis is presented in Figure 1.4.

Through a series of applied studies, this thesis addresses the following aims:

(1) To assess the current scale and density of on-water rowing biomechanics research relevant to on-water rowing performance,

(2) Using a multiple methods approach, explore physical and technical characteristics associated with rowing performance,

(3) To propose and describe the importance of movement competency in rowing and its relevance to rowing performance,

(4) To better understand technique characteristics of successful rowing through model-based functional data analysis of temporal biomechanical profiles.

The primary research questions this thesis addresses are:

(1) What biomechanical metrics are relevant to on-water rowing performance?
    - Addressed in Chapters two, three, five and six
(2) How are the physical and technical characteristics of rowing performance related?
    - Addressed in Chapters three and five
(3) How can temporal biomechanical profiles improve our understanding of successful rowing performance?
    - Addressed in Chapter two and six

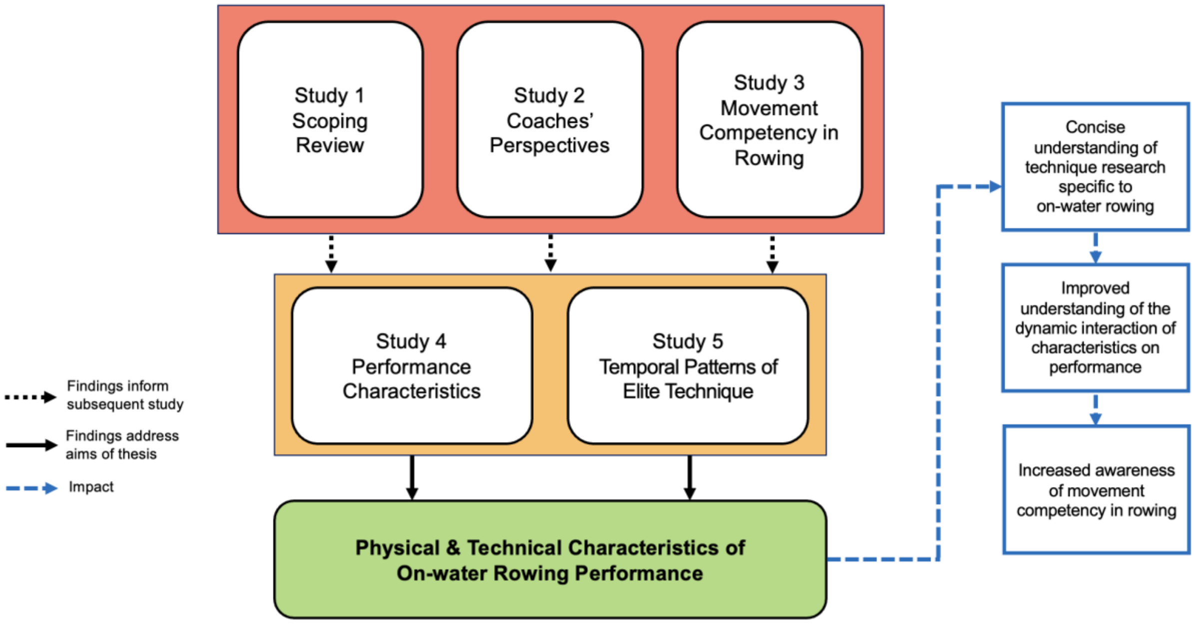


Figure 1.4: Visual display of the completed studies and their intended impact

1.8 Study Aims & Significance

1.8.1 Study One: On-water Rowing Biomechanical Assessment – A Scoping Review

The aims of the study were to describe the current scale and density of rowing biomechanics research specific to on-water rowing and to provide a guide for practitioners and researchers on future directions for on-water rowing biomechanics research.

This research is significant as it was the first known systematic scoping review of the rowing literature to provide an overview of biomechanical variables pertinent to rowing performance utilising on-water assessment. Recommendations may influence future rowing biomechanics research methodology and design to standardise reported variables and environmental conditions for on-water testing.

1.8.2 Study Two: "A Feeling for Run and Rhythm": Coaches' Perspectives of Performance, Talent, and Progression in Rowing

The aim of this study was to report coaches' recommendations for developing effective technique and physical attributes to optimise training practices among talented junior rowers who have the potential to transition to elite competition.

This was the first study to explore coaches' perspectives on rowing performance indicators for competitive rowing providing insight on key focus areas for development in junior rowers. The findings identify aspects of technical training and physical ability considered by coaches to be important in developing junior rowers. Moreover, this study highlighted how integrating coaches' experiential knowledge into an area of limited research can help inform novel quantitative studies to develop innovative knowledge.

1.8.3 Study Three: Movement Competency in Rowing

The aim of this study was to propose and describe the concept of movement competency specific to rowing, relating it to the execution of an effective technical rowing stroke that minimises injury risk and enhances performance. Further, the study proposes the potential benefits to the wider rowing community if the concept of movement competency in rowing was established.

This study was significant because movement competency has previously only been considered and researched in the context of rowing injury. However, performance related outcomes are relevant given certain physical attributes of mobility and stability are required to be able to execute a technically effective rowing stroke to transfer the physiological capacity into boat speed. Furthermore, incorporating movement competency requirements such as minimal benchmark standards for key movements and joint positions and associated screening tools for safe and effective rowing can influence technical training through coach education and provide positive outcomes for rowing participation and performance.

1.8.4 Study Four: Physical and Technical Attributes Associated with On-water Rowing Performance in Junior and Elite Rowers

The aims of this study were to describe key physical and technical variables for elite and junior rowers and examine the associations between these variables to develop an understanding of how they inter-relate to produce on-water rowing performance outcomes. This study examined male and female rowers, as the research to-date tends to predominantly favour male participants, it was important to highlight sex specific characteristics and guidelines.

This was the first rowing study to combine and explore on-water biomechanical performance variables with a comprehensive physical profile of the athletes. Baseline performance characteristics are presented, and the inter-relatedness was explored. This information may provide valuable knowledge for coaches, athletes, and support staff in how they approach physical and technical aspects of training and competing at the development pathway and elite levels.

1.8.5 Study Five: Elite Rowing Technique – Single Sculling Signature Profiles of World Class Men and Women Rowers

The aim of this study was to explore and describe features of gate force, stretcher force and boat acceleration that distinguish technique characteristics during single sculling in a representative group of world class male and female rowers.

This study was important as it employed a novel application to explore temporal biomechanical profiles of force and acceleration using a world class cohort of rowers.

This study presents a unique approach to technical analysis for rowing utilising model-based functional data analysis clustering to develop a deeper understanding of the time series data in the context of rowing profile signatures. Moreover, the graphical displays present the data that is translatable for coaches to comprehend and implement into practice to help inform elite and junior development in the future.

As this thesis is a compilation of published or submitted manuscripts seeking to address the same overall aims, there is a degree of overlap within some chapters, particularly within the introductions and discussions. Figure 1.4 provides an overview of the compilation and sequence of studies, with studies one, two and three conducted to help inform studies 4 and 5. The cumulative findings address the aims of the thesis.

Chapter 2

On-water Rowing Biomechanical Assessment – A Scoping Review

As per the manuscript published in *Sports Medicine - Open*:

Legge, N., Draper, C., Slattery, K., O'Meara, D., Watsford, M. On-water Rowing Biomechanical Assessment: A Systematic Scoping Review. *Sports Medicine – Open* **10**, 101 (2024). https://doi.org/10.1186/s40798-024-00760-2

Abstract

Biomechanical parameters can distinguish a skilled rower from a less skilled rower and can provide coaches with meaningful feedback and objective evidence to inform coaching practices on rowing technique. Therefore, it is critical to understand which technical characteristics can be related to the fundamental rowing performance indicators. The aim of this study is to describe the current scale and density of rowing biomechanics research specific to on-water rowing and provide a guide for practitioners and researchers on future directions for on-water rowing biomechanics research. All peer-reviewed publications involving the on-water assessment of rowing biomechanics were reviewed from four databases (SPORTdiscus, PubMed, Sage online journals, and Web of Science). Search results returned 1659 records, of which 27 studies met the inclusion criteria for the review. All reported variables were collated and summarised according to the three main measurements of basic mechanics: time, space and force. Study characteristics were collated to provide a descriptive overview of the literature. The main categorical variables included time, distance, velocity, acceleration, force, power and crew synchrony. Data extraction revealed gate force, horizontal oar angle and boat velocity as the most reported variables with numerous subcategories of metrics within each measure. A framework to help guide and standardise on-water rowing biomechanical assessment and the establishment of standards for environmental data collection could help guide practitioners and researchers in the on-water rowing environment. This scoping review was registered on the Open Science Framework (https://osf.io/8q5vw/).

2.1 Introduction

Attributes of rowing performance incorporate all facets of the athlete including physiology, psychology, biomechanics and technique (Murphy, 2009). The physical attributes of power, strength, anaerobic and aerobic capacity are critical and an effective transfer of these qualities from the rower to the boat is essential for optimal rowing performance. Furthermore, poor rowing technique can be detrimental to performance and increase the risk of injury (Buckeridge et al., 2015a; Murphy, 2009). The main performance indicator of rowing is race time over 2000m. Consequently, boat velocity and propulsive force are also closely associated with performance (Baudouin & Hawkins, 2002; B. Smith & W. Hopkins, 2012; Smith & Loschner, 2002; Soper & Hume, 2004). Rowing biomechanics research has attempted to identify technique characteristics of successful rowing, however, it is unclear which characteristics can be related to the fundamental performance indicators (Soper & Hume, 2004). On-water rowing research is challenging due to the logistical difficulty in controlling the environmental conditions (Binnie et al., 2023; B. Smith & W. Hopkins, 2012) and as a result, much of the biomechanical rowing research has been conducted on rowing ergometers in laboratory settings (Miarka et al., 2018). However, biomechanical instrumentation systems for the rowing boat are becoming more accessible, reliable, and valid for practitioners and researchers to transition more research and technical assessment out of the laboratory and into the rowing boat (Coker, 2010; Coker et al., 2009; B. Smith & W. Hopkins, 2012).

There are two types of rowing: sculling and sweep rowing. Sculling involves two oars, with an oar handle in each hand, whilst in sweep rowing each person only has one oar with both hands gripping the same oar handle (McArthur, 1997). In addition, there are a range of boat categories within each type of rowing. Sculling includes the single (1x), double (2x) and quadruple scull (4x) whilst sweep rowing includes the pair (2-), four (4-) and coxed eight (8+). The pair, four and quadruple scull can be coxless or coxed which refers to the addition of a coxswain to steer the boat and motivate the crew during the race (McArthur, 1997). Lastly, there are two weight divisions: lightweight and heavyweight for both men and women. Lightweight men and women are required to have a crew average for body mass of 70 kgs and 57 kgs respectively although this will no longer be contested at the Olympic level following Paris 2024. These classifications are unique to rowing and increases the variability of reported outcomes in the rowing biomechanics literature. Therefore, depending on the participant characteristics and demographics within each study, it is difficult to collate and compare results across previous studies.

Technique in relation to performance is often evaluated and taught subjectively by the coach using their experience and innate ability to observe and provide verbal feedback (Legge et al., 2023). It is measured less frequently by objective measures of biomechanical assessment (Soper & Hume, 2004). Performance in its simplest form can be measured by race results and boat speed, however, performance level can also be defined by an evaluation of skill and technique against a standard set of biomechanical criteria (Doyle et al., 2010a). In such scenarios, the complexity is in establishing the benchmark parameters. Research focussed on biomechanical parameters to distinguish a skilled rower from a less skilled rower can provide coaches with more meaningful feedback and objective evidence to inform coaching practices on rowing technique (Baudouin & Hawkins, 2002). Boat mechanics and body kinematics continue to be areas of research interest in rowing due to the implications for both performance outcomes and injury risk (McGregor et al., 2005). Where available, this information can support and inform the coach, athlete and support staff when assessing and refining technique for improving on-water performance.

Rowing in training, testing and racing environments are affected by weather conditions; specifically, wind direction and speed, and water temperature (Binnie et al., 2023) and the somewhat limited research can be partly attributed to the logistical difficulties and environment variability experienced during on-water rowing (B. T. Smith & W. G. Hopkins, 2012). Certain environmental aspects can be managed through using enclosed waterways with no tidal flow, monitoring wind and water temperature, and conducting testing sessions on a buoyed racecourse. Further, kinematic rowing research is limited in the on-water environment due to the reliance on video digitization to assess joint position and movement. Inertial sensors are emerging as devices that can precisely assess various biomechanical aspects of rowing. However, the literature is currently lacking guidelines on methodology and appropriate analysis in the on-water environment (Worsey et al., 2019).

Research in rowing has narratively summarised fundamental principles relevant to improving performance, such as maximising the propulsive impulse and minimising drag impulse on the system (Baudouin & Hawkins, 2002). Extensive review of force application profiles has been reported, however, a lack of experimental research exploring the stretcher forces has been highlighted (Warmenhoven et al., 2018b). Recommendations suggest that ideal profiles of force should be investigated, including the stretcher forces, to determine if there is an optimal interval of sequencing between the gate and stretcher throughout the stroke cycle (Soper & Hume, 2004). Differences between ergometer rowing and on-water rowing continue to be a point of interest, however, due to the convenience of the laboratory setting, ergometer research continues to dominate the literature (Millar et al., 2015; B. Smith & W. Hopkins, 2012). The assessment of joint position and body segment coordination for rowing have predominantly been undertaken on instrumented rowing ergometers, due to the availability of accurate motion tracking equipment in a laboratory setting (Buckeridge et al., 2015b; Yusof et al., 2022). Criterion-standard motion analysis systems can provide reliable and accurate information on body kinematics (Armstrong & Nokes, 2017; Kim et al., 2016), however, on-water instrumentation systems remain limited in this area and have the additional difficulty of variable environmental conditions (R. S. Barrett & J. M. Manning, 2004). Measures of rowing performance have been reviewed, although not specific to on-water assessment, with a summarised account based on the validity and reliability of known systems and devices (B. Smith & W. Hopkins, 2012). Despite conclusive statements in published research predicting that on-water performance measures may eventually surpass ergometer measures, over the past 20 years ergometer measures for rowing performance have continued to outpace on-water assessment options (B. Smith & W. Hopkins, 2012). Systematic reviews are increasingly popular in rowing, however, the scope of each review has been expansive. Multiple disciplines being included in single review articles including biomechanics, physiology, hydrodynamics and electromyography has led to summaries that are non-specific and arguably too broad (Miarka et al., 2018; Yusof et al., 2022). In contrast, this scoping review addresses this gap by focussing exclusively on the on-water rowing literature. A scoping review is appropriate for this topic as it presents an overview of a diverse body of rowing biomechanics literature. The aim of this systematic scoping review was to describe the current focus and density of rowing biomechanics research specific to on-water rowing and providing a guide for practitioners and researchers on future directions for on-water rowing biomechanics research.

2.2 Methods

2.2.1 Design and Search Strategy

This scoping review was completed according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) (Tricco et al., 2018). A systematic search of the literature involving biomechanical variables associated with rowing performance was conducted using four online databases to perform the electronic search: SPORTdiscus, PubMed, Sage online journals, and Web of Science. A search strategy was developed to identify all relevant studies related to rowing biomechanics and performance. Systematic searches were conducted in each database. All databases were initially searched from the earliest record up to and including April 2020. The search was updated with new results from all databases to include up to 29 September 2023. The search strategy combined terms following the PCC framework with a full list of terms in Table 1 (Pollock et al., 2023). The term “on-water” was not specified in the search strategy and “ergometer” was not an excluded term as part of the search strategy. This was deliberate to allow for an assessment of the literature on the ratio of rowing ergometer and on-water rowing studies could be completed as part of the scoping review. This review protocol was registered with Open Science Framework (https://osf.io/8q5vw/).

2.2.2 Study Selection

The database search was conducted by one author (NL) using the search strategy detailed in Table 2.1, and the search results were uploaded to the web-based screening software, Covidence (Veritas Health Information, Melbourne, VIC, Australia) for the screening process. Duplicates were automatically removed. The title and abstracts were screened by two reviewers (NL and CD) using the inclusion and exclusion criteria in Table 2.2. Any disagreements about study inclusion or exclusion that could not be resolved through discussion were decided by a third author (MW). After the title and abstract screening, all articles for full text screening were retrieved and assessed by two authors (NL and CD) using the same inclusion and exclusion criteria. Reference lists from full text studies and reviews were also screened for potentially relevant articles to be included in the full text screening. Attempts were made to contact authors of select studies to request full text articles that were unavailable or to retrieve any missing relevant information. Studies were eligible for inclusion if they were assessing, examining, or exploring biomechanical variables that may have an association with on-water rowing performance.

Table 2.1: Search Term Strategy

Population	Title or Abstract: 'rowing OR rower'	
Concept	(All text) – (biomechanics OR kinetic OR kinematic OR force OR velocity OR acceleration OR power OR stroke length)	AND
Context	(All text) – (performance OR "sport performance" OR technique OR skill OR "level of expertise")	AND

2.2.3 Data Extraction

To generate an overview of the existing on-water rowing biomechanics literature, data was extracted pertaining to study details (duration, country), population (sample size, age, training level and status, performance level), instrumentation systems used, and specific variables reported. Extracted data was entered into a customised online spreadsheet allowing review by multiple authors. As scoping reviews do not necessarily synthesise all extracted data, a tabular summary has not been provided in this text. No risk of bias assessment was conducted due to this being a descriptive scoping review, and effects or prevalence were not reported.

Table 2.2: Inclusion and Exclusion Criteria

Inclusion Criteria	**Exclusion Criteria**
Published in English	Systematic reviews, meta-analyses, other review articles, conference proceedings

Publication from any year	Articles without an abstract and/or no full text available
Peer-reviewed Journal articles	Population: para-rowers, spinal cord injury or paraplegic participants
Study design: experimental, quasi-experimental, non-experimental, or observational	Study is investigating equipment, modelling simulation methods, motor learning or feedback methods
Study includes on-water rowing assessment in relation to rowing performance	Study utilises the rowing ergometer as the modality for assessment
Study involves observing, evaluating, or investigating some aspect of rowing biomechanics in relation to rowing performance	Validity and reliability studies on new equipment or systems

2.3 Results

2.3.1 Study Characteristics

From the initial 1430 articles that were screened by title and abstract, 31 articles were assessed by full text and 27 articles were subsequently included for review. The flow of articles from identification through to inclusion is presented in Figure 2.1. Across the 27 studies, on-water biomechanical rowing testing was conducted in various boat classes ranging from single sculls to coxed eights. This included 11 studies using single sculls, 9 studies using coxless pairs, 1 study using double sculls, 2 studies using coxless fours and 4 studies using coxed eights. Small boat categories including the single for sculling and the coxless pair for sweep rowing were dominant across the literature reflecting an interest in individual rower output rather than the combination of a larger crew. The majority of the included studies in this scoping review were observational and cross-sectional in design. Ten of the 27 studies comprised only male participants, 3 studies involved only female participants, and 13 studies included both male and females. One study did not define the participant demographics other than it was a group of elite and sub-elite rowers (Smith & Loschner, 2002). According to authorship, 10 nations have contributed to the peer-reviewed, on-water rowing biomechanical literature, with a slight increase in the number of publications since 2015 (Figure 2.2). Both commercial and custom-built instrumentation systems have been utilised to measure the specific variables of interest to each study. Table 2.3 summarises the study characteristics including author group, journal source, sample size, and participant demographics.

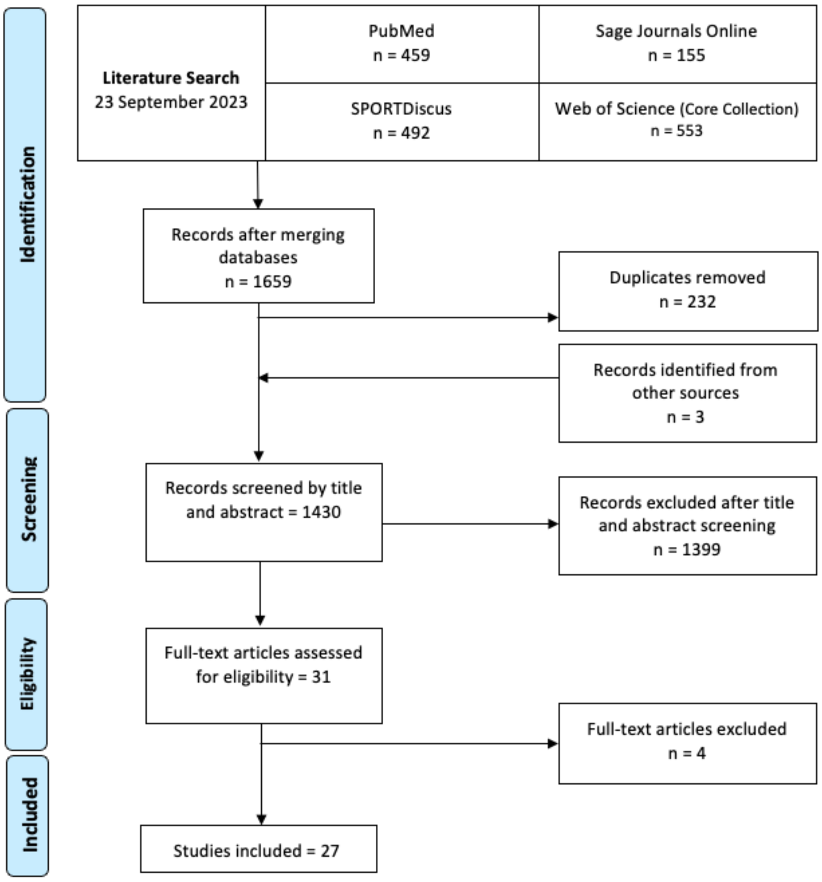


Figure 2.1: PRISMA flowchart of the literature search and screening process

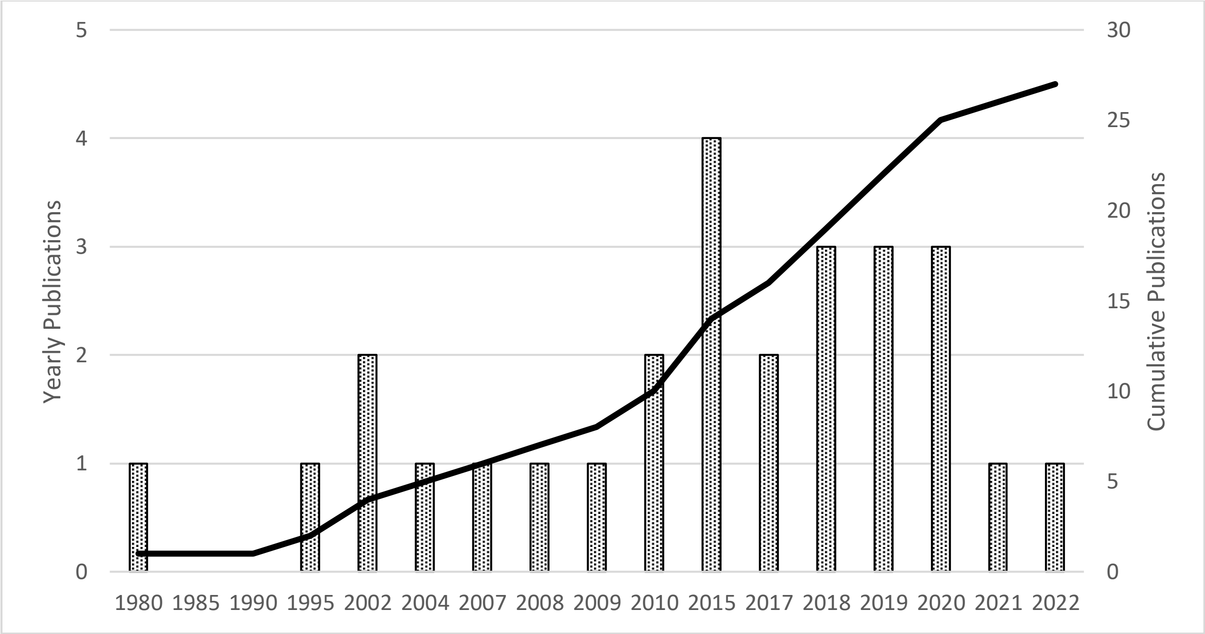


Figure 2.2: Number of on-water rowing biomechanics publications by year (Cumulative publications – black line)

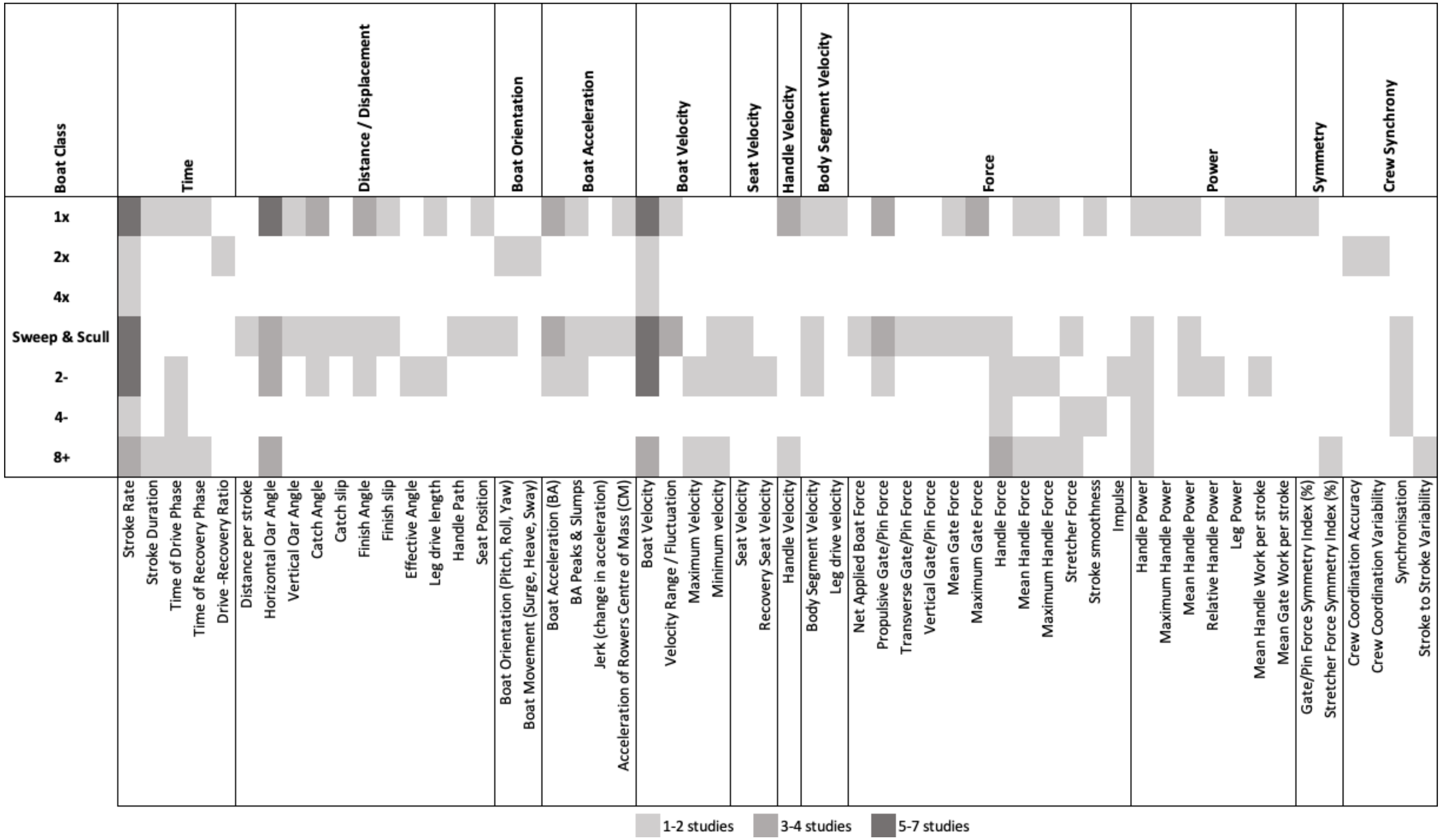
Table 2.3: Study Characteristics

No.	Author(s) & Year of Publication	Author Affiliations	Journal	Instrumentation System	Sample Size	Age (years)	Age Category	Training Level / Status	Boat Class	Weight Category
1	Baudouin & Hawkins 2004	USA	J Biomech	Custom instrumented oar force and angle (foil strain gauges and linear potentiometer)	8M	unknown	university age	Collegiate	2-	HW
2	Cuijpers et al. 2017	Netherlands	Scand J Med. Sci Sports	Custom instrumented oar force and angle (foil strain gauges and linear potentiometer)	24M, 3F	20 ± 7	unknown	National	2x	HW & LW
3	Doyle et al. 2008	Australia	Impact of Technology on Sports II	Custom Oarlock 2D load transducers, Horizontal oar shaft potentiometer, Seat drum & reel transducer	28M	unknown	unknown	International	2-	HW & LW
4	Doyle et al. 2010	Australia	Sports Biomech	Custom Oarlock 2D load transducers, horizontal oar shaft potentiometer, seat drum & reel transducer	28M	22.8 ± 3.7	underage and senior	National	2-	HW & LW
5	Gravenhorst et al. 2015	Switzerland, Australia	Int J Comput Sci Sport	Minimaxx (accelerometer & gyroscope), Peach Innovations (gate force & gate angle)	4F	unknown	senior	International	2x	unknown
6	Hill 2002	Germany	J Sports Sci	Four strain gauges (HBM, Darmstadt, Germany) glued onto Concept 2 Macon bladed oars	20M	22-31	senior	International	4-	LW
7	Hill & Fahrig 2009	Germany	Scand J Med Sci Sports	MMS2000 (FES, Berlin, Germany, Bohmert & Mattes 2003)	15M	17-31	underage, senior	Club, National	2-	HW

8	Hofmijster et al. 2007	Netherlands, Australia	J Sports Sci	RowSys measurement & telemetry system (Uni Sydney & NSWIS - Smith & Loschner, 2002)	6M, 3F	19-26	underage, senior	"Experienced" rowers (2-12yrs experience)	1x	HW
9	Kleshnev 2010	Australia, UK	J. Sports Eng. Technol	BioRowTel, Berkshire, UK	294 crews	unknown	unknown	National & International	multiple	HW & LW
10	Lintmeijer et al. 2018	Netherlands	J Sports Sci	Peach PowerLine instrumentation systems (Peach Innovations, UK)	5M, 4F	19-42	underage, senior, masters	"Experienced" rowers (2-20yrs experience)	1x	HW & LW
11	Liu et al. 2020	China	Sports Biomech	Custom system built similar to ROWX system (Weba Sport)	10M	21.8-29.4	senior	International	1x	HW
12	Martin & Bernfield 1980	USA	Med Sci Sports Exerc	Video analysis	8M	unknown	senior	International	8+	HW
13	Mattes & Wolff 2019	Germany	Int J Perform Anal Sport	MMS2000 (FES, Berlin, Germany, Bohmert & Mattes 2003)	16M, 16F	under 19	juniors (under19)	International, Junior	8+	HW
14	Mattes et al. 2015a	Germany	J Hum Sport Exerc	MMS2000 (FES, Berlin, Germany, Bohmert & Mattes 2003)	156	under 19	juniors (under19)	International, Junior	8+	HW
15	Mattes et al. 2015b	Germany	Int J Perform Anal Sport	MMS2000 (FES, Berlin, Germany, Bohmert & Mattes 2003)	24M	under 23	juniors, under 23	International, Junior	4-	HW & LW
16	Mattes et al. 2019	Germany	Biol Exerc	MMS2000 (FES, Berlin, Germany, Bohmert & Mattes 2003)	12M	unknown	senior	International, National	1x	HW & LW
17	Millar et al. 2015	NZ	Sports	Peach PowerLine instrumentation systems (Peach Innovations, UK)	4M, 4F	19-24	underage	National, Junior	1x	HW & LW

18	Perić et al. 2019	Serbia	Int J Perform Anal Sport	BioRowTel, Berkshire, UK	12M	23-29	senior	International, Collegiate	2x	HW
19	Smith & Loschner 2002	Australia	J Sports Sci	Rowsys2 system (custom integrated system)	unknown	unknown	unknown	National, International	1x, 2-	HW & LW
20	Warmenhoven et al. 2017	Australia, Ireland	Scand J Med Sci Sports	Rowsys2 system (custom integrated system)	27F	25.6 ± 4.9	senior	National, International	1x	HW & LW
21	Warmenhoven et al. 2018d	Australia, Ireland	Scand J Med Sci Sports	Rowsys2 system (custom integrated system)	27F	25.6 ± 4.9	underage, senior	National, International	1x	HW & LW
22	Warmenhoven et al. 2018a	Australia, Ireland	J Sci Med Sport	Rowsys2 system (custom integrated system)	20M, 20F	25.6 ± 4.9	underage, senior	National, International	1x	HW & LW
23	Wing & Woodburn 1995	UK	J Sports Sci	Custom instrumented oar force (metal foil strain gauges)	5M, 4F	19-24	university age	Club	8+	HW
24	Holt et al. 2020	Australia	Front sports act Living	Peach PowerLine instrumentation systems (Peach Innovations, UK)	14M, 17F	18-24	underage, senior	National, Junior	1x, 2-	HW
25	Holt et al. 2021	Australia	PLoS One	Peach PowerLine instrumentation systems (Peach Innovations, UK)	23M, 21F	18-24	underage, senior	National, Junior	1x, 2-	HW
26	Holt et al. 2022	Australia	Scand J Med Sci Sports	Peach PowerLine instrumentation systems (Peach Innovations, UK)	14M, 16F	18-24	underage, senior	National, International	1x, 2-	HW
27	Held et al. 2020	Germany	Eur J Sport Sci	BioRowTel, Berkshire, UK	69	18-22	underage	Club - National	1x	HW

KEY: HW = heavyweight rowers; LW = lightweight rowers; M = male; F = female; USA = United States of America; UK = United Kingdom; NZ = New Zealand; 2D = two-dimensional; 1x = single scull, 2x = double scull, 2- = coxless pair, 4- = coxless four, 8+ = coxed eight



Boat Class	Time					Distance / Displacement										
	Stroke Rate	Stroke Duration	Time of Drive Phase	Time of Recovery Phase	Drive -Recovery Ratio	Distance per stroke	Horizontal Oar Angle	Vertical Oar Angle	Catch Angle	Catch slip	Finish Angle	Finish slip	Effective Angle	Leg drive length	Handle Path	Seat Position
1x	▓	░	░	░			▓	░	▒		▒	░		░		░
2x	░				░											
4x	░															
Sweep & Scull	▓					░	▒	░	░	░	░	░			░	░
2-	▓		░				▒		░		░		░	░		
4-	░		░													
8+	▒	░	░	░			▒									

Boat Class	Boat Orientation		Boat Acceleration				Boat Velocity				Seat Velocity		Handle Velocity	Body Segment Velocity	
	Boat Orientation (Pitch, Roll, Yaw)	Boat Movement (Surge, Heave, Sway)	Boat Acceleration (BA)	BA Peaks & Slumps	Jerk (change in acceleration)	Acceleration of Rowers Centre of Mass (CM)	Boat Velocity	Velocity Range / Fluctuation	Maximum Velocity	Minimum velocity	Seat Velocity	Recovery Seat Velocity	Handle Velocity	Body Segment Velocity	Leg drive velocity
1x			▒	░		░	▓	░					▒	░	░
2x	░	░					░								
4x							░								
Sweep & Scull	░		▒	░	░	░	▓	▒		░	░			░	
2-			░	░			▓		░	░	░	░		░	
4-															
8+							▒		░	░			░		

Boat Class	Force											
	Net Applied Boat Force	Propulsive Gate/Pin Force	Transverse Gate/Pin Force	Vertical Gate/Pin Force	Mean Gate Force	Maximum Gate Force	Handle Force	Mean Handle Force	Maximum Handle Force	Stretcher Force	Stroke smoothness	Impulse
1x		▒			░	▒		░	░		░	
2x												
4x												
Sweep & Scull	░	▒	░	░	░	░	░			░		
2-		░					░	░	░			░
4-							░			░	░	
8+							▒	░	░	░		

Boat Class	Power							Symmetry		Crew Synchrony			
	Handle Power	Maximum Handle Power	Mean Handle Power	Relative Handle Power	Leg Power	Mean Handle Work per stroke	Mean Gate Work per stroke	Gate/Pin Force Symmetry Index (%)	Stretcher Force Symmetry Index (%)	Crew Coordination Accuracy	Crew Coordination Variability	Synchronisation	Stroke to Stroke Variability
1x	░	░	░		░	░	░	░					
2x										░	░		
4x													
Sweep & Scull	░		░									░	
2-	░		░	░		░						░	
4-	░											░	
8+	░								░				░

░ 1-2 studies ▒ 3-4 studies ▓ 5-7 studies

Figure 2.3: Heat map of biomechanical variables reported in the literature for on-water rowing

2.3.2 Biomechanical Variables

All reported variables in rowing are derived from one or a combination of the three main groups of basic mechanical measurements: time, space, and force (Kleshnev, 2016). The heat map in Figure 2.3 visualizes the prevalence of various biomechanical variables reported by the 27 studies, categorizing them into domains including timing, oar angle, positioning, force, velocity, acceleration, power, and crew synchronization. The heat map arranges broader categories along the top fields with corresponding specific metrics detailed on the lower axis, accentuating the extensive range and diversity of biomechanical measurements in rowing research. This visualization underscores the widespread variability in the biomechanical metrics reported within the literature. Reported stroke rate ranged from 20 strokes per minute (spm) up to 41 spm. A number of studies used a step rate testing protocol (Hill & Fahrig, 2009; Peric et al., 2019; Smith & Loschner, 2002), where a short distance, such as 250 m, is completed by crews and repeated over a series of increasing stroke rates, providing a spectrum of performance outputs as intensity increases. However, some studies only extracted one or two stroke rates for analysis and to address their research question (Smith & Loschner, 2002; Warmenhoven et al., 2018d). The second measurement group: space, includes length, distance and angles. Reported examples include stroke length, distance per stroke, and horizontal oar angle. The third measurement group: force, has been reported in up to two planes: horizontal and vertical, and measured in a variety of locations including the gate, pin, handle and foot stretcher. Holt et al. (2021) describes differences in the force sensor location between the gate, pin and handle. Moreover, velocity and acceleration are products of time and space, and the combination of time, space and force produces mechanical rowing power. Further details on all reported variables can be found in the supplementary material where Table 2.4 displays reported variables by individual study.

