The Evaluation of an Instrumented Paddle Device for Analysing Kayak Sprint Performance

Eric T. Harbour

MSpEx

A thesis submitted to Auckland University of Technology in partial fulfillment of the requirements for the degree of Master of Sport and Exercise

2019

School of Sport and Recreation

Abstract

Technological innovation has coincided with rapid improvements in performance in kayak sprint. With breakthroughs in materials, sensors, and wireless telemetry, instrumented equipment has unlocked new methods of quantifying and analysing performance. While some research has identified key biomechanical factors associated with performance, there is limited information available from on-water paddling and from new instrumented paddle devices. Thus, this thesis will improve the understanding of kayak performance through the examination of a novel instrumented paddle device. The device, developed by High Performance Sport New Zealand (HPSNZ), is capable of measuring blade force and velocity during normal on-water training conditions and may be adapted for ergometer use. A multi-level paddle protocol was created in partnership with coaches and support staff in order to replicate training and race intensities with maximal specificity. In Chapter 3, a study was performed to examine the validity and comparative reliability of the smart paddle (SP) relative to a popular kayak ergometer (DS). The SP and DS were practically identical in detecting stroke rate (SR) (limits of agreement = 0.02 ± 9.02%; $R^2 = 0.98$; $p < 0.01$), but there were detectable differences in pull time (T_{Pull}) (limits of agreement = 10.1 ± 18.4%, $R_2 = 0.78$, $p < 0.01$) and peak force (F_{Peak}) (limits of agreement = 8.8 ± 30.1 N, $R^2 = 0.94$, $p < 0.01$). Regardless, cyclical power variables were similar between SP and DS (SP IR and DS power; $R^2 = 0.98$, SE = 0.045, $p < 0.01$) across all intensities. Chapter 4 uses the SP to compare kinetic and kinematic variables between on-water and kayak ergometer paddle environments. Large significant differences in T_{Pull} (d = 5.9 ± 0.39), air time (T_{Air}) (d = 3.7 ± 0.27), mean force (F_{Mean}) (d = 1.06 ± 0.19), peak force (F_{Peak}) (d = 1.92 ± 0.22), Impulse (d = 2.62 ± 0.23), and impulse rate (IR) (d = 2.10 ± 0.21) were found between environments. Kinetic differences expanded at higher intensities, which were visually apparent in statistical parametric mapping (SPM) analyses. Notably, IR was quite similar at maximal intensity (d = 0.28 ± 0.27). In Chapter 5, the previous results and other literature were used to examine correlations between performance variables and boat speed. The strongest correlations and predictive power for kayak velocity (V_{Kayak}) were with IR ($R^2 = 0.98$, SE = 0.31, z = 1.86, $p < 0.01$) and cycle power (P_{Cycle}) ($R^2 = 0.95$, SE = 0.035, z = 2.08, $p < 0.01$). Allometric scaling increased the predictive power of most kinetic relationships. Strong correlations were observed between DPS and F_{Peak} (r = 0.69 ± 0.10), F_{Mean} (r = 0.68 ± 0.11), peak power (P_{Peak}) (r = 0.72 ± 0.10), and impulse (r = 0.65 ± 0.18). Paddling efficiency (e_p) was estimated between 0.65-0.75, on average, for all intensities. These data expand the body of knowledge surrounding kayak sprint biomechanics, suggesting that specific performance variables can predict performance and detect differences between athletes, paddling intensity, and environments. Instrumented paddle devices are a powerful tool with more potential to be explored.

Contents

List of Figures 5

List of Tables 6

List of Equations 7

List of Appendices 7

List of Common Abbreviations 8

Attestation of Authorship 10

Co-Authored Works 11

Acknowledgements 12

Ethical Approval 13

Confidential Material 14

Chapter 1. Introduction 15

Background and Rationale 15

Purpose and Significance of Research 16

Thesis aims 17

Thesis organization 17

Chapter 2. Biomechanics of Kayak Sprint: A Narrative Review 19

Abstract 19

History 19

Mechanics 20

Key Performance Indicators 28

Technologies 35

Conclusion 40

Chapter 3. Comparative Validity and Reliability of a Novel Smart Paddle System 41

Preface 41

Abstract 41

Introduction ... 42

Methods ... 43

Results ... 49

Discussion ... 55

Chapter 4. Biomechanical Differences Between Ergometer and On-Water Paddling ... 60

Preface ... 60

Abstract ... 60

Introduction ... 61

Methods ... 62

Results ... 66

Discussion ... 74

Chapter 5. Biomechanical Determinants of Kayak Sprint Performance ... 81

Preface ... 81

Abstract ... 81

Introduction ... 82

Methods ... 84

Results ... 94

Discussion ... 108

Chapter 6. General Discussion and Applications ... 114

Introduction ... 114

Practical Applications ... 114

Limitations ... 120

Future Research Direction ... 123

Recommendations for CRNZ ... 123

Conclusions ... 123

References ... 1

Appendices ... 9

Appendix 1. Ethics approval and amendment form ... 9

Appendix 2. Tools ... 13

Appendix 3. Instrumented ergometer information 22
Appendix 4. Smart Paddle documentation .... ***Error! Bookmark not defined.***

List of Figures

Figure 1. Boat movements of a kayak........ 22
Figure 2. A sagittal view of blade-water dynamics during the paddle stroke........ 24
Figure 3. Blade force profiles of an elite kayaker........ 26
Figure 4. Blade force components at different paddle shaft angles........ 27
Figure 5. Kinematic determinants of kayak sprint........ 29
Figure 6. Events and phases of the kayak paddle stroke........ 31
Figure 7. Computation of force-profile smoothness........ 33
Figure 8. Relationship between V_{Kayak} and paddle power........ 33
Figure 9. Kinetic components of the kayak-athlete-paddle system........ 34
Figure 10. Kayak ergometer in use during CRNZ testing........ 37
Figure 11. Previously studied instrumented paddle shaft designs........ 39
Figure 12. Paddle protocol for ergometer testing........ 43
Figure 13. Experimental setup of the paddler, DS, DP, and SP........ 45
Figure 14. Passing-Bablock regression analysis of DS and SP SR........ 50
Figure 15. Bland-Altman plot of the relation between DS and SP SR........ 51
Figure 16. Passing-Bablock regression analysis of DS and SP T_{Pull}........ 52
Figure 17. Bland-Altman plot of the relation between DS and SP T_{Pull}........ 52
Figure 18. Passing-Bablock regression analysis of DS and SP F_{Peak}........ 53
Figure 19. Bland-Altman plot of the relation between DS and SP F_{Peak}........ 54
Figure 20. Regression of SP IR to DS P_{Mean}........ 55
Figure 21. Bland-Altman plot of the relation between DS and SP T_{Air}........ 56
Figure 22. Regression of DP P_{Cycle} to DS P_{Mean}........ 58
Figure 23. Scatterplots of stroke phase parameters to SR........ 66
Figure 24. Scatterplots of primary kinetic variables to SR........ 68
Figure 25. Scatterplots of impulse to SR and T_{Pull}........ 70
Figure 26. Scatterplot of IR to SR........ 72
Figure 27. Force-time profiles of ergo and H2O groups across intensities........ 73
Figure 28. SPM results........ 74
Figure 29. Individual scatterplots of F_{Peak} and SR........ 76
Figure 30. Force-time profiles for one athlete at increasing intensity........ 78
Figure 31. Force-time profiles of ergo and H2O groups for full T_{Stroke}........ 78

Figure 32. Boat speed phases....87
Figure 33. Scatterplots of DPS to V_{Kayak} and SR....91
Figure 34. Scatterplot of DPS to V_{Kayak} with SR groups....92
Figure 35. Box-and-whisker plot of P_{Mean} at each test level....94
Figure 36. Passing-Bablock regression analysis of Rover GPS and SP SR....95
Figure 37. Bland-Altman plot of the relation between Rover GPS and SP SR....96
Figure 38. Scatterplot of F_{Mean} to V_{Kayak}....98
Figure 39. Scatterplot of P_{Mean} to V_{Kayak}....98
Figure 40. Scatterplot of IR (scaled) to V_{Kayak}....99
Figure 41. Scatterplots of P_{Cycle} (scaled) to V_{Kayak} by sex....100
Figure 42. Scatterplots of mean P_{Cycle} to V_{Kayak} by test level....101
Figure 43. Scatterplots of mean IR and kayak velocity by test level....101
Figure 44. Scatterplots of EWS to SR and V_{Kayak} by test level....102
Figure 45. Scatterplots of EWS to SR and V_{Kayak} by athlete....103
Figure 46. Scatterplots of F_{Mean}/F_{Peak} ratio to V_{Kayak}....104
Figure 47. Scatterplot of DPS to F_{Peak}....106
Figure 48. Scatterplot of V_{Kayak} to stroke efficiency index by test level....107
Figure 49. Scatterplots of stroke efficiency index to F_{Peak}, P_{Mean}, and EWS....107
Figure 50. Scatterplots of DPS SI to F_{Peak} and P_{Peak} SI by level....108
Figure 51. Scatterplot of F_{Peak} to SR by athlete....111
Figure 52. Scatterplots of P_{Cycle} to SR by athlete....112
Figure 53. Proposed effective strategies to increase V_{Kayak} and V_{Race}....118
Figure 54. Research approach framework for exploring constraints and their effect upon performance....121

List of Tables

Table 1. Boat movements and their causes....22
Table 2. Physical characteristics with potential effects on kayak performance....35
Table 3. Biomechanical variables previously examined via instrumented paddle system....40
Table 4. Biomechanical variables examined between DS, DP, and SP....47
Table 5. Descriptive statistics of DS and SP stroke identification....50
Table 6. List of biomechanical variables examined by SP on ergo and H2O....64
Table 7. Collection protocol sample details for ergo and H2O....65
Table 8. Descriptive statistics and effect sizes for stroke phase parameters for ergo and H2O...66
Table 9. Descriptive statistics and effect sizes for primary kinetic variables for ergo and H2O.69

Table 10. Descriptive statistics and effect sizes for impulse and impulse rate for ergo and H2O 71
Table 11. SPM results for difference between ergo and H2O force-time profiles by test level ..73
Table 12. Descriptive statistics and effect sizes for biomechanical variables of ergo and H2O paddling at maximal intensity 75
Table 13. List of biomechanical variables examined during on-water paddling by Rover GPS and SP 88
Table 14. Correlations between kayak kinematics and SP variables during on-water paddling..97
Table 15. Estimated drag forces and paddling efficiency for athlete subsample 105

List of Equations

Equation 1. Calculation of blade drag force 23
Equation 2. Definition of biomechanical propulsive efficiency 24
Equation 3. Calculation of cycle force 49
Equation 4. Equivalence of cycle force and impulse rate 49
Equation 5. Calculation of cycle power 57
Equation 6. Calculation of peak power symmetry index 89
Equation 7. Calculation of effective work per stroke 89
Equation 8. Linear regression formula for log-transformed variables 90
Equation 9. Calculation of stroke efficiency 92
Equation 10. Linear regression formula inclusive of drag 93
Equation 11. Calculation of net kayak force at constant V_{Kayak} 93
Equation 12. Calculation of paddling efficiency....94

List of Appendices

Appendix 1. Ethics approval and amendment form 9
Appendix 2. Participant information sheet 13
Appendix 3. Consent form 17
Appendix 4. Ergometer trial checklist 19
Appendix 5. On-water trial checklist 20
Appendix 6. Instrumented ergometer information 22
Appendix 7. Smart Paddle documentation .... **Error! Bookmark not defined.**

List of Common Abbreviations

HPSNZ	High Performance Sport New Zealand; a Crown Entity Subsidiary organisation responsible for the leadership of New Zealand high performance sport
CRNZ	Canoe Racing New Zealand; national governing body of canoe and kayak racing disciplines in NZ
BM	Body mass (kg)
DS	Dansprint ergometer
DP	Instrumented Dansprint system
SP	KZ2 smart paddle system, previously Powerblade
GPS	Global positioning system
V_{Kayak}	Kayak velocity (km/h); mean horizontal boat velocity during one stroke cycle T_{Stroke}
V_{Race}	Race velocity (km/h); mean V_{Kayak} across a given distance
α_{Kayak}	Kayak acceleration (m/s^2); rate of change in V_{Kayak} during a given time t
T_{Stroke}	Stroke time (s); time elapsed during one stroke cycle from paddle blade entry to entry of contralateral side
SR	Stroke rate; measured in R+L cycles/min, equal to $(1/T_{Stroke}) * 60$
T_{Pull}	Pull time (s); time elapsed from blade entry to exit
T_{Air}	Air time (s); time elapsed from blade exit to entry of contralateral side
DPS	Distance per stroke (m); horizontal boat displacement during T_{Stroke}
V_{Blade}	Blade velocity; mean linear blade velocity during pull (tangential velocity) measured from 1/3 length of blade surface
F_{Mean}	Mean blade force; mean force perpendicular to paddle shaft during T_{Pull} measured from 1/3 length of blade surface
F_{Peak}	Peak blade force; peak force perpendicular to paddle shaft during T_{Pull} measured from 1/3 length of blade surface
P_{Mean}	Mean blade power; product of $F_{Mean} * V_{Blade}$

P_{Peak}	Peak blade power; product of F_{Peak} * peak V_{Blade}
P_{Cycle}	Cycle power; P_{Mean} averaged across T_{Stroke}, equal to (P_{Mean} * T_{Pull}) / T_{Stroke}
IR	Impulse rate; rate of blade impulse transmitted during T_{Stroke}, equal to impulse * SR * constant
e_p	Propulsive efficiency
D_F	Drag force; hydrodynamic drag component horizontal to boat
D_P	Passive drag; horizontal drag force occurring at a given constant V_{Kayak}
D_A	Active drag; horizontal drag force occurring due to α_{Kayak} and aberrant boat movements (yaw, pitch, heave, roll, sway)
d	Cohen's *d* effect size; standardised difference between two means
CI	Confidence interval
SE	Standard error of the regression; the square root of the MSE of the full model

Attestation of Authorship

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person (except where explicitly defined in the acknowledgements), nor material which to a substantial extent then submitted for the award of any other degree or diploma of a University or other institution of higher learning.

Signed …………………………………………

Date 16/4/2019……………………………………………

Co-Authored Works

Chapter 3. Harbour, E., Neville, J., and McAlpine, P. Comparative Validity and Reliability of a Novel Smart Paddle System. *Journal of Sports Sciences,* in preparation.	Harbour, E. (90%) Neville, J. (5%) McAlpine, P. (5%)
Chapter 4. Harbour, E., Neville, J., McAlpine, P, and Borotkanics, R. Biomechanical Differences Between Ergometer and On-Water Paddling. *Sports Biomechanics,* in preparation.	Harbour, E. (85%) Neville, J. (5%) McAlpine, P. (5%) Borotkanics, R (5%)
Chapter 5. Harbour, E., McAlpine, P., and Neville, J. Biomechanical Determinants of Kayak Sprint Performance. *International Journal of Sports Physiology and Performance,* in preparation.	Harbour, E. (90%) McAlpine, P. (5%) Neville, J. (5%)

Eric Harbour

Paul McAlpine

Jono Neville

Robert Borotkanics

Acknowledgements

My postgraduate journey would be impossible without the support of several important individuals. At each stage, I was lucky to have family, friends, and colleagues that could provide key advise, earnest encouragement, or simple loving company.

Jono – you challenge me intellectually while keeping valuable perspective of the big picture. You looked after me in the important ways and gave me autonomy to learn the process of quality research. Always keen for more Aussie lessons, Soccerby, and Bioluminescent swims.