Velocity

Boat velocity is the key performance indicator in rowing and was reported in 23 of the 27 studies. The positions within a stroke where minimum and maximum velocity occurred (Doyle et al., 2008; Martin & Bernfield, 1980) and timing from the catch to minimum velocity (Holt et al., 2020) were also of interest. To provide context to the phases of the stroke cycle, Figure 2.4 presents a representative temporal boat velocity per stroke cycle (Smith & Loschner, 2002). Fluctuations in boat velocity and velocity range have been discussed in reference to performance (Holt et al., 2020; Holt et al., 2022; Smith & Loschner, 2002). Further, there were other metrics using boat velocity as the outcome comparator. For example, in sweep rowing, the oarside arm was compared to the non-oarside arm in terms of contribution to boat propulsion via measurements of gate force, foot force, power and boat velocity (Mattes et al., 2015b) and variations in foot stretcher height were also compared observing the effect on boat velocity (Liu et al., 2020).

Handle velocity has been measured based on the angle of the oar shaft sensor or gate angle sensor depending on the instrumentation system (Gravenhorst et al., 2015; Mattes & Wolff, 2019). Maximal handle velocity during the drive phase has been associated with boat velocity, assuming the blade was completely submerged in the water. A higher handle velocity during the drive phase leads to greater boat acceleration and therefore is positively associated with boat velocity (Gravenhorst et al., 2015).

Seat velocity has been examined in combination with other segment velocities of the handle and trunk and related to the effects on boat acceleration and boat velocity (Doyle et al., 2008) using custom instrumentation systems that included a drum and reel transducer as described by Kleshnev (2000) and Draper (2005). Body segment velocities of the legs, trunk and arms were included in two studies as part of calculating the acceleration of the rower’s centre of mass (CM). Through using the CM acceleration, one of these studies described the temporal phases of the stroke cycle through accelerations of the boat and rower (Kleshnev, 2010) while the second study used the rower’s CM acceleration in relation to the determination of mechanical power output (Lintmeijer et al., 2018).

Acceleration

Boat acceleration was reported in 8 studies (Doyle et al., 2008; Gravenhorst et al., 2015; Holt et al., 2021; Kleshnev, 2010; Lintmeijer et al., 2018; Liu et al., 2020; Millar et al., 2015; Smith & Loschner, 2002). This variable is known to be used in applied sport science settings as a method of technical analysis, however, this is yet to be reflected in the peer-reviewed literature (Holt et al., 2021). Specific metrics of boat acceleration reported include maximum negative drive acceleration (Holt et al., 2021), first and second peak during the drive (Holt et al., 2021), time to positive acceleration from the catch (Millar et al., 2015), time to peak acceleration from the catch, the first dip after the catch, the finish dip (Kleshnev, 2010), and the zero acceleration point before and after the catch (Doyle et al., 2008). Jerk quantifies the rate at which the boat's acceleration changes and is measured in m.s^{-3}. Six measures of jerk have been reported between the peaks and troughs within a stroke (Holt et al., 2021). Furthermore, specific features of the temporal profiles have been described by Kleshnev (2010) as microphases within the stroke cycle. This detailed examination delineates five specific micro-phases during the drive, the propulsive segment of the stroke cycle, and three micro-phases throughout the recovery when the rower prepares for the subsequent stroke. These micro-phases demarcate critical transition points where acceleration interchange between the rower and the boat occurs, highlighting moments of potential kinematic and kinetic optimisations. Figure 2.4 displays the representation of these dynamics of the temporal boat acceleration pattern per stroke cycle.

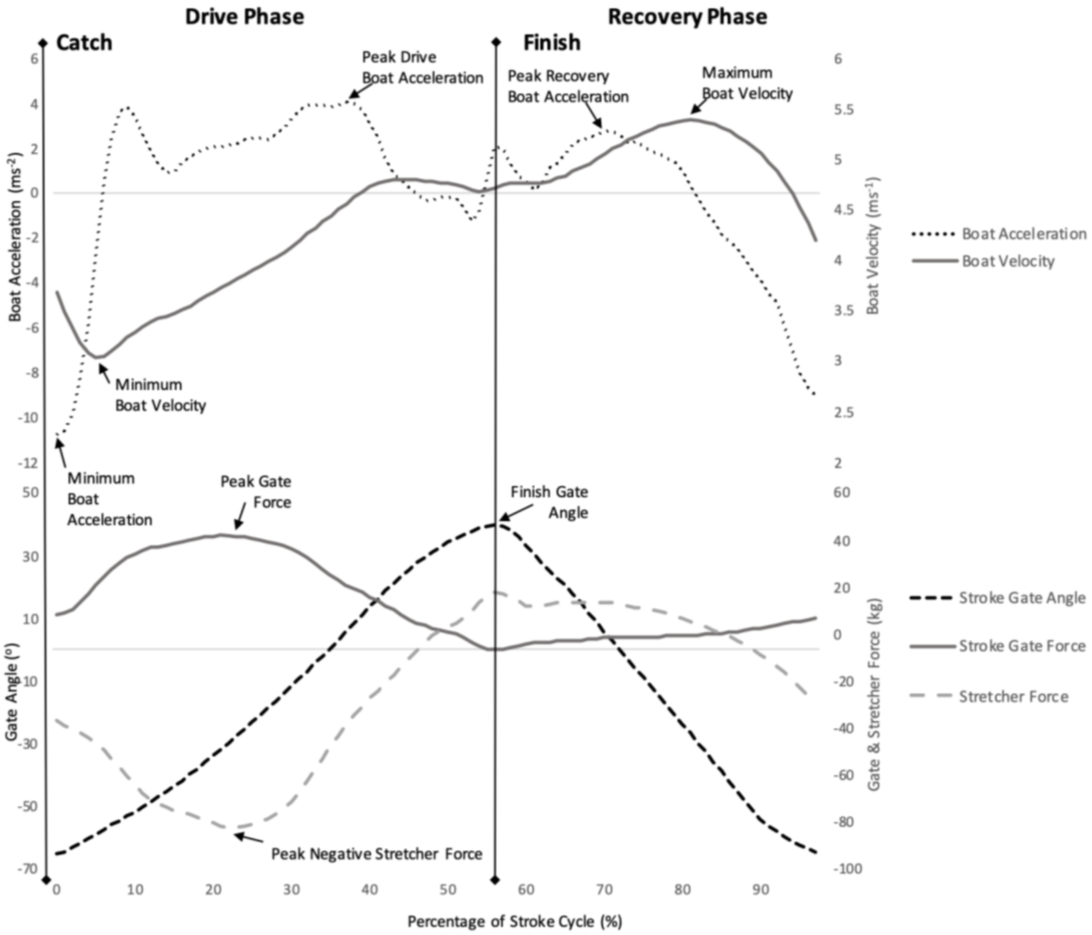


Figure 2.4: Temporal profiles per stroke – boat acceleration, boat velocity, gate angle, gate force & stretcher force

Stroke Rate

Stroke rate was reported in all except one study, ranging from 20-41 spm. Lower stroke rates were incorporated when other aspects of the rowing stroke were being assessed such as changes to the foot stretcher height or comparing contributions from the oarside and non-oarside arm in sweep rowing (Mattes et al., 2015b; Mattes et al., 2019). Other studies reported a range of stroke rates and examined how certain metrics changed with higher stroke rate, including shortening of the recovery phase (Held et al., 2020; Peric et al., 2019). Although stroke rate was a common metric, it was not uniformly treated as a primary research variable instead it was often included as a parameter in study methodologies.

Stroke Length

Stroke length was a focal point of investigation reported in 18 of the 27 studies, with 17 of those examining stroke length in association with the catch and finish angles of the rowing stroke. Measures of stroke length included total angle and effective angle calculated either inclusive or exclusive of the catch and finish slips respectively (Peric et al., 2019). The catch and finish slips were quantified by the angular distance covered when the gate force was diminished, falling below a predefined gate force threshold of 196N for the catch and 96N for the finish for sculling (Holt et al., 2020), with these measurements and thresholds captured using the Peach PowerLine customised software (Peach Innovations, UK). It is important to note the variability arising from the different methodologies utilised to measure these angles. Gate angle calculations were independent of the oar shaft's positioning and were assessed using sensors integrated within the oarlock (Holt et al., 2020). In contrast, oar angle measurements were obtained through a potentiometer affixed directly to the oar shaft to register its movements across all three axes (Doyle et al., 2010b).

Force

Gate force has emerged as a prevalent focus in on-water biomechanical rowing research, reflecting its important influence on performance outcomes (Warmenhoven et al., 2018b). In this current review, 19 force-related metrics were identified. Forces were reported in two planes: horizontal and vertical (Smith & Loschner, 2002). Key attributes of force throughout the rowing cycle were considered such as peak force, mean force, rate of force development, mean to peak force ratio and stroke smoothness (Smith & Loschner, 2002) with Figure 2.4 providing a visualisation of the temporal patterns of gate force and stretcher force across the stroke cycle. In addition, some variables, such as peak force, were further considered in terms of where they occur during the stroke cycle and were examined in terms of gate angle position or as a percentage of the cycle at which the peak force was achieved (Warmenhoven et al., 2018b). Further, the contrasting forces exerted by the inside and outside hands on the oar handle were compared (Mattes et al., 2015b). Similarly, in sculling studies, the stroke side (rower’s right-hand side) and bow side force (rower’s left-hand side) profiles were compared for symmetry and the subsequent contribution to boat velocity and boat movements, each of which are elements vital to technical performance optimization (Warmenhoven et al., 2018a; Warmenhoven et al., 2018d).

Foot stretcher forces, which also play an essential role in contributing to the overall boat propulsion, were measured and reported in 3 of the 27 studies included in this review. Smith (2002) incorporated foot stretcher force along with gate force to explore the net applied boat force, interpreting its relationship with boat acceleration, and how it affected boat speed in two case studies using the coxless pair and single scull. Net applied boat force plays a crucial role in contributing to the overall boat propulsion and was reported in one study included in this review (Smith & Loschner, 2002). The concept of net applied boat force is extensively valued as it captures the real-time interplay of multivariate forces acting on the boat. The net applied boat force is the resultant of the propulsive pin and foot stretcher forces along with air and water resistance and displays the continuous interaction of the two major opposite-acting forces during the entire stroke cycle (see Figure 2.5) (Smith & Loschner, 2002). The two other studies that investigated the foot stretcher force were in relation to sweep rowing; specifically the asymmetric patterns of the oarside and non-oarside arm pull and the effect on stretcher force application (Mattes et al., 2015b) along with the asymmetrical patterns evident in the stretcher forces during coxed eight rowing in junior rowers (Mattes & Wolff, 2019).

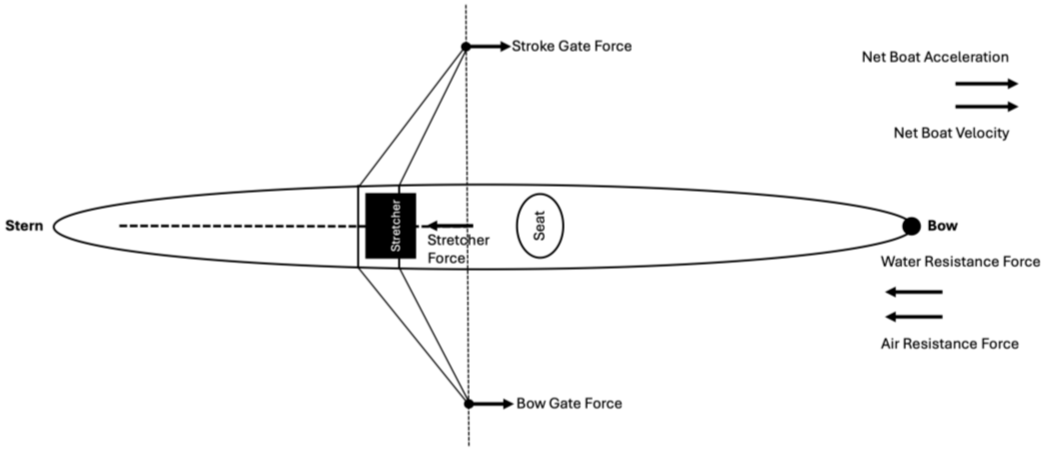


Figure 2.5: Gate & stretcher forces in a single scull

Power

Power measurements were reported in 14 of the 27 studies included in this review. The studies detailed both average and maximal power outputs per stroke, alongside relative power metrics normalised for bodyweight, which is particularly important in on-water rowing due to varying athlete stature and body mass. Maximum handle power has shown a strong association with boat velocity, underlining its significance as a performance indicator (Gravenhorst et al., 2015). Temporal patterns of power output have not been reported in the same way as velocity, acceleration and force measurements and accordingly limited intra-stroke discrete metrics have been explored in on-water rowing. In contrast, mechanical power has been discussed based on two different theories; the common proxy and the true averaged power method (Lintmeijer et al., 2018). According to Lintmijster (2018) the common proxy method estimates on-water power output as the "time average of the dot product of the moment of the handle force relative to the oar pin and oar angular velocity" (Lintmijster et al., 2018, p.2138). Whereas the true averaged power output also incorporates a residual power related to the mass of the rower, CM acceleration and boat velocity (Lintmeijer et al., 2018).

Crew Synchrony

Crew synchrony was reported in 5 of the 27 studies with calculated metrics focusing on the precision, consistency, and coordination of crew movements. Coordination and synchrony in sculling crews was assessed through measurements of boat rotation quantified by pitch, roll, and yaw angles (Smith & Loschner, 2002) as well as an examination of translational boat movements, including surge, heave, and sway (Cuijpers et al., 2017). Synchronisation in coxless fours was assessed through detailed analysis of force curve profiles whereby timing differences at the onset and finish of the stroke were considered a synchronisation indicator (Hill, 2002). In addition, a range of variables were reported such as differences in the area under the force curve and form differences examined in the force curve profiles, where the individual's force curve pattern was presented as a percentage difference of the average force curve for the crew (Hill, 2002). Baudouin (2004) hypothesized that crew performance could be predicted from total propulsive power, level of synchronisation and total rower drag contribution. Timing differences and the adaptability of the force curve profile that occurred with changes to rower combinations were observed. Specifically, comparisons of crew synchrony were assessed through the interpretation of propulsive blade force profiles where rowers demonstrated the ability to adapt their biomechanics appropriately based on the feedback within the rowing system or crew after only a brief period of time (Baudouin & Hawkins, 2004). Likewise, the coordination and consistency of the bow four rowers in a coxed eight were assessed through the force-time profiles. The average and variability of force-time profiles were determined to characterise the patterns of variation in maximum force, stroke duration and inter-stroke interval (Wing & Woodburn, 1995). Such detailed assessment of force-time traits is essential to interpret the complexities of crew synchrony and its impact on collective rowing efficiency.

2.4 Discussion

This scoping review aimed to describe the current scope and density in the field of on-water rowing biomechanics and provided a guide for practitioners and researchers on future directions for the advancement of biomechanical studies in on-water rowing. Measurement systems, study characteristics and reported biomechanical variables were collated to describe the state of the on-water rowing literature and to provide a guide for future directions for rowing biomechanics research. Data extraction revealed stroke rate, gate force, horizontal oar angle and boat velocity as the most reported variables with numerous subcategories of metrics within each measure. Boat acceleration has been the focus of less research in comparison to force and velocity, although has the potential to provide further insights as an important boat outcome measure.

2.4.1 Study Characteristics

The majority of the included studies in this scoping review were observational in design. Further, given the logistical and environmental considerations of on-water rowing assessment, the majority of the studies included in this review were cross-sectional. The criterion of on-water rowing assessment for this review reduced the number of relevant research studies, with 18 rowing ergometer studies excluded during the screening process for utilising the rowing ergometer as the assessment platform. These studies involved some aspect of biomechanical assessment related to rowing; however, the outcomes of these studies cannot definitively be extrapolated to on-water rowing outcomes due to the recognised technical differences between ergometer and on-water rowing (Elliott et al., 2002; Fleming et al., 2014; Kleshnev, 2005; Lamb, 1989). Many of the participants in the included research were from elite or sub-elite populations which often leads to small sample sizes; however, such populations elicit a high level of ecological validity. To increase sample size and statistical power, along with the applicability of the findings towards youth, masters and developmental pathways, larger demographic groups could be examined in future research to expand the scope of investigation, including club, collegiate and masters rowing populations.

2.4.2 Biomechanical Variables

Boat Velocity

Boat velocity and 2000 m race time are generally considered to be the most fundamental performance outcomes in on-water rowing (B. Smith & W. Hopkins, 2012) and expectedly boat velocity was one of the most reported outcome measures across the studies in this review. Boat velocity can be a difficult parameter to compare between studies due to the variability of the environmental conditions (Binnie et al., 2023). With an increase in water temperature, boat velocity can increase significantly (Pomerantsev et al., 2022). Therefore, it is common to use time margins and 500 m time splits for comparison across races, competitions and venues (Muehlbauer & Melges, 2011). Average boat velocity can also be misleading as a measure, however, discrete metrics including minimum, maximum, range and fluctuations in velocity can provide a more detailed appraisal of performance (Doyle et al., 2008). Intra-stroke fluctuations in boat velocity have been discussed in reference to performance. Further, intra-stroke velocity fluctuation relates to the interaction between the drive and recovery phases and the efficiency of the rower to maximise their average boat velocity while minimising disruptions to the boat run (Legge et al., 2023). A reduction in velocity fluctuations will likely lead to superior average boat velocity and subsequently enhanced performance (Holt et al., 2020; Holt et al., 2022; Smith & Loschner, 2002). Exploring the velocity profile pattern of a rower or crew has the potential to provide deeper insight and highlight different technical strategies, particularly when average boat velocity is similar between crews (Doyle et al., 2008). Subsequent analysis of other variables, such as acceleration, force or body segment coordination may assist in the explanation of variance in crews' technical strategy (Holt et al., 2021).

Handle and Seat Velocity

Handle velocity during the drive phase has a strong positive association with boat velocity (Gravenhorst et al., 2015), and handle velocity during the drive phase increases with faster stroke rate (Mattes & Wolff, 2019). Furthermore, handle velocity is reduced with increased gearing ratios unless handle force is elevated to maintain handle velocity with the higher gearing (Held et al., 2020). Seat velocity was reported alongside body segment velocities at the handle and trunk, representative of the three main body segment movements during the stroke cycle: leg drive, trunk swing and arm draw (Kleshnev, 2010). Handle, seat, and trunk velocity remain similar across all stroke rates, however, the recovery velocity of legs, trunk and arms increases significantly with increasing stroke rate, which occurs across all boat categories (Kleshnev, 2016). The on-water rowing research lacks information about body segment coordination and it is not known which rowing style is the most effective at generating gate force and boat propulsion (Fletcher et al., 2015). This area of rowing biomechanics has largely been explored using rowing ergometers in laboratory settings where access to motion capture equipment is readily available. Further, a large proportion of rowing literature utilises the rowing ergometer rather than on-water rowing due to the convenience and environmental stability of the laboratory. In addition, some aspects of biomechanics research require the use of equipment that is not available in the mobile aquatic environment such as motion capture systems that facilitate the biomechanical assessment of body segment and joint position tracking. Markerless motion capture systems are emerging and have the potential to assess on-water rowing kinematics, however, have not been validated in the on-water rowing environment (Armitano-Lago et al., 2022). Therefore, there is currently no equivalent substitute for three-dimensional motion capture in the on-water environment, however, sensor technology is quickly gaining traction and may be applicable to on-water rowing movement assessment in the near future (Brice et al., 2022; Worsey et al., 2019).

Assumptions can be made about rowing technique through the observation of seat velocity during the drive phase as it signifies the beginning and end of the leg drive, revealing how rowers coordinate their power output (Smith & Loschner, 2002). A comparison between lightweight and heavyweight male coxless pair crews exhibited similar boat velocity even though the heavyweight crew displayed higher force and work outputs, suggesting different technical strategies enable the lightweight crew to efficiently achieve equivalent boat velocity (Doyle et al., 2008). Future studies investigating the combination of seat velocity, handle velocity and trunk velocity have the potential to better understand body segment coordination and the technical strategies that affect performance outcomes such as boat velocity and boat acceleration. Inertial sensor technology has the potential to provide the requisite instrumentation, however, further development is required (Worsey et al., 2019).

Acceleration

Boat acceleration is measured per stroke and several intra-stroke metrics have been identified in on-water rowing (Holt et al., 2021; Kleshnev, 2010). Boat acceleration metrics that have been associated with superior performance outcomes or greater boat velocity have been primarily focussed within the drive phase of the stroke cycle with a particular focus ranging from the catch to peak acceleration. The catch and initiation of force application during the propulsive drive phase are critical aspects of the rowing stroke cycle, however, key areas through the finish and recovery phase have the potential to inform and improve technique (Holt et al., 2021). The finish signifies the beginning of the recovery, and the rower is executing a technical movement pattern to compress the body throughout the recovery without disrupting the boat run whilst maintaining boat velocity to prepare for the next catch and drive phase. The conservation of momentum and inertia is vital to maintaining boat velocity that was generated earlier in the drive phase. Figure 2.4 displays an example of typical force, acceleration and velocity profiles for one stroke cycle, highlighting the catch, drive, finish and recovery sections of the stroke.

Boat acceleration is an outcome measure in rowing biomechanics and provides a reflection of the force applied at both the gate and foot stretcher, often referred to as the applied net boat force (Smith & Loschner, 2002). Discrete metrics of boat acceleration have been reported in the literature, however, some conflicting results have made the interpretation of optimal profiles challenging (Holt et al., 2021; Kleshnev, 2010; Smith & Draper, 2006). The gate angle at peak acceleration has been identified as a variable that could distinguish between different levels of rower (Gravenhorst et al., 2015), with an earlier peak force in the stroke cycle related to superior performance. If the force output can be maintained through to the blade release, a sustained force will provide a higher mean force along with greater mechanical work done and subsequently sustain boat velocity (Warmenhoven et al., 2018b). Olympic champion level rowers displayed a deeper negative acceleration peak around the catch when compared to national level rowers (Smith & Loschner, 2002) and based on the assumption this is due to a faster leg drive, this was associated with superior performance outcomes (Liu et al., 2020). Moreover, foot stretcher height has been investigated through known metrics including boat acceleration to optimise performance and the results suggested a higher foot stretcher height increased the negative acceleration peak around the catch (Liu et al., 2020).

Changes in jerk (rate of change of acceleration), measured in single sculls and coxless pairs over 2000 m races have been considered in relation to boat velocity. Greater absolute values of jerk in the early drive, mid-drive and late recovery were associated with superior performance outcomes across a sample of single scull and coxless pair crews (Holt et al., 2021). Along with jerk, time to positive acceleration was used to distinguish between the perception of ‘good’ and ‘bad’ strokes using rower’s performance-based judgements (Millar et al., 2015). In addition to the assessment of the discrete metrics, the characteristic shape of the boat acceleration pattern per stroke represents the outcome of an individual’s technique, therefore it has the potential to provide objective feedback in the on-water daily training and competition environment (Hohmuth et al., 2023; Kleshnev, 2010). Research utilising functional data analysis to assess the temporal force curve patterns in on-water rowing (Warmenhoven et al., 2017b) can be applied to the temporal pattern of boat acceleration to further understand the idiosyncrasies of individual signature profiles (Warmenhoven, 2017a). Further research is warranted utilising higher dimensional statistical approaches such as functional data analysis with the potential to explore time series analysis of temporal patterns of biomechanical rowing variables such as velocity, acceleration and force to better understand technical strategies related to performance (Warmenhoven et al., 2018b).

Stroke Rate

All studies reported stroke rate with the exception of one study (Wing & Woodburn, 1995), however, the stroke rate was often reported in the methodology as a procedural requirement and was not part of the research question. Stroke rate can vary in range depending on prescribed intensities in training or race conditions on the day of competition. Further, reporting of stroke rate differs between studies, making comparison challenging. The majority of on-water rowing training is completed at relatively lower stroke rates (McArthur, 1997), however, the application of force, power, and the management of momentum of the rower-oar-boat system is markedly different when rating 20 spm compared to 40 spm (Bechard et al., 2009). Stroke rate during Olympic final races range from an average of 34 spm in the women's single scull event up to an average of 40 spm for the men's eight event (BioRow, 2024). The prescribed stroke rate chosen for a research study should best reflect the research question. For example, if the purpose of the study is to assess an aspect of performance, race rating and race conditions would be optimal. However, given a large proportion of on-water rowing training is completed at lower stroke rates (McArthur, 1997), research questions may specify a lower stroke rate or range of stroke rates for assessment.

Stroke Length

Stroke length was reported in 18 out of 27 of the studies included in this review. The choice of angle measurement technique in on-water rowing can substantially influence the recorded stroke length data, emphasizing the importance of standardization of methods across studies to enable meaningful comparisons. For example, the predefined gate force threshold used to calculate the catch and finish slips are applied the same across all sexes, ages and weight classes. This may be a limitation given the peak forces are different across these different demographic groups. This methodological distinction is of paramount importance for interpreting biomechanical data, as it may influence the perceived effectiveness of each rowing stroke.

A longer stroke length reportedly relates to superior performance, resulting in greater average boat velocity (Elliott et al., 2002), as it provides a longer drive distance to generate force on the gate. Stroke length directly affects stroke rate; however, stroke length has shown to remain stable in stroke rate ranges from 20 spm to 28 spm (Peric et al., 2019). However, at 36 – 40 spm, a relatively high range of stroke rate, the stroke length may decrease by 3 – 4 degrees in sweep rowing and 5 – 6 degrees in sculling (Peric et al., 2019). Stroke length varies depending on sculling or sweep rowing, boat category, weight category and athlete demographics. From the studies in this review stroke length ranged from 78 – 88 degrees for sweep rowing and 100 – 106 degrees for sculling. Effective angle, which excludes catch and finish slip angles from total stroke length was unable to discriminate between elite and sub-elite rowers under race conditions (Peric et al., 2019). However, the finish slip was identified as the most discriminating feature between a group of world-class female rowers (Gravenhorst et al., 2015). Further, catch and finish slips, highlight the degree of gate angle where the force applied does not reach a pre-determined threshold and does not contribute to boat propulsion or influence boat velocity (Holt et al., 2020).

Reporting the percentage of stroke length for certain discrete metrics is also common in this domain. For example, the angle at peak force is a commonly reported measurement and earlier peak force has been associated with superior performance outcomes in small boat categories including the single scull and coxless pair (Holt et al., 2020). In addition, if peak force is achieved earlier and maintained longer, this results in a greater mean force per stroke which is also associated with higher performance (Warmenhoven et al., 2017b). However, greater mean force per stroke does not necessarily translate to a faster boat velocity (Doyle et al., 2010a; Doyle et al., 2008) and further consideration of other variables is required to understand the technical efficiency and strategy of a crew.

Force

Gate force or handle force in the on-water rowing literature has generated considerable attention and inquiry over the last 5 decades given its direct connection to boat propulsion and performance (Warmenhoven et al., 2018b). Assessment of temporal force profiles have been extensively explored alongside discrete metrics of force, including peak, mean, time to peak, mean to peak ratio and rate of development. The catch and finish force gradients reflect how quickly the rower applies the force after the catch and how long they can maintain the force at the back end of the stroke leading towards the finish based on a predetermined threshold of 30% of peak force at either end of the drive phase (Peric et al., 2019). The ability to maintain force for longer into the finish of the stroke was a distinguishing feature of elite rowers when compared to sub-elite (Peric et al., 2019) and practitioners could use this information when planning training drills around specific elements of the stroke.

Vertical force is measurable at the gate, handle, and foot stretcher dependant on the instrumentation system. Vertical gate force is influenced by the pitch of the oar blade (Smith & Loschner, 2002) and is important when considering the non-propulsive forces on the boat and subsequent effects on propulsive boat acceleration, velocity and movement (Smith & Loschner, 2002). Multi-axial forces are measured in rowing biomechanics, however, one or two dimensions are most commonly reported (Loschner & Smith, 2002; Warmenhoven et al., 2018). In addition, force can be measured as propulsive (Smith & Loschner, 2002) or the normal component (Kleshnev, 2010). Therefore, when making comparisons of forces between studies, it is essential to clarify the method used to measure the force.

The addition of foot stretcher instrumentation adds complexity to the measuring system, reducing portability, increasing set up time and is therefore a less common inclusion to on-water rowing studies (Smith & Loschner, 2002). However, along with drag and water resistance, foot stretcher forces are an important component in the applied net boat force (Smith & Loschner, 2002) and this variable relates to the boat acceleration when comparing temporal profiles across the stroke cycle (Draper, 2005). The temporal pattern of the propulsive net applied boat force features the qualitative differences between rowers' individual technique and also reflects the boat propulsion. In sweep rowing, a characteristic asymmetry of the stretcher force has been thought to be caused by the rotation of the sweep oar around the pin followed by the rower's movement through the stroke cycle (Mattes & Wolff, 2019). With these findings in mind, future research should incorporate foot stretcher force as applied net boat force incorporates gate force and foot stretcher force to provide a more detailed picture of the propulsive forces acting on the boat (Warmenhoven et al., 2018b).

Power

The accuracy of quantifying mechanical power in on-water rowing is important to gauge and predict performance (Lintmeijer et al., 2018). Two methods have been reported in the reviewed studies: the common proxy method and the averaged true power method (Hofmijster et al., 2018; Kleshnev, 2000). As with a multitude of sporting activities involving propulsion, power is lost within the rowing cycle, as the boat does not travel at a constant velocity (Hofmijster et al., 2007). The mechanical power lost to drag associated with intra-stroke velocity fluctuations is related to the 3rd power of velocity (v^3). A proportion of the net mechanical power is used to overcome the resistance caused by the velocity fluctuations within each stroke cycle and can be quantified in terms of the velocity efficiency estimated to be around 5-10% of the net mechanical power (Hill & Fahrig, 2009; Hofmijster et al., 2007).

Power per kilogram of body weight in relation to boat speed has been investigated to compare heavyweight and lightweight men's coxless pair crews (Doyle et al., 2010a). The heavyweight crews consistently achieved significantly higher power per kilogram of body weight at five different stroke rates varying from 20 spm up to race conditions. However, the higher peak and average handle forces elicited by the heavyweight rowers were not reflected in the boat velocities, with two lightweight crews exhibiting equivalent boat velocities to the heavyweight crews. It was evident that lightweight crews were potentially able to perform to a similar level by adopting more effective technical strategies (Doyle et al., 2010a), with this information able to inform the development of race tactics or squad selection strategies.

Power application from a technical perspective in on-water rowing should also be prioritised along with force application and boat velocity (Holt et al., 2020). The mean power needed to achieve a race performance level, can be used as a target in setting training strategies and prescription (Holt et al., 2022). The research has directed attention toward understanding how stroke rate influences net mechanical power (Hofmijster et al., 2018; Holt et al., 2021) along with the subsequent effects on boat acceleration and boat velocity (Hill & Fahrig, 2009; Holt et al., 2021). These findings are instrumental for understanding the complex interplay between rowing technique, power application, and resultant performance, revealing avenues for targeted enhancements in competitive rowing. However, the relationship between rowing power output and stroke rate, gearing and drag factor have been reported with results suggesting there is no optimum relationship with stroke rate, or gearing to elicit maximum power in rowing (Held et al., 2020). This was in contrast to other sports such as cycling and swimming, where an optimal trend has been reported (Held et al., 2020). In swimming, velocity decreases if stroke rate exceeds a certain value (Garland Fritzdorf et al., 2009) and in cycling, specific power outputs can be linked to an optimal stroke rate which is linked to muscle activation efficiency (Van Soest & Casius, 2000). There is an absence of conclusive literature in this area and there is likely a complex and dynamic combination of factors that influence optimal stroke rate for an individual or crew. Further investigations are needed to ascertain the importance and relevance of the determination of an optimal stroke rate in on-water rowing.

Finally, Holt (2020) investigated measures of rowing technique and performance and their relationship with boat velocity, taking into consideration differences in boat classes and sex. Improving the force generating capacity of the rower was recommended as a key component for power output in the pursuit of rowing performance improvement (Holt et al., 2020). Moreover, a degree of asymmetry of the stretcher force is necessary in sweep rowing for a high-power output, however, excessive foot stretcher asymmetry may lead to an increased risk of overloading the lumbar spine due to shear forces, with no optimal range specified (Mattes & Wolff, 2019). It is clear that power is a critical measure to incorporate into monitoring and controlling training loads for rowing and while this has been extensively studied on the rowing ergometer and in relation to strength training and assessment for rowing (Akça, 2014; Lawton et al., 2013). However, further investigations may improve our understanding on power application during on-water rowing to optimise performance.

Crew Synchrony

For a rowing crew to be successful, a high level of coordination and synchrony between crew members is required to achieve optimal performance (Hill, 2002). Crew synchrony can be defined as the simultaneous actions of all crew members and is essential in crew rowing in relation to detrimental boat movements and lateral stability (Cuijpers et al., 2017). Cuijpers (2017) demonstrated that crew coordination was more consistent with increased stroke rate and superior crew synchronisation. However, fluctuations in boat movements including surge (forward-linear motion), heave (vertical-linear motion) and pitch (lateral axis rotation) increased while lateral movements measured as roll (long axis rotation) decreased. These results suggest superior crew synchronisation may relate to enhanced lateral stability, however, inevitably involves lower biomechanical efficiency. This was largely due to the fluctuating nature of the rowing stroke cycle, where heightened coordination can potentially lead to greater power production as a crew (Cuijpers et al., 2017). Boat movements including pitch, roll and yaw were only explored in relation to crew synchronization (Cuijpers et al., 2017), however, excessive additional boat movement and rotation negatively affects boat propulsion and reflects the technical efficiency of a crew or rower (Loschner et al., 2000b). It is clear that this area of inquiry is in its infancy and more research can be undertaken in this area to inform practice.

The literature pertaining to on-water rowing synchrony included in this review reveals a focus on small boat categories to assess the individual contribution to the boat output rather than the crew performance. From a research perspective it is important to improve our understanding of the biomechanical factors associated with successful technique and enhanced performance. However, the synchrony within a crew, the selection of a crew and the most appropriate seating order within a crew to achieve success are also relevant research questions, particularly given the coxed eight is often considered the most prestigious event in the regatta schedule (Secher & Volianitis, 2009). Coaches seeking to optimise crew selection can also consider the suitability of individual rowers in a crew through the adaptability of a rower’s force-time profiles to increase the level of synchrony and how that affects boat movement and performance outcomes (Baudouin & Hawkins, 2004).

2.4.3 Summary

This scoping review has identified a range of biomechanical variables that have been assessed during on-water rowing and presents a myriad of applications of these attributes in relation to rowing performance. The average boat velocity over a measured distance or interval, in racing or training is considered a fundamental performance outcome together with race time. Intra-stroke metrics of interest for boat velocity were minimum, maximum and range measurements (Hill & Fahrig, 2009). Velocity has also been measured at the handle and the seat, in relation to gearing and body segment movements respectively. Power has been reported in absolute and relative measures of maximum and average power per stroke and measured at the gate and handle (Held et al., 2020; Warmenhoven et al., 2017b). Force measured at the gate, handle or oar has received a large degree of research attention given its relationship to boat propulsion (Warmenhoven et al., 2018b). The temporal gate or handle force pattern has been extensively dissected and descriptively characterised over many decades and discrete force metrics of interest include peak force, mean force, mean to peak force ratio, gate angle or time to peak force and catch and finish gradients of force (Holt et al., 2022). The ability to achieve a rapid rate of force development early in the drive as well as maintaining that force for longer into the finish are considered distinguishing features of successful on-water rowing performance (Holt et al., 2020; Peric et al., 2019). Stretcher force was a less common inclusion in the literature due to increased complexity of the instrumentation system set up. However, the combination of gate force and stretcher force measurements facilitates the assessment of net boat force which offers a more comprehensive assessment of the propulsive forces acting on the boat and can be related to the boat acceleration temporal profile (Smith & Loschner, 2002).

Discrete metrics of boat acceleration reportedly relate to changes in acceleration between the boat and rower and may be associated with individual technique characteristics and performance outcomes (Kleshnev, 2010). Peaks and slumps have been identified in the boat acceleration during the drive and recovery phase that relate to certain points during the stroke cycle (Holt et al., 2021), yielding implications for training design for coaches and performance analysts. Moreover, jerk has been associated with performance based on the impact to the boat velocity (Holt et al., 2021), however, additional research is required to more thoroughly investigate the discrete metrics and temporal profiles of boat acceleration in relation to performance and rowing technique to establish conclusive recommendations. The measurement of boat acceleration is non-invasive and requires no adjustment to the boat or rigging set up, therefore it has the potential to provide the athlete, coach and support staff with objective feedback in the daily training and competition environment. The cost effectiveness of inertial sensors and the availability of relevant software in smart devices, makes boat acceleration an accessible metric for all levels of the sport. Further, the measurement of boat acceleration encompasses the drive and recovery phases of the stroke, making it a suitable measurement tool for on-water technique assessment.

The recovery phase of the stroke cycle is perceived by coaches to require a high level of skill including balance, coordination, rhythm and feel for the boat run (Legge et al., 2023) as the oars are out of the water and minimal mechanical work is occurring during this time. This phase is concerned with managing the momentum that has been gained during the drive phase and it is clear that further understanding of the recovery phase and its contribution to maintaining boat speed throughout the stroke cycle is required. Conceivably, the on-water metric of distance per stroke provides an all-encompassing measure of both the drive and recovery phases, given it decreases with an increased stroke rate, however, the sequencing of body segments from finish to catch and the effect on the boat velocity and acceleration during this time may provide further insights. Additional research is required into the assessment of body segment coordination and joint position in the on-water rowing environment as the evidence from the rowing ergometer literature does not reflect entirely what is occurring in on-water rowing. Investigations examining coordination of the three main body segments alongside identifying joint motion in the hips, ankles, trunk and shoulders with boat outcome measures could provide valuable understandings on the mechanisms responsible in relation to the most effective rowing technique. Moreover, rowing technique and biomechanical variables assessed at regular intervals over an extended period of time involving the same participants has the potential to demonstrate the extent to which some technical changes are possible and can be measured and monitored through an individual's temporal profiles of force, acceleration and velocity.

In summary, the literature has reported on an extensive range of biomechanical metrics encompassing time, space and force that are relevant to rowing performance. The variability of reported measures throughout the different boat classes, gender and skill levels makes the collation of data challenging. However, establishing a guide may provide recommendations to standardise the description of variable names, assessment methods and on-water testing protocols. This could assist to advance on-water rowing biomechanical assessment so that systematic reviews and meta-analyses in the future can provide robust conclusive statements on biomechanical factors and their association with rowing technique and performance.

2.5 Conclusion

This is the first scoping review of the on-water rowing biomechanics literature, with the search including all peer-reviewed papers published until 29 September 2023. The results provide an overview of the extent of peer-reviewed knowledge in on-water rowing biomechanics measurement and associations with performance. The review also provides an overview of the participant characteristics and range of variables reported in the on-water rowing literature. Rowing biomechanics research has additional layers of complexity given there are two types of rowing: sculling and sweep rowing, two categories of rowers, lightweight and heavyweight, as well as multiple boat categories involving one person in a single scull and up to eight people in a coxed eight. This makes the collation of results across the body of literature into a succinct summary challenging. The single scull and coxless pair were the most common boat categories for research studies, unsurprisingly, given they are the small boat categories that best represent the individual output on the boat. The coxless four and double scull were underrepresented while the quadruple scull was not represented in the research at all.

On-water rowing assessment has well-established parameters on the interpretation of force profiles, with discrete and temporal analyses applied to sculling and sweep rowing studies. The rate at which a rower can apply force and the ability to maintain the force into the finish are distinguishing features of elite rowing. In on-water rowing, prioritizing the measurement and application of power is essential for effectively monitoring and controlling training loads, as well as for refining technique. Boat acceleration is considered a reflection of the applied net boat force, however, higher dimensional statistical approaches such as functional data analysis should be explored to understand the temporal differences in boat acceleration that lead to superior performance.

Ultimately, the development of a standardized framework for on-water rowing biomechanical assessment, coupled with established protocols for environmental data collection, would provide practitioners and researchers with a structured approach for navigating the on-water rowing context. The standardisation of an on-water testing protocol to include a range of stroke rates and distances, dependant on the research question, may assist in future collation of original rowing research. Furthermore, the development of guiding principles on reporting the specifications of instrumentation systems, sampling rates and sensor locations may assist with the standardisation of methodologies and facilitate more direct comparison across studies. The implementation of such standardisation has the potential to foster increased research that employs on-water assessment techniques, thereby deepening the understanding of the technical intricacies and performance metrics unique to the sport of rowing.

Supplementary Material

Table 2.4: All reported biomechanical variable by study group

	Metric	Lintmeijer 2018	Liu 2020	Hofmijster 2007	Mattes 2019b	Warmenhoven 2018a	Warmenhoven 2018b	Warmenhoven 2017	Gravenhorst 2015	Held 2020	Millar 2015	Cuijpers 2017	Holt 2020	Holt 2021	Kleshnev 2010	Holt 2022	Smith 2002	Baudouin 2004	Doyle 2008	Doyle 2010	Hill & Fahrig 2009	Peric 2019	Mattes 2015b	Hill 2002	Wing 1995	Martin 1980	Mattes 2019a	Mattes 2015a
	Boat Class	1x	1x	1x	1x	1x	1x	1x	1x	1x	1x	2x	Sweep & Scull	Sweep & Scull	Sweep & Scull	Sweep & Scull	Sweep & Scull	2-	2-	2-	2-	2-	4-	4-	8+	8+	8+	8+
	Stroke Rate	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X
Time	Stroke duration			X																					X	X		
Time	Time of Drive Phase				X					X											X			X		X		
Time	Time of Recovery Phase									X																X		
Time	Drive -Recovery Ratio											X																
Disatnce / Displacement	Distance per stroke												X															
Distance / Displacement	Horizontal Oar Angle		X	X	X	X	X			X	X		X		X	X	X	X		X		X			X		X	X
Distance / Displacement	Vertical Oar Angle					X											X											
Distance / Displacement	Catch Angle		X		X		X		X				X							X		X						
Distance / Displacement	Catch slip												X															
Distance / Displacement	Finish Angle		X		X		X						X							X		X						
Distance / Displacement	Finish slip								X				X															
Distance / Displacement	Effective Angle																					X						
Distance / Displacement	Leg drive length		X							X												X						
Distance / Displacement	Handle Path																X											
Distance / Displacement	Seat Position				X												X											
Boat Orientation	Boat Orientation (Pitch, Roll, Yaw)											X					X											
Boar Orientation	Boat Orientation (Surge, Heave)											X																
Boat Acceleration	Boat Acceleration (BA)	X							X		X			X	X		X		X									
Boat Acceleration	BA Peaks & Slumps		X											X	X				X									
Boat Acceleration	Jerk (change in acceleration)													X														
Boat Acceleration	Acceleration of Rowers Centre of Mass (CM)	X													X													
Boat Velocity	Boat Velocity	X	X	X	X			X	X		X	X	X	X	X	X	X	X	X	X	X	X	X			X	X	X
Boat Velocity	Velocity Range / Fluctuation		X										X			X	X											
Boat Velocity	Maximum Velocity																		X							X		
Boat Velocity	Minimum velocity												X						X							X		
Seat Velocity	Seat Speed																X		X									
Seat Velocity	Recovery Seat Speed																		X									
Handle Velocity	Handle Velocity	X							X		X																X	X
Body Segment Velocity	Body Segment Velocity	X													X				X									
Body Segment Velocity	Leg drive speed		X																									

Force	Net Applied Boat Force															X												
Force	Propulsive Gate/Pin Force	X				X	X				X		X			X	X	X										
Force	Transverse Gate/Pin Force																X											
Force	Vertical Gate/Pin Force																X											
Force	Mean Gate Force		X					X					X															
Force	Maximum Gate Force		X				X	X			X		X				X											
Force	Handle Force														X					X			X	X	X		X	X
Force	Mean Handle Force									X												X			X			
Force	Maximum Handle Force									X												X			X			
Force	Stretcher Force																X						X				X	
Force	Stroke smoothness		X																					X				
Force	Impulse																				X							
Power	Handle Power								X	X			X								X		X				X	X
Power	Maximum Handle Power							X																				
Power	Mean Handle Power	X												X		X		X				X						
Power	Relative Handle Power																			X								
Power	Leg Power									X																		
Power	Mean Handle Work per stroke									X												X						
Power	Mean Gate Work per stroke			X																								
Symmetry	Gate/Pin Force Symmetry Index (%)					X																						
Symmetry	Stretcher Force Symmetry Index (%)																										X	
Crew Synchrony	Crew Coordination Accuracy											X																
Crew Synchrony	Crew Coordination Variability											X																
Crew Synchrony	Synchronisation																X	X						X				
Crew Synchrony	Stroke to Stroke Variability																								X			

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Thesis Relevance and Sequence

Chapter two was a systematic scoping review focussed on determining the extent of rowing biomechanics literature specific to on-water assessment. The purpose of this review was to collate the known variables that have been shown to relate to 2000 m rowing performance. The results of the review were intended to help inform the subsequent on-water original research in Chapters five and six. In combination with the following chapter which explores coaches' perspectives on rowing performance, to further inform the direction of the studies in Chapters five and six. Coaches were asked targeted questions, however probing questions led to open-ended responses which resulted in wide-ranging discussions on all aspects of rowing performance. The key concepts and themes from this chapter pertinent to this thesis further informed Chapters Five and Six.

Chapter 3

“A feeling for run and rhythm”: Coaches’ perspectives of performance, talent, and progression in rowing

As per the published manuscript in the Journal of Sports Sciences:

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Abstract

The understanding of rowing performance has been predominantly gained through quantitative sports science-based research. In combination with this objective information, coaches' experiences may provide important contextual information for how this quantitative evidence is implemented into training programs. The aims of this study were to (1) explore coaches' perspectives of performance indicators for competitive rowing in junior rowers, and (2) identify coaches' recommendations for developing effective technique and movement competency among junior rowers who have the potential to transition to elite competition. Twenty-seven semi-structured interviews were conducted with experienced rowing coaches through purposive sampling of an accredited coaching network. Participants' coaching experience ranged from 5 to 46 (22 ± 10) years. Data was analysed using thematic analysis. Three overarching themes were identified including, (1) getting the basics right, (2) targeting types of talent, and (3) complexities of performance. Based on these findings, sequence and boat feel, supported through the movement competency provided by hip flexibility and the trunk musculature, were considered critical for executing correct technique. Developing talent and understanding successful performance are both complex concepts when considering the individual athlete. Coaches' perspectives provided insight into key components of performance to enhance our understanding of how to better develop junior rowers.

Keywords: rower, attributes, coaching, movement competency, technique

3.1 Introduction

Research on both the physiological and technical aspects of rowing performance has predominately used quantitative research methods (Yusof et al., 2020). Alongside such information, coaches' knowledge gained through years of experience evolving and refining training for junior rowers to become successful elite athletes may provide important contextual information for how quantitative evidence is integrated for superior performance outcomes (Burnie et al., 2018). Yet, the expertise of coaches has often been overlooked as a source of information to ask and answer important research questions (Bishop, 2008; Greenwood et al., 2012; Roberts, 2021). Coaches' perspectives are generated from their experience witnessing performance at the highest level, consistency in judgement, discriminative ability, behavioural characteristics and knowledge (Shanteau et al., 2002). This insight can inform upon sport science concepts that are difficult to establish through objective experimental assessment. For example, when coaches' philosophies were explored on resistance training and its transfer to elite cycling performance, it was perceived that resistance training was essential and that this was best achieved through a combination of non-specific resistance training and resisted sport movement training (Burnie et al., 2018). Given the high degree of freedom involved in designing training studies to quantitatively investigate this finding, without the collective input from coach expertise, this type of observation may have remained unknown. Similar examples of expert coaches enhancing our understanding of the complexity of sports performance have been reported in cricket, gymnastics, and track and field (Greenwood et al., 2014; Phillips et al., 2014). Accordingly, coaches' perspectives can provide a rich source of highly relevant information which can contribute to our understanding of rowing performance.

Rowing is a demanding sport. Successful elite performance requires physical, psychological, tactical and technical expertise (Soper et al., 2004). Rowers must have a high level of skill for the effective transfer of force from the rower to the boat. Large foot forces are applied to the foot stretcher and transferred through the human kinetic chain to the oar handle to propel the boat forward (Buckeridge et al., 2015a; Kleshnev, 2016) (See Warmenhoven (2018b) for a more detailed description of the rowing stroke). Physiological and technical performance indicators both contribute to the overall boat speed. With this in mind, increasing technical efficiency for the same physiological output is a substantive reason for future studies to integrate the technical and physiological attributes of rowing more closely (McGregor et al., 2007). Much of the existing rowing research has focussed on physiological attributes such as aerobic and anaerobic capacity (Mikulic, 2008; Otter-Kaufmann et al., 2020), however, this information has not yet been contextualised to the technical output of the rower (McNeely, 2019). For example, an array of biomechanical parameters associated with rowing performance have been recognised (Baudouin & Hawkins, 2002; Soper et al., 2004; Warmenhoven et al., 2018b), such as stroke to stroke consistency and stroke smoothness as key technical indicators that discriminate between rowers of different skill levels (Smith & Spinks, 1995). Likewise, resistance training in rowing has been addressed in the literature (Lawton et al., 2011; Thiele et al., 2020). For example, elite rowers have been shown to be significantly stronger than their sub-elite and non-elite counterparts (Lawton et al., 2011). However, it appears that the relationship between physical and technical attributes in a performance context are yet to be integrated.

Movement competency provides an avenue to integrate physiological and technical attributes of an athlete. By definition, movement competency refers to the fundamental movements required of the athlete and is a combination of the biomotor qualities of force development capacity, flexibility and neuromuscular coordination (Missitzi et al., 2004; Rogers et al., 2020a). Collectively, these fundamental qualities support skill execution by providing an athlete with a platform to perform a variety of multi-modal activities in an optimal manner (Kritz et al., 2009; Rogers et al., 2020a). For example, maximal force transmission can be reduced if a rower lacks the flexibility to achieve an optimal catch position or lacks the stability provided through the hip and trunk musculature to anchor the pelvis and develop force through the leg drive (Young, 2019). While the rowing injury literature has addressed the movement competency requirements of the rower for the purposes of injury prevention and treatment (Clay et al., 2016; Soper & Hume, 2004), the use of movement competency for performance-based outcomes are yet to be fully explored (Rawlley-Singh & Wolf, 2023). Despite some evidence in on-water rowing, the relationship between movement competency, technical efficiency and performance is well established in other sports. For example, a strong relationship exists between running technique, economy and performance, demonstrated through kinematic variables such as trunk forward lean to explain the variability in energy cost and performance (Folland et al., 2017). Similarly, sport specific strength training interventions have resulted in improved biomechanical parameters, physiological efficiency and subsequent performance for swimming and cycling, respectively (Morais et al., 2018; Vikmoen et al., 2016). Understanding the importance of the movement competencies of junior rowers and the influence on their technical output during on-water rowing is critical to performance and progression to the senior level. McGregor (2007) noted the importance of increasing biomechanical efficiency for the same physiological workload, however, it is still not clear what aspects of technique are important for predicting on-water rowing performance. A notable gap remains in the understanding of how the development of movement competency could be integrated with biomechanical parameters of technique for superior performance outcomes (McGregor et al., 2007).

Performance-based research can lead to more practical applications for coaches, athletes, and support staff. Furthermore, the physical readiness of a developmental athlete can have a substantial impact on their transition from the junior to senior level of their sport. Identification of the movement competency required to be able to execute a technically efficient rowing stroke is essential to better understand junior athlete development (Rogers et al., 2020a), however the literature is currently limited. This research sought to leverage coach experiential knowledge to further our understanding of how to nurture and develop potential talent through the provision of appropriate training and resources (Baker et al., 2012). Rather than investigate talent identification, which is a systematic process of detecting potential ability in a sport and involves a comprehensive model leading to successful results (Nurjaya et al., 2020). Adopting a qualitative approach, coaches’ perspectives of key performance indicators for competitive rowing including the physical capacity and technical requirements of the athlete and how these attributes affect rowing performance was explored. This differs to the “coaches’ eye” which refers to the coach’s ability to assess and identify talent and make decisions about talented athletes in sport (Jokuschies et al., 2017; Lath et al., 2021; Roberts, 2021). Further, the research aimed to report coaches’ recommendations for developing effective technique and movement competency to optimise training practices among talented junior rowers who have the potential to transition to elite competition.

3.2 Methods

Participants

Rowing coaches were recruited to participate in interviews via an invitation letter that was sent to accredited coaches through the National Coaching Accreditation Scheme (NCAS) within Rowing Australia. Inclusion criteria required a minimum of 5 years coaching experience, regardless of the level of athlete they were coaching. Ethical approval was obtained from the University of Technology Sydney Human Research Ethics Committee (ETH19-4384) and all participants provided written or verbal informed consent before the interview commenced.

Twenty-seven coaches (22 male and 5 female) were recruited through purposive sampling of an accredited coaching network. Participants' coaching experience ranged from 5 years up to 46 years, with a mean of 22 years (SD = 10). Most of the participants had coached at multiple levels of the sports pathway at different stages of their career including school rowing programs, local clubs, national teams, and Olympic crews. In addition, all coaches had experience coaching different genders during their careers. At the time of the interviews six participants were primarily coaching female athletes, eight participants were coaching male athletes, and thirteen coaches were coaching both genders. Coaches were asked to draw on these diverse experiences when answering the questions.

Procedures

One-on-one interviews lasting approximately 45 minutes were conducted via an online platform to explore coaches' perspectives on performance indicators in rowing at elite and junior levels of competition. A semi-structured interview guide was utilised to allow the researcher to identify specific areas of enquiry, while providing flexibility in the conversation for the participants to raise new topics that the researcher could further probe (Clarke & Braun, 2013). The guide was divided into four topic areas: key performance indicators in rowing, rowing technique in development rowers, movement competency in development rowers and participant background and personal coaching experience. Interviewing techniques, such as the use of probing and follow-up questions were used to encourage depth and authenticity of the responses (Rubin & Rubin, 1995). Questions in the interview guide started with indicators and attributes associated with rowing performance. Subsequent topics narrowed the focus on development rowers' technique, movement competency and path for progression to an elite level over the course of the interview. For example, one question asked the coach to discuss areas of technical focus that tend to be executed poorly in junior rowers regarding performance when compared to elite rowers. The terms junior and development in this study refer to athletes under 19 years of age who are progressing through the various and undulating stages of their sport (Gulbin et al., 2013). Each question limited responses to three attributes with the purpose of narrowing coaches' focus and encouraging them to prioritise the most important performance attributes (DeWulf et al., 2017). However, this approach did not restrict further probing and exploration of topics that arose during the interviews. Participants were assigned a number when the interviews were transcribed, and names were removed at this stage of the data process. Pilot interviews were conducted to assess timing of the interview and clarity of the questions.

All the coaches were interviewed individually, providing each participant the time to respond to all the questions in a non-competitive environment and elaborate when they had further insights. The lead author (NL) conducted all twenty-seven interviews and transcribed all the audio recordings verbatim into word processing software. KS and MW both reviewed a sample of interviews with the transcriptions to check for accuracy. The lead author had experience as a sports science service provider with rowing, dealing with elite coaches and athletes, and an understanding of the colloquial language of the sport. This helped to establish a rapport with the participants and assisted in the interpretation of results (Patton, 1990).

For the purpose of the interview the physiology and physicality of the developing rower were considered two separate attributes, and these were clearly explained to the participants before the interview commenced. Physiology was defined as the aerobic, anaerobic, and force generating capacity of the rower (Secher & Volianitis, 2009).

Physicality referred to the movement competency of the athlete and the rower's ability to move through a range of movement that is required to execute an effective rowing stroke (Rogers et al., 2020a). This included the force development capacity, neuromuscular coordination and flexibility to hold an effective and safe posture throughout the stroke. Appropriate physicality allows large foot forces to be transferred from the foot stretcher through the human kinetic chain to the oar handles and blade connection with the water to propel the boat forward (Buckeridge et al., 2015a; Kleshnev, 2016).

Data analysis

Interviews were audio recorded to a secure online platform (AARNet CloudStor, Chatswood NSW, Australia), transcribed using Microsoft Word (Version 16.52), and analysed using NVivo12 software (Version 6.5.1) and Microsoft Excel (16.52).

Using an iterative process with data collection and transcription, inductive thematic analysis was utilised to analyse the data (Braun & Clarke, 2019, 2021a; Braun et al., 2016). The analysis was approached from a critical realist standpoint, recognising that whilst an objective reality exists, people's experiences and interpretations of reality provide a basis for knowledge (Archer et al., 2013). Herein, coaches' perspectives are understood to be a reflection of their unique characteristics and experiences of rowing and coaching athletes. Thematic analysis is often used when the existing body of knowledge on a topic is limited, such as coaches' knowledge on technical and movement competency attributes associated with rowing performance in junior rowers (Quesnel, 2016). This method of data analysis emphasised exploring, recognising and discovering patterns and identifying themes within the data set (Braun & Clarke, 2006). Initially the researcher became familiar with the data through careful and repetitive reading of the transcripts to recognise common patterns. During the subsequent phase of analysis, the initial coding was completed using codes in NVivo12. The data was analysed according to each of the three main topics by coding and categorizing responses. The topics were subsequently classified into categories and sub-categories. For example, boat feel was a category, and sub-categories were rhythm, run and recovery. Categories were named based on the most common concepts shared by the sub-categories.

In the next phase of analysis, organized codes were clustered to develop candidate themes (Smith & Sparkes, 2016). These themes were discussed and reflected on by NL, PS and KS. From these higher-level patterns, finalized themes were named through rich analysis ensuring the themes related back to the research question and aims of the study. Table 3.1 provides an overview of themes, subthemes, and codes. Sample size was determined in advance for the purpose of ethical obligation, however interviews continued until the lead author made an interpretative judgement that participant responses grew repetitive, and the goals of the analysis had been achieved (Braun & Clarke, 2021b). The reporting of this study aligns with the Consolidated criteria for Reporting Qualitative Research (COREQ) (Tong et al., 2007). The COREQ checklist can be found in the appendix.

Table 3.1: Overview of themes, subthemes, and codes from the thematic analysis.

Themes	**1. Getting the Basics Right**	**2. Targeting types of talent**		**3. Complexity of performance**
	Key differentiators between elite and junior rowers	*Consideration of innate versus trainable qualities in junior rowers*		*Critical factors to develop physically competent and technically effective junior rowers*
Subthemes		Innate Qualities	Trainable Qualities	
Codes	Sequence – drive & recovery	Boat feel	Aerobic capacity	Physiological talent
	Coordination of the sequence	Boat run	Connection	Natural power
	Timing	Rhythm	Training consistency	Strength at the catch position
	Blade Skills		Core stability, strength & strength endurance	Hip mobility and range of movement
				Gluteal engagement and force development capacity

3.3 Results

Three overarching themes were identified including, (1) getting the basics right, (2) targeting types of talent, and (3) complexities of performance. In line with current literature, each sub-theme is described by two coach quotations (Eccles et al., 2009; Eldh et al., 2020; Greenwood et al., 2012).

Getting the Basics Right

Coaches identified key differentiators between junior and elite rowers across areas of technique, training consistency and movement competency characteristics that they described as fundamental attributes for rowing success. From a technique perspective, the sequence and timing of the rowing stroke was the main concept when discussing technical skills in junior rowers. For elite rowers, from the moment the blade is placed in the water, the blade movement becomes horizontal, the rower's weight is lifted from the seat and suspended between the handle and foot stretcher. The force is initially created through knee extension but quickly shifts to hip extension as the trunk swings open (Kleshnev, 2016). Three quarters of all coaches interviewed recognised that junior rowers are still developing this appropriate sequence of movements to be able to generate optimal force production during the drive phase and maintain optimal boat run during the recovery phase. Coaches believed this was a key factor that separated them from the more senior elite rowers. C13, a national team coach with 20 years' experience, describes the technical faults and areas required for development they have commonly seen in sequencing amongst junior rowers,

> *[In junior rowers] the sequencing, lifting the body early, instead of the leg drive and not getting the body over enough at the recovery, so off the back (around the finish).*

C21, a national team coach with 13 years' experience further explains,

> *More prevalent in the development age athletes would be that they pull the oar rather than push the feet, there is a lot more lift, a lot more arm engagement, they have very little trust in their leg strength… they*

> *think rowing is a pulling sport, rather than trying to push the seat away from the feet… it's actually a pushing sport.*

Consistency in junior rowers' stroke-to-stroke technique and in their application to the training workload was also recognised as deficient in comparison to their elite counterparts. This is not unexpected given the age and maturity of this group of athletes as explained by C10, a national team coach with 15 years' experience,

> *Young rowers' physical maturity and their ability to handle work… an older athlete can handle 20-30 kilometres day in, day out, but junior rowers might have a good session and then the next day is terrible, they can just be inconsistent with everything.*

The concept of being able to tolerate the workload required to be successful was also identified by C5, a former Olympic coach with 46 years' experience who reflected on what is essential,

> *Successful athletes require a desire to work physically hard and accelerate the boat every stroke, consistency over time, most young kids can be heroes for a minute.*

Another fundamental area that the coaches commonly observed junior rowers lacking was movement competency. In rowing, this refers to a specific range of movement and force development capacity to be able to execute an effective rowing stroke. For junior rowers, discussions focussed on how flexibility and trunk musculature limited the ability of less experienced rowers to support their body during the stroke. Interestingly, a wide range of terms were used to describe movement competency. Coaches referred to trunk musculature and its force generating capacity using the terms, "core" and "posture" in combination with stability, strength, and strength endurance. The coaches' term, "trunk strength" refers to the force development capacity of that body region. The words core and posture were used interchangeably in reference to the rower's trunk strength during the stroke. C21, a national team coach, with 13 years' experience describes this generalised characteristic of junior rowers,

> *They just can't get out there (the catch position) for a good length… core strength is a bit of a ubiquitous sort of term but these kids' ability to hold themselves up to hold themselves in a good position, to sit on top of their pelvis a bit and not collapse underneath it, they are still developing a lot.*

Flexibility in the lower body from the hips through to the ankles was an area where coaches also saw junior rowers struggling to achieve certain positions in the rowing stroke. Poor flexibility was commonly discussed, specifically in reference to young male rowers, often as a limiting factor in relation to the catch position which is considered very difficult as it requires full hip flexion, knee flexion and ankle dorsiflexion whilst maintaining a neutral spine. C27 an international coach with 20 years' experience, explains the difficulty of the catch position for young rowers,

> *Hip pivot, compression into the front end, just being able to get your seat really close to your ankles while still maintaining a good posture at the same time. I suppose two aspects of that is being able to slide into that position but also being able to hold that position, so often it's a difficult position to sit in, it's like sitting in a squat.*

Junior rowers are often still growing and physically maturing, and this can alter their flexibility and ability to move during this period. The gender difference amongst junior rowers was well described by one coach (C20; national team coach with 9 years' experience) who primarily coached junior male athletes, explained,

> *If the boys don't stretch, they don't have the right posture, and they if don't have the right posture, there is too much pressure on the lower back… we see the boys still growing when they are 16, 17, and 18 and this is when their level of training is much higher whereas the girls finish growing usually by 14 before the training workload really starts to increase.*

The notion of gender specificity in junior rowers suggests that research investigating potential differences is essential (Johnston et al., 2018). This, in accordance with that literature, signifies how men and women respond differently to certain training stimuli and how gender should be considered when prescribing a training program (Altavilla et al., 2017). Sequence, timing, and movement competency were identified as fundamental attributes for junior rowers, however, this may require consideration to distinctive requirements for men and women rowers during different stages of their development.

Targeting Types of Talent

When coaches considered the most important aspects of performance, it drew them to consider types of talent and how to best target talent. Two related sub-themes were established out of this concept around talent: trainable qualities and innate qualities.

Trainable qualities referred to how coaches largely appreciated that rowing is predominantly an aerobic sport, and a high aerobic capacity is essential for success. C8, a national coach with 20 years' experience explained,

> *The application of power in the drive phase is what makes someone a champion… when it comes to the physical it's hard to define it exactly because there is a range of people that are successful but aerobic capacity must be the most important factor when we are talking physical attributes.*

However, there was a concept that developed within a small group of coaches who through experience noted that aerobic capacity appears to be more easily trainable than strength. These coaches would preferentially choose naturally strong athletes over athletes with a naturally high aerobic capacity. The coaches' responses were based around their experience that it is easier to train and improve an athlete's aerobic capacity than it is to train an athlete to be stronger. C2, an Olympic coach with 35 years' experience explained,

> *Endurance is super important, you need strength-endurance, but the athletes that have pure power are able to over time train their aerobic capacity whereas the ones that have just a really high level aerobically aren't able to always push the strength.*

C4, another Olympic coach with 30 years' experience further explained,

> *I've always felt that strength is really important because it's the thing that you can probably change the least in a rower and you have to be strong naturally… I think that's probably a pretty important physical attribute for a rower because it's the hardest thing in my mind to change, if someone is just basically weak, they are just basically weak, I can get them fitter and improve their endurance base, but I haven't been able to make them stronger, so they've got to be genetically strong.*

This concept of trainable qualities, comparing aerobic capacity and strength is not currently reflected in the literature and certainly warrants further investigation with potential benefits for future talent identification.

Further to the idea around identifying talent was innate qualities. Discussions revealed an understanding of boat feel and rhythm to be more of an intrinsic trait or innate quality associated with technically competent and efficient rowers. Similarly, swimmers refer to a feel for the water, and its association with talent in swimming (Ganzevles et al., 2019; Toussaint & Beek, 1992). An understanding and feel for the boat run may be associated with minimising fluctuations in boat velocity throughout the stroke cycle which directly relates to better rowing performance outcomes (Hill & Fahrig, 2009). C13, a national team coach with 20 years of experience describes this innate quality of boat run and rhythm,

> *One that's hard to quantify is just feel for the water… they either get the feeling or they don't get the feeling, of catching the water, accelerating the boat underneath them and they can feel it in other things they do too… some of them may be a good skateboarder or bike rider, they can feel movement.*

Similarly, C26, a national team coach with 16 years' experience describes the innate feel for boat run and rhythm,

> *A feeling for run and rhythm, so that you're able to time the front turn and apply yourself well, to pick the boat up sharply is quite important and that's the ability to feel for the boat run and rhythm, to time your*

> *movements through the front turn and be able translate that into the boat pick up.*

Coaches' awareness of these innate qualities, and the ability to identify athletes who possess these traits may assist identifying potential talent. In addition, educating current junior rowers on these attributes such as specific training drills to improve boat feel may progress their development and subsequent performances.

Complexity of Performance

Further to the theme on talent was the complex and dynamic process to assess performance. The interview structure limited coaches to selecting their top three attributes in relation to different aspects of performance for both elite and junior athletes. Over the course of the interview, coaches frequently mentioned the difficulty in narrowing performance down to the top three parameters. This highlights the complex and dynamic process coaches use to assess performance. In response, C6, an international coach with 25 years of coaching experience explained,

> *This is such a hard question to answer because we have twenty-four athletes, they are all different and they are all successful. Some of our best athletes are some of our weakest athletes in the gym but what do they bring? It's their ability to move the rowing boat, it's a really difficult question to answer.*

C9, a national coach with 17 years' experience described the difficulty in narrowing performance down to their three most important attributes, whilst also highlighting the differences between being a successful junior and successful elite rower,

> *It's difficult… you can't necessarily have 3 priorities and then sort of disregard the rest. I know it's just a question, but you have to be strong in half a dozen areas if you want to make it that far, whereas if you're looking at juniors you could have one of six things and be really good at that and you could make a junior team.*

The sport of rowing magnifies the complexities of sports performance and the attributes required for success with multiple boat categories involving one, two, four or up to eight people in a crew. In addition, there are two types of rowing: sculling and sweep rowing. In sculling, each person has two oars and in sweep rowing, each person has one oar each. C3, an Olympic coach with 16 years coaching experience explained how the requirements of single sculling (i.e., one person in a boat with two oars) differ to that of crew boat rowing,

> *I can't help but think performance is being the fastest and… sculling performance is quite unique and more influenced by a narrower set of factors probably than in rowing sweep or crew boat rowing where there are just so many examples of people where they just might be missing one of those three attributes but they have two of the others, I can just think of too many variations of very successful people… in single sculling I'm a little bit more narrow minded about it.*

Further, C4 an Olympic coach with 30 years' experience, provides an example that describes the variable aspects of performance presented by successful crews, reinforcing the complex nature and individual variability of elite and successful sports performance whilst highlighting some psychological traits that are required for success,

> *I think there has to be some degree of synergy and I can think of a previous Olympic gold medal crew in an eight who were untouchable, probably one of the best eights that's ever been put out but technically they were terrible… water coming off the shafts, but they were awesome and I think in that category of boat, the eight, you can get away with quite a lot of sloppy stuff if you've got very good engines and a real good camaraderie, confidence, and team morale type focus.*

Psychological aspects of performance were mentioned early in the interviews when the initial topic of performance attributes was being introduced and the scope of the discussion was not yet focussed on movement competency and rowing technique. Rubin and Rubin (2011) identify these initial questions as tour questions as they provide a tour of the topic. Mental attributes desired by the coach's included determination, focus, resilience, intent, and motivation as traits when considering talent for future rowing success. In the context of developing talent, C12 an Olympic coach with 43 years' experience describes the need for intent,

> *The ratio of the person in front of me, their shape, flexibility, coordination, power and their intent is a psychological construct, their intent, and their motivation to pull hard and get some kick out of that, these are things people need to bring to the party.*

In summary, the themes that were developed through higher-level analysis whilst addressing the research question, highlighted the complex nature of athlete development, talent identification and performance outcomes in the context of rowing. Coaches recognised that the main focal areas for the technical efficiency and movement competency in junior rowers involves getting the basics right, including important characteristics (i.e., aerobic capacity and innate boat feel) when identifying talent, whilst also appreciating the complexities and dynamic nature of performance.

3.4 Discussion

Experimental research has individually highlighted the physiological (Otter-Kaufmann et al., 2020) and technical requirements (Holt et al., 2020) for rowing performance. How these factors interrelate and contribute to competitive success has not yet been explored. Rowing coaches' experiential knowledge can help to evolve our understanding of the relationship between movement competencies and technical efficiency in junior rowers. Elite rowing performance requires talent, physical and psychological attributes and technical qualities across many areas (Nurjaya et al., 2020) and coaches confirmed their understanding of this concept. 'Getting the basics right' was a theme that highlighted key differentiators between junior and elite rowers and if the basic fundamental movement and skill requirements are not established as a junior athlete, progression to the elite level may be hindered along with the opportunity to further develop higher order skills like crew synchrony and boat feel (Millar et al., 2013). In line with results from previous experiential research (Burnie et al., 2018), characteristics of technique, training consistency and movement competency were identified as important factors that contribute to successful rowing performance.

Coaches' knowledge on the importance of movement competencies, such as flexibility and trunk force development capacity in junior rowers was apparent (Gee et al., 2011; Steinacker et al., 2020). Further the subsequent impact to the on-water rowing technique due to poor movement competency was also highlighted by some coaches. A recent study by Rawlley-Singh (2023) highlights the importance of recognising range of movement and force capability requirements specific to the rowing stroke. However, the literature is limited, and each discipline has often been studied in isolation. For example, movement competencies, such as flexibility and posture, have been considered in the context of injury prevention, not specific to on-water performance and technique (Nugent et al., 2021; Wilson et al., 2013). Rowing technique has been studied in the sports science subdiscipline of biomechanics with intent to improve performance, yet this has been undertaken in isolation from the movement competency required to execute the technique (Cerne et al., 2013; Mattes et al., 2015a). Future research should investigate the effect of improving aspects of junior athletes' movement competencies and explore the effect on their on-water rowing technique. This has the potential to inform training practices, improve junior performance, promote progression to the elite level and potentially reduce the risk of injury which directly relates to performance (Buckeridge et al., 2015a; Nugent et al., 2021).

Gender differences were noted by coaches, with junior males believed to be more limited in flexibility through the hips and ankles leading to increased injury risk. The combination of substantial increases in training load and phases of rapid growth and physical maturity at this age were suggested as contributing influences. Further, in line with the coaches' opinions, prolonged and intensive training loads in growing individuals are considered a risk for sustaining an overuse injury (Dalton, 1992) and overuse injuries are more common than acute injuries in rowing (Trease et al., 2020). Regular monitoring during periods of high growth in adolescents has been recommended to detect changes in flexibility that may be considered potentially high-risk phases for injury (Wild et al., 2013). This may allow for modifications in the training program to potentially reduce the risk of injury and loss of training time in junior (particularly male) rowers during these periods.

Getting the basics right in developing junior rowers progressed discussions to targeting types of talent. Two concepts of importance were trainable qualities and innate qualities for rowing performance. Innate talent in a sporting context can be defined as an attribute that is inborn or natural (Baker & Wattie, 2018). Boat feel and boat run were frequently mentioned as innate qualities in the present study. A 'feel' for the water is pertinent in other sports like swimming to improve stroke technique. Talent in swimming has been associated with feel for the water through athlete's ability to achieve the optimal angle at attack to the water (Toussaint & Beek, 1992). Swimming coaches are familiar with athletes improving their feel for the water, and although a subjective expression, it is an important aim when training elite athletes (Ganzevles et al., 2019). Further, this suggests a connection between the feel for the water and optimising the intra-stroke velocity fluctuations due to the propulsive actions of arms and legs (Ganzevles et al., 2019). Similarly, in rowing, there is an intra-stroke velocity fluctuation cycle. This could be considered an important connection between the subjective expression of feel for the water and the objective measurement of intra-stroke velocity fluctuation which has been linked to increased efficiency in competitive rowing (Hill & Fahrig, 2009). Interestingly, a qualitative research study has explored interpersonal coordination in elite crew boats and how crew synchrony is achieved through extrapersonal sources such as the feel for the boat and water (Millar et al., 2013). Results suggested more fundamental attributes such as force development capacity and stroke length were pre-requisites to elite performance and thus as highly practiced individuals, allows them to make use of higher order invariants such as feel for the boat and water. In the absence of having an innate feel for the water in rowing, more fundamental attributes may need to be achieved prior to addressing the higher order skill of feel for the water.

Trainable qualities referred to the concept that force development capacity was more important because it is less trainable than aerobic capacity. In the context of a rowing race typically comprised of 80% aerobic metabolism (Yusof et al., 2020), this is a unique perspective not currently reflected in the literature. Further research may be warranted in a talent identification environment to assess prioritising naturally strong athletes over naturally aerobic athletes. In addition, current junior rowers and coaches may benefit from learning about the importance of these attributes, both innate and trainable, as it may assist in their development and level of performance achieved in the future.

Targeting types of talent flows into the final theme, complexities of performance, as the acquisition of becoming an expert or elite performer in any sport is a nonlinear process where athletes develop skills at different rates through their own unique pathway (Phillips et al., 2014) making a “one size fits all” approach to talent identification almost irrelevant (Baker et al., 2018; Vaeyens et al., 2008). Similarly, successful elite performance can be comprised of many different combinations of attributes, skills, and qualities. Limiting the list of performance indicators to a narrow subset of parameters for each coach was difficult, highlighting the complex nature of performance and the individual variability that exists even at the elite level of sport (Gulbin et al., 2013; Rose et al., 2013). It was challenging for coaches to rationalise the most important attributes for rowing performance. Despite the interview being an exercise in listing attributes in a priority order, coaches were drawn to discuss the variability they see amongst their own athletes who in some situations could all be considered successful at an elite level. This highlights the importance of the individual variability rather than the statistical average when describing performance (Rose et al., 2013).

Strengths and limitations of this research must be considered when interpreting the findings. The study findings are strengthened by the relatively large sample of coaches (n = 27) with an average of 20 years coaching experience, including twenty-three coaches with national team representation. However, the recruitment of coaches was restricted to the Rowing Australia network and, although there are standard techniques for on-water rowing, various performance and coaching styles have been adopted in different regions of the world (Kleshnev, 2016). Thus, the present findings may not be transferable to other contexts or technical models. In addition, the sports systems in Australia may vary to other countries, including approaches to talent identification and development in junior level athletes. Accordingly, the generalisability of the results across rowing programs in other nations may be limited. Regardless, the prolonged general success of Australia as a rowing nation in the past few decades means that the emerging themes identified in this research are ecologically valid in the context of a high performing development environment.

Coaches' responses were interpreted and reported based on the interview transcriptions. Coaching language does not often reflect the preciseness of scientific and academic literature, and the disconnect between sport science research and coaching practice is well documented (Eisenmann, 2017; Williams & Kendall, 2007). Examples in this study include the use of the term core by the coaches in reference to the force development capacity of the trunk. Coaches used the terms strength and power interchangeably in reference to the force generating capacity of the athlete or body region depending on the specific topic of the discussion. This paper aimed to bridge the gap between coaching practice and sport science research through integrating coaches' language in a sport science publication. It is hoped coaches and support staff concerned with rowing find the study insightful and accessible.