Paul – your trust and investment in me as a rookie at HPSNZ helped shape my professional and personal ambitions in incredible ways. I envy your wisdom, life balance, and beard-growing skills. Hope to see you on the snow very soon.

Mike – you welcomed me to AUT from the beginning and I'm so grateful to have you on my team through the finish. From career planning to finer details, thank you for your sage guidance.

Allan – your work on the ergometer and data was invaluable for project execution. Thank you for your work and commitment to robust, thorough scientific inquiry.

CRNZ – Fred, your involvement and passion for the project enabled its success. I will forever treasure our chats about kayak, work, and life. Big additional thanks to Keeno, Hamish, Jasper, Dan, the athletes, and the rest of the organisation for your various helpful contributions.

SPRINZ – If we behave like the average of the people we spend most time with, I'm lucky to have called SPRINZ home. The time there was filled with incredible conversations, everyday inspiration, and a dynamic atmosphere. Shout-outs to Dustin, Josh, Kechi, Jess B, Enora, Matt C, Scott B, Farhan, and so many more.

I'm so lucky to be surrounded by loving and supportive family and friends. Whether helping with editing or providing caring hospitality, you all contributed to a critical piece of this document. I can't express my appreciation adequately with words but I'll do my best to show you.

Ethical Approval

Ethical approval for this research was granted by the Auckland University of Technology Ethics Committee (AUTEC; 18/151) originally on 30 April 2018, with minor amendments approved on 4 December 2018.

Confidential Material

This bachelor thesis contains confidential data of High Performance Sport New Zealand (HPSNZ) and Canoe Racing New Zealand (CRNZ). This work may only be made available to the first and second reviewers and authorised members of the board of examiners. Any publication and duplication of this master thesis - even in part – is prohibited. An inspection of this work by third parties requires the expressed permission of the author and the company HPSNZ/CRNZ.

Chapter 1. Introduction

Background and Rationale

Canoeing, once an indispensable form of transportation for people to navigate oceans and waterways, is now also a competitive endeavor elevated to Olympic status. Although the essential components are similar – boat, paddle, and paddler – canoe racing has evolved into several distinct disciplines. Kayaking, a discipline of paddle sports within canoeing, is distinguished by a double-bladed paddle and a narrow, long-hulled boat. Paddling begins with paddle entry into the water, followed by an aggressive pull phase (T_{Pull}), paddle exit, and a brief recovery phase when both paddles are not in the water (T_{Air}) before opposite paddle entry. Although it may appear that the arms perform much of the force generation, the trunk and leg muscles are also quite active (Brown, Lauder, & Dyson, 2010; Nilsson & Rosdahl, 2016). The paddler transfers the force from the paddle blade through their body and against the boat, causing forward horizontal acceleration (α_{Boat}). Increasing V_{Race} is the goal of kayak sprint, and there are two main ways increase it. Paddlers can increase boat speed by generating greater propulsive impulse or maximising propulsive efficiency (e_p).

As the sport has matured, the boat, paddle, and paddler have been optimised for performance. Innovation in boat construction, paddle design, and athlete training have contributed to a steady improvement in world record performances during the last century (McKenzie & Berglund, 2019, p. 15). The impact of technology upon performance is undeniable, although difficult to quantify. For example, the introduction of the winged paddle in 1986 convinced the majority of athletes to use it in the 1988 Olympics. It took four years for researchers to demonstrate its superiority, claiming 14% better propulsive efficiency over the old "flat" blades (Jackson, Locke, & Brown, 1992). Despite superior performance at the paddle blade, there was an unexpected effect of the new blade style upon athlete technique, causing more lateral blade motion (Jackson, 1995). Unfortunately, paddle innovation, as well as other modern developments in the sport, outpace the understanding of their effect on technique and general biomechanics of canoeing. Only recently has the combination of advanced engineering and advancement in the field of performance analysis enabled the assessment of boat, paddle, and paddler performance.

Kayak sprint racing is measured objectively by time from start to finish. As such, the primary method of performance analysis is overall race time and split times. In the past two decades, coaches and researchers seeking more detailed information have utilised video, GPS accelerometers, and other instrumented components to measure their athletes' performance (Li, 2017). However, these methods are fundamentally flawed: on-water analysis primarily measures boat or paddler movements, but not their causes (kinetics) As in other paddle sports, specialised stationary ergometers have been developed to replicate kayaking. Kayak ergometer testing is ubiquitous for measurement of aerobic capacity and mechanical power output (Bjerkefors, Tarassova, Rosen, Zakaria, & Arndt, 2018; Campagna, Brien, Holt, Alexander, & Greenberger, 1982; Michael, Smith, & Rooney, 2009). Ergometer testing can measure kinetics and physiological capacity (among other performance variables), but its biomechanical specificity to kayaking is debatable (Fleming, Donne, Fletcher, & Mahony, 2012; Michael, Rooney, & Smith, 2008).

The exact biomechanical variables associated with performance are not fully understood. This is due to a paucity of research and technological limitations (McKenzie & Berglund, 2019, p. 21). Ultimately, V_{Kayak} is the product of stroke rate (SR) and stroke distance (distance per stroke, DPS). While there is a well-established positive correlation between SR and V_{Kayak} ($r = 0.76$), the relationship with DPS is less clear (McDonnell, Hume, & Nolte, 2013). Nonetheless, other kinematic and kinetic variables have demonstrated associations with V_{Kayak}, including T_{Pull} ($r = -0.65$), T_{Air} ($r = -0.63$), peak blade force (F_{Peak}, $r = 0.66$), and force-time profile shape (Gomes et al., 2015; McDonnell et al., 2013; Warmenhoven, Cobley, Draper, & Smith, 2018). The evidence for these associations is mixed; diverse study protocols, proprietary analysis devices, and small sample sizes imply that more research is needed.

Purpose and Significance of Research

Instrumented paddle devices have been used in laboratory settings and during on-water paddling (Gomes et al., 2011; Nates & Colloud, 2016; Sturm, Yousaf, Brodin, & Halvorsen, 2013). Until recently, no commercial device was available for this purpose. Instrumentation of the paddle shaft or blade may improve the understanding of biomechanical variables and their relationship to kayak performance. Whilst observation of the system kinematics may be useful, it is affected by other factors such as wind, current, and hydrodynamic drag (D_F). Conversely, paddle kinetics may be less affected by those factors, and provide detailed insights into the neuromuscular demands and power output of the paddler (Higgens et al., 2016; Michael et al., 2009). Not only are such insights useful for analysis, but also for training prescription, as popularised in cycling (Bini & Diefenthaeler, 2009) and rowing (Hofmijster, Landman, Smith, & Van Soest, 2007). For that purpose, an instrumented paddle would need to fit specific design guidelines. It must be waterproof, light, unobstrusive, technologically sound, and identical or superior in performance to athletes' normal paddle (Aitken & Neal, 1992; Lok, 2013). HPSNZ have developed an instrumented paddle device (SP) that fits the above specifications. After years of development, this research project was proposed to evaluate the value, potential, and accuracy of the SP. Although the SP had been in use with CRNZ for many months, its validity and reliability has not been assessed in a scientifically sound manner. If the paddle can be found to be accurate, then it could be used for advanced performance analysis. An accurate instrumented paddle could examine many of the current gaps in the literature including: ergometer task specificity, kinetic determinants of boat speed (V_{Kayak}), and proposed hypothetical performance variables. Therefore, a sound scientific method of evaluating the SP and these other aims has been developed in partnership with HPSNZ and CRNZ to advance the understanding of the tool and kayaking biomechanics.

Thesis aims

The specific aims of this thesis were to:

1) Determine the accuracy of the SP device in comparison to a reference device
2) Use the SP device to compare paddle biomechanics during ergometer and on-water paddling
3) Determine the association between biomechanical variables measured by the SP and boat kinematics measured by a GPS accelerometer during an on-water paddling
4) Assess the value of the SP for performance analysis of kayak for HPSNZ and CRNZ.
5) Provide future research direction for HPSNZ, CRNZ, and others in paddle sports.

Thesis organization

This thesis is presented in a pathway two format. It is a collection of six publication style chapters, including a narrative literature review (chapter 2) and three experimental chapters (chapters 3, 4, and 5), and a general discussion with practical applications (chapter 6).

Chapter 2: A narrative review of published literature related to the background, mechanics, and performance analysis of kayak sprint. After a thorough description of the sport its basic principles, biomechanical variables associated with performance are discussed. Important technologies for analysing kayak performance are presented to understand the innovation ecosystem within the sport.

Chapter 3: An observational study evaluating ergometer paddling with multiple technologies. The popular Dansprint ergometer was instrumented with a custom strain gauge system and compared against the SP to determine comparative validity and reliability. An experimental protocol was developed to examine the spectrum of paddling intensities experienced during training and racing. This chapter was necessary in order to understand the accuracy of the SP device before performing the other studies in Chapters 4 and 5.

Chapter 4: An observational study comparing ergometer and on-water paddling biomechanics. The experimental protocol from Chapter 3 was repeated on-water with the SP. The kinematic and kinetic differences between the on-water and Chapter 3 data were measured across intensities using the SP.

Chapter 5: A study examining the relationship between SP outputs and resultant boat movement during on-water paddling. The protocol from Chapter 3 was used with a larger sample participating in data collection. This study builds upon existing literature suggesting hypothetical and measured correlations between biomechanical variables and V_{Kayak}. Other investigations were performed to examine the association between V_{Kayak}, BM, D_F, and efficiency.

Chapter 6: A general discussion, with practical applications for paddle sports, future research directions, and specific recommendations for CRNZ.

This thesis is formatted in APA (American Psychological Association) 6th style. Because it is formatted for publication the chapters are designed as standalone documents. As such, there is some overlap and repetition of content. Specifically, Chapters 2 and 3 both summarise many of the technologies used in kayak performance analysis, although Chapter 3 includes more detail on their accuracy and validity. Similarly, Chapters 2 and 5 both review the reported biomechanical variables associated with kayak performance; Chapter 5 includes an abbreviated summary. Chapters 3, 4, and 5 all utilise the same paddle protocol and similar variable selection processes, but the latter two recap critical details and slight changes unique to that study. Chapter 6 summarises many of the findings of Chapters 3, 4, and 5, but they are described in context of their practical application and future study for CRNZ.

This thesis was funded in part by a scholarship on behalf of AUT and HPSNZ. Because HPSNZ considers the SP a competitive edge, any research outputs were considered sensitive and classified. Therefore, the content within this thesis will not be eligible for publication until after the 2020 Summer Olympics. Then these chapters will be re-evaluated by the authors for publication.

Chapter 2. Biomechanics of Kayak Sprint: A Narrative Review

Abstract

Canoeing has evolved from a transportation method to an internationally-recognised multidisciplinary competitive sport. Its growing popularity over the last century has led to significant innovation and professionalism in attempts to improve performance. However, there is discordance within the sport regarding the best methods and techniques to do so. In order to understand performance, an intricate knowledge of boat, paddle, and paddler mechanics must be established. This review begins by summarising the sport of kayak sprint and its basic physical principles before detailing the factors that are most closely related to kayak performance and boat velocity (V_{Kayak}). Key performance indicators have been studied in detail, though much more so for kinematic variables than kinetics. Exactly how these variables affect propulsive impulse and propulsive efficiency has been implied, but not yet studied. The paucity of information in this field could be due to the lack of accurate, accessible assessment tools, of which previous ones are discussed. Luckily, there is a greater depth of literature among the wider spectrum of paddle sports (e.g. rowing, canoe sprint) that lend valuable additional insights. This review will define performance and summarise the strategies that sports biomechanists have employed to answer the question, “what makes a boat go fast?”

History

Humans are naturally drawn to water as the primary source of life. The creation and use of watercraft allowed for travel over the water in ways that feet and hooves cannot, enabling exploration, hunting, fishing, and trade for humans in earlier times (Malm, 1995). Boat design has evolved significantly in the few millennia; evidence of dragon boating dates back to China over 2000 years ago, and records of Māori waka indicate over 500 years of history in New Zealand (Johns, Irwin, & Sung, 2014; McKenzie & Berglund, 2019). Canoes are woven into the foundational myth of North America, where they enabled early colonists to travel along the many inland rivers for trapping, trade, and migration.

In New Zealand, Māori waka finds dating to the 1400s demonstrate advanced building techniques producing sophisticated craft comparable to Polynesian voyaging watercraft of that era (Johns et al., 2014). Traditional waka were constructed using a Totara tree selected by hapū. The building process took up to one year, with the final product weighing up to three tonnes, and capable of service for many decades (O'Malley, 2013). Types of waka include waka taua (war canoes) and waka ama (outrigger); the latter were common in historical records from the early 18th century. After the arrival of European settlers, Māori acquired new materials for waka construction and appear to have abandoned traditional construction techniques altogether to adopt European styles. Despite the relative disappearance of traditional waka ama from New Zealand in the early 20th century, there has been a large resurgence in waka ama construction in the last 40 years in the South Pacific, with outrigger racing one of the largest growing types of boat racing.

After the second industrial revolution, the boom in recreational sport inspired a new passion in North America and Europe for racing canoes and kayaks. The first racing clubs in the Western hemisphere were the Royal Canoe Club in England (1866) and the New York Canoe Club (1870), amongst others in Canada and Eastern Europe (McKenzie & Berglund, 2019). Yearning for organised international competition, a wave of multinational meetings sprang up in Northern Europe. The Internationale Repräsentantenschaft Kanusport (IRK) congresses in Denmark during the early 20th century eventually became the International Canoe Federation (ICF) which now governs and leads the world of canoe and kayak competition. Since the inclusion of canoe racing in the 1924 and 1936 Olympics, it has become more competitive, with modern, creative approaches towards winning and going faster.

Flatwater sprint kayaks race head-to-head over 200, 500, and 1000m distances. In competition, it is common for athletes to race up to three times per day in various individual heats and team boat events. Success is primarily dependent on strength, technique, and fitness to improve times (M. B. Brown et al., 2010; Laurent et al., 2013; Nilsson & Rosdahl, 2016). Technological innovation has also contributed partial advantages. Boat design, winged paddles, and peripherals improvement coincided with rapid improvement in world record times over the last 60 years (MK1 1000m, 50 seconds faster between 1956-2008) (Michael et al., 2009). New devices and research approaches have identified core mechanical principles, key performance indicators (KPIs) and novel technologies to advance understanding of the sport and elite performance (Li, 2017).

Mechanics

An understanding of paddling technique and boat mechanics is required for any athlete, coach, or scientist to analyse and improve performance. Athletes' paddling style emerges as a result of individual anthropometrics, strength, flexibility, balance, stability, and other individual and equipment constraints (McKenzie & Berglund, 2019, p. 18). Unfortunately, for athletes and practitioners within kayak, there is a lack of research surrounding what factors constitute and influence ideal technique and what modifications might be most impactful. A universally ideal paddling technique likely does not exist as large inter-individual differences can be seen even at elite levels of the sport (López López & Ribas Serna, 2011). Additionally, there is no consensus upon optimal equipment setup (such as seat-to-footbar distance and paddle size), further complicating progressive performance improvement. Regardless, to improve performance, paddlers must look to increase effectiveness and efficiency as much as possible within their unique constraints.