3.5 Conclusion

To our knowledge, this was the first study to explore coaches' perspectives on rowing performance indicators for competitive rowing with a focus on junior rowers. The experiential knowledge of expert rowing coaches interviewed in this study has contributed to the understanding of performance indicators and attributes pertinent to junior rowers. The sequence of the rowing stroke was highlighted as a critical technical focus for junior rowers, learning to coordinate the leg drive, body swing and arm draw for optimal force production. Concepts around movement competency concentrated on flexibility and trunk force development capacity for junior rowers. Subsequently these focal areas of fundamental movement skills and basics of effective technique led to targeting talent and achieving successful performance outcomes. Identifying talent and assessing what makes up successful performance are both complex concepts when considering the individual athlete. Talent identification has been popular in recent decades however, more recent research emphasises the concept of talent development (Vaeyens et al., 2008). The results of this study highlight aspects of both movement competency and technique required to enhance development in junior rowers. In addition, although not a focus of this study, psychological aspects of performance are an essential aspect of performance, and this was identified by the coaches. Future research could further explore coaches' knowledge on psychological aspects of training and performance in the context of talent development. To compliment the current findings of this experiential knowledge, experimental research could explore the effects of a training intervention targeting movement competencies specific to junior athletes' rowing technique and subsequent on-water performance. Such an approach could assist the development pathway including junior rowers, school rowers, coaches, and sport scientists in the utilisation of best practice training methods to achieve optimal and effective rowing performance outcomes, whilst also reducing the risk of injury at such an early stage of development.

Contribution of authorship to the chapter

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Thesis Relevance and Sequence

Chapter Two has established the biomechanical variables relevant to on-water rowing performance alongside the coaches' perspectives in Chapter Three where physical attributes of the rower were recognised in relation to executing effective technique, particularly in junior rowers. The physical attributes were discussed and clarified as a unique set of characteristics to the physiological capacities such as aerobic and anaerobic metabolism. The use of language was challenging and required explanation when interviewing the coaches in relation to these physical attributes and this is where the concept of movement competency specific to rowing was established. Chapter four aims to define and propose the concept of movement competency in rowing. Thereby establishing the importance of certain physical attributes that aid in achieving the required body positions and coordinated movements to be able to optimise force development and maximise boat velocity.

Chapter 4

Movement Competency in Rowing

As per the manuscript in preparation for submission to Sports Medicine:

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Abstract

Movement competency is about fundamental patterns and movement quality that enables the confident and competent execution of activities, games, sports and everyday tasks. Developing appropriate movement competency early in the sporting pathway such as in rowing is critical to ensure physical readiness for participating in sport from the grassroots level through to the high-performance domain. This article addresses the lack of a clear definition and guidelines in relation to the sport-specific movement competency required for safe and effective rowing, particularly in the context of enhancing performance. In our opinion, the movement competency requirements in rowing should be emphasised together with the physiological attributes of rowing performance. However, the physiological determinants of rowing performance are associated with the work capacity of the rower including aerobic and anaerobic capacity, muscular strength and endurance. Sport-specific movement competency for rowers incorporates physical attributes of mobility and stability through the shoulders, trunk, hips, knees and ankles along with the associated muscular strength and endurance to be able to coordinate and execute a technically effective stroke. Rowers must be able to coordinate different regions of the body through appropriate joint positioning and coordinated movement patterns to optimise force development capacity during the stroke cycle. Moreover, assessment and management of an athlete's sport-specific movement competence requires multi-disciplinary consideration, communication, and input. This current opinion paper proposes the notion of movement competency for rowing. This concept has the potential to provide benefits for rowing participation, technical rowing efficiency, injury prevention and performance enhancement.

4.1 Introduction

Movement competency refers to the fundamental patterns underlying movement that facilitates the confident and competent execution of activities, games, sports and everyday tasks (Pill & Harvey, 2019; Rogers et al., 2020b). Developing appropriate movement competency early in the sporting pathway such as in rowing is critical to ensure physical readiness for sports participation through to high-performance (Myer et al., 2011; Rogers et al., 2020b). The movement competency specific to a sport is related to the execution of technique, whereby technique is defined as a coordination pattern that provides a movement solution specific to a sport (Bennett & Fransen, 2023). In contrast, movement competency can be distinguished from the skill of a sport since skill is more so concerned with how the athlete can adapt technique to produce an appropriate behaviour that leads to a successful performance outcome (Bennett & Fransen, 2023; Gorman & Maloney, 2016). Movement competency in sport has largely been examined in relation to sports injury (Bergeron et al., 2015; Myer et al., 2011); its relationship with sport specialisation in youth populations (Woods et al., 2016); and its association with athlete's meeting the demands of a particular sport (Rogers et al., 2020a). Despite a growing body of work, the literature is limited on movement competency requirements in the context of enhancing sports performance.

Sport-specific movement competency and enhanced performance outcomes have been documented for some sports. For instance, netballers who improved physical performance measures such as balance, agility and peak power after a 6-week neuromuscular training intervention also improved their movement competency through the assessment of a modified movement screening tool specific for netball (Hopper et al., 2017). In contrast, early specialisation has been shown to improve movement competency and increase efficiency in footballers (Zoellner, 2023), however this has not been consistently reported (Zoellner et al., 2021). In a sporting context, competency across a range of movements has been recommended for safe, effective and long-term athletic development of young athletes (Lloyd et al., 2016; Rogers et al., 2020a). Recent systematic reviews evaluating fundamental movement skills and movement competency in relation to sporting success have highlighted the need for clearer definitions and methods to define and measure sport-specific movement competence (Basman, 2019; Kliethermes et al., 2021; Zoellner, 2023). Guidelines focussed on sport-specific movement competency are needed to provide coaches and athletes with important benchmarks that reflect the movements of a certain sport. These may include attributes such as stability, mobility, balance, coordination or muscular strength that are considered important to be able to effectively execute correct technique and safely meet the demands of the sport.

In rowing, there is a lack of clarity on the sport specific movement competency required. The rowing literature refers to various physical qualities such as functional movement patterns (Newlands et al., 2015), physique (Slater et al., 2005), physical capacity (Zoellner et al., 2021), physical attributes (Mikulic, 2008), athleticism (Brewer, 2017) and core stability (Simon et al., 2023). Yet these terms and definitions do not wholly describe the concept of movement competency. For example, physique incorporates an anthropometrical profile not related to movement (Slater et al., 2005) and athleticism relates to physiological and physical attributes (Brewer, 2017). Moreover, the inconsistency of language utilised in rowing research can lead to confusion and misunderstanding of important physical attributes that can impact performance and injury (Buckeridge et al., 2015a). Essential movement competencies in rowing such as greater hip flexion, anterior pelvic tilt and trunk muscle endurance have been highlighted in relation to injury (Nugent et al., 2021). However, an all-encompassing term with a clear definition has not been established to reflect these attributes. Establishing a clear understanding of the movement competency requirements for rowing is required, including quantitative performance-related benchmarks and guidelines for movement competency assessment specific to rowing. This has the potential to improve performance, reduce injury and retain participation in the sport. This current opinion paper proposes the concept of movement competency specific to rowing.

4.2 Movement Competency for Rowing Performance

Rowing requires physical, technical and psychological attributes for success (Nolte, 2011). It is considered a technical sport that involves coordinating movements of the whole body to generate force on the oars that propel the boat forward (Kleshnev, 2016).

In our opinion, the movement competency requirements in rowing should be distinguished from the physiological determinants of rowing performance. The physiological determinants are dependent on aerobic and anaerobic energy pathways (Izquierdo-Gabarren et al., 2010), muscular strength and endurance (Lawton et al., 2011, 2013). The physiological attributes in isolation do not entirely explain differences in on-water rowing performance as there is more demand for technical skill during on-water rowing as well as the drag factor that directly influences boat speed (Baudouin & Hawkins, 2002; Otter-Kaufmann et al., 2020). For example, elite heavyweight and lightweight male rowers exhibited the same boat velocity even though the heavyweight rowers displayed superior mean and peak force (Doyle et al., 2010a). Rather than physiological factors, technical differences such as the coordination of movement patterns were identified between the crews. These key differences were related to identified performance outcomes related to boat velocity and acceleration properties (Doyle et al., 2008). Specifically, while the lightweight crew recorded a greater minimum boat acceleration, they were able to achieve a more rapid return to positive acceleration leading to less time spent in deceleration across the stroke cycle. Moreover, body segment and boat velocities increased earlier in the stroke cycle for the lightweight crew which may compensate for the reduced peak force compared to the heavyweight crew. These technical differences may be related to physical attributes that enable the lightweight rowers to approach the stroke with an advantageous technical strategy. As such, sport-specific movement competency for rowers incorporates physical attributes of mobility and stability that are inter-related with the technical ability to coordinate and execute an effective stroke (McGregor et al., 2016; Newlands, 2013; Nugent et al., 2021). To achieve rowing-specific movement competency the rower must be able to achieve a certain degree of mobility through the hips, knees, ankles, shoulders, and trunk specific to the rowing stroke. Mobility is defined as the range of movement around a joint in combination with the associated flexibility which refers to the length of a muscle (Teichmann et al., 2021). Stability is defined as the restriction of joint movement controlled by several static and dynamic structures and mechanisms including ligaments and joint capsules, proprioceptive positional sense and muscular strength (Blackburn et al., 2000).

4.3 Main Phases of the Rowing Stroke

There are 4 main phases of the rowing stroke (see Figure 4.1). Rowing is a cyclical sport whereby the stroke is repeated over 200 times during a 2000 m race. A cyclical sport involves a pattern of movements where all phases that exist in one cycle are present in other cycles (Cherkesov et al., 2021). The application of movement competency in a cyclical sport such as rowing has the potential to play an effective role as opposed to field sports which are acyclic and display a much higher degree of variability in movement such as jumping, catching, and tackling. The catch position is the most unstable position and technically challenging aspect of the rowing stroke where the blade is placed in the water and force is rapidly developed to propel the boat forward. This requires a body position involving maximal hip flexion, knee flexion and ankle dorsiflexion while the trunk ideally remains in a relatively neutral position, and the upper limbs place the oar in the water with a degree of finesse that minimises disruption to the momentum of the boat (Nugent et al., 2020; Thompson, 2016). The drive phase involves extension through the hips, legs and trunk to transfer force from the foot stretcher to the oar handle and blade in the water to propel the boat forward. The finish signifies the end of the drive phase where the blade is extracted from the water in preparation for the recovery (Thompson, 2016). The knees are fully extended at the finish position, the ankles are plantarflexed and the hips have finished extending however remain in a relatively flexed position due to the upright seated posture (Nugent et al., 2020; Wilson, 2018). The recovery is the non-propulsive phase of the rowing stroke, however, this phase requires coordination and balance to mirror the sequence of body movements of the drive phase, executed in the reverse order to the drive to set up the optimal position for the next catch. Movement competency requirements are specific to each of these four main phases.

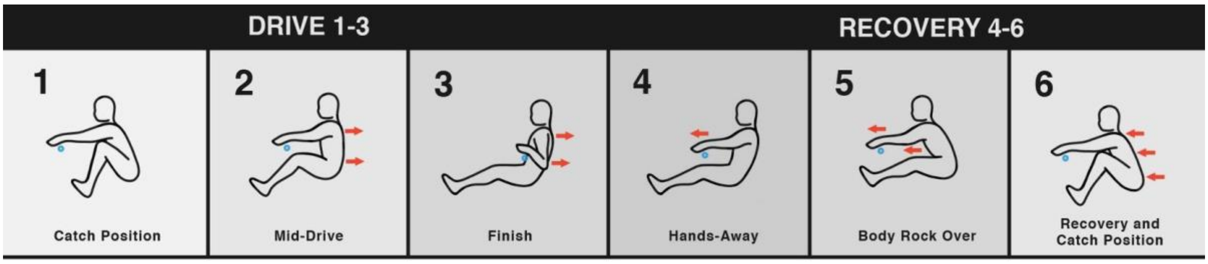

Figure 4.1: Phases of the Rowing Stroke Cycle

Catch

The catch is a precise and challenging movement and to successfully execute this part of the stroke requires appropriate range of movement to achieve the body positions alongside the associated force producing capabilities to maintain optimal posture for the development of boat propulsion (Iguchi et al., 2020; Rawlley-Singh & Wolf, 2023; Wilson, 2018). With the legs and trunk producing 80% of rowing power (Kleshnev, 1998) particular focus is required on the hips and trunk regions. Appropriate hip flexion has been reported in the range of 130^o (Wilson, 2018) and trunk stability required for rowing includes the muscular strength and endurance to maintain the required posture for the duration of a race (Simon et al., 2023; Wolf, 2020). Without these physical attributes a rower may succumb to technical faults that are biomechanically inefficient and place undue repetitive loading through the lumbar spine and hips (Nugent et al., 2021; Trease et al., 2020).

Although there is limited literature on the degree of ankle dorsiflexion required for an effective catch position and stretcher force application, an increase in passive ankle dorsiflexion range is thought to allow for a steeper foot-stretcher angle that can optimise propulsive force capabilities (Liu et al., 2020; Soper et al., 2004). Conversely if ankle dorsiflexion is limited, reducing heel contact on the stretcher, the foot-stretcher angle and height may need to be reduced, impacting the ratio of horizontal to vertical stretcher forces. Such alterations can lead to a reduction in propulsive stretcher force (Draper, 2005; Liu et al., 2020). Further research is required to understand the performance and injury implications of a sub-optimal range of ankle dorsiflexion. There are challenges to measuring ankle joint position in the boat during on-water rowing, due to the hull of the boat obstructing the view of the ankle joint. Future development in the use of inertial measurement units (IMU) for rowing may overcome this limitation (Worsey et al., 2019).

Shoulder stability is required at the catch as force is applied on the handle simultaneously with the foot-stretcher (see Figure 4.1, Image 1). A stable shoulder girdle will allow for a more efficient transfer of force between the trunk and the oar handle (Young, 2019). Chest wall injuries including rib stress injuries are common in rowing and although the aetiology is unclear (Harris et al., 2020; Vinther & Thornton, 2016), excessive shoulder protraction can alter the balance with the shoulder retractors and lead to abnormal forces directed on the posterior aspect of the rib cage (McDonnell et al., 2011). Similarly, in other sports such as football, Australian football and rugby league, where hip adduction to abduction strength ratios have been established to predict risk of groin injury and implemented as a screening measure throughout the season (Crow et al., 2010; Engebretsen et al., 2010; O'Connor, 2004). The serratus anterior and external abdominal oblique muscles have been implicated as causing repetitive bending force to the lateral aspects of the ribs (Karlson, 1998). Although other factors are likely involved from an injury perspective, addressing issues and establishing standards related to joint stability and muscle balance around the shoulder girdle and thoracic cage has the potential to positively impact both injury and performance and should be considered an important aspect of movement competency for rowing.

Drive

The early to mid-drive phase is critical for a rapid rate of force development (Holt et al., 2020) and the lumbo-pelvic positioning should be relatively neutral with the primary movement generated through hip extension (Young, 2019). The trunk acts as a lever throughout the drive phase and has been shown to be a major power producer in the kinetic chain as the connection between the legs and arms (Simon et al., 2023). Trunk extensor muscle activity dominates up to 60% of the initial drive phase along with the hip extensors while trunk flexor activity is involved during the remaining 40%, contributing around the late drive and executing a braking action leading into the finish (Pollock et al., 2009; Simon et al., 2023). Strength training for rowing focusses on the drive phase given this is the propulsive phase of the stroke where peak force is achieved around the mid-drive (McGregor et al., 2004; Rawlley-Singh et al., 2021; Young, 2019). However skilful rowers are able to apply force earlier in the drive as well as maintain force for longer into the finish compared to less skilled rowers and this requires effective and coordinated movements from the catch to finish for each stroke (McGregor et al., 2004; Simon et al., 2023).

Finish

The finish requires abdominal strength to maintain the trunk in a relatively neutral position and to prevent posterior rotation of the pelvis which leads to excessive lumbar flexion (McGregor et al., 2002; Nugent et al., 2021). At this stage of the stroke cycle, the dominance of the trunk extensors and posterior chain muscles have transferred to the trunk flexors, acting as a break to slow the trunk into the finish in preparation for the change of direction in movement and the initiation of the recovery phase (Simon et al., 2023). The ability of the rower to plantarflex the ankles around the finish has been suggested to increase stroke length and allow for a smoother extraction of the blade from the water (Soper et al., 2004). However, the passive range of motion of ankle plantarflexion has been shown to be greater than that achieved during rowing thereby it is less likely to be a limiting factor (Soper et al., 2004). This shows that to achieve movement competency for the finish phase rowers require ample plantarflexion for an optimal finish length and blade extraction and appropriate trunk strength and endurance to maintain posture and change direction to initiate the recovery phase.

Recovery

The movement sequence from the finish to the recovery is typically described in coaching resources as a sequence starting with the arms moving away from the body towards the stern of the boat, followed by a trunk rockover and lastly the legs move the seat forward on the slides towards the stern of the boat to reach the catch position (Nugent et al., 2020; Thompson, 2016). The recovery phase has limited research from a technical and physical perspective, however, coaches refer to attributes of coordination, balance and ‘boat feel’ when talking about an athlete’s ability to execute an effective recovery (Legge et al., 2023). Maximal velocity is achieved during the recovery therefore there are two aims during this phase: to set up the body position for the next catch and to minimise any disruption to the boat run during this process (Thompson, 2016). Minimising both intra-stroke and inter-stroke fluctuations in boat velocity has been associated with superior rowing performance and this stage of the stroke cycle is critical given there is no propulsive force application, and the body is moving against the direction of momentum (Hill & Fahrig, 2009).

The ability to be able to ‘rockover’ through the hips is a key aspect of movement competency during the recovery phase (see Figure 4.1, image 5). Therefore, hip mobility including hamstring flexibility are essential along with the trunk strength and endurance to maintain a neutral spine position. Excessive trunk flexion particularly in the lumbar spine may result as a compensatory movement due to lack of hip mobility (Buckeridge et al., 2012; Nugent et al., 2021).

Research is limited on the recovery phase of the rowing stroke in relation to quantifiable performance outcomes. This non-propulsive phase of the stroke cycle has the potential to provide gains in boat speed without greater physiological effort. Optimal body sequencing has been suggested by coaches as a key area for development in junior rowers to maximise boat run (Legge et al., 2023). However, further research needs to provide quantifiable standards for both junior and elite rowers along with the movement competency requirements to be able to execute the necessary movement patterns (Legge et al., 2023).

4.4 Movement Competency & Rowing Injury

Rowing research concerned with the kinematics of rowing technique frequently aims to address injury-related questions (McGregor et al., 2016; Nugent et al., 2021) rather than assessing the impact on performance. It has been suggested that rowers without low back pain (LBP) display distinct kinematics to those that have experienced LBP (Nugent et al., 2021). Neutral or anterior pelvic rotation at the catch, greater hip mobility, a more neutral spine position at the finish and dominant trunk extensor muscles with less trunk flexor activity have been associated with rowers without LBP (Nugent et al., 2021).

LBP and chest wall injuries are the most common and burdensome injuries for male and female rowers, respectively (Thornton et al., 2017; Trease et al., 2020) with chest wall injuries accounting for the greatest number of training days lost, undoubtedly affecting training progression and performance (Trease et al., 2020). The aetiology of chest wall injuries in rowing is unknown and current literature is largely anecdotal (Harris et al., 2020; Neville, 2022; Thornton et al., 2017; Vinther & Thornton, 2016). In addition, in relation to LBP, lower-limb asymmetries have been identified in rowers, with poor hamstring relative to quadricep strength (Koutedakis et al., 1997). Hamstring weakness impacts the lumbo-pelvic rhythm, therefore the degree of hip flexion attained at the catch may be impacted by this muscle imbalance and directly related to the movement competency required for rowing (Buckeridge et al., 2012). Accordingly, rowing kinematics are applicable to movement competency, providing objective appraisal to inform on injury and performance related outcomes (Buckeridge et al., 2015a).

Sporting injuries are often a multifactorial phenomenon and attributing an injury to one factor is improbable (Perich, 2010). Therefore, all risk factors associated with certain injuries should be considered. In rowing, as with many injury scenarios, a history of LBP is one of the most relevant risk factors for developing LBP in the future (Newlands et al., 2015; Wilson et al., 2021). A common factor discussed around overuse rowing injuries is loading and fatigue and how this leads to changes in the biomechanics, particularly increased lumbar flexion (Nugent et al., 2021). There are injury and performance implications if altered biomechanics are continually practiced along with altered technique (Arumugam et al., 2020; McGregor et al., 2016). Therefore, injury implications and performance outcomes are undoubtedly inter-related. Injury in sport can often lead to diminished training time which directly impacts training progression and performance (Palmer-Green et al., 2013). In addition, research has highlighted injury as a contributing factor to sport drop out, directly affecting participation levels (Crane & Temple, 2015).

4.5 Movement Competency Screening in Rowing

Once understood, a key aspect of movement competency is the ability of the rower to identify and coordinate different regions of the body through appropriate joint positioning and coordinated movement patterns to optimise force development capacity during the stroke cycle. Therefore, it is important to adopt a functional testing protocol specific to the rowing stroke movements as opposed to traditional athlete physical screening (Young, 2019). Athlete physical screening is common in many sports with traditional tests performed in an isolated manner, measuring joint range of movement, muscle strength and flexibility (Comerford, 2006; Garrick, 2004; Newlands, 2013). However, a more functional approach adopted by some practitioners is to evaluate an individual's physical capacity tailored to sport-specific requirements (Cook et al., 2006; Newlands, 2013). Rowing-specific limitations such as lack of hip flexion, lack of ankle dorsiflexion or shoulder instability can increase the risk of injury and also impact upon performance. Accordingly, such properties need to be assessed in an integrated manner that reflects the combined movement patterns of the rowing stroke (Newlands, 2013; Young, 2019). Further, pelvic and spinal kinematics can change during rowing with increased durations and intensities. Therefore it is important to consider an individual's movement competency when prescribing training and make adjustments based on known recommendations such as the maximal duration of ergometer prescriptions. (Nugent et al., 2021).

The functional movement screen (FMS^{TM}) is a well-established movement screening tool which has been evaluated in relation to rowing injuries and the comparison of movement competency in athletes of different sports (Arslan et al., 2021; Clay et al., 2016; Torrisi, 2015). Two studies examining seasonal data on collegiate rowers suggest the information obtained from FMS^{TM} is not effective for injury prediction for rowing athletes. However, rowers demonstrated superior mobility and stability when compared to football players, unsurprisingly, given the physical demands of rowing and football are vastly different (Arslan et al., 2021). For sport-specific movement competency, screening tests should reflect movements, coordination and loading patterns that reflect the sport. These studies reinforce the need for movement competency guidelines specific to rowing given the distinctive set of physical attributes specific to a rowing race, rowing training demands, and the four main movement phases of the rowing stroke cycle.

To maximise performance, minimise injury and to tolerate the demands of training and competition in rowing it is essential young athletes develop the necessary physical attributes (Legge et al., 2023; Young, 2019) and this is where an awareness of movement competency can have an impact early in the sporting pathway. As an example, adequate muscular strength and endurance around the hip and trunk to allow for maximal force transmission of the leg drive as well as sufficient mobility through the hips to achieve an optimal catch position are common attributes lacking in less skilled rowers and should be a key focus for addressing movement competency in development athletes (Legge et al., 2023; Thompson, 2016; Young, 2019). Moreover, trunk and scapular stability around the catch and finish positions are important physical attributes to optimise force development and decrease the likelihood of injury (Pollock et al., 2012; Wilson et al., 2013). Common technical faults of a less skilled rower include incorrect sequencing of the body movements during the rowing stroke (Legge et al., 2023). This relates to movement competency when a lack of mobility and trunk strength are preventing the athletes from achieving the required positions to optimise their force development capacity (Nugent et al., 2020; Simon et al., 2023). We propose these critical physical attributes provide rationale and justification that a clear definition should be established and description for movement competency in rowing. Further recommendations for a rowing-specific movement competency screen should be developed and promoted within the rowing community.

4.6 Practical Applications & Future Perspectives

Strength and conditioning programs such as those presented by Young (2019) provide useful insights into training the movement competency and strength requirements for rowing. Further research that attempts to quantify movement competency for rowing can support such programs and the development of evidence-based appropriate movement competency assessment tools will potentially have a greater impact and influence on training practices at all levels of the rowing community. Practical applications should involve implementing resources into rowing organisations and governing sporting bodies, particularly in the school-age rowing environment, where young rowers are prone to overtraining, overuse injury and early departure from the sport (Crane & Temple, 2015; Keats et al., 2012). Incorporating movement competency requirements such as minimal benchmark standards for key movements and joint positions and associated screening tools for safe and effective rowing can influence technical training in coach education and provide positive outcomes that will improve and increase rowing participation levels.

Assessment and management of an athlete’s sport-specific movement competence requires multi-disciplinary consideration, communication, and input (Rawlley-Singh & Wolf, 2023). The physical therapist and strength and conditioning coach alongside the head coach can deliver an integrated approach to address the movement competency and technical efficiency of each individual and incorporate these aspects into the on-land and on-water training program. We propose that establishing clear guidelines on movement competency for rowing can be beneficial for rowing participation, technical rowing efficiency, injury prevention and performance enhancement (Nugent et al., 2020). More quantitative research is required to establish such guidelines in collaboration with some of the leading experts in rowing including coaches, strength and conditioning coaches, physical therapists, rowing biomechanists and applied researchers.

4.7 Conclusion

The purpose of this current opinion paper was to present and describe the concept of movement competency specific to rowing and to relate it to the execution of each phase of an effective technical rowing stroke that minimises injury risk and enhances performance. In our opinion, movement competency in rowing incorporates the physical attributes required to be able to execute a technically effective stroke through appropriate stability and mobility specific to rowing. Movement competency is pertinent to general youth physical development, however it can also be sport specific. Both applications encompass the definition of movement competency, however, when applied to a particular population serve a distinctive purpose. Mobility and stability are required to achieve effective and coordinated positions throughout the rowing stroke cycle including the catch, drive, finish, and recovery to optimise performance and minimise injury.

Contribution of authorship to the chapter

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Thesis Relevance and Sequence

Chapters Two, Three and Four have established the physical and technical attributes relevant to on-water rowing performance through a multiple methods approach. These three chapters combine the results of a systematic scoping review alongside the qualitative assessment of coaches' experiential knowledge and lastly expanding on the ideas from the coaches' perspectives to propose the concept of movement competency specific to rowing. The purpose of Chapter Five was to implement this knowledge into a cross-sectional study looking at junior and elite, male and female rowers. The aim of Chapter Five was to establish and explore a set of performance characteristics that will make an important contribution to the limited on-water literature and provide a novel insight into how physical and technical variables inter-relate to produce successful performance outcomes. A greater understanding of the physical attributes combined with on-water technical and performance measures may aid coaches when prescribing training for junior and elite rowers.

Chapter 5

Physical and technical attributes associated on-water rowing performance in junior and elite rowers

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Abstract

On-water rowing performance consists of the integration of physical and technical attributes. This exploratory study aimed to describe key physical and technical variables for male and female, elite and junior rowers and examine the associations and predictive capacity of these variables with on-water rowing performance outcomes. Twenty-eight junior (16 females, 16 ± 0.8 years and 12 males, 17 ± 0.7 years) and 24 elite rowers (12 females, 24 ± 2.7 years and 12 males, 27 ± 2.6 years) completed an on-water, single sculling biomechanics assessment combined with a series of physical tests. Elite men and women were superior in mean gate force, distance per stroke and recovery distance compared to junior groups ($p < 0.017$). Large associations ($p < 0.01$) were evident between anthropometry, strength and power assessments with the on-water measures of catch angle, mean gate force, recovery distance and boat speed. Differences in range of movement (ROM) and flexibility attributes did not distinguish between elite and junior rowers. Linear discriminant analysis revealed that individual rowers can be appropriately categorised by sex and performance level based on their physical and technical attributes. This battery of testing with world class athletes represents an excellent level of ecological validity for the assessment of rowers pertinent to on-water performance.

Keywords: on-water rowing, sculling, performance, technique, physical attributes

5.1 Introduction

On-water rowing performance consists of the integration of both physical and technical attributes. A number of researchers have established standards on physical measures for rowing performance (Akça, 2014; Lawton et al., 2012; Slater et al., 2005), however, research on specific technical attributes is limited. Guidelines are unclear on the characteristics of technique that leads to optimal boat velocity (Holt et al., 2020; McGregor et al., 2007) and a deeper understanding of on-water rowing performance is required, specifically, understanding how the physical attributes of the rower are associated with the on-water technical performance (Legge et al., 2023). In the context of the rowing stroke, range of movement requirements are essential at the hip, knee, and ankle along with associated force producing capabilities that ensure critical positions can be maintained for the duration of the rowing stroke and repeated over extended periods of time (Rawlley-Singh & Wolf, 2023). It is therefore important to have a holistic view of the rower's performance through capturing the physical and technical aspects of performance. Further, exploring these performance related attributes for junior and elite rowers can provide coaches, athletes, and support staff with knowledge to inform the development pathway alongside gold standard references from current successful elite athletes (Otter-Kaufmann et al., 2020).

Muscular strength and power have been closely linked to 2000 m ergometer performance (Akça, 2014; Gee et al., 2011; Thiele et al., 2020). While related to some aspects of rowing performance, ergometer rowing is significantly different to on-water rowing, particularly from a technical perspective (Fleming et al., 2014). Altered acceleration and deceleration of the body segments on the ergometer as well as shorter drive lengths and higher handle forces all contribute to a reduced representative design for ergometer rowing in comparison to on-water rowing performance (Elliott et al., 2002; Kleshnev, 2005). Therefore, results from ergometer-based biomechanical assessments likely do not directly relate or transfer to on-water rowing performance. On-water rowing reveals differences in both amplitude and temporal aspects of handle forces compared to ergometer rowing, implying distinct demands of the on-water task (Millar et al., 2017). The strength requirements of on-water rowing have been established through specially instrumented measurement devices that fit onto the oar or oarlock during on-water rowing (Draper, 2005; Nolte, 2011). To further understand the physical requirements of on-water rowing and the interrelationship with technique it is important to incorporate on-water rowing assessment as a performance outcome measure (Millar et al., 2017).

Along with the physical and technical aspects of rowing assessment, the anthropometric profile of rowers at both junior (Bourgois et al., 2000) and elite levels (R. Barrett & J. Manning, 2004) is an important component of rowing performance (Bourgois et al., 2001). Further, range of movement is an essential biomotor quality at certain joints during the rowing stroke to be able to achieve the required positions to accommodate optimal force producing capacity (Rawlley-Singh & Wolf, 2023). Range of movement and flexibility requirements for rowing have typically only been of interest in research pertaining to rowing injuries rather attributes being associated with performance (Thornton et al., 2017), however, there may be additional applications of such measurements given the importance of stroke length, body position, and force producing capability throughout the stroke cycle (Rawlley-Singh & Wolf, 2023). Assessing and describing these variables for junior rowers is important to evaluate their position on the development pathway while exploring such measures in elite cohorts provides a gold standard comparison and this information may play an important role in predicting future success (Clephas & Brückner, 2020).

Descriptive performance characteristics of representative groups of junior and elite level rowers reported by sex may highlight important differences for male and female performance measures which have the potential to inform different stages of the rowing development pathway (Olszewski-Kubilius et al., 2019). Research has shown that male and female rowers exhibit characteristic differences in measures of anthropometry, strength and power therefore training methods should be considered based on age and sex group (Podstawski et al., 2022). In the sporting context, exploring current performance levels in certain attributes can provide a critical gauge to predict an individual’s current or future potential of success against established elite benchmarks (Lawton et al., 2012). Given the absence of information in this domain, it is clear that a greater understanding is required about the associations between certain physical attributes and technical attributes of on-water rowing to produce optimum boat velocity. Using a novel approach, this study encompassed an on-water rowing biomechanical assessment in a single scull as the primary performance outcome measure. Demographic characteristics, anthropometry, range of movement, flexibility, strength, and power assessments in combination with an on-water biomechanical sculling assessment were explored. The aim of this exploratory study was to describe key physical and technical variables for male and female, elite and junior rowers. Additionally, the study examined the associations and predictive capacity of these variables to explore the interaction of physical and technical attributes with on-water rowing performance outcomes. This information may provide valuable knowledge for coaches, athletes, and support staff in how they approach physical and technical aspects of training and competing at the development pathway and elite levels.

5.2 Methods

Participants

Fifty-two rowers volunteered to participate in the study and provided written informed consent prior to any testing. The participants comprised 28 junior (16 females, 16 ± 0.8 years and 12 males, 17 ± 0.7 years) and 24 elite heavyweight rowers (12 females, 24 ± 2.7 years and 12 males, 27 ± 2.6 years). The elite male and female rowers reported 11.7 ± 3.0 years and 8.0 ± 2.3 years of rowing experience, respectively. Elite participants were classified as world-class (McKay et al., 2022), recruited through the national rowing network and were all competitors at recent world championships. The male and female junior rowers had 3.8 ± 1.0 and 3.9 ± 1.1 years, respectively and were a combination of trained developmental pathway and highly trained national level participants. All junior participants were recruited through promotional information sheets that were sent to rowing clubs and school rowing programs (McKay et al., 2022) in NSW, Australia. Junior rowers were competent and competitive scullers with at least 2 years of rowing experience, under 19 years of age, and currently training a minimum of 6 hours per week. Ten of the 28 junior participants were current junior national representatives. The study protocol was approved by the Human Research Ethics Committee of the University of Technology Sydney (ETH21-6136).

Overview

Participants completed two separate testing sessions in the early stages of a rowing season. The first was an on-water rowing assessment in a single scull conducted on an enclosed waterway with no tidal flow and a buoyed racecourse. The second was a series of physical tests conducted in a high-performance training facility. Both testing sessions were scheduled within a two-week period for each participant to minimise training effects between testing sessions. Descriptive statistics and correlation analysis were reported for on-water technical attributes and physical assessments. Furthermore, a linear discriminant analysis (LDA) was applied to identify whether a combination of physical and technical variables selected from the dataset could accurately distinguish individuals to their correct rower category.

On-water Testing Procedures

The Peach PowerLine Instrumentation system (Peach Innovations, UK) including instrumented gates, foot stretcher, boat sensor (GPS) and accelerometer sampling at 50 Hz were installed on each single scull to measure the on-water biomechanical assessment. The single sculls were set up according to each individual's standard rigging measurements and the set up was completed in consultation with their coach. The Peach PowerLine instrumentation system is used frequently within elite and school rowing environments for monitoring purposes. Established levels of validity for the system has been reported with the standard error of the estimate (SEE) ≤ 8.9 N for gate force, ≤ 0.9^{o} for gate angle and an r^2 of 1.00 for both variables (Coker et al., 2009).

Environmental conditions including wind direction and speed, water temperature and air temperature were recorded periodically during every testing session to ensure conditions were comparable across all testing days. Venue environmental conditions (measured using the Kestrel 5500 Weather Meter) were: 19.1 ± 3.4^{o}C air temperature (mean ± SD), 20.1 ± 1.7^{o}C water temperature, and 0.8 ± 1.0 $m \cdot s^{-1}$ wind speed, ranging in direction from calm to a light cross-tail direction. The on-water testing included a 1000 m piece with a set stroke rate of 28 strokes per minute (spm) for the first 500 m and 30 spm for the 2nd 500 m. The stroke rate selected for analysis represented an intensity level that was comparable across the two groups, elite and junior. Some of the junior athletes struggled in the single scull to maintain their technique when the rate exceeded 30 spm. This study was completed as part of a larger project and the protocol included a range of stroke rates, including 20, 24, 28, 30, 32 spm and a self-selected open rate. Based on observations during the data collection, the stroke rate selected for analysis was 30 spm across the cohort as this represented a stroke rate that was consistently performed by the junior and elite rowers in order to compare technical rowing ability across all variables measured. For analysis purposes, a sample of 20 strokes were extracted from the data for each participant, representing a mid-section of each testing piece at 30 spm. Each stroke cycle was identified from catch to catch using the horizontal gate angle, where the catch was at the largest negative and the finish at the largest positive angle. The stroke rate selected for analysis was 30 spm across the cohort as this represented a rating that was consistently performed by the junior and elite rowers in order to compare technical rowing ability.

Raw data files were downloaded using the Peach Innovations software and time-series data (50 Hz) was exported as csv files for processing. Discrete data was determined from time-series data using a custom script written in the R platform (http://www.r-project.org/). Gate angle time-series data was filtered with a low-pass 4th order Butterworth filter at a cuff-off frequency of 20 Hz to assist in determining catch and finish events. The peakdet R function (Eli Billauer, http://www.billauer.co.il/peakdet.html) was used to determine local minima and maxima in the horizontal gate angle time series data which corresponded to catch and finish events respectively. Discrete metrics were determined per stroke by calculating between catch events and total gate force was the sum of bow side (left) and stroke side (right) horizontal gate force sensors. Drive distance was determined from the distance travelled between the Catch and Finish events, while Recovery Distance was the distance travelled between the Finish to the next Catch.

Physical Testing Procedures

All participants undertook a standardised warm up before the physical testing session including dynamic stretching and exercises as directed by a strength and conditioning professional. All anthropometrical measures were assessed as per the International Society for the Advancement of Kinanthropometry (ISAK) guidelines (Norton et al.,

2004) by an accredited exercise scientist. Measurements included body mass (A&D FG-150KAM Platform scale, Adelaide Australia), stature (Harpenden wall-mounted stadiometer, Crosswell, UK), sitting height (Holtain Sitting Height Table, Crosswell, UK), leg length and arm span (segmometer, Crawley, Australia). Range of movement and flexibility measurements were completed by a qualified allied health professional and included sit and reach (steel Baseline Sit N Reach Box, New York, USA), knee to wall dorsiflexion, hip flexion, and active knee extension (12-inch Prestige paddle Goniometer, Dublin, Ireland).

The Isometric Mid-Thigh Pull (IMTP) and Squat Jump (SJ) were completed using the ForceDecks FDMax Dual Force Platforms (ForceDecks, London, UK) sampling at 1000Hz. The set up and positioning for the IMTP followed the description by Comfort (2019). The instructions to the participants involved a gradual ramping over a count of 2 seconds followed by a maximum push for 5 seconds. The Net Peak Force was calculated by subtracting the individuals body mass from their peak force. This was to avoid any discrepancies in pre-tension applied by participants (Brady et al., 2020). The IMTP provides a reliable measure of isometric strength of the lower body (Comfort et al., 2019) while the SJ has been shown to be associated with 2000 m ergometer performance (Giroux et al., 2015). The SJ set up, positioning and instructions followed the methods as described by Sebastia-Amat (2020). The Biering Sorensen test was performed as described by Latimer et al. (1999). Participants held their body in a horizontal position for as long as possible with their head and neck in a neutral position staring at the ground and their arms crossed on their chests. Ergometer performance tests were conducted using the Concept 2 Rower Model D and included the 7-stroke maximum power test (Nugent et al., 2019) and the 500 m test for average power (Smith, 2000). 2000 m ergometer score is considered a reliable measure to simulate a 2000 m race (Bourdin et al., 2017; Schabort et al., 1999) and all-time personal best scores were reported by participants as part of a demographic questionnaire.