Fluid dynamics

The physical behavior of water in contact with the boat and paddle blade is integral to resultant kinematics and kinetics. Water creates drag forces (D_F) upon the boat and paddle, composed of both passive (D_P) and active drag (D_A). D_P describes the drag forces associated with a boat travelling through water at an average speed V_{Race}. This value is an estimated sum of friction, wave, and pressure drag forces as a function of V_{Kayak} (Gomes et al., 2017). It is largely determined by the wetted area of the kayak, but also linked to water temperature and the Reynolds number (friction) inherent in the properties of the boat surface. The wetted area of the kayak is affected by system mass, boat movement, and boat shape (Jackson, 1995). D_P has been modeled and measured for various forms of aquatic locomotion (Pendergast et al., 2005) and for sprint kayaks (Gomes et al., 2015; Jackson, 1995). Ultimately, boat design limits D_P reduction; ICF rules and manufacturing capabilities prevent innovation in, for example, superhydrophobic coatings or ultralight materials (Gomes et al., 2017). D_A is similar to D_P but encompasses the added drag forces created by aberrant boat movements during locomotion: yaw, roll, pitch, heave, sway, and surge (Figure 1). These forces have been measured by Pendergast et al. (2005) and are further described in Table 1. Aerodynamic drag also affects the boat and the paddler, but is less than 10% of total drag, and is considered fixed and negligible (Jackson, 1995). In summary, constant V_{Kayak} only occurs when the total D_F is opposed by equal and opposite propulsive forces. Thus, to increase V_{Kayak}, one must either increase propulsive power (P_{Mean}) or paddling efficiency (e_p) (via drag reduction).

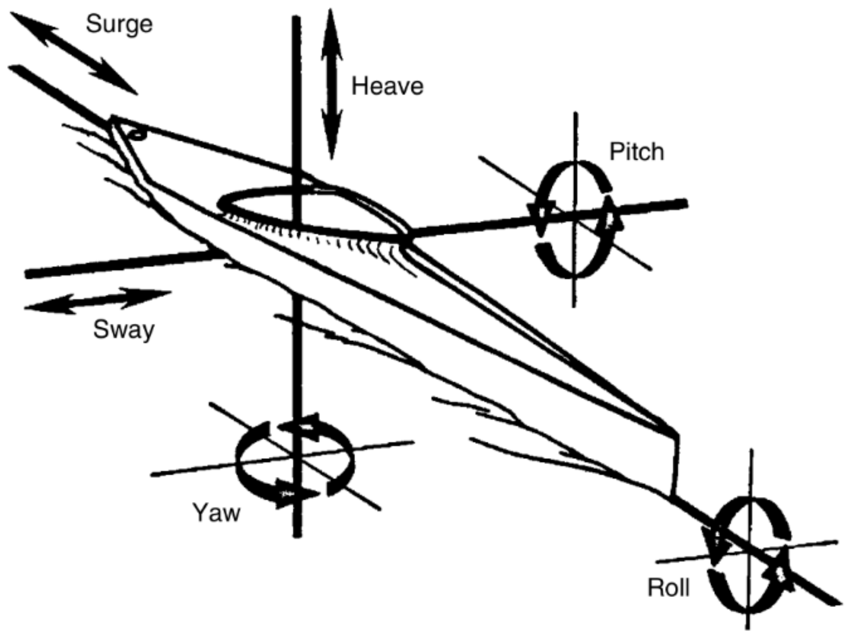

Figure 1. Boat movements of a kayak

Reprinted from "Canoeing: An Olympic Sport" by Toro, A. (1986) Olympian Graphics.

Table 1. Boat movements and their causes

Boat movement	Detail
Pitch	Caused by forward and backward body movements during the stroke, and the direction of forces applied by the paddle, particularly at the end of the pull. Increases in pitch have a large effect on drag.
Roll	Caused by the lateral movement of the centre of mass in relation to the base of support (i.e. the seat and paddle, while the paddle is in the water).
Yaw	Caused by the off-centre application of paddle forces. This can increase as the blade is moved away from the boat in kayaking. In canoeing, the yawing is kept to a minimum when the blade is kept close to the boat.
Heave	Caused by the vertical movement of the centre of mass during the stroke. More significant in canoeing during the transition from one stroke to the next.
Sway	The lateral movement of the boat during paddling. Most common in the K4.
Surge	This is desired movement as a direct result of paddle forces, and it can be modified by the forward and backward movement of the body during paddling.

Notes. Movements shown with reference to kayak in Figure 1. Reprinted from "Canoeing: International Canoe Federation," by McKenzie, D., & Berglund, B. (2019), p. 21.

Propulsion

The kayak paddle is effectively the only means of forward momentum available to the paddler. When placed in the water, movement of the blade surface creates drag and lift forces proportional to surface area and blade velocity (V_{Blade}). The component of horizontal force parallel and longitudinal with respect to the boat is opposed by the paddler, thus causing forward acceleration of the boat. Thus, the paddler remains relatively fixed in the water while the boat is moved forward past the blade. The ratio of propulsive impulse that is translated into forward momentum, though, is modulated by blade slip and propulsive efficiency (McKenzie & Berglund, 2019, p. 23; Morgoch, Galipeau, & Tullis, 2016).

Blade slip is an unavoidable outcome of the kinetic energy lost at the blade surface during paddling. Theoretically, zero blade slip would equal perfect force transmission; however, observable posterior displacement of the paddle relative to the boat occurs during all paddling (Figure 2). As a result, greater blade slip reduces boat displacement during a given stroke (McKenzie & Berglund, 2019, p. 22). However, the magnitude of slip has been observed between 1-33cm amongst elite paddlers, suggesting that large inter-individual variability exists (Fernandez-Nieves & De Las Nieves, 1998). This could contribute to the lack of research surrounding this important topic. It has been reported that blade slip is greatest during the first 1/3 of the pull phase of the stroke, and negative slip (anterior displacement relative to the boat) occurs during the middle 1/3 of the pull. The calculation of drag (Equation 1) suggests that other factors of blade drag and resultant slip invite further investigation, such as water temperature, blade size, V_{Blade}, materials, and blade orientation. Paddle orientation, for example, could have a substantial impact on blade slip and resultant forces if not parallel to the desired direction of movement; this is discussed later.

Equation 1. Calculation of blade drag force

$$F_D = 1/2 \rho A v^2 C_d$$

Where F_D is the drag force, which is the force component in the direction of V_{Blade},

ρ is the mass density of the fluid,

v is the blade velocity relative to the water,

A is the surface area, and

C_d is the drag coefficient – a dimensionless variable related to shape, surface friction, and form drag. In general, C_d depends on the Reynolds number.

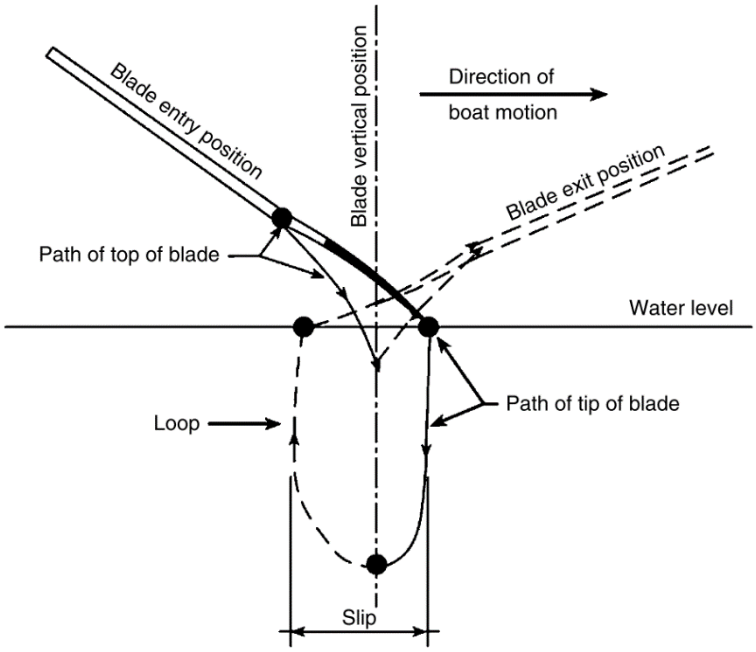

Figure 2. A sagittal view of blade-water dynamics during the paddle stroke

Adapted from "About the Propulsion System of a Kayak and of Basiliscus Basiliscus," by Fernandez-Nieves, A., & De Las Nieves, F. (1998), European Journal of Physics, 19(5), 425.

Propulsive efficiency describes the amount of paddler power output that causes horizontal α_{Kayak}. As stated above, zero blade slip would result in perfect propulsive efficiency equal to 1 (Equation 2). However, kinetic energy is always lost at the blade, and its loss increases proportionally to V_{Blade} and mass of water moved (blade area).

Equation 2. Definition of biomechanical propulsive efficiency

$$e_p = P_D/P_O$$

Where e_p = propulsive efficiency,

P_D = power needed to overcome D_F, and

P_O = total power output of the paddler.

Propulsive paddling efficiency is increased by reducing D_F or blade slip. The former may be achieved through reduced BM or reduction of aberrant boat movements. Indeed, Jackson (1995) reported that modeled kayak performance could increase velocity as much as 0.8% through a reduction of BM by 3%. Yaw, roll, and pitch appear to have the greatest effect on active drag

(D_A), although their relationship with V_{Kayak} is dependent on individual, equipment, and environmental constraints (McKenzie & Berglund, 2019, p. 25; Vadai & Gingl, 2016). A governing factor for such boat movements also affects blade slip: paddling technique. As observed in elite paddlers, lateral paddle movement may reduce blade slip and kinetic energy loss (Caplan, 2009, p. 25; McKenzie & Berglund, 2019). This characteristic appeared after the introduction of the winged paddle and warrants further investigation due to its inferred positive effect upon e_p.

Forces

Kayak sprint is characterised by large, high sustained forces and clear phases of boat acceleration and deceleration. F_{Peak} in elite athletes has been reported as 290 and 375 N for females and males, respectively (Sperlich & Baker, 2002). Gomes et al. (2015) added to this normative data by reporting F_{Peak} across a range of SR; from 60-124 strokes per minute, F_{Peak} was 126-153 N and 225-274 N for females and males, respectively. These data match estimated and measured D_F, supporting their validity (McKenzie & Berglund, 2019, p. 25). Specifically, if propulsive impulse and total drag force must be equal during constant velocity paddling, then their measurement as equal is biomechanical proof of their magnitude. Other characteristics of elite paddlers are kinetic asymmetries and early vertical paddle shaft orientation. Though the former is a common attribute of elite athletes, the latter is a less studied and potentially significant technique nuance (McKenzie & Berglund, 2019, p. 28). In elite paddlers, vertical shaft orientation occurs at around 1/3 duration of the pull phase (Figure 3). Coincidentally, this is also when F_{Peak} occurs. The resolution of force vectors highlights why vertical shaft orientation is so important: when the paddle is not 90º from horizontal, vertical blade forces are created, resulting in boat pitch (Figure 4). Pitch increases D_A, thus decreasing e_p. Although shaft and blade orientation are always a limiting factor, the amount of individual variation and potential for technique modification is unclear.

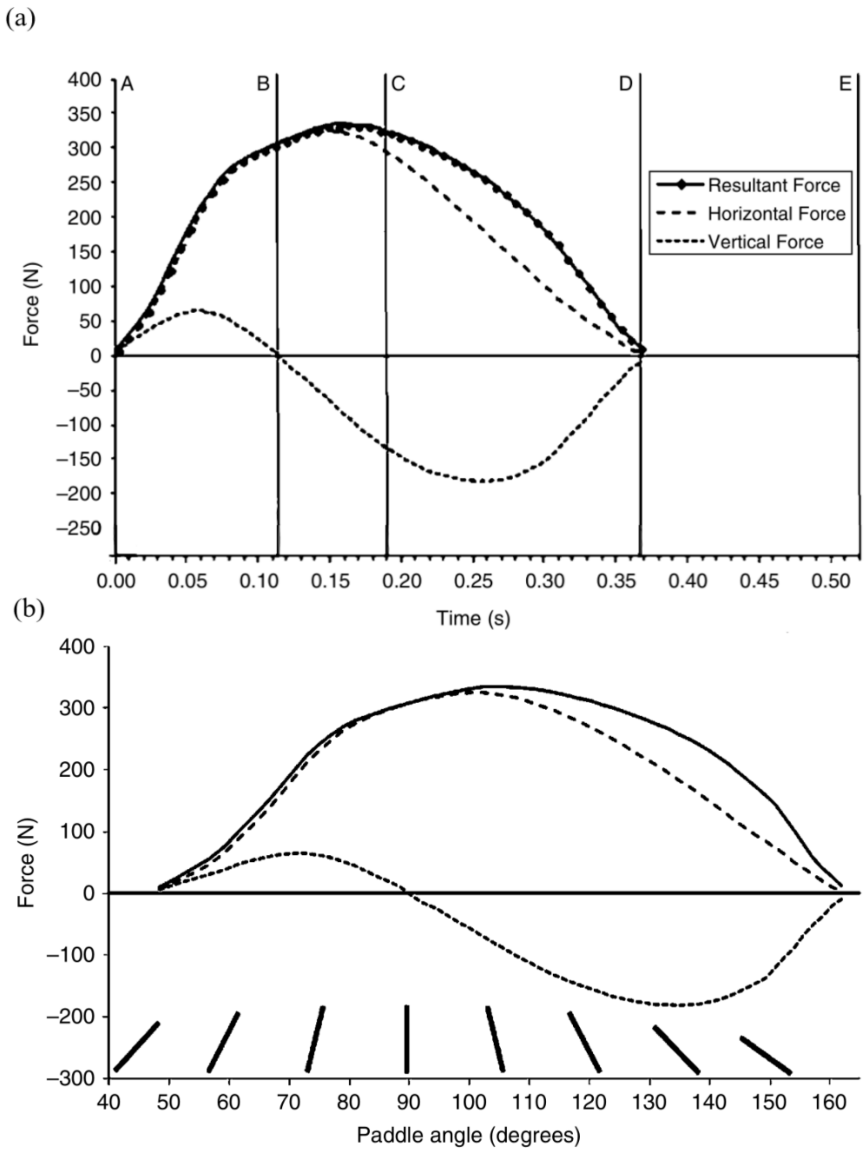

Figure 3. Blade force profiles of an elite kayaker

Typical average resultant (solid line), horizontal (dashed line), and vertical (dotted) paddle force from an international-level kayaker at 500m race pace. (a) Force-time curve. The data shown are from the start of the stroke to the beginning of the next (opposite side) stroke. A, contact; B, paddle *vertical; C, point of maximal V_{Kayak}; D, release; E, contact. (b) Force-angle curve in relation to the sagittal plane paddle angles (illustrated on chart).*

Adapted from "Canoeing: International Canoe Federation," by McKenzie, D., & Berglund, B. (2019), p. 27-29.

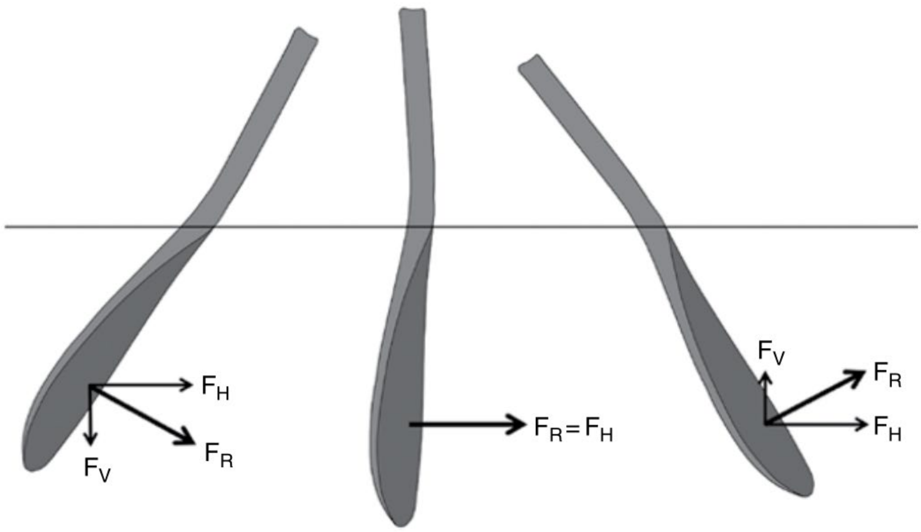

Figure 4. Blade force components at different paddle shaft angles

Component of blade force showing resultant force (F_R), horizontal force (F_H), and vertical force (F_V). When blade force is vertical, horizontal force is equal to the resultant force.

Adapted from "Canoeing: International Canoe Federation," by McKenzie, D., & Berglund, B. (2019), p. 24.

During paddling, other critical forces occur at the footrest and seat, the only points of contact between paddler and boat. Foot forces equal or greater than blade force occur at or just before paddle entry into the water (Nilsson & Rosdahl, 2016). The feet have opposing action, with the ipsilateral side pushing, and the contralateral side pulling. This causes pelvic rotation, and, subsequently, trunk rotation, which increases paddle force (Mickaël Begon, Colloud, & Lacouture, 2008). It has been reported that pelvis rotation contributes 6% of the propulsive force, and leg action contributes 16-21% of total force (M. B. Brown et al., 2010; Klitgaard, de Zee, & Hansen, 2018; Nilsson & Rosdahl, 2016). There is a need for thorough investigation of the complex interplay of these forces and their relation to V_{Kayak} and e_p.

Key Performance Indicators

Small improvements in race time (0.3-0.6%) can mean the difference between achieving a podium or not (Bonetti & Hopkins, 2010). Ultimately, the athlete wins who has the highest average speed over the race distance. According to McDonnell et al. (2013) this is termed average race velocity (V_{Race}) (Brown, Lauder, & Dyson, 2011). This is not to be confused with mean kayak velocity (V_{Kayak}), the average boat travelling speed during one stroke cycle (Hay & Yanai, 1996). In order to properly appraise race performance, the inverse transformation from time into race velocity is prudent to create a normal distribution for analysis (Nevill & Whyte, 2005). Thus, increased V_{Race} is the overall goal of kayak sprint. However, it is derivative from average V_{Kayak} and the many ways of achieving a positive (or negative) result; the factors influencing V_{Kayak} help explain the KPIs of kayak sprint. Generally, performance enhancement fits into the following categories: propulsive efficiency, improved technique, increased kinetic output, D_F reduction, and equipment design. Kinematic and kinetic variables affect all these aspects in diverse ways; the strongest and most relevant variables are discussed here.

Various kinematic factors have strong correlations with V_{Kayak}; the most commonly studied are stroke timing, paddle displacement, velocity, and orientation, and body range of motion (Li, 2017; Lok, 2013). There has been much investigation by temporal and stroke phase analysis of the paddle stroke, which is summarised succinctly by McDonnell et al. (2013) Figure 5. Naturally, V_{Kayak} = stroke distance (DPS) / time (T_{Stroke}); this may be rewritten as DPS * SR (McDonnell et al., 2013). SR is easily calculated as the inverse of T_{Stroke}, represented in strokes per minute (spm). Both SR and DPS are universal terminology in sprint kayak and will be used henceforth.

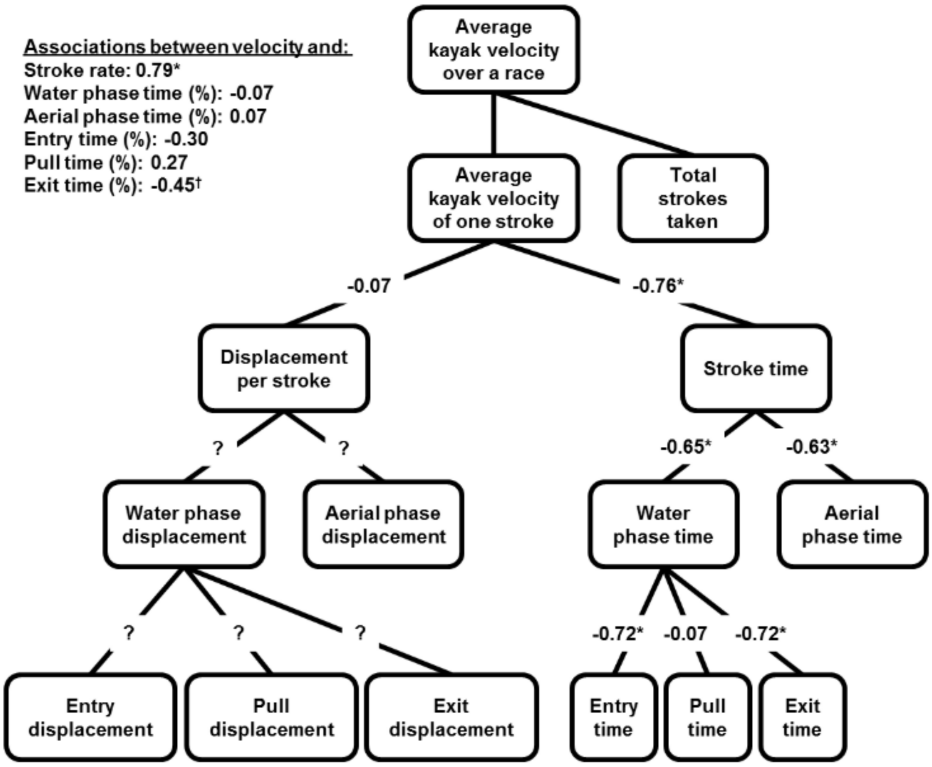

Figure 5. Kinematic determinants of kayak sprint

**Indicates statistical significance, $p < 0.05$; † non-significant, but a likely correlation. Additional correlations were calculated for common related variables: SR and relative phase times as a percentage of the stroke cycle*

Adapted from "The Effect of Stroke Rate on Performance in Flat-Water Sprint Kayaking," by McDonnell, L. (2013), Auckland University of Technology. Retrieved on 14 December 2018 from http://aut.researchgateway.ac.nz/handle/10292/6028

The association between V_{Kayak} and SR is self-evident and well-supported in the literature (Baudouin & Hawkins, 2002; Hofmijster et al., 2007; McDonnell et al., 2013). This is directly related to increased propelling efficiency and decreased power loss (Greidanus, Delfos, & Westerweel, 2016; Hofmijster et al., 2007; Kleshnev, 1999). Also, it appears that elite paddlers are able to produce incrementally more force as SR increases (Macdermid & Fink, 2017). There appears to be a ceiling to increasing SR, though, where physiological (Baudouin & Hawkins, 2002) and technical (McDonnell, Hume, & Nolte, 2012b) variables impose an upper limit, suggesting that there exists an optimal SR unique to each athlete. Nevertheless, there is strong consensus for increasing V_{Kayak} by increasing SR; a synopsis of the related literature (McDonnell et al., 2013) reported a mean correlation of $r = 0.66$, $p < 0.01$, with correlations as high as $r = 0.89$ (Mononen & Viitasalo, 1995) when eliminating outlier studies (Brown et al., 2011).

Increasing either SR or DPS would have a positive effect on V_{Kayak}. However, DPS fundamentally decreases as SR increases, a phenomenon well-known by coaches and in research (Bourgois, Vrijens, Verstuyft, Zinzen, & Clarijs, 1998; Hay & Yanai, 1996; McDonnell et al., 2013). It is possible that DPS naturally decreases because of shortened phase times and a smaller window for force production (Brown et al., 2011; Nakashima, Ito, & Nakagaki, 2019). Select studies have reported a strong relationship between DPS and V_{Kayak} when controlling for SR ($r = -0.77$, $p < 0.05$ for a subsample) (Baker, Rath, Sanders, & Kelly, 1999), but the evidence is mixed, with most studies showing no correlation ($r = -0.19$, $p = 0.62$) (Kendal & Sanders, 1992). More research is needed to clarify the relationship between DPS and V_{Kayak}, especially as SR increases.

Stroke Phase Parameter Analysis

Maximising the pull time between blade entry and exit (T_{Pull}) is essential for increasing propulsive efficiency (Figure 6) (Kendal & Sanders, 1992). Absolute T_{Pull} had a strong negative correlation with V_{Kayak} among elite paddlers ($r = -0.83$, $p < 0.05$) (Hay & Yanai, 1996), explained by the decrease in T_{Stroke} and increase in SR at higher speeds. Relative T_{Pull} (T_{Pull} / T_{Stroke}, pull %) is perhaps a more important parameter considering that T_{Air} is non-propulsive and negatively affects V_{Kayak}. Observed values range from 50 to 70% among international-level competitors (Brown et al., 2011; Hay & Yanai, 1996; Kendal & Sanders, 1992). Theoretically, longer relative T_{Pull} would imply that a greater percentage of T_{Stroke} is generating F_X, and, therefore, horizontal α_{Kayak} (Brown et al., 2011). Shorter T_{Pull} could mean higher V_{Blade}, contributing to a greater velocity component of P_{Mean} (F_{Mean} * V_{Blade}).

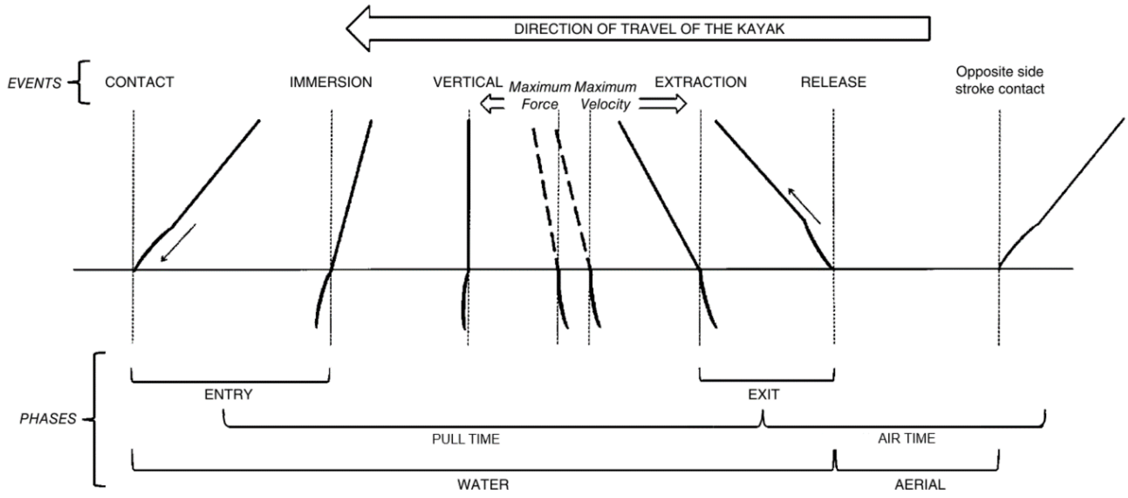

Figure 6. Events and phases of the kayak paddle stroke

There is individual variation in the length and location of some events, especially F_{Peak} and peak V_{Blade}.

Adapted from "Canoeing: International Canoe Federation," by McKenzie, D., & Berglund, B. (2019), p. 30.

Intuitively, one of the most effective ways to improve propulsive efficiency is by maximising force transmission from blade to water. As discussed earlier, this may be achieved by keeping the blade surface perpendicular to the boat and the paddle shaft vertical for as long as possible (Aitken & Neal, 1992; Morgoch et al., 2016). Thus, the drag force upon the blade is acting entirely horizontal to the boat, optimising the efficiency during T_{Pull}. Another way to achieve this specific technique is through longer forward reach and less draw past the hip, preventing detrimental pitch forces near stroke exit (Gomes et al., 2015; Kendal & Sanders, 1992; Wainwright, Cooke, & Low, 2016). Although modelled data suggest that this stroking style is superior, the ideal stroke length, entry, and exit points have not been examined.

Theoretically, minimisation of T_{Air} should increase e_p. During the recovery phase (air time, T_{Air}), neither paddle is in the water, so D_F causes horizontal kayak deceleration (Mann & Kearney, 1980). Because higher SR and pull % are both associated with faster V_{Kayak}, then shorter absolute and relative T_{Air} would be effective strategies to go faster (Brown et al., 2011; McDonnell, Hume, & Nolte, 2013). Hay and Yanai (1996) reported mixed results regarding the strength of the correlation between T_{Air} and V_{Kayak}. Normative data ranges quite significantly (absolute = 0.13-0.30s; relative = 28-56%), implying that research methodology or measurement methods vary substantially (Brown et al., 2011; Hay & Yanai, 1996; Kendal & Sanders, 1992; Qiu, Wei, Liu, & Cao, 2008). Ideally, future studies could benefit from continuously improving technology and examine the effect of increasing SR and other constraints upon absolute and relative phase durations.

Paddle Kinetics

Although kinematic measurements have significant relationships with kayak performance, it is critical to examine the forces that cause motion. As kinematics describe the resultant outputs of performance, kinetics illuminate the source of those movements. Paddle force was theorised to be one of the primary determinants of V_{Kayak}; only the investigation of recently developed instrumented paddles (Macdermid & Fink, 2017; Tullis, Galipeau, & Morgoch, 2018) have allowed the accurate measurement of it in situ. Many training interventions attempt to improve propulsive impulse, but increases in impulse amongst elite athletes are not necessarily correlated to improved performance (McKenzie & Berglund, 2019, p. 32). This could be due to blade slip or other technique factors. However, there is mounting evidence demonstrating the strong relationship between paddling power (Macdermid & Fink, 2017), F_{Peak}, mean force (F_{Mean}), force-time profile shape (squareness, the F_{Mean}/F_{Peak} ratio (Gomes et al., 2015); smoothness (Figure 7, (Hill, 2002)), and impulse during first 1/3 of pull phase (Wainwright et al., 2016). For example, the F_{Mean}/F_{Peak} ratio reveals the importance of a more "rectangular" force-time profile, or greater proportion of the T_{Pull} near peak force. Increasing this ratio is one method of improving the e_p of the pull phase. Nonetheless, the exact relationship between paddle kinetics and V_{Kayak} is complicated; more research is needed to examine whether these kinetics cause greater V_{Kayak}, or simply increase concurrently. As suggested by (Pendergast et al., 2005; Pendergast et al., 2003), perhaps the relationship [between paddle kinetics and V_{Kayak}] should be understood as what forces are required to overcome D_F occuring at a given speed. In this way, paddling kinetics can be examined as a function of speed (as plotted in Figure 8). On the other hand, the relationship between paddle kinetics and α_{Kayak} may be different. As reported by Wainwright et al. (2016), blade impulse during the first 2/3 of the stroke is associated with increased α_{Kayak} ($R^2 = 0.27$-0.38). There is also a theoretical basis for increasing the "smoothness" of the force-time profile, defined as any deviation from the naturally parabolic shape of the force-time curve. Visible in a force-time curve, these deviations could cause unwanted boat deceleration, or indicate improper force transfer between paddler and boat (Figure 9) (Hill, 2002; Warmenhoven et al., 2018). More studies are needed to delineate the relationship between paddle kinetics and V_{Kayak} versus α_{Kayak}, especially considering the large number of added extraneous factors affecting the boat between each stroke (e.g., hull yaw, enviromental affects) (Lok, 2013; Nakashima, Kitazawa, Nakagaki, & Onoto, 2017).