Statistical Analysis

Descriptive statistics were calculated for on-water technical attributes and physical assessments and the data was checked for normality using the Shapiro Wilkes test. The mean, standard deviation and 95% confidence intervals were calculated for each measured variable and presented in Tables 5.1 and 5.2. T-tests (two tailed, equal variance) were used to compare the elite and junior rowers within each sex, with significance level determined using an alpha level of 0.0017. This value was calculated based on the standard p-value cut-off of 0.05 divided by the number of assessed variables (n=29) to account for multiple comparisons. Effect Size (Cohen's d) was calculated to represent the magnitude of the difference between groups, with values represented as: Effect size values of <0.20, 0.20–0.60, 0.61–1.20, 1.21–2.00 and >2.01 represented trivial, small, moderate, large and very large differences, respectively (Hopkins et al., 2009). Pearson's correlation coefficients between the physical and on-water technical attributes were calculated to determine the strength of these relationships. Correlation magnitudes were based on the guidelines of Hopkins et al. (2009); <0.1: trivial, 0.1 ≤ small < 0.3, 0.3 ≤ moderate < 0.5, 0.5 ≤ large <0.7, 0.7 ≤ very large < 0.9, ≥ 0.9: extremely large. All descriptive statistical analyses were conducted using SPSS v29.0 (SPSS Inc., Chicago IL, USA). Linear discriminant analysis (LDA) was applied using the R platform (http://www.r-project.org/) and utilising the MASS package (Venables & Ripley, 2002) to identify whether a combination of physical and technical variables selected from the dataset could accurately distinguish individuals to their correct rower category (Williams, 1981). Variables were first screened to ensure they met the assumptions of LDA. Histograms and QQ plots were used to determine if the data was normally distributed. Sample independence was assessed using correlation analysis. Homogeneity of covariance matrices was checked using the Box M test. Relative measures were used to ensure the data was not skewed based on absolute strength and athlete weight. The selected variables, hip flexion, leg length, IMTP relative net peak force, relative 7 stroke peak power and on-water distance per stroke, were chosen by the authors, as variables related to performance, based on the literature (Lawton et al., 2012; Podstawski et al., 2022) and designed to represent the different attribute groups of rowing. The chosen variables represent range of movement, anthropometry, strength, power, and on-water rowing technique. The four categorical groups were elite men (M), elite women (W), junior men (B) and junior women (G).

5.3 Results

The descriptive analysis identified differences between junior and elite rowers separated by sex in several physical and on-water characteristics. The on-water biomechanics assessment (Table 5.1) identified elite female rowers to be superior in catch angle, stroke length, mean total gate force, distance per stroke, drive distance, recovery distance, and boat speed when compared to the junior females. Male elite rowers demonstrated significantly greater peak total gate force, mean total gate force, distance per stroke, recovery distance and boat speed than the junior males.

The anthropometric, range of movement and flexibility characteristics are presented in Table 5.2, along with the strength and power characteristics. Differences were identified in elite rowers compared to their junior counterparts in peak power measured during the seven-stroke ergometer maximal power test and the average power for the 500 m ergometer test. In addition, the elite female rowers revealed higher maximal strength in IMTP net peak force, IMTP relative net peak force, and the relative average power for the 500 m ergometer test compared to the juniors. Pearson's correlation coefficients revealed some *large* relationships between height, weight, and ergometer power tests with the on-water metrics of mean and peak force for both men and women (Tables 5.3 and 5.4).

Table 5.1: On-water single sculling biomechanics metrics for male and female rowers (Mean ± SD, 95% CI)

	Males		Females	
Metrics	Junior	Elite	Junior	Elite
Catch Angle (°)	-62.8 ± 2.9 (-64 – -61)	-66.4 ± 3.8 (-69 – -64)	-55.2 ± 5.8 (-58 – -52)	-65.1 ± 2.6*# (-67 – -64)
Finish Angle (°)	42.9 ± 3.1 (41 – 45)	43.6 ± 2.6 (42 – 45)	42.3 ± 4.8 (40 – 45)	42.8 ± 2.5 (41 – 44)
Stroke Length (°)	105.7 ± 3.9 (104 – 108)	110.0 ± 4.3 (108 – 112)	98.5 ± 5.0 (96 – 101)	108.0 ± 2.3*# (107 – 109)
Peak Total Gate Force (N)	980 ± 74 (938 – 1022)	1144 ± 75*# (1102 – 1186)	760 ± 97 (713 – 808)	866 ± 96 (815 – 916)
Mean Total Gate Force (N)	493 ± 39.2 (470 – 515)	602 ± 40*# (579 – 624)	365 ± 41 (345 – 385)	446 ± 57*# (416 – 476)
Mean to Peak Ratio of Force (RAM)	50.4 ± 2.9 (49 – 52)	52.6 ± 2.2 (51 – 54)	48.2 ± 2.6 (47 – 50)	51.5 ± 3.9 (50 – 54)
Gate Angle at Peak Force (°)	-21.1 ± 4.5 (-24 – -19)	-18.6 ± 5.5 (-22 – -16)	-18.0 ± 6.6 (-21 – -15)	-23.6 ± 6.9 (-27 – -20)
Distance per Stroke (m)	8.32 ± 0.3 (8.2 – 8.5)	9.06 ± 0.3*# (8.9 – 9.2)	7.51 ± 0.4 (73 – 7.7)	8.41 ± 0.2*# (8.3 – 8.5)
Drive Distance (m)	3.87 ± 0.3 (3.7 – 4.0)	4.21 ± 0.2 (4.1 – 4.4)	3.59 ± 0.2 (3.5 – 3.7)	4.06 ± 0.1*# (4.0 – 4.1)
Recovery Distance (m)	4.45 ± 0.3 (4.3 – 4.6)	4.85 ± 0.2*# (4.8 – 4.9)	3.92 ± 0.3 (3.8 – 4.1)	4.35 ± 0.2*# (4.2 – 4.5)
Boat Speed ($m.s^{-1}$)	4.21 ± 0.2 (4.1 – 4.3)	4.61 ± 0.1*# (4.6 – 4.7)	3.86 ± 0.2 (3.8 – 4.0)	4.30 ± 0.1*# (4.3 – 4.4)

KEY: CI = Confidence Interval; ° = degrees; N = Newtons; kg = kilogram; $m.s^{-1}$ = metres per second

* Significantly different from junior cohort for same sex ($p<0.0017$), # Large effect size compared to junior cohort for same sex ($d > 1.2$).

Table 5.2: Anthropometry, range of movement, flexibility, strength, and power characteristics for male and female rowers (Mean ± SD (±95% CI))

	Males		Females	
Metrics	Junior	Elite	Junior	Elite
Weight (kg)	82.2 ± 7.0 (78.2 – 86.1)	91.8 ± 3.1*# (90.0 – 93.6)	69.5 ± 8.8 (65.2 – 73.8)	76.6 ± 8.2 (72.3 – 80.9)
Height (cm)	184 ± 4.5 (181.0 – 186.1)	191 ± 4.5*# (188.2 – 193.3)	173 ± 5.3 (170.3 – 175.5)	179 ± 5.5 (176.0 – 181.8)
Sitting height (cm)	97.2 ± 3.1 (95.5 – 99.0)	99.3 ± 2.7 (97.8 – 100.8)	91.4 ± 3.0 (89.9 – 92.8)	93.4 ± 2.5 (92.0 – 94.7)
Arm span (cm)	187 ± 6.4 (183.6 – 190.8)	196 ±5.9 (192.3 – 199.0)	176 ± 6.6 (172.4 – 178.9)	182 ± 8.2 (177.9 – 186.6)
Leg length (cm)	95.4 ± 2.1 (94.2 – 96.6)	100 ± 3.2*# (98.2 – 101.9)	91.2 ± 4.5 (89.0 – 93.4)	95.3 ± 4.1 (93.1 – 97.4)
Sit & reach (cm)	6.29 ± 7.8 (1.9 – 10.7)	14.1 ± 6.6 (10.3 – 17.8)	13.5 ± 8.0 (9.6 – 17.4)	19.2 ± 5.8 (16.2 – 22.2)
Hip flexion (°)	122 ± 5.3 (119 – 125)	130 ± 4.3*# (128 – 132)	131 ± 7.7 (128 – 135)	135 ± 7.1 (132 – 139)
Active knee extension (°)	-28.0 ± 13.0 (-35.4 – -20.7)	-16.6 ± 8.4 (-21.3 – -11.8)	-22.3 ± 10.2 (- 27 – -17)	-3.96 ±6.9*# (-8 – 0)
Knee to wall dorsiflexion (cm)	9.89 ± 4.8 (7 – 13)	14.9 ± 4.2 (12 – 17)	13.7 ± 1.8 (13 – 15)	15.0 ± 3.4 (13 – 17)
IMTP Net Peak Force (N)	2300 ± 519 (2006 – 2593)	2926 ± 487 (2650 – 3201)	1487 ± 339 (1321 – 1653)	2184 ± 277*# (2039 – 2329)
Relative IMTP Net Peak Force (N.kg^{-1})	28.1 ± 6.5 (24.4 – 31.8)	31.9 ± 5.4 (28.9 – 35.0)	21.6 ± 4.70 (19.3 – 23.9)	28.6 ± 2.93*# (27.1 – 30.2)
7 Stroke Peak (Watts)	648 ± 81 (603 – 694)	816 ± 98*# (761 – 872)	403 ± 43 (382 – 424)	525 ± 64*# (491 – 558)
Relative 7 Stroke Peak (Watts/kg)	7.89 ± 0.73 (7.5 – 8.3)	8.92 ± 0.85 (8.4 – 9.4)	5.85 ± 0.74 (5.5 – 6.2)	6.77 ± 0.39*# (6.6 – 7.0)
500 m Avg Power (Watts)	515 ± 55 (484 – 546)	624 ± 59*# (591 – 658)	312 ± 33 (296 – 329)	406 ± 45*# (382 – 429)
Relative 500 m Avg Power (Watts / kg)	6.28 ± 0.5 (6.0 – 6.6)	6.84 ± 0.7 (6.5 – 7.2)	4.52 ± 0.5 (4.3 – 4.7)	5.29 ± 0.3*# (5.1 – 5.5)
Biering Sorensen Trunk Endurance Hold (s)	122 ± 40 (99 – 145)	165 ± 30 (148 – 182)	157 ± 21 (147 – 168)	155 ± 24 (143 – 168)
SJ Peak Power (Watts)	4144 ± 543 (3837 – 4452)	4563 ± 580 (4235 – 4892)	2857 ± 459 (2632 – 3081)	3343 ± 355 (3157 – 3529)
SJ Relative Peak Power (Watts/kg)	50.5 ± 5.8 (47 – 54)	49.7 ± 6.4 (46 – 53)	41.3 ± 5.4 (39 – 44)	43.0 ± 4.6 (41 – 45)
SJ Height (cm)	34.0 ± 4.7 (31 – 37)	34.0 ± 9.4 (29 – 39)	25.3 ± 4.2 (23 – 27)	27.4 ± 3.5 (26 – 29)

KEY: CI = Confidence Interval; SD = standard deviation; cm = centimetres; N = Newtons; kg = kilograms; ° = degrees; s = seconds

* Significantly different from junior cohort for same sex (p<0.0017), # Large effect size compared to junior cohort for same sex (d > 1.2).

Table 5.3: Pearson's Correlation Between Anthropometric & Range of Motion Characteristics and On-water Biomechanical Variables for Male and Female rowers

	Sex	Weight	Height	Sitting height	Arm span	Leg length	Sit & reach	Knee to wall dorsiflexion	Hip flexion	Active knee extension
Catch Angle	Male	-0.47*	-0.64**	-0.40	-0.59**	-0.58**	-0.27	-0.28	-0.56**	-0.16
	Female	-0.45*	-0.54**	-0.28	-0.56**	-0.59**	-0.17	-0.23	-0.05	-0.43*
Finish Angle	Male	-0.02	-0.10	-0.39	0.18	0.09	-0.27	-0.33	0.13	-0.20
	Female	-0.15	0.08	0.27	-0.07	-0.03	-0.21	-0.11	0.08	-0.03
Stroke Length	Male	0.38	0.47*	0.09	0.60**	0.53**	0.05	0.03	0.55**	0.01
	Female	0.34	0.57**	.441*	0.51**	0.53**	0.09	0.14	0.04	0.44*
Peak Gate Force	Male	0.79**	0.70**	.463*	0.67**	0.66**	0.37	0.36	0.49*	0.18
	Female	0.55**	0.45*	0.20	0.53**	0.38*	0.24	0.21	-0.12	0.36
Mean Gate Force	Male	0.72**	0.68**	0.38	0.68**	0.68**	0.39	0.37	0.61**	0.32
	Female	0.51**	0.50**	0.18	0.51**	0.46*	0.15	0.29	-0.02	0.47*
Mean to Peak Ratio of Force	Male	0.09	0.15	-0.07	0.22	0.24	0.20	0.17	0.43*	0.41*
	Female	0.09	0.24	0.02	0.13	0.28	-0.13	0.20	0.14	0.34
Gate Angle at Peak Force	Male	0.07	0.06	0.00	-0.06	0.18	0.29	0.28	0.20	0.25
	Female	-0.15	-0.33	-0.12	-0.37	-0.38*	-0.18	-0.36	0.20	-0.16
Distance per Stroke	Male	0.74**	0.63**	0.27	0.71**	0.72**	0.46*	0.42*	0.65**	0.32
	Female	0.34	0.45*	0.32	0.40*	0.33	0.21	0.14	0.08	0.62**
Boat Speed	Male	0.72**	0.62**	0.32	0.61**	0.64**	0.40	0.42*	0.72**	0.22
	Female	0.30	0.44*	0.35	0.40*	0.34	0.26	0.16	0.09	0.62**
Drive distance	Male	0.59**	0.53**	0.25	0.59**	0.52**	0.30	0.28	0.68**	0.18
	Female	0.22	0.49**	.449*	0.41*	0.41*	0.24	0.17	-0.10	0.56**
Recovery Distance	Male	0.56**	0.44*	0.18	0.50*	0.60**	0.41*	0.37	0.31	0.31
	Female	0.33	0.27	0.11	0.28	0.16	0.12	0.08	0.20	0.48**

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

Table 5.4: Pearson's Correlation Between Strength & Power Characteristics and On-water Biomechanical Variables for Male and Female rowers

		7 Stroke Peak Power	Relative 7 Stroke Peak Power	500m Average Power	Relative 500m Average Power	Prone suspension hold	IMTP Net Peak Force	Relative IMTP Net Peak Force	SJ Peak Power	SJ Relative Peak Power	SJ Jump Height
Catch Angle	Male	-0.45*	-0.32	-0.42	-0.20	-0.18	-0.02	0.14	-0.35	-0.07	0.00
	Female	-0.63**	-0.35	-0.58**	-0.34	0.11	-0.60**	-0.45*	-0.53**	-0.17	-0.26
Finish Angle	Male	-0.20	-0.23	-0.28	-0.30	0.07	-0.15	-0.18	0.04	0.05	0.27
	Female	-0.01	0.17	0.07	0.27	-0.01	-0.03	0.05	-0.28	-0.19	-0.26
Stroke Length	Male	0.24	0.12	0.17	-0.02	0.20	-0.07	-0.22	0.31	0.09	0.17
	Female	.624**	0.45*	0.62**	0.50**	-0.14	0.59**	0.51**	0.35	0.07	0.10
Peak Gate Force	Male	0.62**	0.34	0.60**	0.20	0.28	0.33	0.03	0.25	-0.27	-0.23
	Female	0.60**	0.26	0.60**	0.32	-0.18	0.53**	0.29	0.41*	-0.03	-0.06
Mean Gate Force	Male	0.57**	0.33	0.56**	0.21	0.37	0.28	0.01	0.27	-0.20	-0.15
	Female	0.65**	0.35	0.67**	0.44*	-0.30	0.53**	0.32	0.40*	0.00	-0.02
Mean to Peak Ratio of Force	Male	0.10	0.10	0.11	0.12	0.34	0.03	0.02	0.12	0.08	0.13
	Female	0.35	0.30	0.41*	0.40*	-0.30	0.17	0.15	0.10	0.05	0.05
Gate Angle at Peak Force	Male	0.17	0.32	0.05	0.12	0.23	0.46*	0.46*	0.17	0.15	0.09
	Female	-0.26	-0.17	-0.18	-0.08	-0.08	-0.26	-0.24	-0.29	-0.22	-0.28
Distance per Stroke	Male	0.55*	0.30	0.49*	0.11	0.21	0.31	0.03	0.36	-0.12	-0.09
	Female	0.72**	0.61**	0.75**	0.73**	-0.06	0.66**	0.58**	0.35	0.06	0.07
Boat Speed	Male	0.58**	0.36	0.62**	0.31	0.39	0.32	0.05	0.35	-0.11	-0.05
	Female	.720**	0.67**	0.74**	0.76**	-0.04	0.62**	0.53**	0.36	0.12	0.12
Drive distance	Male	0.39	0.18	0.38	0.09	0.17	0.04	-0.18	0.38	0.01	0.02
	Female	0.64**	0.61**	0.59**	0.61**	-0.08	0.66**	0.66**	0.45*	0.29	0.32
Recovery Distance	Male	0.44	0.27	0.34	0.07	0.14	0.44*	0.24	0.18	-0.19	-0.16
	Female	0.57**	0.42*	0.66**	0.60**	-0.03	0.46*	0.33	0.17	-0.15	-0.15

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

Linear discriminant analysis (LDA) revealed that individual rowers can be appropriately categorised by sex and performance level based on their physical and technical attributes. The predictive statistical modelling of multiple variables to distinguish between all four groups was assessed using LDA with the category of rower as the dependant variable and leg length, hip flexion, IMTP relative net peak force, 7 stroke max power and distance per stroke as the independent variables (Figure 5.1). The Box's M-test resulted in a Chi-Square of 36.126 and a p-value of 0.204, demonstrating the co-variance was not significant, justifying these variables for the LDA. Using the five variables, 100% of the participants were correctly classified to their categorical group including the individuals who appear in the cross-over regions of the scatter plot.

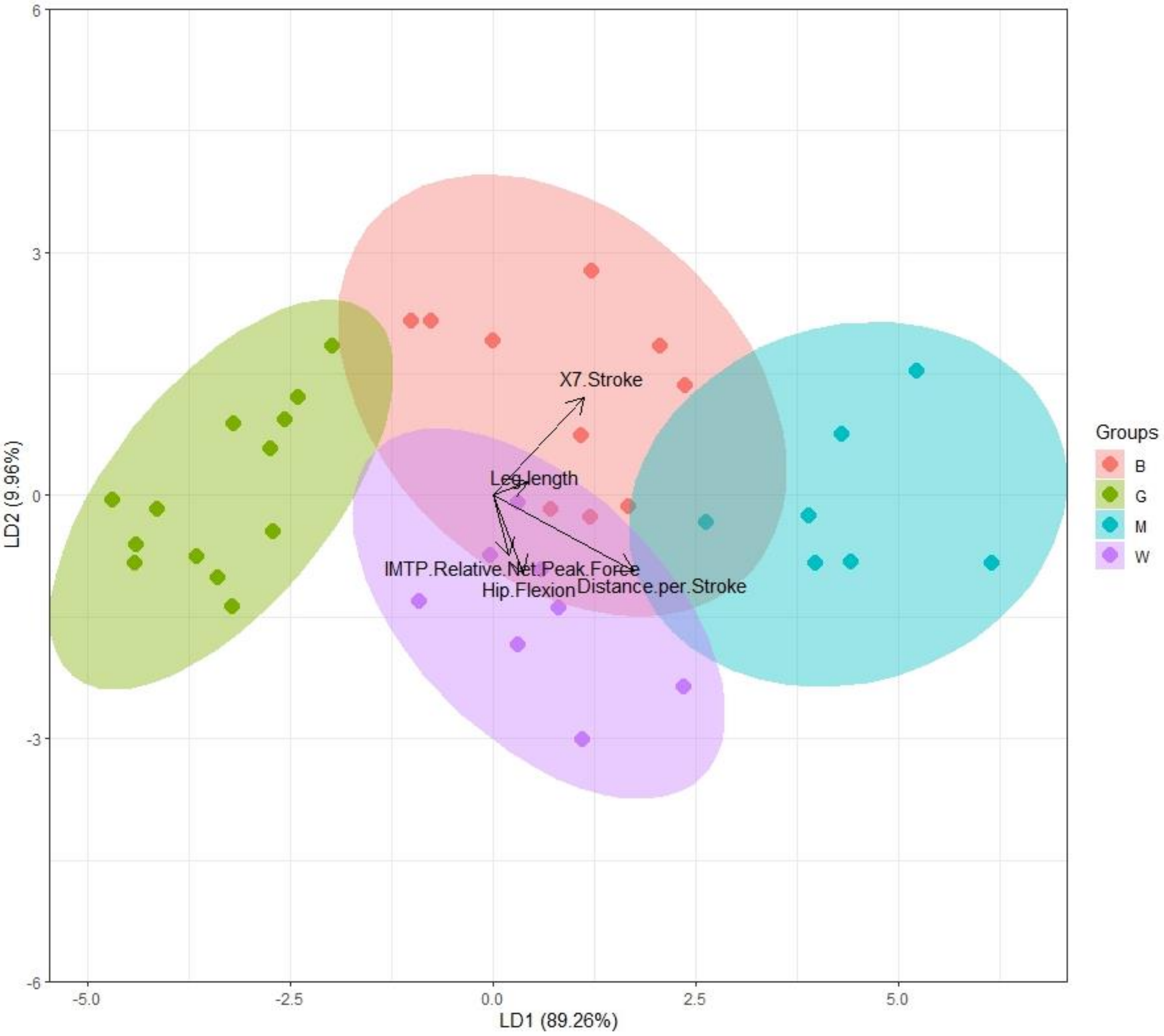

Figure 5.1: Scatter plot of linear discriminant analysis (LDA) model classifications.

B = junior males, G = junior females, M = elite males, W = elite females.

5.4 Discussion

This exploratory study provides a comprehensive descriptive analysis of the associations between physical attributes and on-water rowing biomechanical performance characteristics in junior and elite rowers. When comparing elite to junior athletes, the findings revealed differences in physical attributes for male and female cohorts with implications for development pathways to gauge progress and compare abilities to world-class standards of elite performers. Strong relationships were evident for anthropometry, strength and power assessments with the on-water technical variables of catch angle, peak gate force, mean gate force, distance per stroke, boat speed, and drive and recovery distance. Flexibility measures, including sit and reach and knee to wall dorsiflexion, did not reveal any associations with on-water metrics, however, predictive modelling demonstrated that several variables representing physical and technical attributes of the athletes were able to accurately identify individuals to their categorical group according to sex and performance level.

Research has reported on similar physical characteristics to those measured in the current study with 2000 m ergometer performance or 2000 m race time as the primary performance outcome (Akça, 2014; Lawton et al., 2012; Otter-Kaufmann et al., 2020; Slater et al., 2005). Given the disconnect between ergometer and on-water rowing technique or the use of the global measure of race time, a unique and progressive aspect of the present study was the inclusion of specific on-water rowing biomechanical variables collected on each participant during a single sculling performance. The single scull was specifically utilised so that variables measured were a direct reflection of the individual rower rather than crew skill or synchrony (B. Smith & W. Hopkins, 2012). In accordance with existing literature, the on-water rowing variable of mean gate force was significantly higher in elite men and women when compared to junior men and women, respectively (Holt et al., 2020; Smith & Draper, 2006). In addition, Pearson's correlation tests reinforced the relationship between power attributes and on-water performance with *large* correlations between mean gate force and 7 stroke peak power and 500 m average power for both men and women. Longer stroke lengths achieved through greater angles at the catch and finish are often desired by coaches (Holt et al., 2020). The current results demonstrated significantly longer stroke length in the elite participants which were likely related to greater catch angles, while finish angles were similar across all four category groups. This may reflect the level of difficulty and skill required to achieve an effective catch position (Legge et al., 2023). Moreover, distance per stroke is a measure that reflects performance and a strong predictor of boat speed (Gravenhorst et al., 2015). It encompasses both the drive and recovery phases of the rowing stroke and was significantly greater in the elite men and women cohorts (Holt et al., 2020). Based on these findings, the catch position appears to be a key variable related to greater stroke length, while distance per stroke may be associated with distinguishing rowers by skill level given the incorporation of both the drive phase and recovery phase.

Drive distance and recovery distance were assessed to explore differences between each of the two phases of the stroke cycle. The drive phase represents that main propulsive phase of the stroke cycle where force is generated on the feet and blade to propel the boat forward. Elite women covered significantly more drive distance then the junior women, however, no difference was detected between the elite and junior men. Interestingly, the elite men and women covered significantly more distance during the recovery phase than their junior groups, respectively. This may reflect differences in skill level between elite and junior rowers and might relate to the sequencing of body movements during the recovery. The recovery phase during on-water rowing is an area of research that has largely been overlooked, with the propulsive drive phase dominating on-water rowing research (Draper & Smith, 2006; Warmenhoven et al., 2018d). Elite rowing coaches perceive that the recovery phase requires a high level of skill including balance, coordination, rhythm and feel for the boat run (Legge et al., 2023). The recovery phase is difficult to measure given the oars are out of the water and no mechanical work is occurring during this time. However, this phase has the potential to improve boat speed without increased physiological output (Buckeridge et al., 2015a). Future research should consider the recovery phase, with further development in body sequencing measures required. A better understanding of the subsequent effects on boat speed and acceleration has the potential to guide superior rowing technique in junior and elite rowers.

Elite rowers yielded superior outcomes in rowing specific measures of strength and power when compared to junior rowers (Lawton et al., 2012). This was evident in the ergometer power measures and the maximal strength assessment of the IMTP. The elite women recorded significantly higher outputs than the junior women in power and strength for both absolute and relative measures and this was reflected in the p-values ($p<0.0001$) and effect size ($d>1.6$). The elite men only revealed superior measures in absolute terms with no difference revealed for IMTP, peak power or average power relative to bodyweight. Increases in absolute strength are associated with increased muscle mass (Nuzzo, 2022) and relative strength is considered more important than absolute strength in rowing as more weight or muscle mass in the boat increases the drag forces in the water (McNeely et al., 2005). Moreover, the correlation analysis reinforced potentially strong relationships between some of the strength and power attributes with the on-water technical attributes. *Very large* associations were revealed between the on-water measures of peak force and mean force with 7 stroke peak power and 500 m average power ergometer tests, as well as a *large* correlation with IMTP net peak force. Boat speed, distance per stroke and recovery distance had a *large* to *very large* associations with 7 stroke peak power, 500 m average power, and IMTP net peak force. These physical attributes are clearly associated to the on-water rowing metrics, reinforcing their applicability to on-water rowing performance.

The SJ and Biering Sorensen Trunk Endurance test revealed no differences for either sex when comparing junior to elite participants. However, there was a *large* to *very large* association between SJ peak power and the on-water metrics of boat speed, distance per stroke and recovery distance. Rowing performance and jumping performance may not be related due to the specific technical and training adaptations gained from the sustained practice of rowing (Giroux et al., 2015). Given these equivocal results, further consideration is required in regard to the SJ assessment for rowing performance. Based on the trunk endurance test findings, the isometric qualities of the Biering Sorensen test may not be the most appropriate measure to relate to rowing performance and further considerations are required for future studies. Regardless, trunk strength is undoubtedly an important attribute required for successful rowing (Simon et al., 2023). Trunk extension strength has been strongly associated with rowing ergometer performance

(Ledergerber et al., 2023) with the potential for the trunk to be a power producer and transmitter in the rowing stroke cycle (Simon et al., 2023).

The anthropometrical considerations of rowing are well established in the literature. Rowers tend to be taller, heavier and have longer arm span and leg length than non-rowers (Hume, 2018). However, it is not as clear when anthropometrical characteristics are compared between elite and junior rowers. Lawton (2012) reported no differences between junior and elite rowers in height and arm span. The current results indicated that the elite men were taller, heavier and had longer leg lengths than the junior men, however, elite women and junior women recorded similar height, weight, and limb lengths. *Large* associations were also reported between limb lengths and the on-water metrics of catch angle and stroke length. The absence of differences in female anthropometry in part may be due to the relatively small sample size of each category group. Another comparative study reported on Hungarian female rowers who demonstrated no difference in height, however, the senior rowers recorded significantly higher body weight and arm span than the junior rowers (Podstawski et al., 2022). Comparative anthropometry data on female elite and junior rowers is limited, with the literature more likely to compare within a category group of rowers and distinguish them by competitive success, 2000 m ergometer score (Lawton et al., 2012; Slater et al., 2005) or to a relative group of non-rowers (Bourgois et al., 2001). In addition, maturation status should potentially be taken into account when comparing junior rowers to elite rowers, particularly considering that females mature on average two years earlier than males (Thompson et al., 2003). This may affect results when comparing similarly aged male and female junior athletes with their elite counterparts. Further, it has been perceived by coaches that maturation status may have implications when considering other physical attributes in junior athletes such as flexibility and range of movement (Legge et al., 2023).

Generalised range of movement (ROM) recommendations for rowing have been established in the literature mostly in regard to injury (Buckeridge et al., 2015a; Soper et al., 2004), however, guidelines have not been well-established for junior or elite rowers in relation to performance, and this may be due to the subjectivity of ROM assessment (Gajdosik & Bohannon, 1987). ROM and flexibility can vary within an individual depending on the time of day and frequency of stretching (Bandy et al., 1997; Guariglia et al., 2011) and is influenced by age, sex and training (Monteiro et al., 2008). In the current study, hip flexion for males and active knee extension for females were greater in the elite groups compared to the juniors. *Large* associations for males between hip flexion and the on-water metrics catch angle, stroke length, mean gate force and drive distance and *large* associations for females between active knee extension and the on-water metrics distance per stroke, drive and recovery distance further support the connection between physical attributes such as range of motion and on-water rowing performance. This may reflect training experience and also access to support services that target injury prevention strategies such as flexibility and ROM focussed around the hip and lumbar spine regions, with the lumbar spine being the most susceptible area to rowing injury (Trease et al., 2020). Flexibility and ROM in relation to rowing performance may be better assessed through longitudinal studies that monitor ROM and flexibility measures across a season alongside on-water biomechanical rowing assessment to better understand how these physical attributes affect the execution of the rowing stroke (Rawlley-Singh & Wolf, 2023). For example, anthropometric characteristics may be associated with stroke length, including height, arm span and leg length, however, stroke length may also be influenced by hip flexibility, ankle flexibility and trunk strength (Buckeridge et al., 2015a). Further research is required to better understand the relationships between these attributes and the execution of the rowing stroke and the performance outcomes.

Interestingly, the LDA was able to precisely distinguish individuals to the correct categorical group with a high level of accuracy in the current participant population using a combination of the physical and technical variables independent of boat speed. This demonstrates that the selection of physical variables, including attributes of anthropometry, range of movement, power, and strength, can classify an individual by sex and performance level in rowing, irrespective of the main outcome measures of boat speed or race time. In addition, the elite females and junior males recorded very similar results for boat speed, a primary performance outcome measure. Similar findings have been reported when comparing heavyweight and lightweight male rowers with similar boat velocities, where the heavyweight group exhibited superior mean and peak force during on-water rowing assessment. Furthermore, differences were identified in the acceleration profiles and body segment velocities indicating different technical strategies leading to equivalent boat velocities (Doyle et al., 2008). These findings suggest that rowers can achieve a similar boat speed through the integration of different physical and technical parameters (Doyle et al., 2008; Smith & Draper, 2006) and the strength and power attributes tested in this study are strongly related to a number of on-water rowing performance metrics.

Sports research concerning the physiological and technical aspects of performance are often evaluated mechanistically (Balague et al., 2013) which can lead to a simplistic and limited perspective of athletic performance. There are likely complex interactions between the variables assessed in this study that enabled the LDA to accurately discriminate between individuals by performance level and sex (Balague et al., 2013; North, 2013). This type of analysis has been used in other sports to investigate how independent variables can collectively classify athletes into groups. For example, Taekwondo athletes were correctly discriminated into groups based on kicking torques and velocities according to expertise level (Moreira et al., 2021) while a non-sport-specific testing battery of anthropometric and physical characteristics was able to identify athletes to their nine respective sports (Pion et al., 2015). Elite women and junior men in this study recorded very similar boat speeds in conjunction with differing physical and technical qualities. This highlights the complexities of performance, where the junior men and elite women had different demographics including sex, maturation status and training age alongside varied physical characteristics and attributes. The junior men revealed a higher on-water peak force, 7 stroke peak power and 500 m average power ergometer results and more favourable anthropometry, in height, weight and arm span than the elite women (Bourgois et al., 2000). In contrast, the elite women elicited slightly longer stroke length and catch angle, combined with statistically superior flexibility and ROM compared to the junior men. Subsequently, the resultant outcome was a very similar boat speed across the two groups. Therefore, such data should be viewed in the way these physical, technical, and anthropometrical variables interrelate for each rower, yielding a resultant boat speed.

The findings of this study are strengthened by the use of high-calibre athletes as participants. All elite participants were current national representatives training as part of centralised national squads and considered world-class according to the classification criteria in McKay (2022). Accordingly, the elite level data can be viewed as a descriptive appraisal of the highest performing athletes in the world. Furthermore, the junior participants were all considered members of the national talent development pathway and approximately one-third of the cohort were national junior representatives in the same season as data collection took place. Whilst being a large-scale project assessing a range of variables both on-water and on-land, the sample size was relatively small, with each of the four categories comprised of 10 – 14 participants. While the elite cohort represents the entire population of available world-class level rowers in Australia at the time of testing, it is important to consider this limitation when interpreting the findings. Lastly there is a distinct shortage of on-water testing in peer-reviewed rowing research, particularly in combination with measured physical attributes. Accordingly, the inclusion of this battery of testing with high level athletes represents an excellent level of ecological validity for rowing assessment.

5.5 Conclusion

This exploratory study combined a comprehensive physical assessment with an on-water single sculling biomechanical assessment to explore the interaction of physical attributes with on-water rowing technical variables. In line with the literature, strong relationships were apparent for anthropometry, strength, and power attributes with on-water technical variables including the primary performance outcomes of boat speed and mean force. Differences in ROM, flexibility and trunk strength attributes were less able to distinguish between elite and junior rowers, with other factors potentially involved.

The combination of different categorical performance variables included in the LDA demonstrated how performance can be characterised by a wide range of attributes. This was further exemplified in the comparison of junior men and elite women, who yielded similar boat speed with the expression of distinctively different attributes. This unique comparison provided no performance context, given males and females do not compete against each other, however, it affords an interesting insight into the complex and dynamic nature of performance. In addition, the results provide a descriptive dataset of physical and technical characteristics for elite and junior rowers, of both sexes, which may be useful when evaluating the status of development rowers and to gauge the possibility of achieving further success in the sport.

Supplementary Material

Table 5.5: Peach Gate Sensor Assessment Summary

Date:	**21-Aug-23**			
Unit SN	**Type**	**Resultant Absolute Mean Error (kg)**	**Resultant Mean RMS Error**	**Resultant Force R 2**
11482	**Scull**	**0.3**	**0.2**	**1.000**
10156	**Scull**	**0.2**	**0.0**	**1.000**
10149	**Scull**	**0.1**	**0.0**	**1.000**
11481	**Scull**	**0.7**	**0.8**	**1.000**
10153	**Scull**	**0.4**	**0.3**	**1.000**
11477	**Scull**	**0.7**	**0.6**	**1.000**
11480	**Scull**	**0.3**	**0.1**	**1.000**
10155	**Scull**	**0.9**	**0.8**	**0.998**
10150	**Scull**	**0.1**	**0.0**	**1.000**
10152	**Scull**	**0.3**	**0.1**	**1.000**
11478	**Scull**	**0.2**	**0.1**	**1.000**
2895	**Scull**	**1.2**	**1.6**	**1.000**
11479	**Scull**	**0.3**	**0.1**	**1.000**
10154	**Scull**	**0.2**	**0.1**	**1.000**
	Mean	**0.43**	**0.36**	**1.000**

Table 5.6: Peach Foot Stretcher Sensor Assessment Summary

Date:	15-Sep-22		
Unit SN	**Resultant Absolute Mean Error (kg)**	**Resultant Force R 2**	**Resultant Mean RMS Error**
21537	0.2	1.000	0.097
21538	1.4	1.000	2.764
2734	0.8	1.000	0.779
3030	0.1	1.000	0.036
3032	0.3	1.000	0.181
3033	1.2	1.000	1.722
3035	0.2	1.000	0.044
3036	0.1	1.000	0.013
3038	0.2	1.000	0.071
3039	0.0	1.000	0.004
3040	0.1	1.000	0.032
3042	0.2	1.000	0.069
3466	0.1	1.000	0.014
Mean	0.38	1.000	0.45

Contribution of authorship to the chapter

Conceptualisation: Natalie Legge, Katie Slattery, Mark Watsford, Damien O’Meara

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Writing – Original Draft: Natalie Legge

Writing – Review & Editing: Natalie Legge, Katie Slattery, Mark Watsford, Damien O’Meara

Thesis Relevance and Sequence

Physical and technical performance characteristics were established in Chapter Five providing an important update to the on-water rowing performance literature. This knowledge provides a baseline set of characteristics for coaches and support staff involved in training junior and prospective elite rowers along with insights on the inter-relatedness of these types of variables that result in successful performance. The purpose of Chapter Six is to extend our understanding of the technical variables reported in Chapter Five. The technique of elite rowers was examined in Chapter Six through higher order statistical methods to provide deeper insights into the waveform data of the force and acceleration profiles unique to the cyclical nature of rowing stroke.

Chapter 6

Elite Rowing Technique – single sculling signature profiles of world class men and women rowers

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As per the manuscript submitted to the European Journal of Sports Science:

Legge, N., Draper, C., Slattery, K. M., O'Meara, D., Watsford, M., Warmenhoven. J. (Under Review). Temporal Features in Rowing Biomechanics Associated with Elite Rowing Technique. *European Journal of Sports Science.*

Abstract

The technique athletes employ to achieve optimal boat velocity can depend on individual rowing style and this can be assessed through biomechanical analysis. Traditionally, quantification of rowing technique has involved discrete point analysis, limiting the understanding and interpretation of the stroke cycle. However, higher dimensional statistical approaches, such as functional data analysis (FDA), have more recently been employed to better understand temporal patterns within time series data like the biomechanical profiles in rowing. Twenty-five elite rowers (12 females, 25 ± 2.5 years and 13 males, 27 ± 2.8 years) completed an on-water single sculling biomechanics assessment. This study adapted an established method for the clustering of functional high dimensional data. Gate force, foot-stretcher force and boat acceleration were independently fitted with a clustering model, with separate models created for each sex. Regions of similarity were identified within the stroke cycle as well as areas of higher variability. The area of highest consistency identified a cluster group pattern. Boat acceleration exhibited the most variability of the three independent variables in cluster group patterns and as individual rowers. Results revealed there is more than one approach to achieving optimal boat velocity at the elite level and technical coaching strategies should be based on the individual rather than attempting to replicate successful elite rowers' technique who may exhibit a different set of physical and technical attributes.

6.1 Introduction

Outcomes of elite rowing races at an international level can be determined by fractions of a second, thus necessitating research into optimising boat velocity. The method in which athletes achieve optimal boat velocity can depend on individual style and this can be assessed through biomechanical analysis of velocity, acceleration, force and power (Holt et al., 2020; Holt et al., 2021; Warmenhoven et al., 2018d). The understanding of individuals demonstrating a signature force profile with their own set of unique characteristics has been recognised (Gravenhorst et al., 2015) and largely analysed through discrete point analysis (Draper & Smith, 2006; Hill, 2002). However, higher dimensional statistical approaches, such as functional data analysis (FDA), have more recently been employed to better understand temporal patterns within time series data and the performance differences between rowers by inferring characteristics from the temporal force profile (Warmenhoven, 2017a).

A signature force profile in rowing refers to the appearance and characteristic features of an individual's temporal or positional force (Warmenhoven et al., 2018b; Warmenhoven et al., 2018d). These signatures are most often explored relative to the propulsive pin force measured on the rowing gate, however, these also exist at the foot stretcher, or relative to the non-propulsive forces at the pin in transverse or vertical directions (Draper & Smith, 2006; Warmenhoven et al., 2018d). Optimal rowing performance may be achieved with multiple different signature force profiles and is dependent on various factors relating to the individual athlete (Hill, 2002; Loschner et al., 2000a). Greater peak force application has been associated with superior boat velocity, however, patterns of force-time profiles may display varied approaches to achieving peak force (Hill, 2002; Warmenhoven et al., 2018b). Discrete metrics that have been associated with superior performance include mean force, mean force to peak force ratio, rate of force development and the attainment of peak force earlier in the drive phase (Holt et al., 2020; Warmenhoven, 2017a).

Propulsive net boat force is the sum of propulsive gate and stretcher forces, with air and water resistance also considered (Smith & Loschner, 2002). The boat acceleration is a factor associated with net boat force (Draper & Smith, 2006). Due to the intermittent nature of force application during the drive and recovery phase of repeated rowing stroke cycles, changes in boat acceleration and deceleration are inevitable (Soper & Hume, 2004). Therefore, boat acceleration may be interpreted as an outcome measure and an indicator for evaluating rowing technique (Holt et al., 2021; Shimoda et al., 1995). The gate force and stretcher force are input measures to the boat-oar-rower system, whilst air resistance is considered negligible and water resistance increases with the square of velocity (Held et al., 2020).

Similarly, specific features of boat acceleration have been identified and associated with boat velocity and rowing performance (Holt et al., 2021; Kleshnev, 2010; Warmenhoven et al., 2017b). Greater maximum negative drive acceleration, maximum peak drive acceleration and first peak acceleration have been associated with higher performance (Holt et al., 2021). Further, the gate angle where peak acceleration occurs was identified as a discriminating factor between individual rowers where an earlier peak force leads to superior performance outcomes (Gravenhorst et al., 2015; Holt et al., 2020). These discrete measures have been used in applied sport settings, however, they are not as prevalent in the literature (Holt et al., 2021). Accordingly, there is an evolving need to objectively ascertain specific boat acceleration features that relate to successful rowing performance.

FDA is a suite of statistical techniques that are suitable for higher dimensional datasets such as curves and waveforms in biomechanics (Ramsay & Silverman, 2005). To-date, FDA techniques used in rowing have proven useful for exploring the associations between rowing signatures and performance as well as other constraints (i.e., gender, boat-side, etc.) (Warmenhoven et al., 2017b; Warmenhoven et al., 2018d). However, there has been limited application of FDA in the context of understanding the applicability of these signatures, and whether they differ from athlete to athlete. Therefore, the aim of this study was to explore and describe features of gate force, stretcher force and boat acceleration that distinguish technique characteristics during single sculling in a representative cohort of world class male and female rowers. This study presents a unique approach to technical analysis in rowing using model-based FDA clustering to explore patterns within time series data for propulsive gate force, propulsive stretcher force and boat acceleration within a group of world class rowers.

6.2 Methods

Participants

Twenty-five rowers volunteered to participate in the study and provided written informed consent to prior to any testing. The participants comprised 12 elite female (25 ± 2.5 years) and 13 elite male (27 ± 2.8 years) rowers. The male and female elite rowers reported 11.1 ± 3.0 years and 8.4 ± 2.1 years of rowing experience, respectively. The female participants had a mean height of 178.7 ± 5.7 cm and weight of 76.2 ± 8.5 kgs. The male rowers recorded a mean height of 191.4 ± 3.7 cm and weight of 91.7 kgs ± 3.4kgs. The average boat velocity was 4.91 ± 0.12 ms^{-1} and 4.40 ± 0.09 ms^{-1} for men and women, respectively. These standards correspond to prognostic speeds according to results published by World Rowing of 95.9% and 94.0% for men and women respectively. The sample of participants was of high ecological validity given all were competitors at the most recent world championships. The study protocol was approved by the Human Research Ethics Committee of the University of Technology Sydney (ETH21-6136).

Procedures

The Peach PowerLine Instrumentation system (Peach Innovations, UK) including instrumented gates, foot stretcher, boat sensor (GPS) and accelerometer sampling at 50 Hz were installed on each single scull to measure the on-water biomechanical assessment. The single sculls were set up according to each individual's standard rigging measurements and the set up was completed in consultation with their coach. The Peach PowerLine instrumentation system is used frequently within elite rowing environments for monitoring purposes. Established levels of validity for the system have been reported with the standard error of the estimate (SEE) ≤8.9 N for gate force, $\leq 0.9^{o}$ for gate angle and an r^2 of 1.00 for both variables (Coker et al., 2009). Additional validation was conducted on all gates and foot stretcher sensors prior to testing (see supplementary material).

Environmental conditions including wind direction and speed, water temperature, air temperature and humidity were recorded periodically during every testing session to ensure conditions were comparable across all testing days. Venue environmental conditions measured using the Kestrel 5500 Weather Meter were: 19.1 ± 3.4°C air temperature (mean ± SD), 20.1 ± 1.7°C water temperature, and 0.8 ± 1.0 $m \cdot s^{-1}$ wind speed, ranging in direction from calm to a light cross-tail direction. Following a consistent warm-up, the on-water testing protocol included a 500 m open rate piece. For analysis purposes, a sample of 20 strokes were extracted from the data for each participant, representing a mid-section of the testing piece. Each stroke cycle was identified from catch to catch, where the catch was at the largest negative and the finish at the largest positive horizontal gate angle. Stroke rate was defined as open rate and measured as strokes per minute (spm). The men's group displayed a mean stroke rate of 36.7 ± 2.6 spm and the women 34.1 ± 1.9 spm.

Raw data files were downloaded using the Peach Innovations software and time-series data (50 Hz) was exported as csv files for processing. Discrete data was determined from time-series data using a custom script written in the R platform (http://www.r-project.org/). Gate angle time-series data was filtered with a low-pass 4th order Butterworth filter at a cuff-off frequency of 20 Hz to assist in determining catch and finish events. The peakdet R function (Eli Billauer, http://www.billauer.co.il/peakdet.html) was used to determine local minima and maxima in the horizontal gate angle time series data which corresponded to catch and finish events respectively. Time series data were exported as a .csv file, and the variables of gate force, stretcher force and boat acceleration were included for further analysis.

Analysis

Preliminary FDA

For each gate force, stretcher force and boat acceleration curve, data was normalised to 0-100% of a movement cycle (to 101 data points) using an interpolating cubic spline. To fit functions to the curves for each variable, B-spline basis expansions were used, with no smoothing penalty added due to the data being pre-smoothed using a low-pass filter. 25 basis functions were selected (rather than the maximum of 101) to create simpler functional data objects for entry into the model-based clustering approach used. Landmark registration was performed, isolating a single data point for curve alignment on each curve. This data point corresponded to first zero point, after the catch and served as a proxy for the shift in boat acceleration from deceleration to propulsion, indicating force application in the water. The segment from the catch to the zero point of boat acceleration (see Figure 6.6) when the boat begins to accelerate again is also a point during the stroke cycle that distinguishes skilled from less-skilled rowers (Holt et al., 2021). Figures 6.1, 6.2 and 6.3 display the gate force, stretcher force and boat acceleration profiles and depict the stroke cycle from finish, recovery, catch, drive and back to the next finish, alongside points used for registration.

Model-based clustering of functional data

Each variable (gate force, stretcher force and boat acceleration) was fitted with a clustering model separately. For each athlete the total number of completed strokes over the testing period were entered into the clustering models (this varied between 18 and 20 strokes for each athlete). Separate clustering models were created for each gender.

This study used a clustering approach and adapted an established method for the clustering of functional high dimensional data clustering (funHDDC) (Bouveyron & Jacques, 2011). This is based on a functional latent mixture model and allows for testing of various sub-models that are fitted in group-specific functional subspaces, through constraining model parameters within and between groups. This allows for a broad range of clustering models to be fitted, and the “best” model fit being selected for analysis. The performance criterion for selecting this model was the Bayesian Information Criterion (BIC). Given that this study was focused on the exploration of movement signatures in elite rowers, the number of possible clusters was set between 2 and *n*, with *n* being the total number of athletes, this way allowing for a scenario where each athlete may have their own cluster.

Results were reported descriptively, specifically identifying the number of clusters for each variable for each gender. Additionally descriptive metrics identifying how many clusters each athlete was spread across, and how many strokes each athlete had within a cluster were reported.

6.3 Results

Clustering models for men and women cohorts were generated for gate force, stretcher force & boat acceleration. FDA identified cluster patterns according to each of the 3 variables independently and the total number of cluster patterns for each variable reflects the signature profile variability across the groups of elite men and women. However, the number of clusters an individual drifts across for each variable suggests the inter-stroke variability in the individual's signature profile for force development and boat acceleration. For example, for the women, F1 kept all strokes within cluster C whereas F9 had strokes that fell into different clusters and were spread across cluster patterns B, C and D (Table 6.1). This would suggest F9 exhibits greater stroke to stroke variability than F1. The number of cluster groups that athletes drifted across for each variable can be found in Table 6.1. For the women, there were four cluster groups for gate force, five for stretcher force and four for boat acceleration. For the men, there were three cluster groups for gate force, two for stretcher force and seven for boat acceleration.

The average force-time and acceleration-time profile for each group (see Figures 6.1, 6.2, 6.3) were overlaid as a solid black line with each cluster group pattern. The coloured lines represent all the individual strokes that were measured and fell within that cluster group. The variability within each cluster is evident through the spread of coloured force-time and acceleration-time trace profiles representing every stroke analysed. Regions of similarity can be identified within the stroke cycle as well as areas of inconsistency or higher variability. The area of highest consistency identifies a cluster group pattern.

Group Cluster Patterns

For gate force, five women and three men had all strokes fall within the same cluster suggesting a highly consistent gate force profile, while six women and four men drifted across two clusters and one woman and six men across three clusters. Figure 6.1 displays the gate force profile cluster group patterns for men and women respectively. Clusters 2 and 3 for gate force represent 77% of the strokes across the women's group with 8 of the 12 female rowers fitting into these two cluster patterns. Due to the absolute number of strokes in these two cluster patterns, more variability is seen in these graphs and strokes patterns fall across both sides of the average curve throughout the stroke cycle making it more challenging to identify distinguishing features of these cluster groups. However, force development in the early drive is the most consistent section of the stroke cycle, particularly in cluster C. Cluster D is comprised of strokes from two individuals, with only 5% of all strokes fitting into this cluster pattern, however, this cluster has some of the highest peak forces across all strokes from the women.

The men were more evenly divided across the 3 cluster patterns for gate force with a 43%, 41% and 16% division across clusters A, B, and C respectively. Clusters A and B range above and below the group average curve throughout the stroke cycle, however, the section around peak force appears to be the most inconsistent. Cluster C displays a higher level of inconsistency during early drive force development, however, when referencing individuals' profiles, it appears to be influenced by one individual (M1) who has a delayed force application evident at approximately 50% of the stroke cycle which reflects the onset of force development in the early drive phase.

Two and five cluster patterns were reported for stretcher force for men and women, respectively. Five women and seven men kept all strokes within the same stretcher force cluster while six women and six men drifted across two cluster groups. Therefore, although there is some variability across the groups, as individuals, their approach to generating foot stretcher force is highly consistent and more pronounced than gate force. Figure 6.2 displays the stretcher force profile cluster patterns for men and women. The stretcher force is generated in the negative direction towards the stern of the boat, while the opposing horizontal gate force is in the positive direction towards the bow of the boat (see Figure 6.4) and the sum of the gate and stretcher forces is the applied net boat force (Smith & Loschner, 2002).

Boat acceleration exhibited the most variability of the three independent variables in cluster group patterns and as individuals, with four for the women and seven for the men. Individually, women drifted across up to four clusters and men up to five clusters with two men and three women keeping to one boat acceleration cluster pattern for all strokes analysed. Figure 6.3 displays the boat acceleration profile cluster group patterns for men and women. The boat acceleration from the first peak to the finish slump (see

Figure 6.6 for boat acceleration metrics) shows the greatest section of variability in stroke-to-stroke patterns, characterised by the disorganisation in this part of the cluster pattern profiles.

Individual Cluster Patterns

The individualised presentation of clusters provides a visual display of the combination of patterns or the signature strategy that one rower takes to generate force on the gate and stretcher with the boat acceleration as the resultant output of those forces. The visualisation of each individual's gate force, stretcher force and boat acceleration profile are in figures 6.7 – 6.12 in the supplementary material. When considering some of the individual results for the women rowers, participants F4, F3, and F1 displayed below average peak force, however they were three of the most consistent female scullers, with all 20 strokes falling within the same cluster group pattern for gate force. F2 was also highly consistent with the application of gate force, however, she also demonstrated an above average peak gate force and was ranked first for average boat velocity for the testing piece. In contrast, F8 and F9 had two of the highest peak gate forces, however, were much more variable with their application of force as visualised in their individual gate force profiles (see supplementary material) and were ranked mid-range amongst the group for average boat velocity.

Table 6.1: Cluster patterns for each variable and number of strokes across clusters for each individual athlete

Athlete	Gate Force Clusters					Stretcher Force Clusters						Boat Acceleration Clusters							
	A	B	C	D	Total	A	B	C	D	E	Total	A	B	C	D	E	F	G	Total
F1			20		1				20		1		3	12	5				3
F2			20		1				20		1		9	7	4				3
F3	20				1	20					1	9		11					2
F4	20				1		20				1				20				1
F5	2		18		2	2			18		2				20				1
F6		19	1		2			15	3	2	3	4	1	1	14				4
F7		7	13		2	5			15		2	1	15	2	2				4
F8			19	1	2				19	1	2	2	4	13	1				4
F9		3	5	12	3				16	4	2	8	5		7				3
F10		18	2		2			1		19	2		9	11					2
F11		8	12		2				10	10	2	5	8	7					3
F12		18			1					18	1				18				1
M1		4	17		2		21				1		17	1			1	2	4
M2	4	12	5		3	8	13				2	1		6		5	7	2	5
M3		20			1	20					1	18		1		1			3
M4	11	2	7		3	15	5				2				20				1
M5	2	16			2	17	1				2	3				5	10		3
M6	19	1			2	5	15				2	6		2		6	6		4
M7		21			1	21					1	2		13	1	4	1		5
M8	2	16	2		3	11	9				2					1	19		2
M9	11	7	2		3	20					1	15			1	3	1		4
M10	21				1		21				1			16		3	1	1	4
M11	13	3	3		3		19				1					19			1
M12	17	4			2		21				1	3		4		6		8	4
M13	13	2	6		3	2	19				2	2		3		10	5	1	5

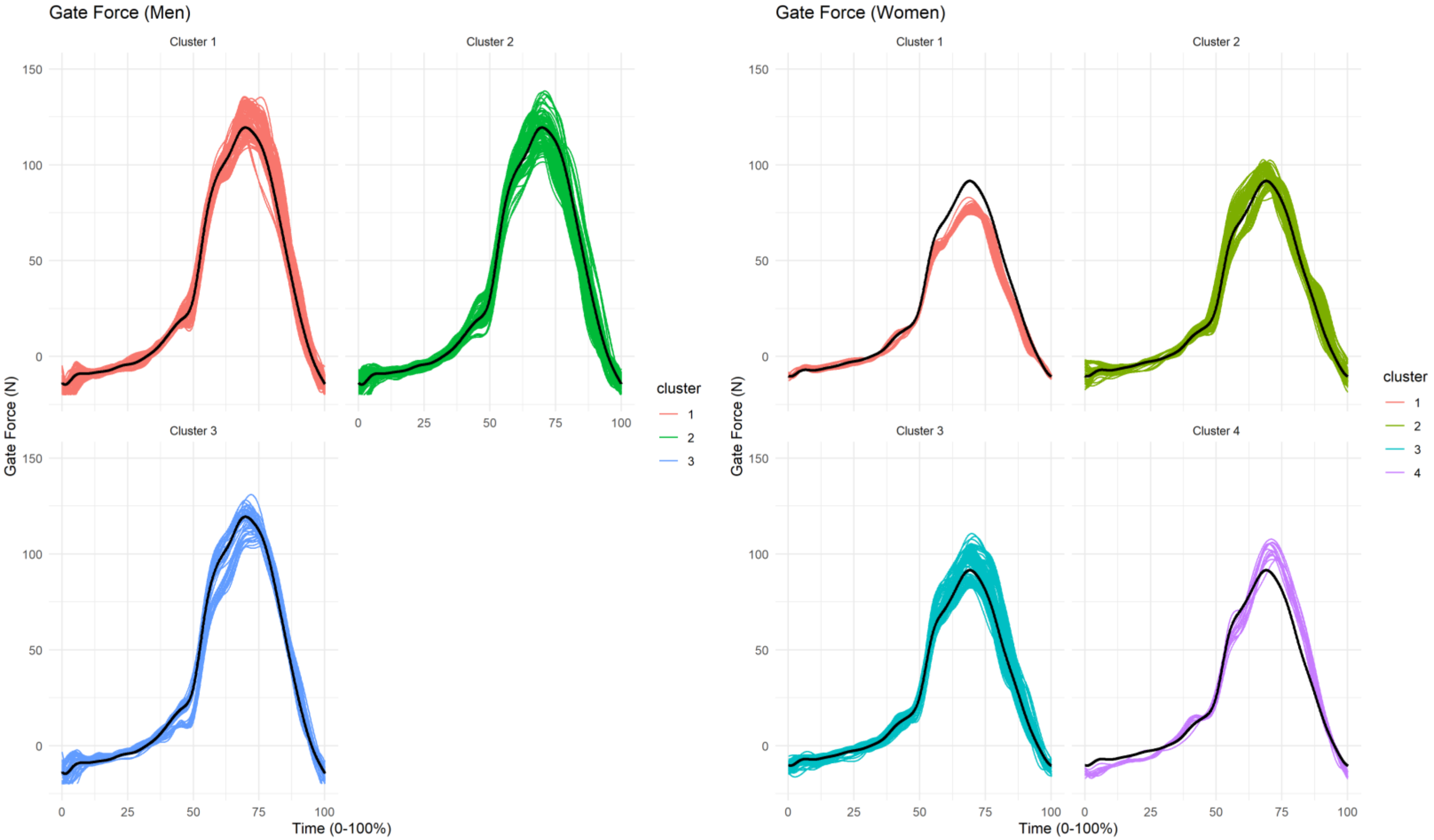

Figure 6.1: Gate force-time cluster groups for men and women. Note: 0-50% of stroke cycle approximately represents the finish and recovery phase and 50-100% approximately represents the catch and drive phase.

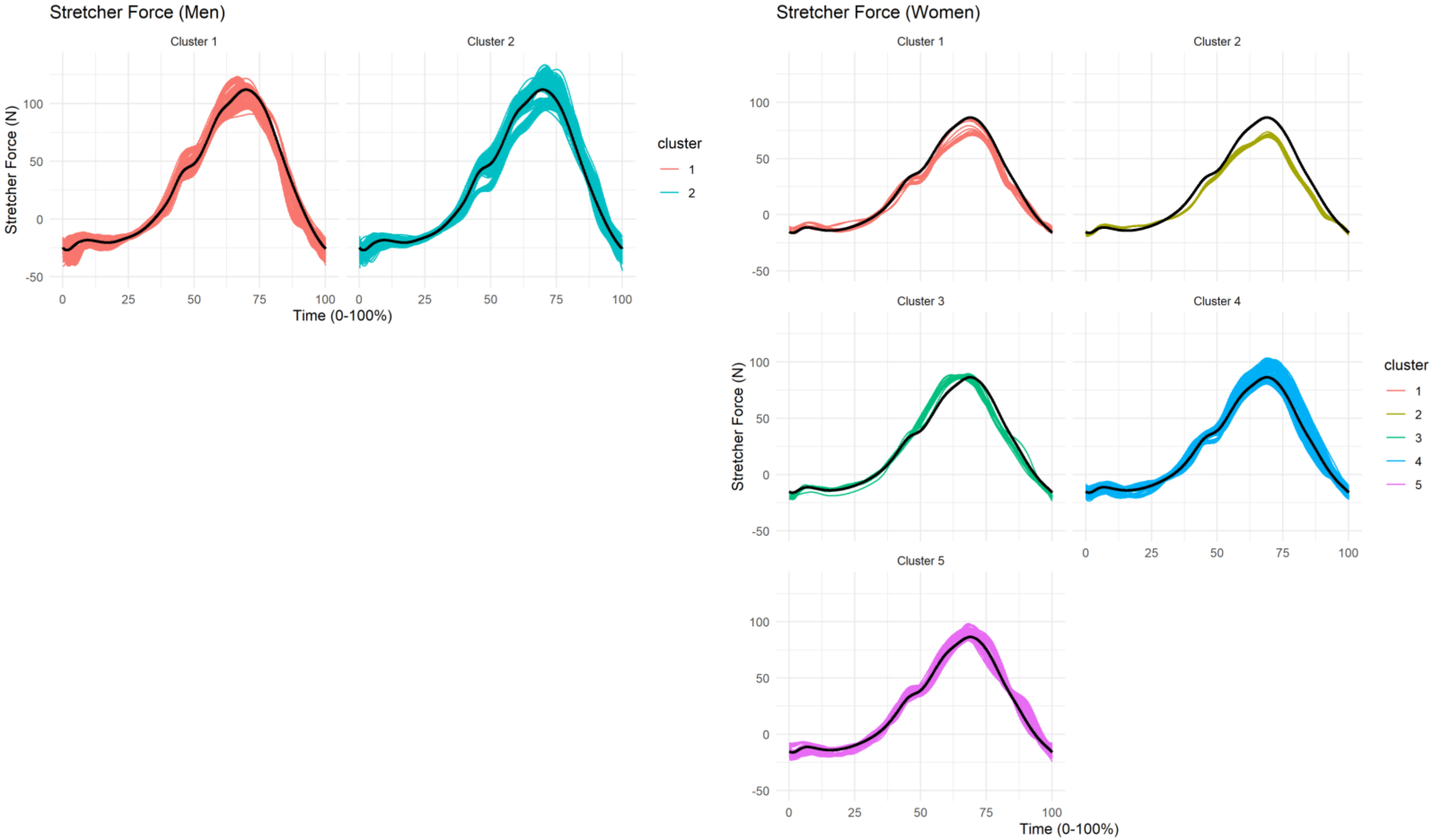

Figure 6.2: Stretcher force-time cluster groups for men and women. Note: 0-50% of stroke cycle approximately represents the finish and recovery phase and 50-100% approximately represents the catch and drive phase.

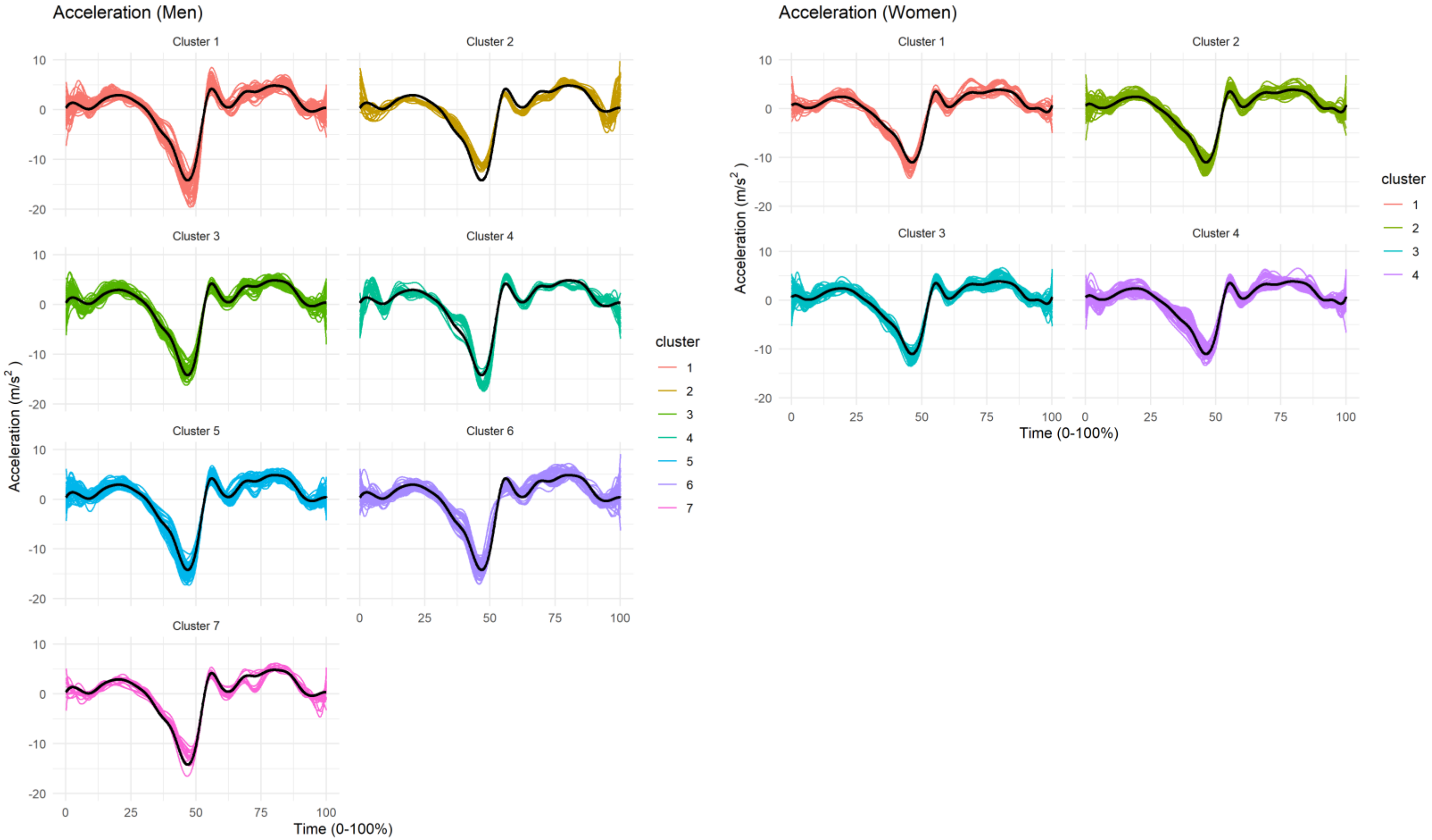

Figure 6.3: Boat acceleration-time cluster groups for men and women. Note: 0-50% of stroke cycle approximately represents the finish and recovery phase and 50-100% approximately represents the catch and drive phase.

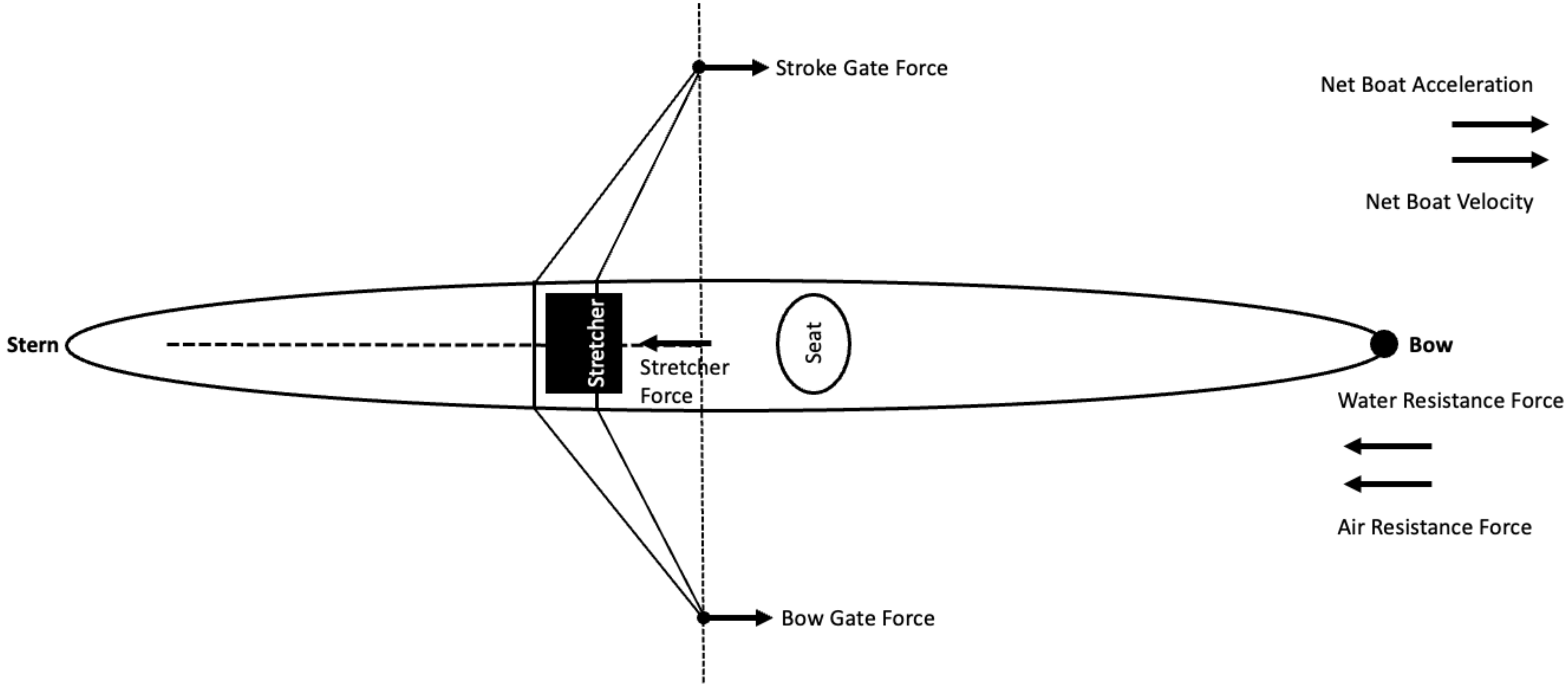

Figure 6.4: Propulsive gate & stretcher forces of the single scull

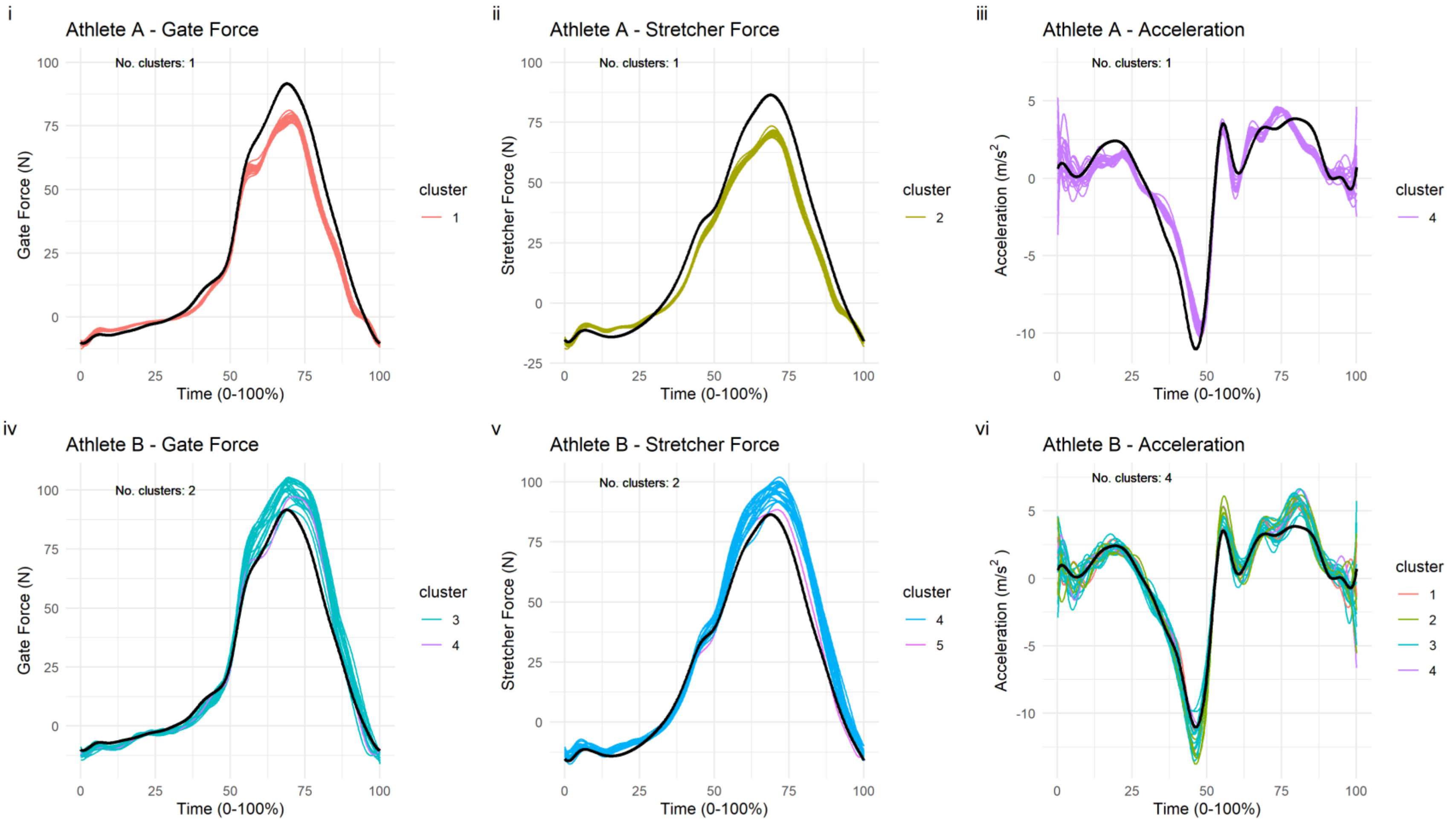

Figure 6.5: Elite rowing examples, 20 strokes; Athlete A - consistent rowing stroke execution and Athlete B - variable rowing stroke execution

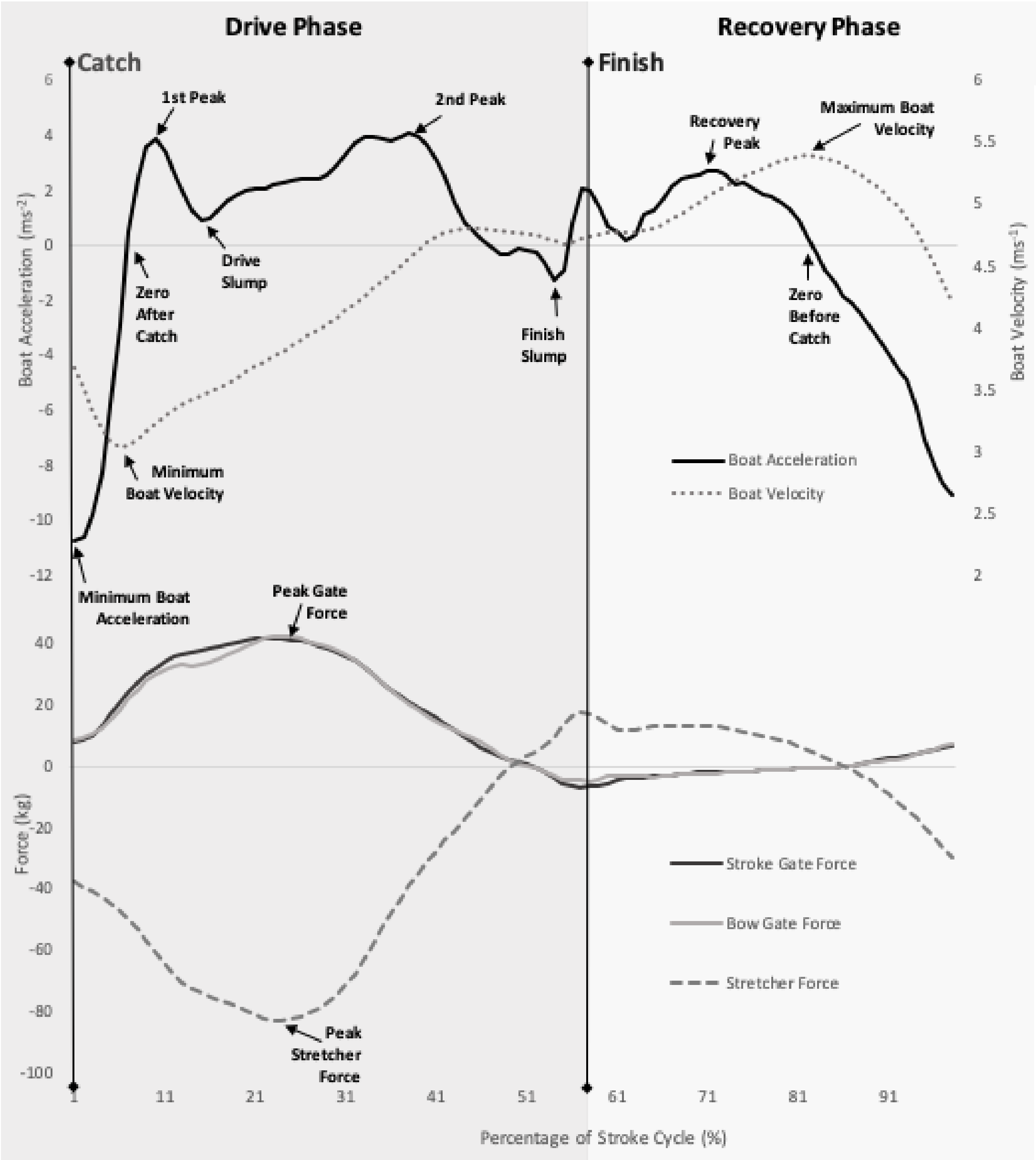

Figure 6.6: Discrete metrics & temporal profiles per stroke cycle – boat acceleration, boat velocity, gate force & stretcher force

6.4 Discussion

The purpose of this study was to utilise model-based FDA clustering to explore and describe features of gate force, stretcher force and boat acceleration that distinguish technique characteristics during single sculling in a representative group of world class male and female rowers. The performance level within each cohort was similar and evident in the narrow range of boat velocity achieved during testing for men (4.95 ± 0.12 $m.s^{-1}$) and women (4.40 ± 0.09 $m.s^{-1}$). These standards correspond to prognostic speeds according to results published by World Rowing of 95.9% and 94.0% for men and women respectively. Therefore, differences reported in force and acceleration signature profiles reveal the individual variability that can result in similar performance outcomes. The pattern of application of force was relatively consistent across both groups, as reflected in the number of clusters for gate and stretcher force and the degree of variability displayed within each of the clusters represented by the spread of coloured traces at certain points on the profiles (Figures 6.1, 6.2). The early to mid-drive phase is a highly consistent region of the stroke cycle for most cluster group patterns where the rate of force development (RFD) is at its highest leading to peak force during the mid-drive phase. This indicates that elite level rowers are very consistent in their approach to this section of the stroke cycle and RFD should be considered an important variable when monitoring athletes in the development pathway. Expectedly, a higher RFD has previously been related to superior performance outcomes when comparing athletes of different skill levels (Holt et al., 2020; Warmenhoven, 2017a).