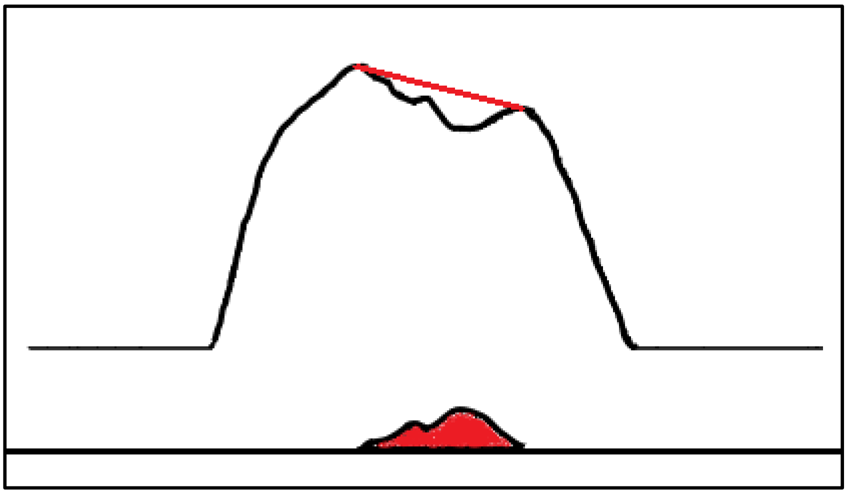

Figure 7. Computation of force-profile smoothness

Red line connects two local maxima with deviation in between. The shaded difference area related to the force pattern area provides the value for smoothness.

Adapted from "Dynamics of Coordination Within Elite Rowing Crews: Evidence from force pattern analysis," by Hill, H. (2002), Journal of Sports Sciences, 20(2), 101-117.

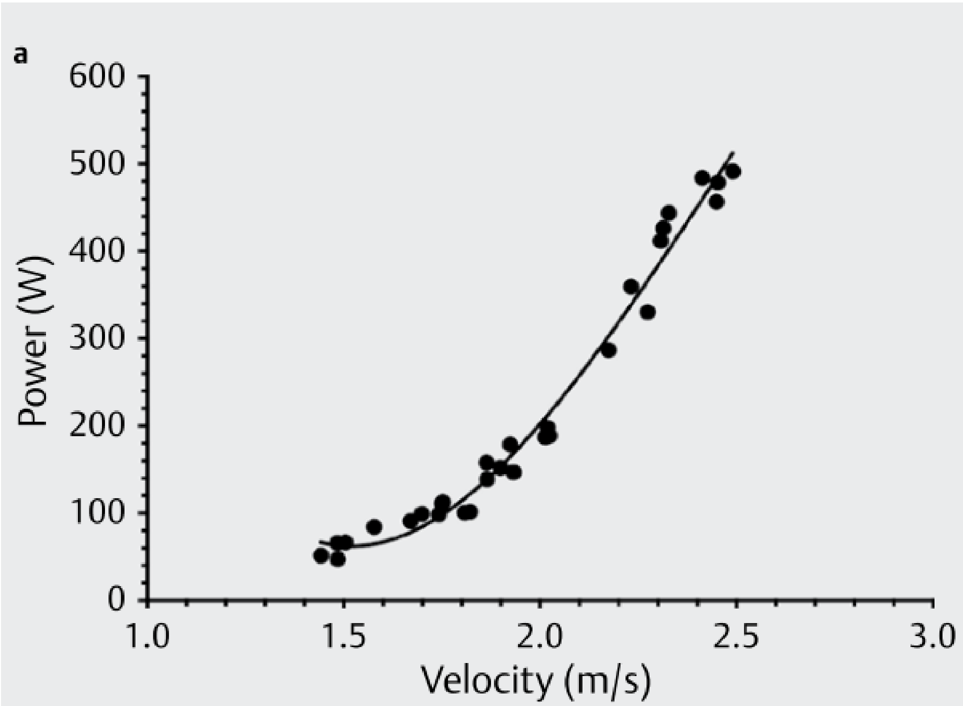

Figure 8. Relationship between V_{Kayak} and paddle power

Reprinted from "The Validation of a Paddle Power Meter for Slalom Kayaking," by Macdermid, P. W., & Fink, P. W. (2017), Sports Medicine International Open, 1(02), 50-57.

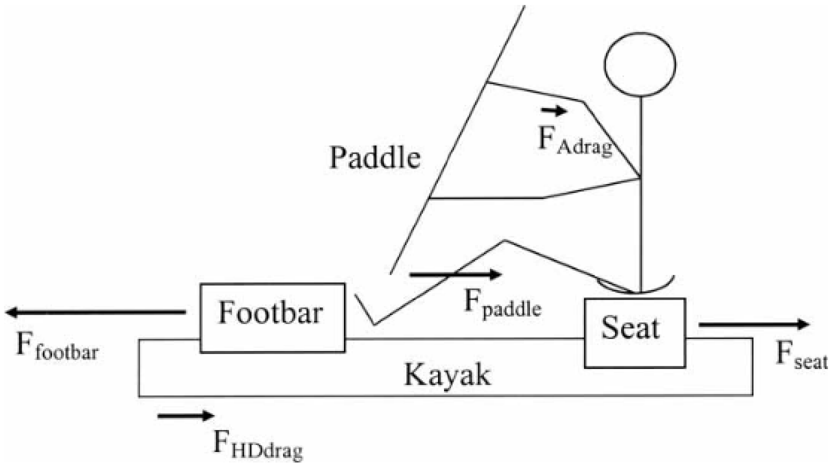

Figure 9. Kinetic components of the kayak-athlete-paddle system

Reprinted from "Science and Medicine of Canoeing and Kayaking," by Shephard, R. (1987), Sports Medicine, 4(1), 19-33.

Paddle kinetics are only responsible for part of the system dynamics; as described earlier, the forces at the footbar and seat are also important. As drawn in Figure 9, the only force vector acting in the direction of desired boat movement is that of $F_{footbar}$. Therefore, that force must be greater than the summed forces in the opposite direction to accelerate. The leg action that generates $F_{footbar}$ is visually apparent when viewing kayak sprint racing. The importance of footbar forces has been well-established in other paddle sports (Baudouin & Hawkins, 2002; Cabrera, Ruina, & Kleshnev, 2006; Kleshnev, 1999). Only one study on sprint kayak could be found measuring $F_{footbar}$ on-water, suggesting a strong relationship ($p < .05$, ES = 1.7-1.9) between leg action and V_{Kayak} (Nilsson & Rosdahl, 2016). Force transfer from blade to boat affects propulsive impulse and e_p. Any residual force difference between these forces is an inefficiency that could be measured with proper research methodology. While maximum friction between paddler and seat would be desired for optimal force transfer, rotation of the paddler upon the seat may be ideal for aiding trunk rotation. There are currently no published studies examining the cumulative effects of the forces described in Figure 9.

Beyond the dynamic variables described here, other established relationships exist between static variables and kayak performance. Although not a primary determinant, details such as paddler mass and kayak shape could affect D_F, and, thus, DPS and V_{Kayak} (K. A. van Someren & Howatson, 2008). Seat development has been on area of recent innovation; swivel seats appear to improve paddler power output by up to 6.5% for elite paddlers. (Michael, Smith, & Rooney, 2010). This could be due to greater trunk range of motion without compromised seat-paddler friction for force transfer. More aspects of performance are listed in Table 2 that warrant further investigation.

Table 2. Physical characteristics with potential effects on kayak performance

Category	Characteristics
Paddler	Anthropometry, strength, physiology
Kayak	Material, size, shape, seat, footbar, rudder design
Paddle	Material, length, grip, shaft shape, rotation offset, blade shape, blade surface area

Notes. Reprinted from "A Deterministic Model Based on Evidence for the Associations Between Kinematic Variables and Sprint Kayak Performance," by McDonnell, L., Hume, P., & Nolte, V. (2013). Sports Biomechanics, 12(3), 205-220.

Technologies

Performance and technique analysis of paddle sports has expanded rapidly in the last 25 years. Early approaches used video (Mann & Kearney, 1980) and ergometers (Campagna et al., 1982) for gathering valuable athlete data. Now, research is divided between study of the paddler and the boat (Lok, 2013). Research and practical applications have examined pacing strategies (Bishop, Bonetti, & Dawson, 2002; Robinson, Holt, Pelham, & Furneaux, 2011; Ualí et al., 2012), boat kinematics (Janssen & Sachlikidis, 2010; Sturm, Parida, Larsson, & Isaksson, 2011; Vadai & Gingl, 2016), boat and blade hydrodynamics (Higgens et al., 2016; Morgoch et al., 2016), 3D athlete kinematics (Limonta et al., 2010; Wang, Wang, Zhao, Yang, & Fortino, 2016), stroke kinetics (Gomes et al., 2015; Macdermid & Fink, 2017; Nates & Colloud, 2016; Sturm et al., 2013), EMG muscle activity (M. B. Brown et al., 2010; Nilsson & Rosdahl, 2016), and training equipment (Jackson, 1995; Kendal & Sanders, 1992; Nolan & Bates, 1982). Additionally, rowing research has inspired many studies within canoe/kayak and there are many similarities (boat hydrodynamics, paddle kinetics) (Harfield, Halkon, Mitchell, Phillips, & May, 2014; Hume, 2017). Accordingly, this review will summarise relevant technologies for kinematic and kinetic analysis used in all paddle sports.

Compared to other cyclic racing sports (cycling, rowing), kayak sprint performance may be more difficult to quantify and examine scientifically. First, the environment is an open, dynamic system with current, wind, and other effects upon the paddler and their performance (Li, 2017; Nakashima et al., 2019). Second, the centre of the paddle is freely moving through space during paddling, which may complicate the calculation of accurate paddle dynamics (Aitken & Neal, 1992). Moreover, analysis techniques such as video are powerful but time-intensive and challenging to implement for coaches (Brown et al., 2011). The complexity of unilateral leg drive (hidden within the cockpit), multi-axis boat motion (Figure 1), equipment constraints, and individual variability also contribute to the relatively small body of research surrounding kayak biomechanics (Mickaël Begon et al., 2008; Lok, 2013). Finally, the variety of experimental protocols and measurement devices used in biomechanical research of paddle sports complicates the replication and assessment of previous work (Macdermid & Fink, 2017). Because of the environmental and task complexity of paddle sports, ergometers are a popular and accessible means of performance assessment (Nevill, Beech, Holder, & Wyon, 2010; Paton & Hopkins, 2006).

Ergometers

Ergometers are ubiquitous for training, especially in the Northern hemisphere when winter prevents outdoor paddling. Several commercial ergometers have been developed specifically for kayaking to replicate the mechanics and demands of paddling (Figure 10). They are also the primary method of off-water athlete profiling (Fleming, Donne, Fletcher, et al., 2012; Paton & Hopkins, 2006), providing a more controlled environment for performance analysis involving physiological or biomechanical assessment. Common protocols are Wingate assessments, steady-state and graduated step tests with respiratory and/or lactate monitoring. These are made possible by air-braked flywheels, which can generate live power (W) output feedback. Thus, ergometers are an accessible means of evaluating athlete aerobic capacity and paddling power (K. van Someren & Palmer, 2003). Nevertheless, the concurrent validity and reliability of some ergometers has been challenged (Borges, Bullock, Aitken, & Coutts, 2017). Also, the ecological validity of these devices is yet undetermined; their biomechanical specificity has been questioned (Mickaël Begon, Mourasse, & Lacouture, 2009; Fleming, Donne, Fletcher, et al., 2012) but it is unknown if there is an associated technique adaptation (Lok, 2013). It is clear that ergometer design could be improved through changes such as flywheel design or force measurement at the paddle, seat, and footrest (Mickaël Begon et al., 2008; Lok, 2013; Shin, Willmott, & Mullineaux, 2018).

Figure 10. Kayak ergometer in use during CRNZ testing

GPS and Accelerometers

Accelerometers and GPS advancement has enabled the analysis of on-water performance in paddle sports; they can provide accurate and reliable speed, SR, and DPS, among other outputs (Janssen & Sachlikidis, 2010). Global positioning system (GPS) units use either the Doppler-shift method or positional differentiation to determine precise distance (Cardinale & Varley, 2016). Proprietary filtering techniques extract further detail desired by the end-user. In paddle sports, those metrics include splits, speed thresholds, and acceleration characteristics (Mononen & Viitasalo, 1995; Sturm, Yousaf, & Eriksson, 2010). There are two predominant methods of determining α_{Kayak} from GPS data: time interval deduction and raw acceleration smoothing (Cardinale & Varley, 2016). While the former may be more accurate, the time interval chosen is critical; the latter is highly affected by device error but is very flexible with the right filtering techniques (Varley, Fairweather, & Aughey1, 2012). Still, the technology has limitations; GPS devices may have a higher CV when α_{Kayak} is high (such as during standing starts) or when average velocity is low (Janssen & Sachlikidis, 2010). Janssen and Sachlikidis (2010) showed that multiple GPS devices underreported kayak intra-stroke velocity by 0.14-0.19 m/s (3%) (McDonnell et al., 2013). Therefore, caution must be exercised when using α_{Kayak} or other derived measures for analysis. These measures may be improved with higher sampling frequencies, advanced algorithms for signal processing, or upgraded chipsets (Cardinale & Varley, 2016; Nagahara et al., 2017). As with any measuring device changes, practitioners must confirm interunit reliability before routine use and research dependent upon output data. Approaches for doing so are explained here (source) (Janssen & Sachlikidis, 2010)

GPS units with IMU are also capable of detailed 3-axis boat motion capture. Various studies have demonstrated the quantification of yaw, roll, pitch, and heave (Vadai & Gingl, 2016). Combined with V_{Kayak}, this could be used to diagnose technical flaws and determine e_p (Vadai et al., 2013). Moreover, boat motion data could be utilised for accurate estimation of D_A. Examples of this are limited to modelled data (Pendergast et al., 2005).

Instrumented Paddles

While ergometers assess athlete's kinetic inputs, and GPS, athletes' boat kinematics, only instrumented paddles can directly measure on-water kinetic inputs. This area has much potential, as kinetic analysis would be immune to the environmental factors affecting physiological variables (Michael et al., 2009) and boat kinematics (Higgens et al., 2016). Compared to rowing, which has benefitted from thorough analysis of resultant paddle forces occurring at the oarlock (Baudouin & Hawkins, 2002; Coker, Hume, & Nolte, 2009; Laschowski & Nolte, 2016), kayak requires the instrumentation of the paddle itself (Figure 11). Solutions are constrained by a numerous factors: waterproofing, system weight, portability, sensor robustness, similarity to original paddle (e.g., length, balance), reliability, and collection capacity (battery, data storage) (Aitken & Neal, 1992; Lok, 2013). Nevertheless, instrumented paddles have been used in research for over 25 years (Aitken & Neal, 1992). Studies have demonstrated the ability to measure forces both on an ergometer (Anna Bjerkefors, Tarassova, Rosén, Zakaria, & Arndt, 2017; Borges et al., 2017) and on-water (Niu et al., 2018; Sturm et al., 2013), providing a basis for normative data and research direction (Table 3). Most devices used load cells or strain gauge bridges integrated at the shaft-blade interface (Bifaretti, Bonaiuto, Federici, Gabrieli, & Lanotte, 2016; Tullis et al., 2018), while some examined the forces at the hands (Macdermid & Fink, 2017; Nates & Colloud, 2016; Sturm et al., 2013). Two solutions have been proposed with sensors applied to the face of the paddle blade itself (Helmer, Farouil, Baker, & Blanchonette, 2011; Niu et al., 2018). The only commercial solution currently available is One Giant Leap paddle power meter (One Giant Leap, Nelson, NZ). The paddle system fits most of the proposed requirements described above: it is about 100g, 60 Hz collection intervals, 5cm adjustable shaft length, changeable blades, IPX7 water resistance, four available stiffnesses, and ANT+ compatibility. An examination of its validity and application by (Macdermid & Fink, 2017) reported that power had a strong relationship with velocity (R^2=0.98) when verified with high-speed video. They found that power and velocity had a cubic polynomial relationship, as described in other water sports (Figure 8)

(Cabrera et al., 2006; Pendergast et al., 2005). With satisfactory calibration results (validity, 0.12–1.4 %, CV = 0.12-1.5%) and the power-velocity relationship, they concluded that the tool is a valid method of measuring paddling power. Additionally, they presented strong relationships between power and SR (R^2=0.99), T_{Pull} (R^2=0.91), T_{Air} (R^2=0.97), F_{Peak} (R^2=0.97), and impulse (R^2=0.87). The study may be limited by its inclusion of only one paddler (n=1) and associated statistical limitations of linear regression.

Figure 11. Previously studied instrumented paddle shaft designs

Images reprinted from "E-Kayak: A Wireless DAQ System for Real Time Performance Analysis," by Bifaretti, S., Bonaiuto, V., Federici, L., Gabrieli, M., & Lanotte, N. (2016), Procedia Engineering, 147, 776-780; "A 6-Component Paddle Sensor to Estimate Kayaker's Performance; Preliminary Results," by Nates, F. M., & Colloud, F. (2016), ISBS-Conference Proceedings Archive, 33(1); One Giant Leap (One Giant Leap, Nelson, NZ)

Table 3. Biomechanical variables previously examined via instrumented paddle system

	Sex	SR (spm)		
		80	100	125
T_{Pull} (s)	Female	0.55 ± 0.02	0.48 ± 0.01	0.43 ± 0.02
	Male	0.50 ± 0.04	0.43 ± 0.03	0.37 ± 0.03
T_{Air} (s)	Female	0.23 ± 0.05	0.17 ± 0.05	0.12 ± 0.02
	Male	0.24 ± 0.03	0.18 ± 0.04	0.14 ± 0.03
F_{Peak} (N)	Female	130 ± 8	146 ± 7	153 ± 11
	Male	234 ± 32	266 ± 33	274 ± 35
F_{Mean} (N)	Female	80 ± 9	157 ± 18	99 ± 15
	Male	128 ± 18	92 ± 13	171 ± 18
Impulse (N-s)	Female	44.1 ± 5.5	44.2 ± 6.3	42.3 ± 6.6
	Male	63.9 ± 7.3	67.7 ± 9.5	63.2 ± 8.4
F_{Mean}/F_{Peak} (%)	Total	57.2 ± 3.9	61.0 ± 3.8	64.8 ± 3.7

Notes. Values are M ± SD; T_{Pull} = pull time; T_{Air} = air time; F_{Peak} = peak force; F_{Mean} = mean force; spm = strokes/minute; s = second; N = Newton. Adapted from "Paddling Force Profiles at Different Stroke Rates in Elite Sprint Kayaking," by Gomes, B. B., Ramos, N. V., Conceição, F. A. V., Sanders, R. H., Vaz, M. A. P., & Vilas-Boas, J. P. (2015) Journal of Applied Biomechanics, 31(4), 258-263.

Conclusion

This review profiles the history and mechanics of kayak sprint from a performance analysis perspective. Although various KPIs have been identified, there is more to learn regarding which factors affect V_{Kayak} and boat performance. Technological innovation has advanced the understanding of paddler biomechanics but must be improved further before successful implementation in the field.

Chapter 3. Comparative Validity and Reliability of a Novel Smart Paddle System

Preface

This chapter will discuss past and current technologies used for off-water kayak performance analysis, which provides context for the subsequent studies using the SP. This study examined the comparative validity and reliability of the SP in comparison to an instrumented ergometer. Additionally, this study introduces key outputs from the devices and evaluates their relevance to performance analysis.

Abstract

Aims

This study sought to determine the agreement and correlation between kinematic and kinetic outputs of the SP, DS, and DP. It was hypothesised that the devices would be similar in kinematic variables, but not in kinetic variables.

Methods

Four elite male athletes performed a standardised warmup followed by a graduated paddle protocol ranging from 30 – 90 cycles/min. The SP, DS, and DP collected kinematic and kinetic data concurrently. Data were analysed via Passing-Bablock regression and Bland-Altman plots to determine differences between collection methods.

Results

The SP and DS were nearly identical in detecting SR (limits of agreement = 0.02 ± 9.02%; $R^2 = 0.98$; $p < 0.01$). There were significant differences in T_{Pull} (limits of agreement = 10.1 ± 18.4%, $R_2 = 0.78$, $p < 0.01$). SP and DP were significantly different in detection of F_{Peak} (limits of agreement = 8.8 ± 30.1 N, $R^2 = 0.94$, $p < 0.01$) and F_{Mean} (limits of agreement = 36.7 ± 27.5%, $R^2 = 0.72$, $p < 0.01$). Cyclical power variables were similar between SP and DS (SP IR and DS power; $R^2 = 0.98$, SE = 0.045, $p < 0.01$).

Discussion

Systematic differences between devices may be explained by the methodological difference in measurement location of kinematic and kinetic variables. Devices were similar for SR and cyclical power metrics, suggesting that the devices are comparable. Practitioners should carefully consider the purpose of ergometer testing before interpreting results.

Practical Applications

DS and SP can both provide valuable information to the paddler and practitioner. The SP may be used to analyse SR, F_{Peak}, and power output during ergometer testing.

Introduction

Regular off-water testing is considered an essential component of the canoe-kayak sport environment. Kayak ergometers were developed and designed to replicate the technical and physical demands of the sport. They first appeared in research in 1976 (Ridge, Pyke, & Roberts, 1976), with air-resisted flywheels added shortly after (Larsen, Modest, Serup, & Secher, 1988). Market research found that there are eight kayak ergometers on the market; the Dansprint, WEBA, and KayakPro are among the most popular and studied iterations (Anna Bjerkefors, Rosen, Tarassova, & Arndt, 2018; Borges et al., 2017; Fleming, Donne, Fletcher, et al., 2012; Gullstrand, Lindberg, Cardinale, Tarassova, & Bjerkefors, 2013). Coaches and support staff use ergometer training to determine the physiological capacities of athletes and monitor training progression. They are also used in parts of the northern hemisphere for training during cold winter months. Key metrics of interest in research and practice include SR, power (W), and work (J). Thus, accurate test procedures and equipment are critical to establish confidence in test results (Gore, Tanner, Fuller, & Stanef, 2013).

A wide range of scientific research has examined the biomechanics of consumer and custom kayak ergometers. Calibration rigs have revealed that most ergometers systematically under-report power across a range of intensities (Anna Bjerkefors et al., 2017; Borges et al., 2017; Gore et al., 2013; Gullstrand et al., 2013). In these studies, ergometer power output was validated against calibration rigs combining force transducers at the rope-shaft interface and 3D motion capture. A range of 21-38% lower power expression (W) was displayed by the DS output when compared with the test rigs. Conversely, Borges et al. (2017) analysed another kayak ergometer, WEBA, and presented values in closer agreement with the calibration rig (4.5 ± 3.5%). These findings also provide insight and normative data upon flywheel/drag factor resistance settings, power conversion factors (from linear regression), kinetic asymmetries (Michael, Rooney, & Smith, 2012), and body segment kinematics (Limonta et al., 2010). Others have demonstrated the impact of DS rope adjustment upon kinetics and kinematics using a test rig (Fleming, Donne, & Fletcher, 2012).

Previous on-water performance analysis technologies are described earlier in Chapter 2. No research could be found comparing kayak ergometer and on-water technologies simultaneously during ergometer paddling. HPSNZ and CRNZ have vested interest in both of these technologies, so an experiment was created to critically evaluate the outputs of each during an ergometer test. Furthermore, since kayak ergometers are popular and accessible to elite and subelite athletes and programs, readers without the SP device can understand the context of the following analysis. Therefore, this study examined of the comparative validity and accuracy of multiple kayak performance analysis technologies.

Methods

Experimental Overview

This study utilised multiple technologies to analyse kayak performance concurrently during a standardised step test. Four athletes performed the step test (Figure 12) under controlled conditions in order to compare the devices for inter and intra-device accuracy.

	Stroke rate	Duration
Mobility/stretching		10:00
Familiarisation/paddle		05:00
Level 1	32	03:00
Rest		01:00
Level 2	36	02:00
Rest		01:00
Level 3	40	01:00
Rest		02:00
Level 4	48	01:00
Rest		02:00
Level 5	60	00:30
Rest		03:00
Level 6	Max	00:15

Figure 12. Paddle protocol for ergometer testing

Participants

Four male elite level kayak sprint athletes were recruited based on predetermined performance criteria. They were all healthy (exclusion criteria, no injuries in the previous two months) and active competitors at the World Junior Championships or above. Athletes were current high performance athletes with Canoe Racing New Zealand during time of testing. Physical characteristics of the sample were: age 17-22 years, height 181.4 ± 4.6 cm, weight 86.9 ± 7.0 kg. They all had significant previous exposure to paddling on the DS for testing and training. Normal training schedules consisted of 8-12 hours of paddling per week as well as 4-8 hours of resistance training per week. Study data collection occurred during a progressive taper one week before the athletes left for international competition. All athletes received oral and written information regarding the study's purpose and signed a consent form to participate in the study prior to the testing. Ethical approval for the study was granted from AUTEC 18/151.

Equipment

Dansprint

The DS was used as the pre-existing default testing device for CRNZ. This ergometer was previously examined for validity and reliability (Borges et al., 2017; Gore et al., 2013; Gullstrand et al., 2013). The drag factor was set to 30 for all athletes in accordance with CRNZ protocols. Athletes had live feedback system during the trial in the form of the DS screen, which displayed time elapsed and SR. Discrete per stroke metrics (SR, power, T_{Pull}, T_{Air}) were saved via the DS software provided. Athletes used the DS stock seat and footplate.

Instrumented Dansprint

The DS was modified in order to gather additional information not provided by the stock DS setup: rope tension and paddle force. The Dansprint power (DP) construction was fundamentally different than other custom builds (Anna Bjerkefors et al., 2017; Borges et al., 2017; Gullstrand et al., 2013); it measured torque applied to the entire flywheel carriage, instead of using force transducers at the shaft-rope interface. The research team hypothesised that the current setup is less obstructive during paddling, since the swing weight of the shaft end is unchanged from normal testing procedures. Therefore, the DP system would not affect normal paddling technique. The effect of force transducers and associated wires attached to the end of the shaft, however, is unknown.

Two strain gauges were arranged in a "sensor sandwich" between the flywheel and device base (Figure 13). The arrangement allowed the calculation of torques applied to the flywheel from the DS rope. Strain gauges collected data at a sample rate of 1000Hz. DP data was collected and analysed via LabVIEW (National Instruments, Austin, USA). More information about the DP is available in Appendix 6.

To standardise the protocol, the DP was used to monitor bungee tension. First, the shaft was moved to zero tension on the ropes so the strain gauges could be reset. Then, the shaft was moved to the footrest and the resting bungee tension noted in the software. Then, the SP shaft was placed behind the seat and the tension noted. The tension parameters were integrated into the paddle force calculation to remove the effect of rope tension on the DP. If the athletes requested a change in rope tension during the protocol, the bungee tension calibration was repeated.

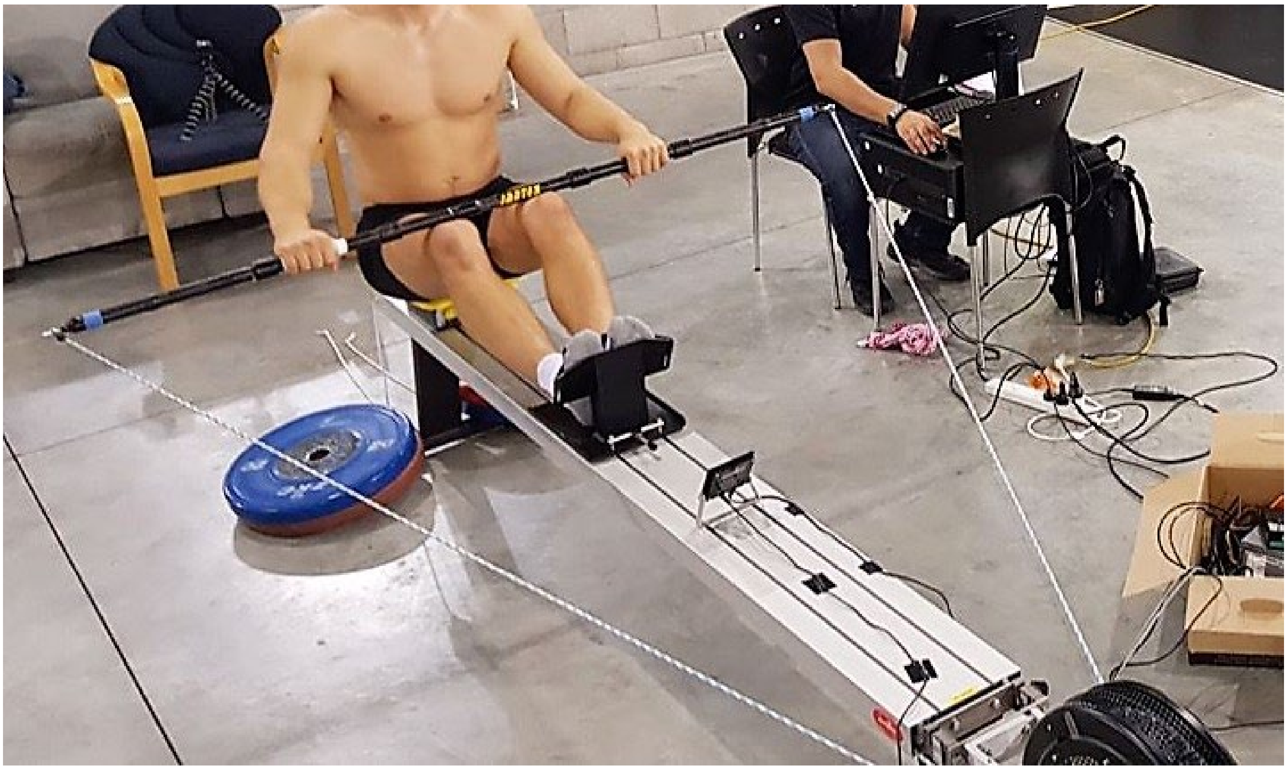

Figure 13. Experimental setup of the paddler, DS, DP, and SP

Smart Paddle

The KZ1/KZ2 smart paddle (SP) device is a custom paddle setup designed and manufactured by Goldmine (HPSNZ, Auckland, NZ). SP technical specifications are outlined in Appendix 7. A Jantex carbon shaft (Banka, Slovakia) was equipped with strain gauge arrays (256 Hz) and an IMU (100 Hz).

The SP was calibrated using a custom protocol: the shaft was fixed horizontally and a known mass was hung vertically from the end. Then, the shaft was rotated 90° until sufficient data points rendered the relative error less than 1% of applied load. The bending moment and known distance from centre of force to strain gauge array were used to generate a calibration scale factor.

The SP shaft was measured to 167cm as the same length of the stock DS shaft for testing. This was done to match athletes' previous experience with the device and to ensure proper tracking of the ropes within the flywheel. The blades were removed, and eye bolts fitted to the shaft in place of blades. Then, the DS ropes were tied onto the eye bolts using two half hitches. The calibration process used the rope attachment point as the centre of force.