Individuals who yielded a higher-than-average number of clusters for gate force were more likely to have a higher-than-average number of clusters stretcher force and boat acceleration. For example, women who had more than five cluster patterns in total across all three variables drifted across more than one cluster pattern for each independent variable. This observation is iterative, given that variable application of gate or stretcher force would likely lead to variable resultant boat acceleration. This suggests that such individuals have a higher level of variability in how they generate force on the handle and stretcher, and this may subsequently effect boat acceleration. This is the first study to explore technical characteristics of gate force, stretcher force and boat acceleration using model-based FDA clustering and despite some promising preliminary results, there is scope for further investigations using these techniques on crew boats to quantify the degree of adaptability and crew synchrony that occurs to optimise crew combinations.

Descriptive trace profiles of stretcher force are limited in the literature; therefore, a comparative assessment is difficult. However, the information obtained from this cohort of world class rowers establishes a comprehensive description of stretcher force for elite men and women and in this current study can be evaluated and compared alongside the gate force and subsequent boat acceleration. Stretcher force was the most consistent variable by group and individual, with 100% of the men's strokes and 74% of the women's strokes falling within two cluster group patterns. The stretcher force profile also seems to generally mirror the gate force in terms of shape and pattern, with the same individuals falling above or below the group average curve profile at certain points during the stroke cycle for both gate and stretcher force. These results align with the concept of the applied net boat force principally made up of these two opposing forces, neglecting the drag and air resistance (Draper, 2005; Smith & Loschner, 2002). For both men and women, there is a noticeable momentary delay in the stretcher force application at approximately 50% of the stroke cycle which represents the catch and early drive phase. This is more pronounced in certain individual's profiles (see figures 6.7 – 6.12 in the supplementary material) however is also evident to a lesser extent in the cluster group patterns. This reflects the point around the front turn of the stroke cycle when rowers are pushing off of the stretcher with an increased vertical force component and subsequent reduction in the horizontal component as they perform a jump-like action at the onset of the early drive (Draper, 2005). Coaching strategies typically aim to minimise this vertical component of stretcher force as it does not directly contribute to boat propulsion (Draper, 2005; Legge et al., 2023; Sinclair et al., 2009). Further studies should look to better understand this feature of the stretcher force application and how it may vary depending on stroke rate. The rowers were executing a maximal effort for this study, and this should be taken into consideration when comparing stretcher force profiles at submaximal efforts.

One notable advantage of model-based FDA clustering is the continuous time series analysis that allows for assessment across the stroke cycle of patterns and deviations from the average which may reflect different technical strategies amongst a group of individuals. Specifically, the stretcher force profile deviations reflect the timing of how an individual applies force on the foot stretcher across the stroke cycle. For example, clusters A and B for the women remain above the group average profile, suggesting these rowers apply less force on average throughout the entire stroke. Cluster C reflects an earlier onset of force on the foot stretcher leading into the catch, however, force is also reduced on the foot stretcher earlier than the average for cluster C. Accordingly, different technical strategies may be applied, with some rowing styles aiming to be "light" on the feet and minimise early application of force on the foot stretcher whilst other rowing styles encourage a swift movement into and out of the catch which can result in greater peak stretcher forces for a shorter period of time (Kleshnev, 2016). These descriptive profile characteristics for stretcher force are an important component of overall boat propulsion and can provide meaningful insights into the technical strategies taken by individuals at all levels of the sport. Knowledge of cluster type and the strategies that certain athletes use to apply force can enhance performance analysis and provide coaches with an objective individualised approach to optimise technical output.

Boat acceleration reflects the net applied boat force and is considered a boat outcome measure (Draper & Smith, 2006; Loschner et al., 2000a). The women's group average boat acceleration profile maintains the drive slump in positive acceleration, translating to the boat continuing to accelerate through this section. In contrast the men's average drive slump is around zero acceleration which corresponds to some of male participants exhibiting a negative drive slump where the boat slows down during this period of the stroke. Several discrete metrics related to boat acceleration have been established in the literature (Holt et al., 2021), however, research is limited on the association between the discrete metrics of boat acceleration and its effect on boat velocity. From a biomechanical standpoint, remaining in positive acceleration where possible would positively impact average boat velocity. Additional inquiry is required to better understand the association between these metrics and average boat velocity. Further, implementing continuous data analysis methods such as FDA or statistical parametric mapping (SPM), may enhance the understanding of these identifiable discrete boat acceleration metrics in relation to superior rowing performance (Serrien et al., 2019; Warmenhoven et al., 2018c).

The finish slump (see Figure 6.6) was noticeably inconsistent across all cluster patterns and relates to the point in the stroke when the blade is released from the water closely followed by a shift in the rower's movement from the bow back towards the stern of the boat to begin preparation for the next stroke (Kleshnev, 2016). This appeared to be more pronounced by the women and may be explained through the women's boat acceleration being confined to four cluster group patterns whereas the men were spread across seven cluster group patterns for boat acceleration, resulting in less strokes per cluster for the men. A more established boat acceleration metric is time spent in negative acceleration, calculated as the time between the zero before and zero after the catch. It is thought that minimising time spent in negative acceleration has an important and positive connection to boat velocity (Holt et al., 2021). Cluster patterns for men and women drifted across both sides of the group average curve during this section of the stroke, reflective of the varied strategies taken to navigate what is thought to be one of the most technically challenging aspects of the rowing stroke (Legge et al., 2023). Boat acceleration represents the outcome of an individual's technique. Therefore, the variability evident during the stroke may reflect the dynamic balance and coordination of force development between the gate and foot-stretcher during the drive phase to achieve maximal boat propulsion. Currently an optimal boat acceleration profile has not been established. In contrast, boat acceleration may be an idiosyncratic representation of an individual's technical output and further research is required to better understand the boat acceleration features that potentially have a positive impact on average boat velocity (Holt et al., 2021).

The results of this study demonstrate there is more than one approach to optimising technique in elite rowing and other factors are likely integrated with and influencing these biomechanical outcomes. Physical attributes and anthropometry are two factors that likely influence how an individual executes their rowing stroke (Bourgois et al., 2001; Bourgois et al., 2000; Podstawski et al., 2022). Future studies should incorporate physical attributes in their analysis to consider the connection between an individual's physical attributes and their characteristic approach to technical execution of the rowing stroke. This world class cohort of male and female rowers displayed varied approaches to developing force during the drive phase although tend to be relatively consistent in their individual execution (Smith & Spinks, 1995). To be able to provide a quantitative technical assessment comparing a group of rowers, the concept of the "sum of the parts" may be appropriate and addresses the idiosyncratic nature of biomechanical temporal profiles in rowing, particularly for boat acceleration. As demonstrated in this study, some rowers demonstrate an early and rapid RFD during the drive phase, whilst others achieve higher peak force or maintain gate force much more efficiently into the finish. All of these technical force metrics have been associated with better rowing performance (Draper & Smith, 2006; Gravenhorst et al., 2015; Holt et al., 2020; Warmenhoven et al., 2018b), however, conceptually the individual who ranks higher across a number of these identifiable metrics may exhibit the best performance outcome. This conceptual idea could be extended to boat acceleration to better understand the uniqueness between rowers.

The relevance of this study is underpinned by the participating high-calibre athletes. All participants were current national representatives and considered world class athletes according to the classification criteria in McKay (2022). Therefore, the data can be viewed as a descriptive assessment of some of the highest performing athletes in the world. However, despite using the entire cohort of the available members of the national training centre, the sample size was relatively small, and it is important to consider this limitation when interpreting the findings. Furthermore, the variability visualised within a cluster group was influenced by the number of strokes that were categorised to that group. For example, the gate force for the women revealed four cluster groups, where cluster C contained 46% of all strokes analysed whereas cluster D only contained 5% of all strokes analysed across the female participants. This created a challenge to visually compare the relative differences between the cluster group patterns. The women displayed a similar level of disparity for stretcher force with 51% of strokes fitting within cluster D while cluster B and C only contained 8% and 7% of all strokes respectively. Future studies using clustering models could consider a relative measure that accounts for the number of strokes in each cluster, so that features of consistency and variability within a cluster can be identified and compared to other clusters with equal density. Finally, stretcher force measurements using the Peach system provide a bilateral stretcher force appraisal. Therefore, an assessment of the unilateral contribution from the right and left foot forces was not possible. However, the inclusion of stretcher force is less common in on-water rowing biomechanics research (Warmenhoven et al., 2018d), and the exploration of gate force and stretcher force in this study using model-based FDA clustering is a unique and novel contribution to the on-water rowing biomechanics literature. With these limitations in mind, there is a distinct shortage of on-water testing in peer-reviewed rowing research and therefore this study provides an excellent level of ecological validity to advance the understanding of on-water rowing assessment. Future research is needed to determine if FDA is capable of distinguishing by skill level or demographic categorisation of the rower. Furthermore, boat velocity needs to be considered alongside gate force, stretcher force and boat acceleration to further understand the relationship with rowing performance using FDA.

6.5 Conclusion

This study explored temporal biomechanical profiles of force and acceleration using a world class cohort of rowers. The input features of gate force and foot stretcher force in combination with boat acceleration were described according to the cluster patterns that were established using functional high dimensional data clustering. Interestingly, these world class rowers exhibited a highly consistent approach to their individual force development and stroke execution. However, across the clusters it was evident that there was more than one approach to achieving the fastest boat velocity at the elite level. Individual profile traces of gate force, stretcher force and boat acceleration revealed how individual strokes drifted from the group average profile, highlighting areas of high consistency such as the force development in the early, mid and late stages of the drive phase as well as areas of variability such as the boat acceleration between the discrete points of the first peak and finish slump, which reflects the main propulsive phase of the stroke cycle. Future studies should explore these methods further and apply cluster modelling methods to the assessment of crew boat synchrony and optimising crew combinations. Finally, an enhanced understanding of the idiosyncratic biomechanical profiles in rowing has the potential to provide coaches and support staff with the knowledge to adapt technical coaching strategies based on the individual rather than attempting to replicate successful elite rowers' technique.

Supplementary Material

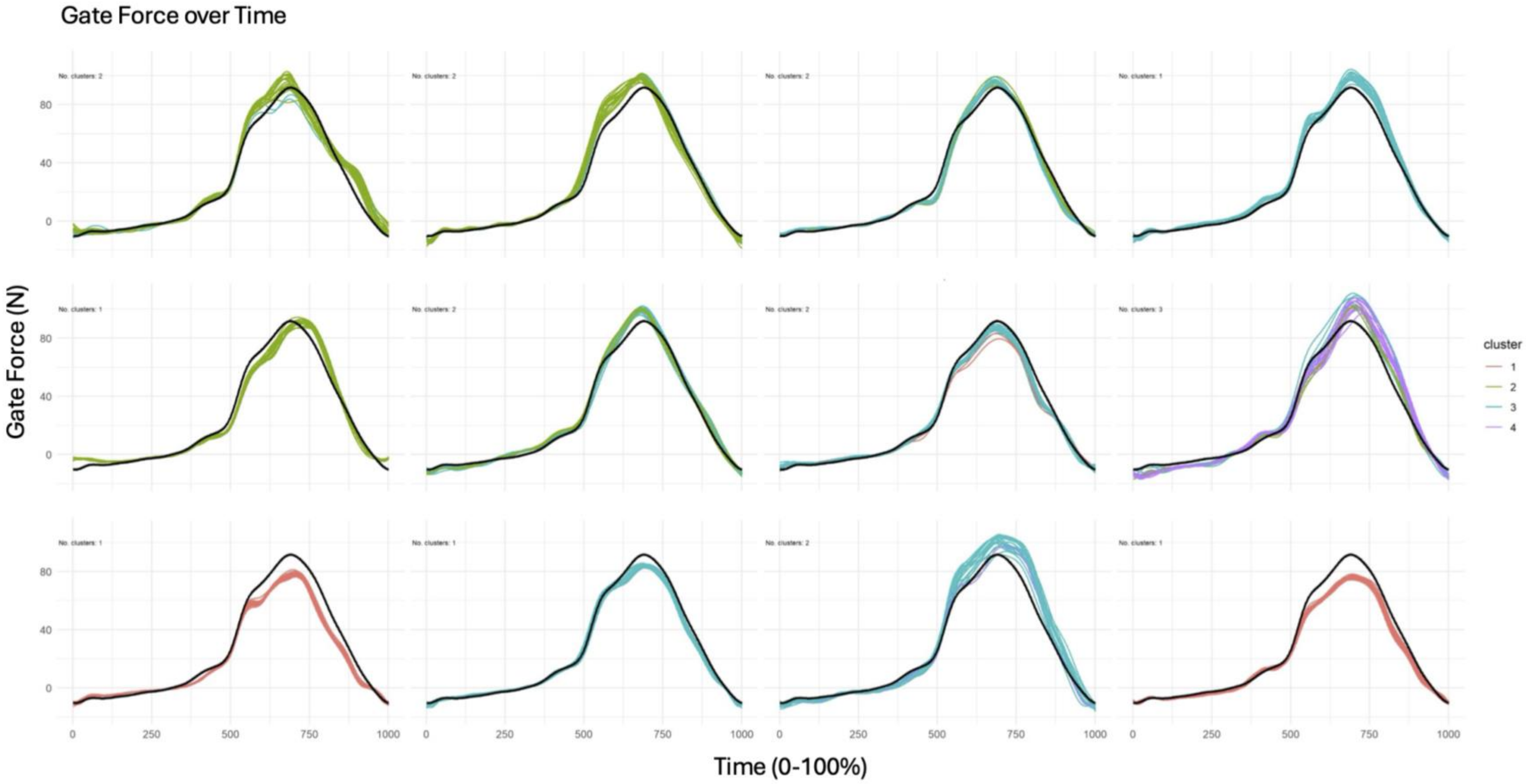

Figure 6.7: Individual gate force-time profiles – women

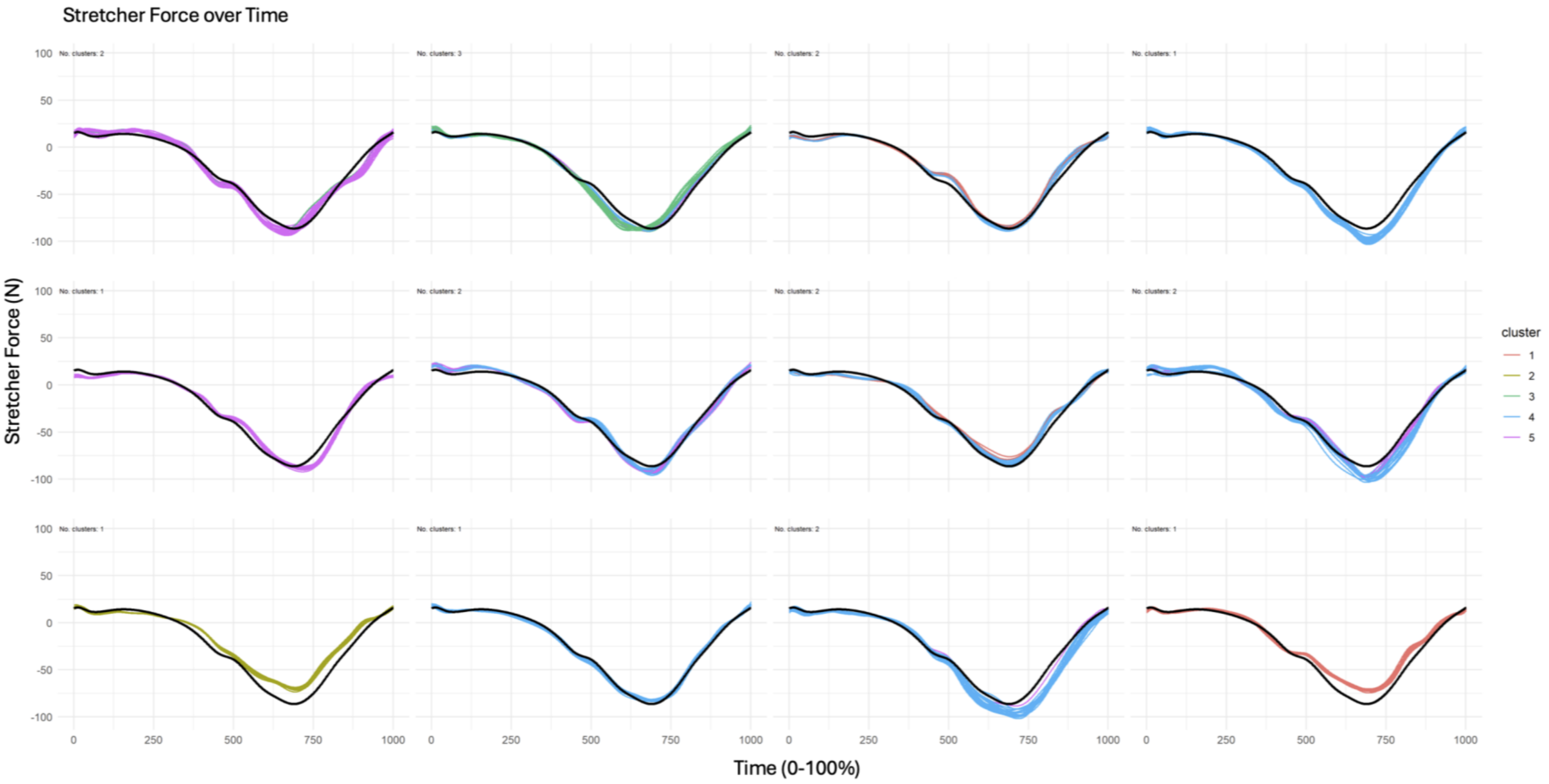

Figure 6.8: Individual Stretcher Force-Time Profiles – Women

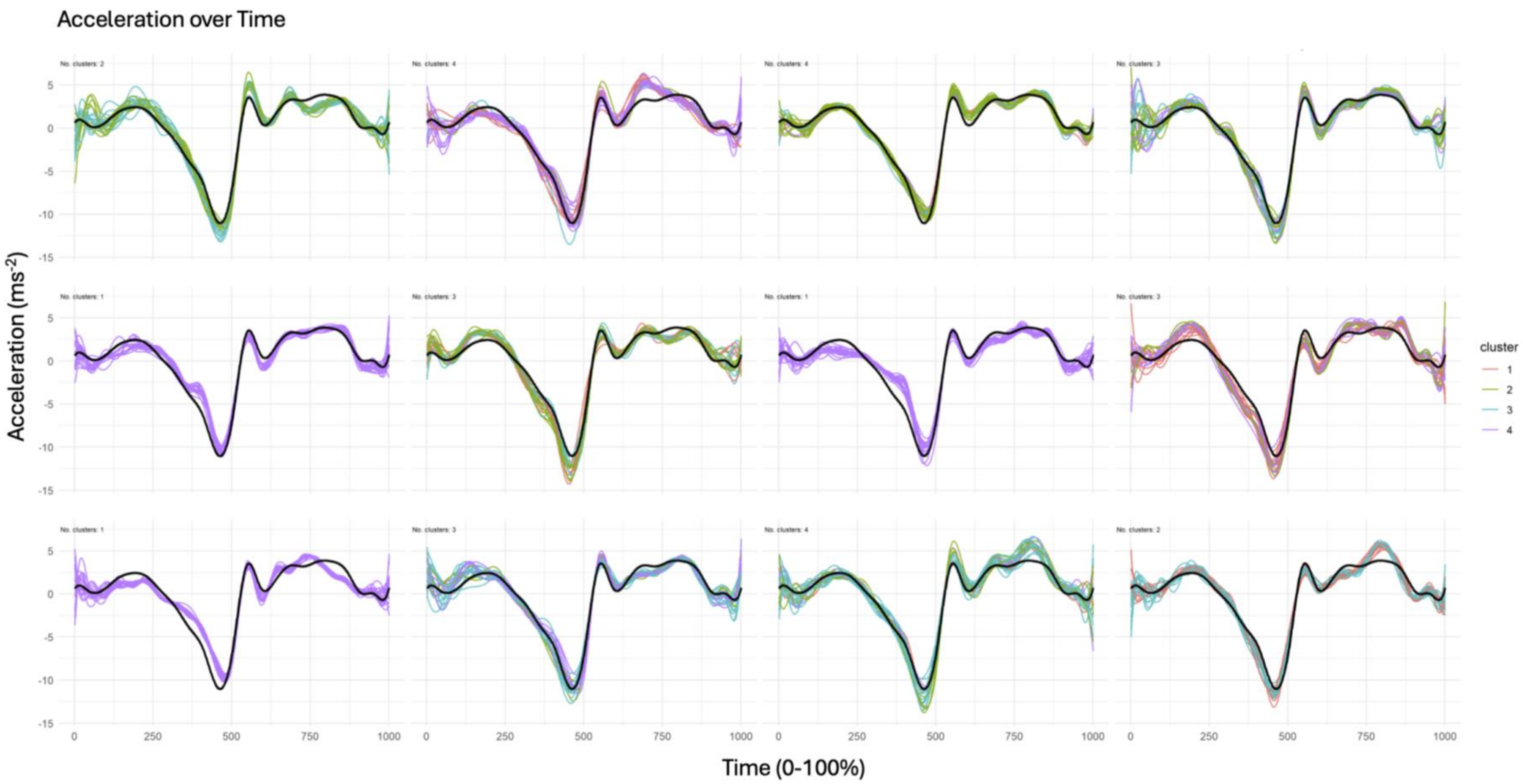

Figure 6.9: Individual Boat Acceleration-Time Profiles – Women

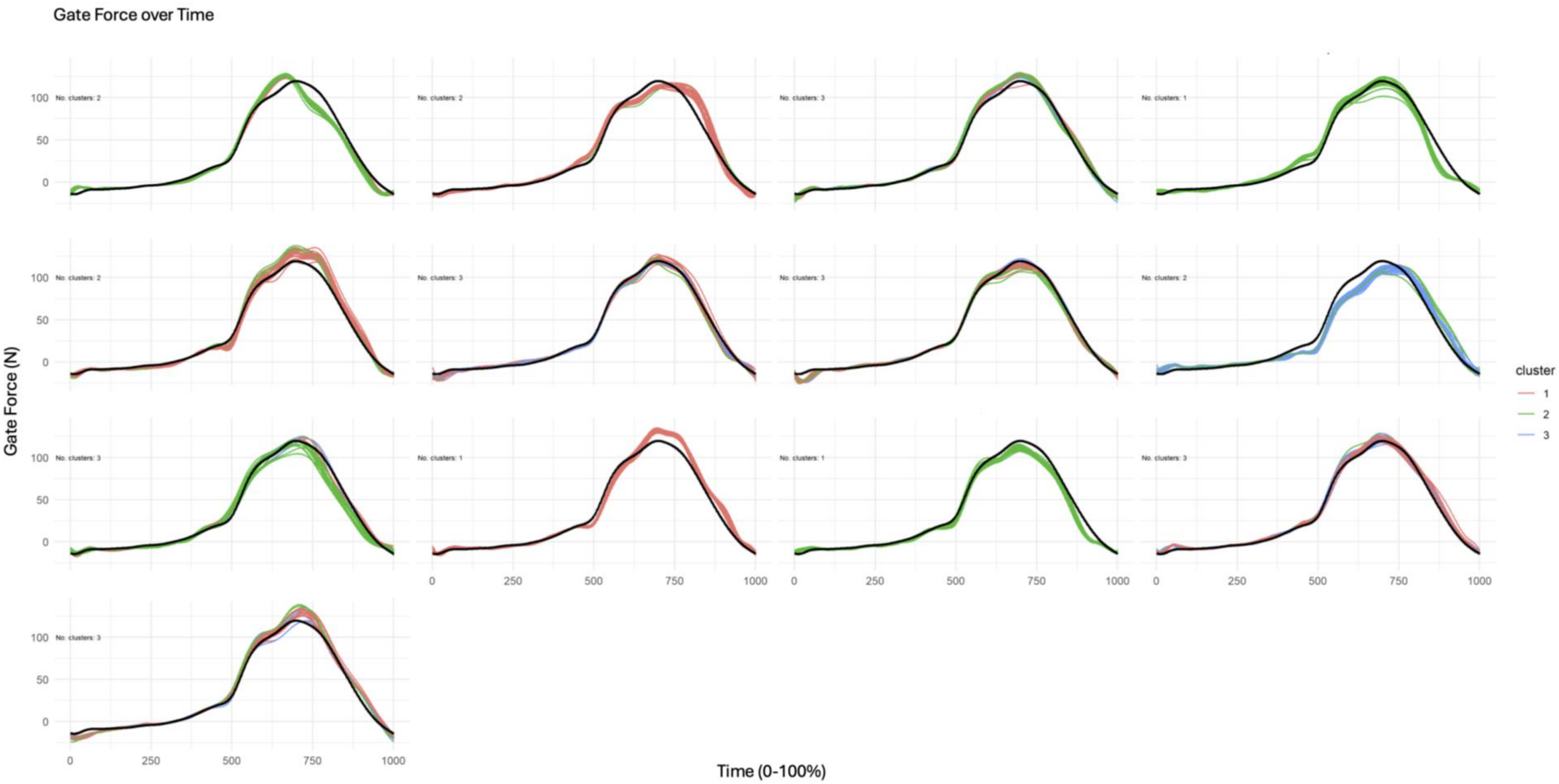

Figure 6.10: Individual Gate Force-Time Profiles – Men

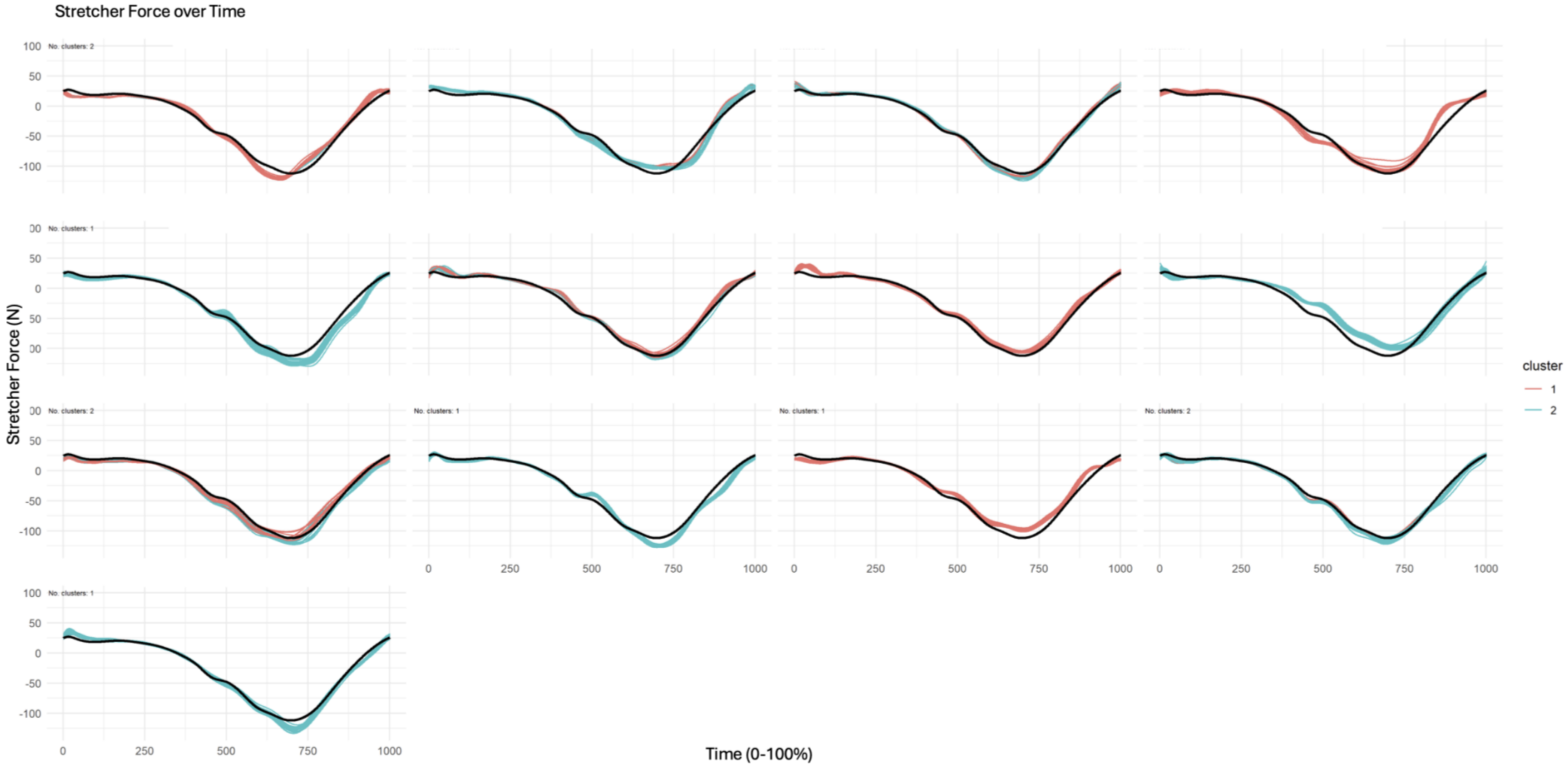

Figure 6.11: Individual Stretcher Force-Time Profiles – Men

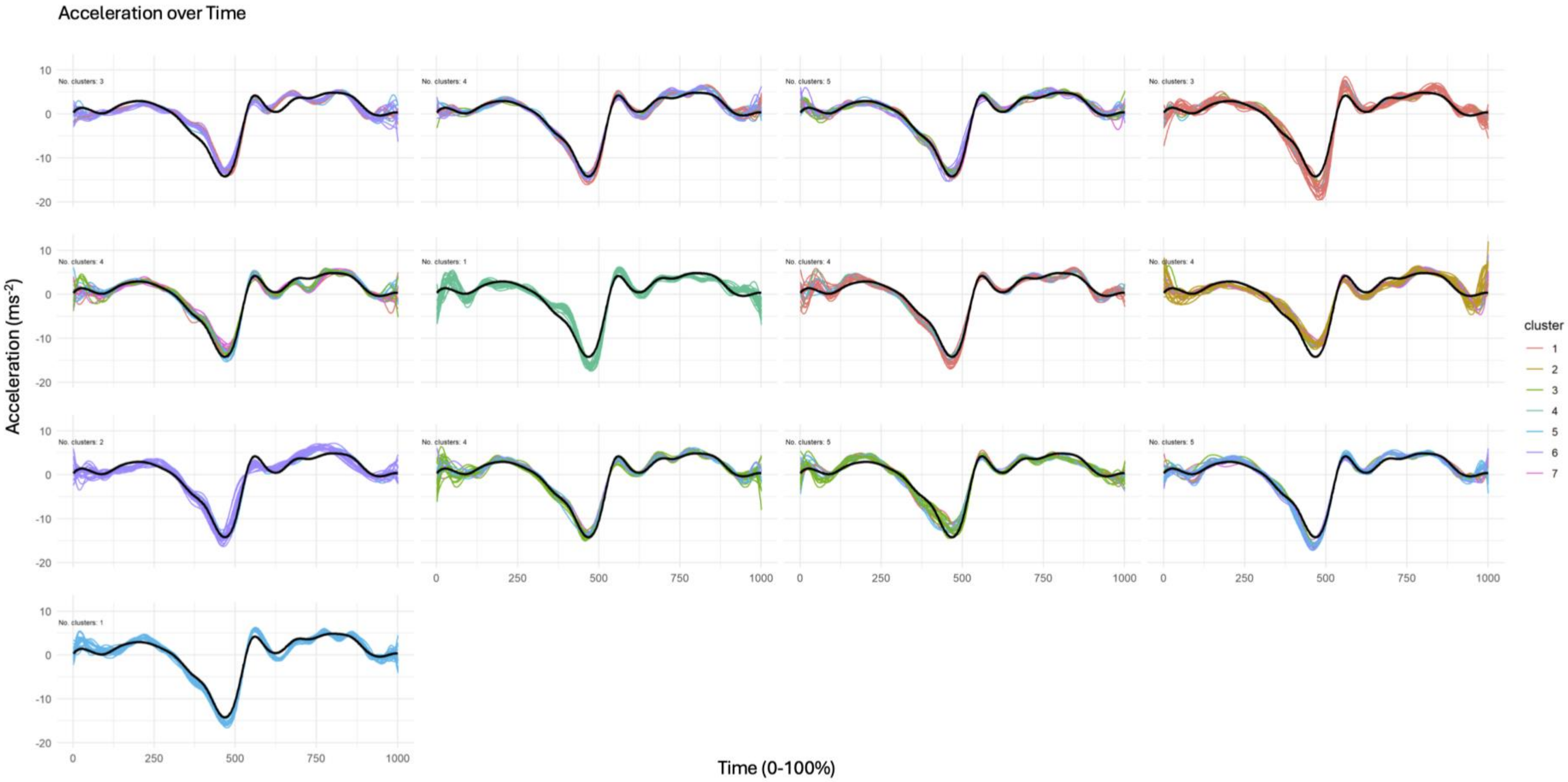

Figure 6.12: Individual Boat Acceleration-Time Profiles – Men

Contribution of authorship to the chapter

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Chapter 7

Discussion

7.1 Main Findings

This thesis described the physical and technical components of rowing performance and explored the interaction of these components in junior and elite, male and female rowers. Results compare and contrast junior and elite rowers, utilising qualitative and quantitative methods. The biomechanical assessment of on-water rowing performance provides objective technical measures of performance and technique (Buckeridge et al., 2015a; Holt et al., 2020) to monitor and evaluate technical progression in training and competition. Measurements of displacement, velocity, acceleration, force and power on the rower-oar-boat system provide comprehensive objective data to inform and support the coach in their assessment of the athlete's technical execution. The scoping review in Chapter two provided an updated understanding of the biomechanical variables pertinent to on-water rowing assessment and how they relate to performance that can be utilised by coaches, support staff and researchers. The movement competency of a rowing athlete, including their mobility and stability, is the foundational ability that allows the athlete to execute an effective rowing stroke (Rawlley-Singh & Wolf, 2023). It was demonstrated through the themes that developed from the coaches' perspectives in Chapter three that the combination of technical skill and movement competency is critical for superior rowing performance, and one component will not lead to success without the other. The physiological capacity of the rower is undeniably an important component to successful rowing performance, however, this is well established with aerobic capacity and anerobic capacity contributing approximately 80% and 20% respectively to a typical 2000 m rowing race (de Campos Mello et al., 2009; Lawton et al., 2011; Pripstein et al., 1999). Other aspects of performance including the biomechanical domain certainly contribute to the execution of powerful rowing strokes and are accordingly worth investigating.

Performance characteristics were established for each categorical group of rowers through two quantitative studies in and the complex nature of sports performance was explored. The multiple-methods approach to this thesis was a strength allowing insights into a research topic that was limited. Furthermore, subsequent studies of the thesis were then able to draw on themes generated from the coaches' experiential knowledge and explore the concepts further through experimental methodologies. Movement competency in rowing was explored as an important concept in chapter 4 based on the outcomes of the coaches' perspectives in chapter 3. Movement competency specific to rowing best describes the physical attributes required to be able to execute a technical efficient rowing stroke including a combination of multiple biomotor qualities (Rawlley-Singh & Wolf, 2023), and to distinguish this from physiological capacity. The literature has extensively explored the physical and technical aspects of performance in rowing, however, these areas have largely been addressed independently rather than as inter-related components (Iguchi et al., 2020; Otter-Kaufmann et al., 2020; Warmenhoven et al., 2018b).

This thesis aimed to explore and understand the technical and physical attributes associated with superior on-water rowing performance in both junior and elite rowers. To achieve this, a multiple methods approach involving both qualitative and quantitative studies was utilised to generate a wider understanding of rowing performance by incorporating coaches' perceptions and current practices, along with contemporary, objective measures obtained from valid and reliable instruments. The outcomes of exploratory and review chapters informed subsequent experimental studies to address the research objectives. Future research recommendations may provide coaches, practitioners, and athletes with new insights on approaching training, preparation and performance by better integrating physical preparation with technical execution in research and practice. Therefore, a series of applied research studies are summarised herein with key findings relevant to the thesis and to address the research questions:

(1) To assess the current scale and density of on-water rowing biomechanics research relevant to on-water rowing performance,

(2) To describe and propose the importance of movement competency in rowing and its relevance to rowing performance,

(3) To explore physical and technical characteristics associated with rowing performance and their interaction of these attributes with on-water rowing performance outcomes.

(4) To better understand technique characteristics of successful rowing through the exploration of temporal biomechanical profiles.