Atmospheric Conditions

All testing was performed in the Avantidrome (Cambridge, New Zealand) with stable environmental conditions (temperature 19.9 °C; humidity 51.0%; pressure 1007.7 hPa)

Procedure

Athletes completed the ergometer trials between 6-8am at the indoor training venue. They were instructed to refrain from caffeine and consume a light snack before arrival. Height and weight were recorded and athletes read and signed the participant information and informed consent forms. They completed an individual warmup followed by a standardised warmup on the spare ergometer. Before each trial, the SP and DS were reset for data separation. Footrest and seat position were adjusted as desired by the athlete. Athletes' body mass was recorded before each trial. The instrumented ergometer system was reset before each stage for each individual in order to separate data and account for any rope tension changes between stages. Video data was captured from both behind and side of the athletes for stroke identification. Athletes followed the prescribed paddle protocol (Figure 12). One athlete had to rest longer than prescribed between levels 3-4 due to equipment adjustment.

The paddle protocol was developed in collaboration with coaches and staff from HPSNZ and CRNZ. It was designed to mimic on-water training intensities used routinely by this cohort. Accordingly, SR was constrained to a small range that matched those intensities. Stage durations were selected to allow for enough strokes of constant velocity paddling to maximise statistical power. During each stage, the athletes received verbal encouragement to stay in the SR range and replicate the feeling (technique) of each level as done for on-water training. Athletes were able to sustain SR at each intensity. Predetermined rest periods were selected to allow adequate recovery between test levels.

Statistical Analysis

SP data was analysed via HPSNZ logger software (custom MATLAB [MathWorks, Matick, USA]). This software extracted continuous, discrete, and average metrics from raw SP paddling data. Table 4 provides a list of the metrics derived from the SP data. The variables were chosen via previous consultation with HPSNZ, CRNZ, and other experts as outlined by Oldham and Millar (2018). It should be noted that the DS output variables are "black box" and no information was reported as to their calculation. Specifically, DS documentation does not specify if power output is a measure of P_{Mean}, P_{Peak}, or otherwise.

Table 4. Biomechanical variables examined between DS, DP, and SP

Type	Variable	Units	Practical
Kinematic	SR	cycles/min	Stroke rate; measured in R+L cycles/min, equal to $(1/T_{Stroke}) * 60$
	T_{Pull}	Seconds (s)	Pull time a.k.a. water time; time between catch and exit as defined by device)
	T_{Air}	s	Air time; from end of stroke to beginning of contralateral stroke
	T_{Stroke}	s	Stroke time; time elapsed during one stroke cycle from paddle blade entry to entry of contralateral side
	V_{Blade}	m/s	Blade velocity; mean linear blade velocity during pull (tangential velocity) measured from 1/3 length of blade surface
	Pull %	%	T_{Pull} / T_{Stroke}
Kinetic	F_{Mean}	N	Mean blade force; mean force perpendicular to paddle shaft during T_{Pull} measured from 1/3 length of blade surface
	F_{Peak}	N	Peak blade force; peak force perpendicular to paddle shaft during T_{Pull} measured from 1/3 length of blade surface
	Impulse	N-s	Sum of net force * T_{Pull}
	P_{Mean}	N*m/s	Mean blade power; product of F_{Mean} * V_{Blade}
	P_{Peak}	N*m/s	Peak blade power; product of F_{Peak} * peak V_{Blade}

Notes. Variables measured by Dansprint (DS), instrumented Dansprint (DP), and smart paddle (SP)

All data was exported and stored as comma separated values (.csv) files. Statistical analyses were done using XLSTAT (Addinsoft, Paris, France) and Tableau (Tableau, Seattle, USA). Outliers (±1 SD) such as those observed during the first and last two strokes of a trial were discarded. Within-group differences were analysed to assess whether the devices ranked the group identically.

Data were summarised using mean ± SD unless otherwise reported. Assumptions of normality and linearity were addressed via examination of the Normal Q-Q plot and scatterplot. Each stroke was considered an independent observation with multiple devices capturing data concurrently. Concurrent samples from each device were compared against each other for comparative reliability. Cohen's *d* effect sizes and 95% CI were calculated to quantify the standardised mean differences between methods, with threshold values of 0.2, 0.5, 0.8, and 1.3 used to represent small, moderate, large, and very large effects, respectively (Cohen, 1988, p. 40; Rosenthal, 1996). Bland-Altman plots and Passing-Bablock regression analyses were used to assess the validity of practical (SP) against criterion (DS, DP) measures (Bilic-Zulle, 2011; Bland

& Altman, 1986). The Passing-Bablock regression procedure fits the intercept (β_0) and the slope (β_1) of the linear equation

$$Y = \beta_0 + \beta_1 X$$

The regression equation, scatterplot and 95% CI of β_0 and β_1 were examined for linearity, correlation, and method agreement. Residual plots and cumulative sum linearity (cusum) test were used to assess random distribution of residuals. Cusum test p value less than 0.05 indicates significant difference from linearity. Bland-Altman plots were used to assess bias, limits of agreement and mean difference. Residual and difference plots confirmed normal-distributed differences. For comparisons with non-normal residuals, limits of agreement were calculated for mean relative differences (%) (Giavarina, 2015). Maximum acceptability of differences was suggested to be 5-10% depending on the measure and linear nature of the bias.

It was critical to perform statistical analyses in a systematic manner to assess each variable. Each step is described in detail below.

1. Determine equivalent measurement of stroke identification. There was a known number of strokes within each trial and it was hypothesised that each device correctly identify the same number of strokes for further analysis. Video footage was used to confirm true stroke count. If stroke detection was identical, then each device should calculate equivalent mean SR (total strokes/trial length [s]) for each athlete-level. Means were compared via a paired-samples t-test.
2. Stroke phase parameters T_{Pull} and T_{Air} were examined independently. This was required to accurately draw kinematic comparisons later between environments. Furthermore, some kinetic variables (impulse and P_{Mean}) require accurate calculation of T_{Pull} for calculation. Bland-Altman plots and Passing-Bablock regression comparisons were used to determine the limits of agreement and correlation coefficients. Standard linear regression was used to determine R^2, SE, and explain if any variation was systematic or irregular.
3. To assess if SR detection was identical, instantaneous SR for each stroke was compared between devices. Bland-Altman plots and Passing-Bablock regression comparisons were used to determine the limits of agreement and correlation coefficients.
4. F_{Peak} was examined as a primary variable of stroke kinetics. This is because of its independence from any time-domain variables. It was theorised that the DP would be a criterion measure and the SP would correlate with bias in a systemic manner. Bland-Altman plots and Passing-Bablock regression comparisons were used to determine the limits of agreement and correlation coefficients. Standard linear regression was used to calculate R2, SE, and the regression equation for scale factor.
5. F_{Mean} was another primary kinetic variable to evaluate. If substroke parameters were inconsistent, it could affect the calculation of F_{Mean}. SP and DP were compared via standard linear regression to evaluate device mean differences, R^2, SE, and regression equations. It was also possible to compare with DS by using power and velocity to calculate F_{Mean} via standard linear regression.
6. In attempts to investigate P_{Mean}, some SP data was determined to be invalid. The athletes in this sample unknowingly allowed for the SP shaft to spin in their hands during paddling, preventing the SP V_{Blade} algorithm from calculating accurate shaft linear velocities. Thus, velocity values, and P_{Mean}, were unusable. Two new metrics were

introduced in order to compare power expression in a statistically valid manner. It was suggested that the inclusion of stroke cycle time combined with kinetic variables would provide a comparable "work rate" that might be compared with DS power. F_{Mean} was averaged across the stroke to generate "cycle force", or F_{Cycle} (N/cycle) (Equation 3). F_{Cycle} is equal to impulse/ T_{Stroke}; the latter calculation has less error due to one less measured variable (Equation 4). This combination of kinetic and kinematic variable had practical equivalence to mean power over a given frequency. Hence, "impulse rate", or IR (N-s/cycle) was used as a surrogate measure of power. DS power was compared with SP IR via linear regression as in step 5.

Equation 3. Calculation of cycle force

$$F_{Cycle} = \frac{F_{Mean} * T_{Pull}}{T_{Stroke}}$$

Equation 4. Equivalence of cycle force and impulse rate

$$F_{Mean} * T_{Pull} = \ stroke\ impulse$$

Then $\frac{impulse}{T_{Stroke}} = SP\ IR$

Results

Stroke Identification

The DS and SP successfully identified all strokes across all but one trial. Stroke detection was mostly consistent between SP and DS, with SP identifying 22 (0.05%) fewer strokes than DS (Table 5). This is due to a device error during one maximal trial for one athlete. The analyses were still performed as planned. Subsequently, SR was compared to assess any significant differences. The Passing-Bablock regression revealed that the DS and SP were statistically similar (β_0 = -0.15 ± 0.26, β_1 = 1.00 ± 0.01, R^2 = 0.98, $p < 0.01$) (Figure 14). The Bland-Altman limits of agreement supported the same conclusion (0.02 ± 9.02 %) (Figure 15); the margins are not large enough to be clinically important (*d* = 0.02 ± 0.16). The variability increased at maximal intensities, observed upon visual inspection of the regression spread (Figure 14). Furthermore, discrete stroke observation diagnosed a consistent error for the SP in detecting accurate SR for the first and last strokes of some trials.

Table 5. Descriptive statistics of DS and SP stroke identification

Test level	Sample stroke count (n)		SR M ± SD			
	DS	SP	DS	SP	*d*	Rating
1	755	755	33.4 ± 1.7	33.6 ± 1.6	0.12 ± 0.10**	Trivial
2	534	534	36.5 ± 1.7	36.6 ± 1.4	0.02 ± 0.12**	Trivial
3	314	314	41.8 ± 2.0	41.8 ± 2.0	0.01 ± 0.16**	Trivial
4	359	359	49.0 ± 2.1	49.0 ± 2.0	0.03 ± 0.15**	Trivial
5	202	202	60.9 ± 3.5	60.9 ± 3.2	0.00 ± 0.20**	Trivial
6	135	113	80.5 ± 5.1	80.4 ± 7.3	0.02 ± 0.25**	Trivial
Total	2299	2277			0.02 ± 0.16**	Trivial

Notes. Values are M ± SD; SR = stroke rate (cycles/minute); DS = Dansprint; SP = smart paddle, d = Cohens effect size.

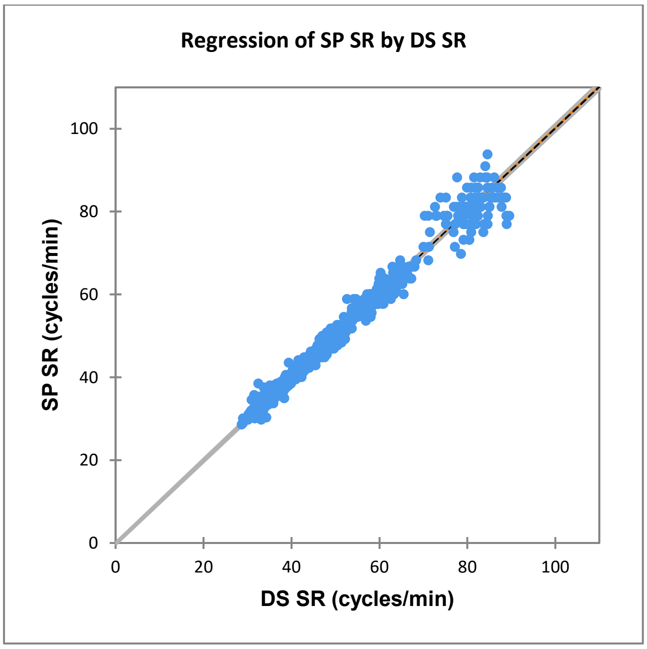

Figure 14. Passing-Bablock regression analysis of DS and SP SR

N = 2277, SR range 14-100, Pearson correlation coefficient r = 0.99, p < 0.01. Regression line equation y = -0.15 + 1.00 x; 95% CI for intercept -0.42 to 0.09 and for slope 1.00 to 1.01 indicated good agreement. Cusum test indicates no significant deviation from linearity (p > 0.05).

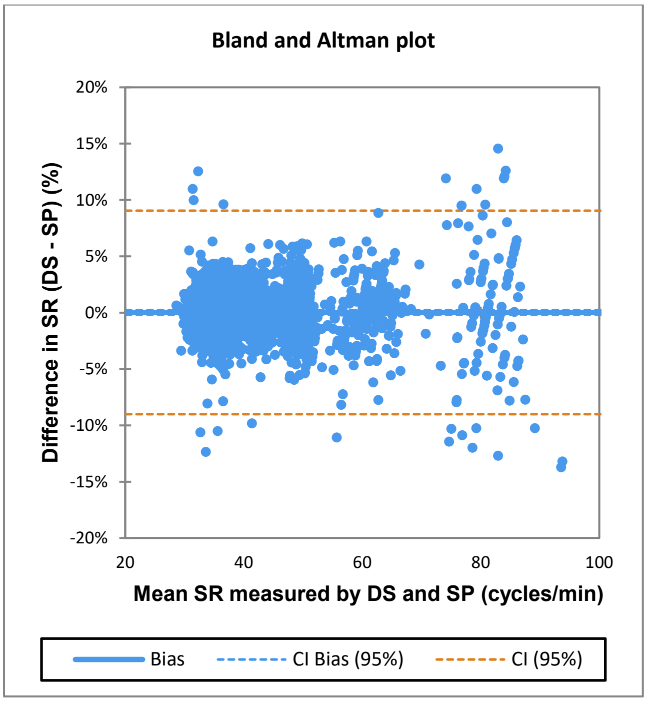

Figure 15. Bland-Altman plot of the relation between DS and SP SR

Stroke Phase Parameters

T_{Pull} and T_{Air} were compared to assess the nature of the observed error in SR. SP and DS T_{Pull} were substantially different ($d = 1.12 \pm 0.17$, $p < 0.01$) and strongly correlated across all trials ($r = 0.89$, $p < 0.01$). Passing – Bablock regression (Figure 16) and Bland-Altman plots (Figure 17) detected significant differences between collection methods ($\beta_0 = 0.003 \pm 0.008$, $\beta_1 = 1.10 \pm 0.03$, $R_2 = 0.78$, $p < 0.01$, limits of agreement = 10.1 ± 18.4 %), indicating that the relationship is nonlinear.

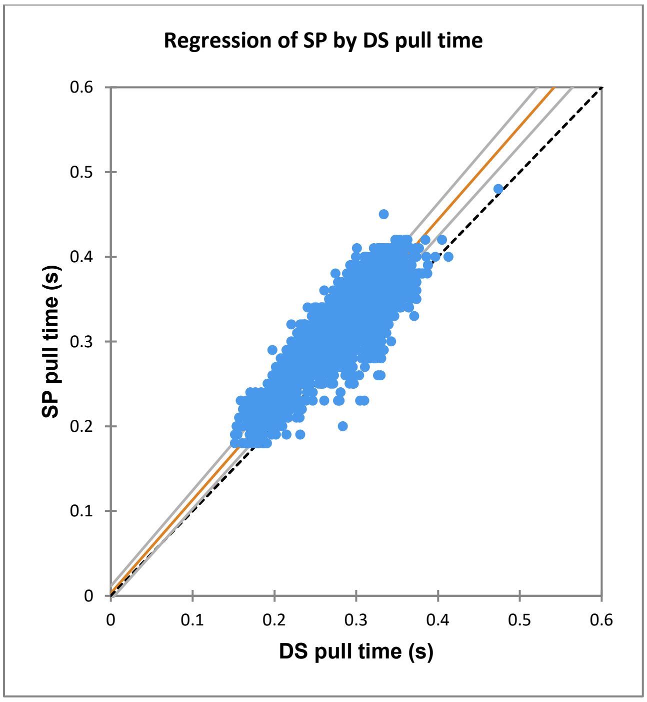

Figure 16. Passing-Bablock regression analysis of DS and SP T_{Pull}

N = 2277, T_{Pull} range 0.13-0.51, Pearson correlation coefficient r = 0.89, p < 0.01. Regression line equation y = 0.003 + 1.10 x; 95% CI for intercept -0.005 to 0.011 and for slope 1.07 to 1.13 indicated no constant and small proportional difference. Cusum test indicates significant deviation from linearity (p < 0.05).