The scoping review presented in Chapter two reviewed the rowing biomechanics literature to understand variables relevant to on-water rowing technique and performance. The low number of studies (n = 27) resulting from the systematic search highlighted the extent of the limited on-water rowing biomechanics research. Results highlighted boat velocity over a measured distance or interval, in racing or training as a fundamental performance outcome together with 2000 m race time (Hill & Fahrig, 2009). Discrete metrics of boat acceleration were identified during the drive and recovery phase that relate to certain points during the stroke cycle (Holt et al., 2021), however, it was clear that additional research is required to establish conclusive recommendations related to performance.

Force measured at the gate, handle or oar received a large degree of research attention given its relationship to boat propulsion (Warmenhoven et al., 2018b). The ability to achieve a rapid rate of force development early in the drive as well as maintaining that force for longer into the finish are considered distinguishing features of successful performance (Holt et al., 2020; Peric et al., 2019). Crew synchrony was described as the need for the crew members to mutually synchronise their movements and was highly relevant to performance when concerned with crew boat combinations. A small number of studies examined crew synchrony through the assessment of three-dimensional boat rotation and boat movement (Cuijpers et al., 2017; Smith & Loschner, 2002), however there was room for more insightful investigations to this important aspect of rowing through additional metrics such as gate angle ad gate force application. The literature has reported on an extensive range of biomechanical metrics encompassing time, space and force relevant to rowing performance. Rowing biomechanics research has additional layers of complexity given there are two types of rowing: sculling and sweep rowing, two categories of rowers, lightweight and heavyweight, as well as multiple boat categories involving one person in a single scull and up to eight people in a coxed eight. However, establishing guidelines to standardise the description of variable names, assessment methods and on-water testing protocols may assist with further advancement of on-water biomechanical assessment. This could assist to advance on-water rowing biomechanical assessment so that systematic reviews and meta-analyses in the future can provide robust conclusive statements on biomechanical factors and their association with rowing technique and performance. The results of this study informed Chapters Five and Six in terms of the biomechanical metrics relevant to rowing performance. A number of these metrics were incorporated into Chapter Five and reported as part of the performance characteristics study. In addition, the scoping review in Chapter Two, revealed that most rowing biomechanics research reported discrete metrics that relate to various time points along the stroke cycle. However, time series analysis has the potential to provide more comprehensive information and had reportedly been utilised by one sole author group. Such an outcome informed Chapter Six, an exploration of temporal biomechanical profiles using model-based functional data analysis clustering methods. Force and acceleration data of the elite men and women were grouped according to identified cluster patterns. Temporal stroke profiles were visualised by cluster group and individual to assess the degree of consistency or variability within a group of world class rowers for men and women.

Following the scoping review outlining the state of the literature pertaining to the assessment of on-water biomechanical assessment in rowing, Chapter Three provided qualitative insights into the opinions and perspectives of highly experienced rowing coaches. The focus was on performance indicators for competitive rowing as well as an exploration of coaches' perceptions on the connection between movement competency and effective rowing technique execution in junior rowers. Three overarching themes were identified through thematic analysis including getting the basics right, targeting types of talent and complexities of performance. Coaches identified key differentiators between junior and elite rowers across areas of technique, training consistency and movement competency. The sequence and timing of the stroke was the main concept when discussing technical skill, however, this was not highlighted in the scoping review. Research on the body segment coordination during the rowing stroke is currently limited in the on-water environment due to the difficulty in accurately measuring body position and movement. However, with advancements in technology, such as inertial measurement units (Worsey et al., 2019) this may become possible in the future. The experiential knowledge of the coaches provided insights from the daily training environment highlighting the connection between physical and technical components of rowing performance and how they inter-relate. Chapter Three, alongside the Scoping

Review (Chapter Two), was designed to inform the subsequent studies in Chapters Five and Six. The results from Chapter Three were then applied in Chapter Five through a quantitative cross-sectional study design exploring performance characteristics in junior and elite rowers. Moreover, the concept of movement competency requirements highlighted by the coaches for effective stroke execution were further explored and clarified in Chapter Four.

Chapter Four introduced the concept of movement competency specific to rowing for superior technical execution and endeavoured to define movement competency in the sport-specific context of rowing. Movement competency is pertinent to general youth physical development, however, it can also be sport specific (Rogers et al., 2020a; Zoellner et al., 2021). Both applications encompass the definition of movement competency, however, when applied to a particular population serve a distinctive purpose. Mobility through the hips and ankles and stability through the shoulders and trunk are examples of movement competencies required to achieve effective and coordinated positions during the cyclical movements of the rowing stroke including the catch, drive, finish and recovery to optimise performance and minimise injury (Young, 2019). Movement competency in rowing is the combination of these physical attributes that enables the rower to execute an effective rowing stroke and maximise propulsive force through the oars and foot stretcher to the boat to optimise boat velocity and race performance (Nugent et al., 2020). Incorporating movement competency requirements and associated screening tools for safe and effective rowing can be beneficial for rowing participation, technical rowing efficiency, injury prevention and performance enhancement (Nugent et al., 2020). Furthermore, the results of Chapter Four reinforce and support the outcomes of Chapter Three, where the coaches' experiential knowledge identified an inter-related connection between the movement competency of the junior rower and their limited ability to execute optimal body sequencing in a coordinated and effective manner. The outcomes of Chapters Two, Three and Four cumulatively established a base of knowledge on the biomechanical indicators and movement competency requirements specific to on-water rowing performance which leads into a cross-sectional study to further explore these characteristics in junior and elite rowers (Chapter Five).

The physical and technical performance characteristics of rowing performance were examined in Chapter Five with the purpose to compare these characteristics between junior and elite male and female rowers. This study built on the concepts uncovered in the scoping review and qualitative appraisal of coaches' insights to rowing performance in that it combined a physical testing profile alongside an on-water single sculling biomechanical assessment. As revealed in Chapter Two, on-water rowing research is limited, and this study aimed to contribute to that knowledge. Attributes between junior and elite rowers were contrasted and compared. Linear discriminant analysis was able to precisely distinguish individuals to the correct categorical group based on performance level and sex with a high level of accuracy using a combination of the physical and technical variables independent of boat speed. Moreover, the LDA highlighted how the elite female and junior male participants recorded very similar boat speed results with distinctive sets of physical and on-water attributes demonstrated through the accurate categorical grouping in the LDA results.

Previous literature suggests elite rowing athletes tend to possess superior strength capabilities than their sub-elite counterparts (Sebastia-Amat et al., 2020), and the results from Chapter Five were in accordance with this observation. However, improvements in strength had previously not been investigated in relation to corresponding on-water rowing performance metrics such as rate of force development and time to positive acceleration (Holt et al., 2021). The results from Chapter Five revealed *large* to *very large* correlations between strength and power assessments with on-water mean and peak gate force. This relates back to the sub-theme in Chapter Three on trainable qualities, where coaches emphasised the importance of physical attributes such as natural strength and power as important qualities for developing athletes. Furthermore, while strength and power assessments have been related to 2000 m ergometer performance (Lawton et al., 2013; Sebastia-Amat et al., 2020), the unique outcomes presented in Chapter Five were the examination of the relationships between strength results to on-water rowing performance, providing a direct connection to the fundamental performance indicator of 2000 m race time.

Chapter Six extended the technical exploration of the rowing stroke from the previous study utilising higher dimensional analytical approaches for the application of time-series data analysis as opposed to the multitude of research examining discrete metrics. This novel study further explored temporal biomechanical patterns and technique idiosyncrasies of elite male and female scullers with applications for junior rowers on the development pathway. This was an important progression of the thesis, to advance beyond the dominance of discrete metrics in rowing biomechanics research. Such an approach was an outcome from the scoping review in Chapter Two and was reported in the results from the performance characteristics study of Chapter Five. Therefore, in Chapter Six, gate force, stretcher force and boat acceleration were analysed using FDA across a group of elite male and female scullers to understand differences and similarities within each group. Given the world class athlete participants, the results are considered a contemporary representation of elite rowing technique and provide descriptive trends for coaches, rowers and support staff to consider when technically training junior rowers looking to transition to the elite level.

FDA was used to cluster temporal force and acceleration profiles into grouped patterns or trends. The cluster patterns revealed that there is more than one approach to achieving optimal boat velocity at the elite level and the temporal profiles displayed an applicable format for coaches and practitioners to understand and utilise. The signature profiles detailed where individual rowers drifted from the group mean during different points of the stroke cycle, signifying where some athletes apply force or acceleration more efficiently during the early-mid drive while others maintain force or acceleration more efficiently during the late drive and through to the release of the blade from the water at the finish. This type of individualised descriptive feedback across the entire stroke cycle has the potential to provide more comprehensive technical feedback in comparison to metrics such as peak force, mean force or mean to peak force ratio which all relate to superior rowing performance but do not directly relate to specific technical strategies. Further research is required to understand similar patterns in sub-elite and developing junior rowers, however, in accordance with these results it would appear that technical coaching strategies should be based on the individual rather than attempting to replicate successful elite rowers' technique who may possess a completely distinctive set of physical and technical attributes. Integrating statistical techniques such as FDA for continuous data analysis of technical attributes with individual's physical characteristics may deepen our understanding of the inter-relatedness of physical and technical attributes associated with successful rowing performance. Such knowledge can guide the talent development pathway and inform technical coaching strategies at all levels of the sport.

The three main themes of the thesis were addressed as per the research questions stated in Chapter One. Specifically, biomechanical metrics related to rowing performance were systematically summarised and presented in Chapter Two. Chapter Three qualitatively explored coaches' perspectives on rowing performance and the rowing development pathway highlighting the complexities of performance and the uniqueness of individuals categorised in the same performance level. Themes from the coaches' discussions led to chapter four where the proposal of a novel concept titled 'movement competency specific to rowing' was explored.

Physical and technical characteristics of rowing performance appear to be inter-related and of a complex nature. This was exemplified in Chapter Five where the elite women and junior men exhibited similar boat speed in conjunction with a distinctive set of physical attributes. Each category group had a distinguishing set of characteristics however resulted in a similar performance outcome. Furthermore, Chapter Five provided an update to the literature of a comprehensive set and unique combination of performance characteristics including on-water biomechanical metrics that were established for each of the categorical groups, men and women, elite and junior rowers. Finally, an extension of the performance characteristics in Chapter Five deepened the understanding of technical strategies through the analysis of temporal biomechanical profiles in Chapter Six, addressing the third research question of the thesis. An increased focus on continuous data analysis rather than discrete point analysis was recommended and explored in chapter six. Established discrete metrics such as mean force, distance per stroke, mean to peak force ratio may be still applicable to rowing assessment, however in combination with FDA, rowing biomechanical profiles have the potential to provide a deeper understanding and individualised approach to coaching technical strategies. Interestingly, the results demonstrated individualised approaches to force generation during the stroke cycle and resultant boat acceleration profiles within a sample of world class male and female rowers further establishing the need for an individualised approach to technique based on the characteristics of the individual rather than attempting to replicate the strategies of successful elite athletes.

7.2 Practical Implications

The findings from this thesis have implications for coaches, strength & conditioning coaches, applied biomechanists, practitioners, athletes, rowing organisations and researchers involved with rowing and the junior development pathway. These include:

- Rowing performance is complex and multifaceted. It appears that there is more than one approach to facilitate successful performance outcomes or comparable results in rowing. An individual's unique combination of physical and technical attributes should be taken into account when considering talent and performance in junior and elite rowers.
- Rowing research related to rowing technique or performance should utilise on-water rowing methodologies where possible, so that results accurately reflect the execution of sculling or sweep rowing, rather than ergometer rowing. Ultimately, a standardized framework for on-water rowing biomechanical assessment, coupled with established protocols for environmental data collection, would provide practitioners and researchers with a structured approach for navigating the on-water rowing context.
- Furthermore, collaborative and applied rowing research projects should be encouraged, through embedded projects in the daily training environment of both junior and elite training facilities in an effort to enhance sample size and statistical power. This could allow for more longitudinal study designs with relevant and applicable outcomes for coaches and researchers.
- Adopting qualitative approaches in a traditionally quantitative field to explore experiential knowledge of high-level coaches can be advantageous in conducting more applied research to provide applicable outcomes to practitioners and coaches as demonstrated in this thesis.
- The assessment of rowing biomechanics involves the analysis of waveform data due to the cyclic and repetitive nature of the rowing stroke. Continuous data

analysis, such as FDA, provides more than just the assessment of peaks and troughs of profiles, rather, it can provide more detailed insights into patterns and trends. Future research examining the relationships between force application strategies across the stroke cycle and subsequent effect on the boat velocity and boat acceleration profiles may assist in enhancing our understanding on optimal technique.

- The use of FDA and more specifically, the model-based clustering of patterns provide a simple visualisation for coaches to interpret. This information has the potential to enhance the coaches' understanding of an individual's technical strategy and allow coaches to adjust their coaching strategy and technical approach accordingly. Further research is needed to establish the use of FDA in rowing biomechanics analysis and its applicability in rowing. In addition, future research requires further exploration incorporating translation strategies with coaches to determine if these visualisations can provide meaningful feedback that leads to improved technical strategies. These applicable outcomes may aid in bridging the gap between research and practice and lead the way for more integrated research opportunities.

7.3 Research Limitations

The limitations of each study included in this thesis have been discussed in the respective chapters. The limitations of the overall thesis are discussed herein.

Environmental conditions must be considered when interpreting results from on-water testing. Strategies to mitigate the variability of the environment and the impact on the results were detailed in the respective studies. Australia is fortunate to have exceptional accessibility to on-water testing venues with year-round access due to the temperate climate. A number of international standard rowing courses with non-tidal water and buoyed 2000 m racecourses provide the optimal environment for on-water testing conditions. A theme from the scoping review is the need for more on-water rowing testing and research to accurately reflect 2000 m race conditions, however, it is recognised this is logistically and practically not always possible in some regions of the world and this is one reason why the rowing ergometer is often utilised in its place.

Psychological attributes were not the focus of this thesis. In contrast, the aims of the studies focussed on the physical and technical attributes of rowing technique and performance, and this was a noted limitation of the sequence of research. Psychological aspects of performance were discussed by the coaches', and this was acknowledged in Chapter Three. The psychology of sport is an important discipline area contributing to sports performance. However, the capacity to examine the multitude of themes within research is limited, and such a topic requires future consideration, perhaps in unison with the physical and technical aspects of rowing.

The studies examining the physical and technical aspects of rowing in Chapters Five and Six consisted of relatively small sample sizes. This was a noted limitation of the research and was due to the limited number of world-class elite rowers available within any given nation. To increase the sample size of elite participants, international recruitment is the only option to maintain the world class performance level of the cohort, however, this was logistically impractical for the purposes of this study. In addition, constraints on time, venue and equipment availability limited the number of junior participants that were recruited.

The results of this thesis reflect Australian rowers only and accordingly, the results may not be generalisable to rowers from other nations. This should be taken into consideration when interpreting the results as rowing styles and training methodologies may vary in other regions of the world due to variations in coaching styles and philosophies, potentially leading to different outcomes. In addition, the coaches that were interviewed in Chapter Three have largely worked in the Australian rowing environment, therefore their perspectives are likely to have Australian biases. However, Australia has a history of success in rowing on the international stage, with consistent podium finishes at world championships and Olympic Games. Therefore, their training strategies, technical perspectives and philosophical approaches should be considered world class.

Chapter 8

Summary and Recommendations

8.1 Summary of the Thesis Contributions

The combined findings of this thesis have contributed to our knowledge through a number of applied studies intended to improve our understanding of the physical and technical attributes associated with on-water rowing performance. Outcomes and practical applications from this thesis will assist coaches, rowers and support staff involved in the training of junior development rowers. The findings of Chapter Two revealed the extent of the on-water rowing biomechanics literature, while Chapter Three explored coaches' perceptions on physical and technical attributes associated with on-water rowing performance. Chapter Three was a qualitative study that generated cross-disciplinary themes on rowing performance and was able to provide experiential knowledge on this topic that was limited in the literature. The results of Chapter Three subsequently informed the study design of Chapter Five which was a quantitative study to further explore the themes evident in Chapter Three. In addition, as a consequence of the themes discussed in Chapter Three with the coaches, the concept of movement competency was generated and this was further expanded and discussed through Chapter Four, to clarify and define the purpose and importance of movement competency specific to rowing.

The findings from the performance characteristics study on the complex inter-relatedness of physical and technical variables leading to performance outcomes was supported by the coaches' perspectives where cross-disciplinary themes were generated including getting the basics right, targeting types of talent and complexities of performance. The inter-relatedness of the measured performance characteristics was established through their accurate predictive capacity, however, further research remains important to extend our understanding of these dynamic and complex aspects of sports performance. The cross-disciplinary themes from the coaches and the measured performance characteristics were also reinforced by the outcomes of the scoping review that summarised the on-water rowing biomechanics literature. After establishing qualitative and quantitative connections between technical and physical attributes with on-water rowing performance, the extended exploration of elite rowing technique intended to deepen our knowledge on rowing technique through functional data analysis of the rowing biomechanical profiles. This study aimed to improve our understanding of temporal profiles in rowing and how they relate to successful rowing performance whilst exploring a contemporary statistical technique that has the potential to provide deeper analysis of rowing biomechanics. Model-based (FDA) cluster analysis was able to identify idiosyncrasies within the temporal waveform patterns by individual and by cluster pattern group within elite rowers demonstrating the need to consider individual variability when prescribing training and assessing technical strategies.

8.2 Directions for Future Research

The exploratory nature of the majority of this thesis has created a pathway forward for further investigations. Novel studies and unique analytical methods have provided new insights into rowing performance in junior and elite, male and females. The development of a guide to standardise methodologies for on-water rowing research is recommended. More specifically, recommendations to standardise the description of variable names, assessment methods and on-water testing protocols. Such a resource could advance on-water rowing biomechanical assessment so that systematic reviews and meta-analyses in the future can provide robust conclusive statements on biomechanical factors and their association with rowing technique and performance. In addition, the inclusion of guidelines for reporting environmental conditions during testing and strategies to mitigate environmental variabilities may encourage researchers to utilise on-water rowing modalities for assessment.

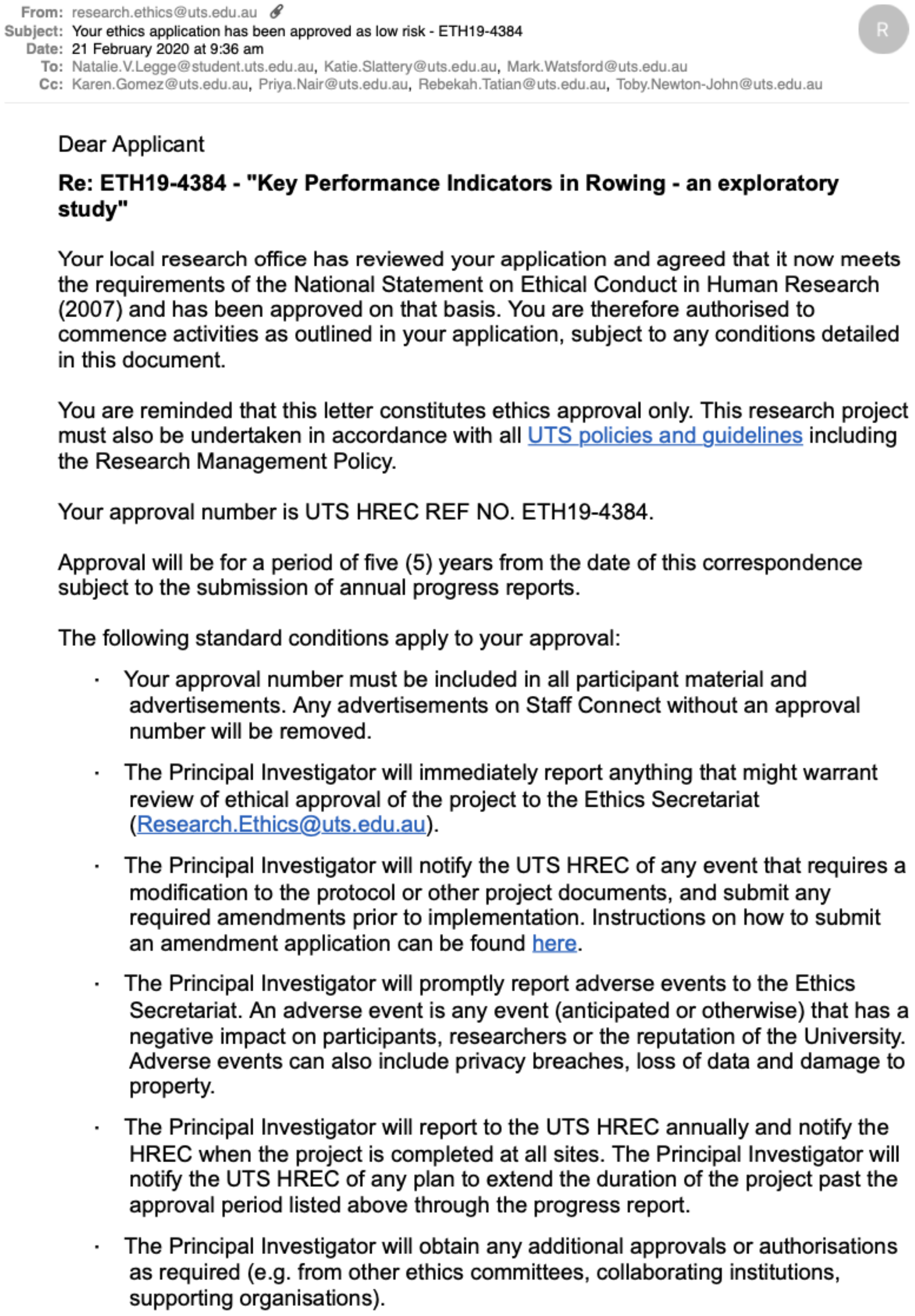
Movement competency in rowing incorporates the physical attributes required to be able to execute a technically effective stroke through appropriate stability and mobility specific to rowing. Guidelines and screening tools for movement competency requirements specific to rowing are applicable to athlete performance, injury and retention in programs. The establishment of a clear definition and evidence-based guidelines are required and can potentially have an impact and influence on training practices at all levels of the rowing community.

The inter-relatedness of cross-disciplinary performance attributes should be considered in future research. Physical, technical, tactical and psychological attributes all contribute to sports performance. This thesis was primarily concerned with the physical and technical attributes pertinent to rowing, and how they inter-relate to produce successful performance outcomes. Future research should consider multidisciplinary study designs to further explore these complexities and the individual variabilities of successful performers.

Functional data analysis techniques should be further explored in future rowing biomechanics research to further our understanding of rowing biomechanical data and the indicators that relate to the most effective technique that leads to successful performance. The adaptability of athletes in other sports has been reported through the assessment of movement tasks and skills for the purposes of talent development (Potter, 2017). This type of approach has the potential to inform the development pathway from a technical perspective. Future research should consider longitudinal methodologies that can monitor technical changes over time as the adaptability of an individual’s on-water signature profile is currently unknown. A deeper understanding of gate force, stretcher force, boat acceleration and boat velocity signature profiles could potentially advance technical coaching strategies and inform the development pathway on identifiable features in talented rowers.

Appendix

Appendix A: Study two – Ethics Approval (ETH19-4384)



From: research.ethics@uts.edu.au
Subject: Your ethics application has been approved as low risk - ETH19-4384
Date: 21 February 2020 at 9:36 am
To: Natalie.V.Legge@student.uts.edu.au, Katie.Slattery@uts.edu.au, Mark.Watsford@uts.edu.au
Cc: Karen.Gomez@uts.edu.au, Priya.Nair@uts.edu.au, Rebekah.Tatian@uts.edu.au, Toby.Newton-John@uts.edu.au

Dear Applicant

Re: ETH19-4384 - "Key Performance Indicators in Rowing - an exploratory study"

Your local research office has reviewed your application and agreed that it now meets the requirements of the National Statement on Ethical Conduct in Human Research (2007) and has been approved on that basis. You are therefore authorised to commence activities as outlined in your application, subject to any conditions detailed in this document.

You are reminded that this letter constitutes ethics approval only. This research project must also be undertaken in accordance with all UTS policies and guidelines including the Research Management Policy.

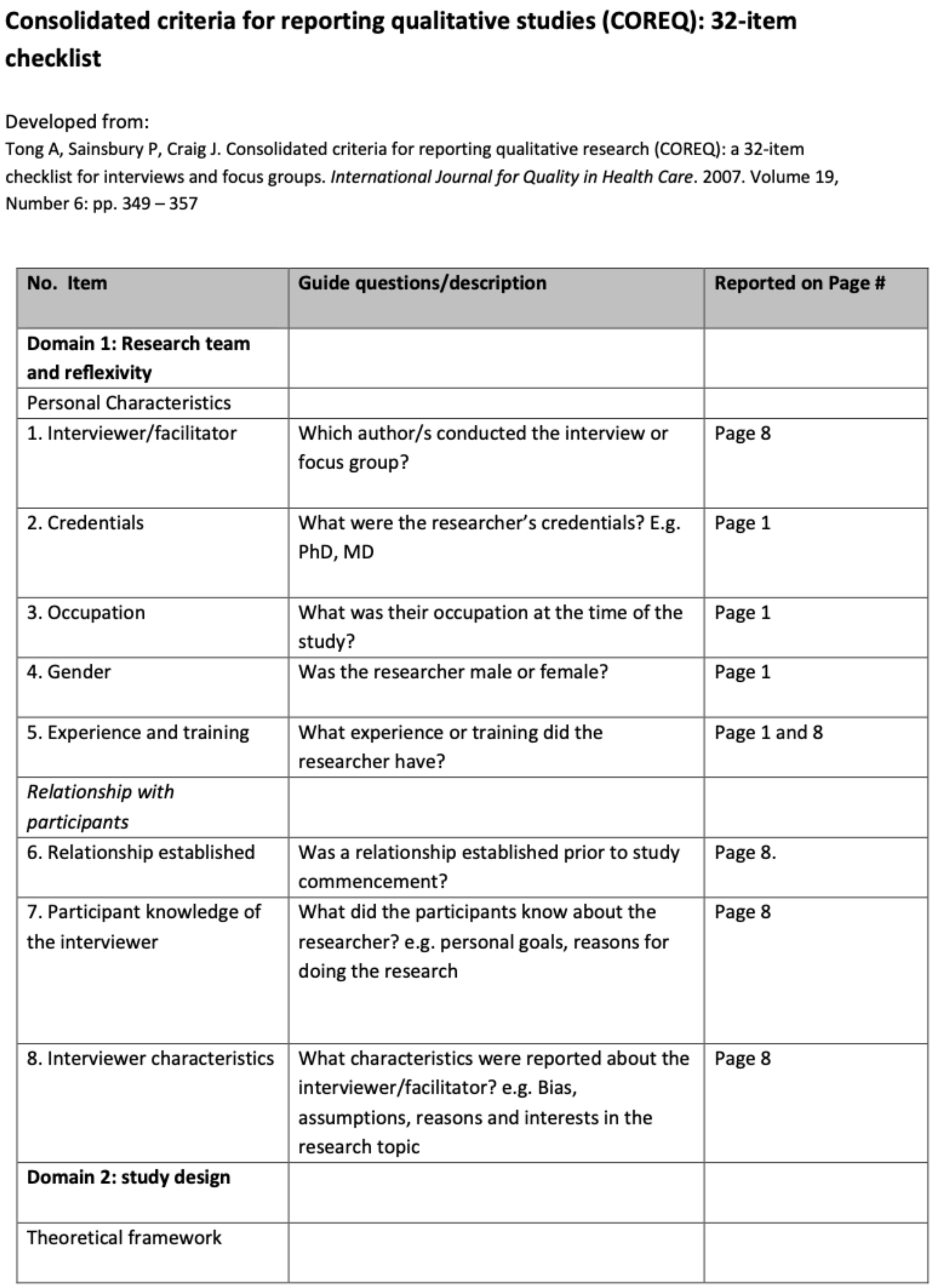
Your approval number is UTS HREC REF NO. ETH19-4384.

Approval will be for a period of five (5) years from the date of this correspondence subject to the submission of annual progress reports.

The following standard conditions apply to your approval:

- Your approval number must be included in all participant material and advertisements. Any advertisements on Staff Connect without an approval number will be removed.
- The Principal Investigator will immediately report anything that might warrant review of ethical approval of the project to the Ethics Secretariat (Research.Ethics@uts.edu.au).
- The Principal Investigator will notify the UTS HREC of any event that requires a modification to the protocol or other project documents, and submit any required amendments prior to implementation. Instructions on how to submit an amendment application can be found here.
- The Principal Investigator will promptly report adverse events to the Ethics Secretariat. An adverse event is any event (anticipated or otherwise) that has a negative impact on participants, researchers or the reputation of the University. Adverse events can also include privacy breaches, loss of data and damage to property.
- The Principal Investigator will report to the UTS HREC annually and notify the HREC when the project is completed at all sites. The Principal Investigator will notify the UTS HREC of any plan to extend the duration of the project past the approval period listed above through the progress report.
- The Principal Investigator will obtain any additional approvals or authorisations as required (e.g. from other ethics committees, collaborating institutions, supporting organisations).

Appendix B: COREQ Checklist



Consolidated criteria for reporting qualitative studies (COREQ): 32-item checklist

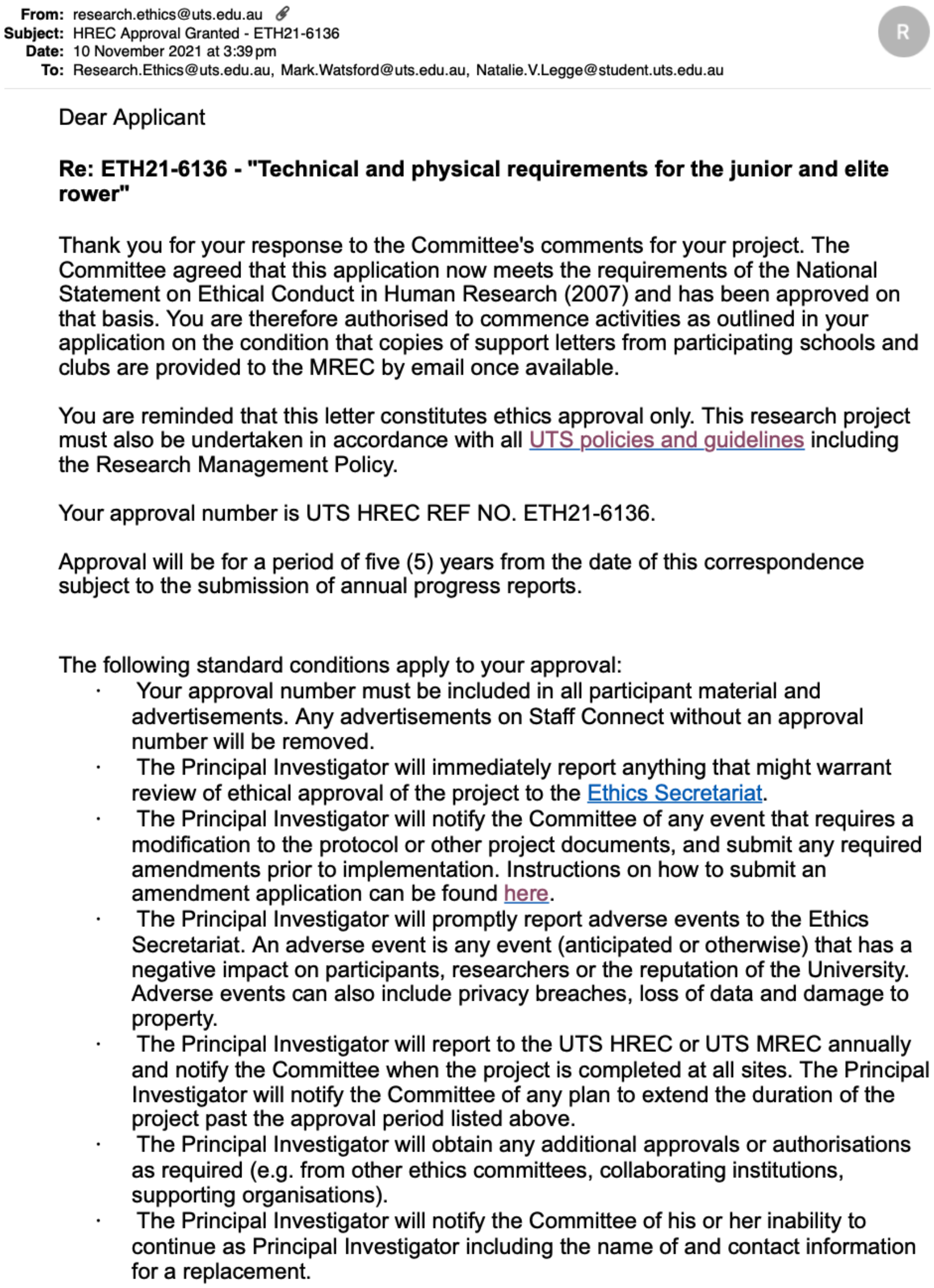
Developed from:
Tong A, Sainsbury P, Craig J. Consolidated criteria for reporting qualitative research (COREQ): a 32-item checklist for interviews and focus groups. *International Journal for Quality in Health Care*. 2007. Volume 19, Number 6: pp. 349 – 357

No. Item	Guide questions/description	Reported on Page #
Domain 1: Research team and reflexivity		
Personal Characteristics		
1. Interviewer/facilitator	Which author/s conducted the interview or focus group?	Page 8
2. Credentials	What were the researcher's credentials? E.g. PhD, MD	Page 1
3. Occupation	What was their occupation at the time of the study?	Page 1
4. Gender	Was the researcher male or female?	Page 1
5. Experience and training	What experience or training did the researcher have?	Page 1 and 8
Relationship with participants		
6. Relationship established	Was a relationship established prior to study commencement?	Page 8.
7. Participant knowledge of the interviewer	What did the participants know about the researcher? e.g. personal goals, reasons for doing the research	Page 8
8. Interviewer characteristics	What characteristics were reported about the interviewer/facilitator? e.g. Bias, assumptions, reasons and interests in the research topic	Page 8
Domain 2: study design		
Theoretical framework		

9. Methodological orientation and Theory	What methodological orientation was stated to underpin the study? e.g. grounded theory, discourse analysis, ethnography, phenomenology, content analysis	Page 9
Participant selection		
10. Sampling	How were participants selected? e.g. purposive, convenience, consecutive, snowball	Page 6
11. Method of approach	How were participants approached? e.g. face-to-face, telephone, mail, email	Page 6
12. Sample size	How many participants were in the study?	Page 7
13. Non-participation	How many people refused to participate or dropped out? Reasons?	Page 7
Setting		
14. Setting of data collection	Where was the data collected? e.g. home, clinic, workplace	Page 7 .
15. Presence of non-participants	Was anyone else present besides the participants and researchers?	Page 7
16. Description of sample	What are the important characteristics of the sample? e.g. demographic data, date	Page 6 and 7
Data collection		
17. Interview guide	Were questions, prompts, guides provided by the authors? Was it pilot tested?	Page 7, 8 and Supplementary Material
18. Repeat interviews	Were repeat interviews carried out? If yes, how many?	No, inferred on page 7
19. Audio/visual recording	Did the research use audio or visual recording to collect the data?	Page 8
20. Field notes	Were field notes made during and/or after the interview or focus group?	Page 8
21. Duration	What was the duration of the interviews or focus group?	Page 7
22. Data saturation	Was data saturation discussed?	Page 7
23. Transcripts returned	Were transcripts returned to participants for	Page 8

	comment and/or correction?	
Domain 3: analysis and findings		
Data analysis		
24. Number of data coders	How many data coders coded the data?	Page 8 and 9
25. Description of the coding tree	Did authors provide a description of the coding tree?	
26. Derivation of themes	Were themes identified in advance or derived from the data?	Page 9
27. Software	What software, if applicable, was used to manage the data?	Page 8
28. Participant checking	Did participants provide feedback on the findings?	Page 7
Reporting		
29. Quotations presented	Were participant quotations presented to illustrate the themes/findings? Was each quotation identified? e.g., participant number	Pages 10-18
30. Data and findings consistent	Was there consistency between the data presented and the findings?	Yes, there was. Pages 19-22
31. Clarity of major themes	Were major themes clearly presented in the findings?	Yes. they were. Pages 19-22
32. Clarity of minor themes	Is there a description of diverse cases or discussion of minor themes?	Yes Pages 19-22

Appendix C: Study four & five – Ethics Approval (ETH21-6136)



From: research.ethics@uts.edu.au
Subject: HREC Approval Granted - ETH21-6136
Date: 10 November 2021 at 3:39 pm
To: Research.Ethics@uts.edu.au, Mark.Watsford@uts.edu.au, Natalie.V.Legge@student.uts.edu.au

Dear Applicant

Re: ETH21-6136 - "Technical and physical requirements for the junior and elite rower"

Thank you for your response to the Committee's comments for your project. The Committee agreed that this application now meets the requirements of the National Statement on Ethical Conduct in Human Research (2007) and has been approved on that basis. You are therefore authorised to commence activities as outlined in your application on the condition that copies of support letters from participating schools and clubs are provided to the MREC by email once available.

You are reminded that this letter constitutes ethics approval only. This research project must also be undertaken in accordance with all UTS policies and guidelines including the Research Management Policy.

Your approval number is UTS HREC REF NO. ETH21-6136.

Approval will be for a period of five (5) years from the date of this correspondence subject to the submission of annual progress reports.

The following standard conditions apply to your approval:

- Your approval number must be included in all participant material and advertisements. Any advertisements on Staff Connect without an approval number will be removed.
- The Principal Investigator will immediately report anything that might warrant review of ethical approval of the project to the Ethics Secretariat.
- The Principal Investigator will notify the Committee of any event that requires a modification to the protocol or other project documents, and submit any required amendments prior to implementation. Instructions on how to submit an amendment application can be found here.
- The Principal Investigator will promptly report adverse events to the Ethics Secretariat. An adverse event is any event (anticipated or otherwise) that has a negative impact on participants, researchers or the reputation of the University. Adverse events can also include privacy breaches, loss of data and damage to property.
- The Principal Investigator will report to the UTS HREC or UTS MREC annually and notify the Committee when the project is completed at all sites. The Principal Investigator will notify the Committee of any plan to extend the duration of the project past the approval period listed above.
- The Principal Investigator will obtain any additional approvals or authorisations as required (e.g. from other ethics committees, collaborating institutions, supporting organisations).
- The Principal Investigator will notify the Committee of his or her inability to continue as Principal Investigator including the name of and contact information for a replacement.

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