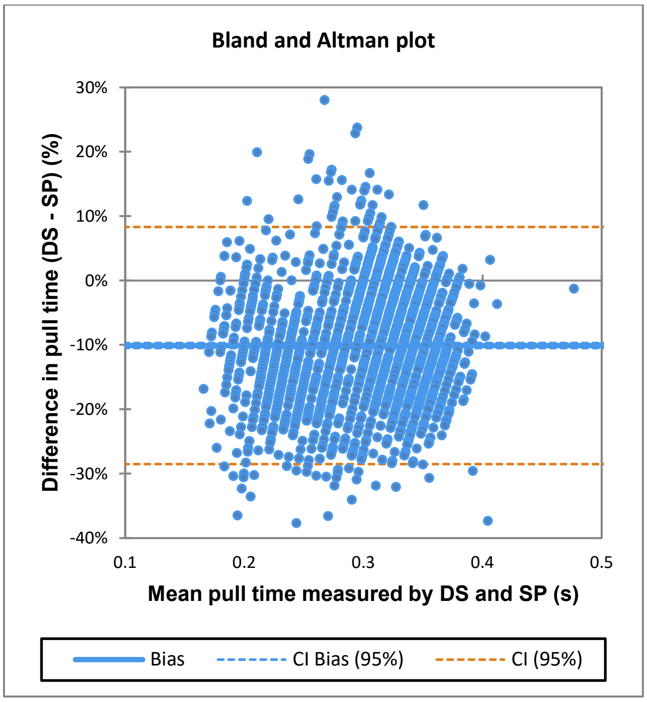

Figure 17. Bland-Altman plot of the relation between DS and SP T_{Pull}

Kinetics

Comparisons between DP and SP began with the Passing-Bablock regression (Figure 18) and Bland-Altman plots (Figure 19) of F_{Peak}. Though the regression had a high coefficient of determination, ($R^2 = 0.94$, $p < 0.01$), there were significant differences between devices suggesting the relationship is nonlinear ($d = 0.32 \pm 0.17$, $\beta_0 = -29.9 \pm 2.4$, $\beta_1 = 1.09 \pm 0.01$, $p < 0.01$, limits of agreement = 8.8 ± 30.1 N).

Next, F_{Mean} was compared between DP and SP. SP F_{Mean} had a strong correlation ($r = 0.85$) but significant measurement bias versus DP ($d = 3.15 \pm 0.26$, $\beta_0 = -31.4 \pm 4.9$, $\beta_1 = 1.8 \pm 0.06$, $R^2 = 0.72$, $p < 0.01$, limits of agreement = 36.7 ± 27.5 %). The derived F_{Mean} from DS was also compared against the other two, with similarly high correlation (vs. SP, $r = 0.94$, vs. DP, $r = 0.88$) but nonlinear regression results.

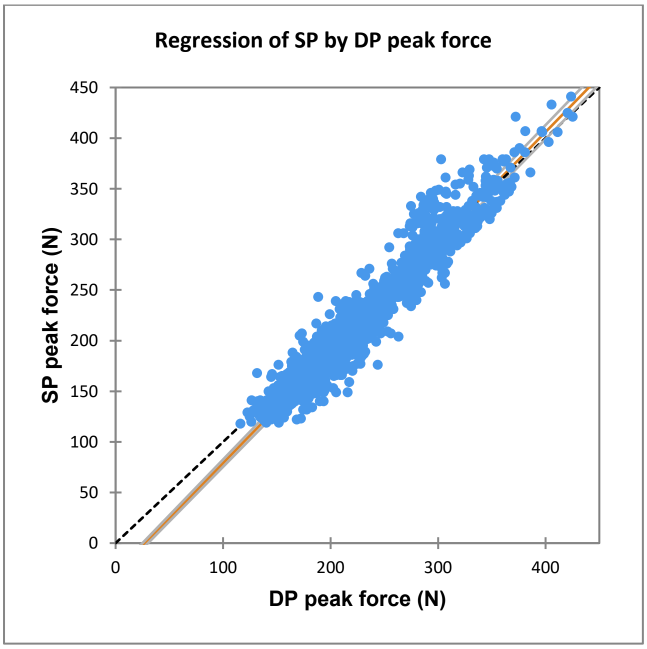

Figure 18. Passing-Bablock regression analysis of DS and SP F_{Peak}

N = 2006, F_{Peak} range 219-441, Pearson correlation coefficient r = 0.97, p < 0.01. Regression line equation y = -29.92 + 1.09 x; 95% CI for intercept -32.52 to -27.49 and for slope 1.08 to 1.10 indicated large constant and small proportional difference. Cusum test indicates significant deviation from linearity (p < 0.05).

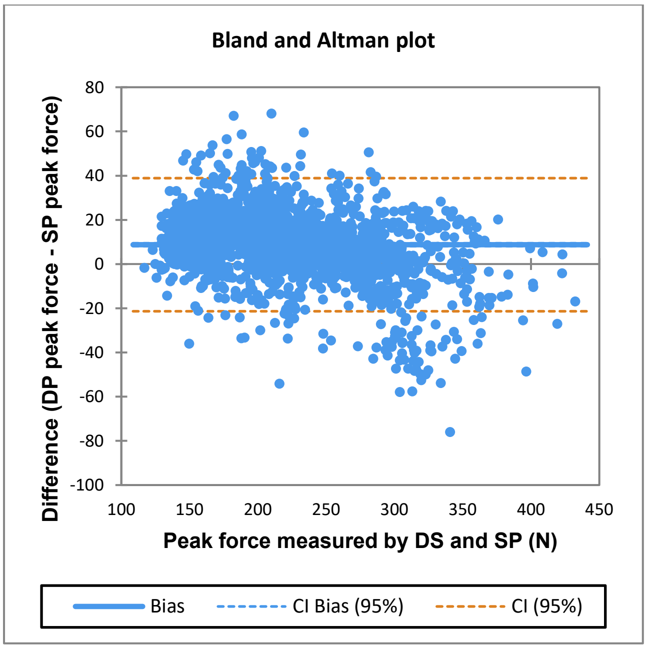

Figure 19. Bland-Altman plot of the relation between DS and SP F_{Peak}

As described earlier, SP IR was compared against power from the other devices. This was possible because, as theorised, SR scales reliably between devices (Figure 14). SP IR was compared to DS power via linear regression of log-transformed data. The model with the lowest root mean square error and evenly distributed residuals was determined to be ln(SP IR) = 0.60 * ln(DS power) + 0.95 (R^2 = 0.98 and SE = 0.045) (Figure 20). The difference plot showed randomly distributed residuals around each test level.

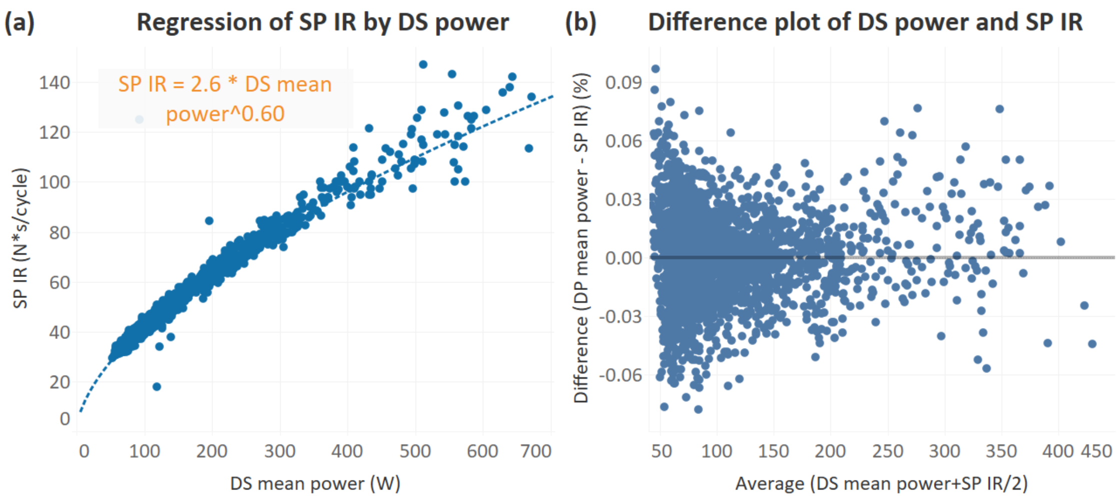

Figure 20. Regression of SP IR to DS P_{Mean}

*(a) Scatterplot with nonlinear trendline was fit via quadratic model SP IR = 2.64 * DS P_{Mean} ^ 0.60 (R^2 = 0.98, SE = 0.04). (b) Difference plot of calculated relative residuals (%) against DS P_{Mean} and SP IR.*

Discussion

This study compared the outputs of three different devices collecting simultaneously during kayak ergometer paddling. First, stroke detection was deemed equivalent between DS and SP: the SP missed 22 of 2302 strokes, with SR effectively identical (d = 0.02 ± 0.16, β_0 = -0.15 ± 0.26, β_1 = 1.00 ± 0.01, R^2 = 0.98, $p < 0.01$). The error that affected one trial was due to a one-time failure of the eye bolt fixture between DS and SP. As seen in the lapse of SP and DP systems to detect the first or last stroke of some trials, a methodological difference in stroke identification causes disagreement in these systems in stroke count, stroke parameters, and other variables across multiple trials. For example, the SP detects an average 10.1 ± 9.4% (R^2 = 0.78, $p < 0.01$) longer T_{Pull} for each stroke as compared to the DS. Subsequently, the SP also detects T_{Air} 7.0 ± 8.4% shorter on average compared to the DS (Figure 21) (β_0 = -0.03 ± 0.01, β_1 = 1.00 ± 0.01, R^2 = 0.92, $p < 0.01$, limits of agreement = 7.0 ± 16.9 %). Regardless, high correlations and good model fits of SR (r = 0.98), T_{Pull} (r = 0.78), and T_{Air} (r = 0.92) suggest that these devices scale reliably with some bias. This supports the conclusion that these devices have comparative reliability, but there is still systematic difference between these collection methods. This is likely due to a difference in flywheel braking forces and different load thresholds. If the devices have dissimilar thresholds for defining the beginning and end of T_{Pull}, that could explain the observed difference. However, the threshold values of DS are unknown. Alternatively, the constant pulling force of the DS rope upon the SP shaft end could trigger premature T_{Pull} detection of the SP before

DS flywheel acceleration. The lack of equivalence between substroke parameters may cause the differences observed in kinetic variables F_{Mean} and P_{Mean} as well. These kinetic variables are calculated as an average during the phase duration of T_{Pull}; any absolute difference in that phase time would affect the calculation of F_{Mean} and P_{Mean}.

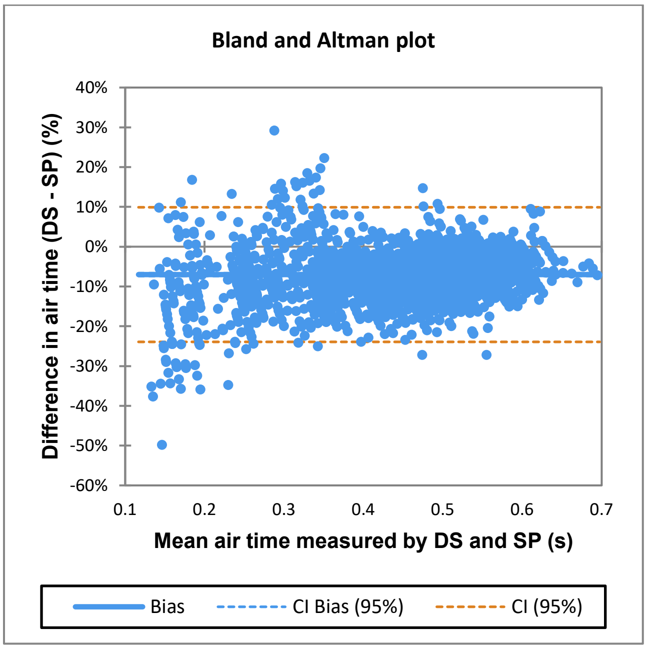

Figure 21. Bland-Altman plot of the relation between DS and SP T_{Air}

There were expected differences in F_{Peak} between DP and SP ($d = 0.32 \pm 0.17$, $\beta_0 = -29.9 \pm 2.4$, $\beta_1 = 1.09 \pm 0.01$, $R^2 = 0.94$, $p < 0.01$, limits of agreement = 8.8 ± 30.1 N). Conversely, the measurement difference of F_{Mean} is very large ($d = 3.15 \pm 0.26$, $\beta_0 = -31.4 \pm 4.9$, $\beta_1 = 1.8 \pm 0.06$, $R^2 = 0.72$, $p < 0.01$, limits of agreement = 36.7 ± 27.5 %). The difference in measurement location (flywheel torque versus blade-shaft interface) could explain the large difference in F_{Mean} and relatively smaller difference in F_{Peak}. While F_{Peak} is similar between devices, the fundamental difference in measurement approach between DP and SP could explain the lack of agreement in F_{Mean}. The reported differences in stroke phase parameters cause the SP to calculate F_{Mean} over a longer interval, perhaps causing it to measure F_{Mean} higher than the DP. Regardless, the difference is systematic and within practically acceptable margins. Moreover, the small differences and good agreement in F_{Peak} demonstrate reasonable comparative validity. This should be considered sufficient for confidence in the kinetic outputs of the SP.

Finally, the use of the DP for monitoring DS rope tension was critical in adjusting kinetic variables for accuracy. The correction for rope tension ranged from 12-43 N between trails; this would have an effect of up to 10% upon kinetic measurements. A potentially impactful future experiment could utilise a similar system for determining the effect of DS rope tension adjustment upon kinetic outputs, as was done by Fleming (2012) for upper body kinematics.

The hardware error of the SP made statistical analysis of velocity measures difficult. However, the generation of cyclical kinetic variables (IR [Equation 4] and P_{Cycle} [Equation 5]) enabled both kinetic and kinematic variables to be compared across devices. SP IR, derived from existing kinetic and kinematic variables, showed a strong relationship ($R^2 = 0.98$, SE = 0.04) with DS power that could be useful for practical implementation or future athlete profiling. The evaluation of concurrent validity between these devices supports DS power as a comparable outcome variable to SP IR. DS power is a "black box" variable, and these results imply that it is a measure of P_{Mean} and frequency. To understand DS power better, its relation to its own kinematic variables and DP kinetic variables was examined. Like IR, P_{Mean} averaged across the stroke cycle may be calculated as "cycle power" (Equation 5). The quality of the regression models between DP kinetic variables and DS power suggests that it is indeed a measure of P_{Cycle} and not P_{Mean}; this hypothesis was further substantiated upon post-hoc analysis of component variables and linear regression of DP P_{Cycle} to DS power (Figure 22).

Equation 5. Calculation of cycle power

$$P_{Cycle} = \frac{P_{Mean} * T_{Pull}}{T_{Stroke}}$$

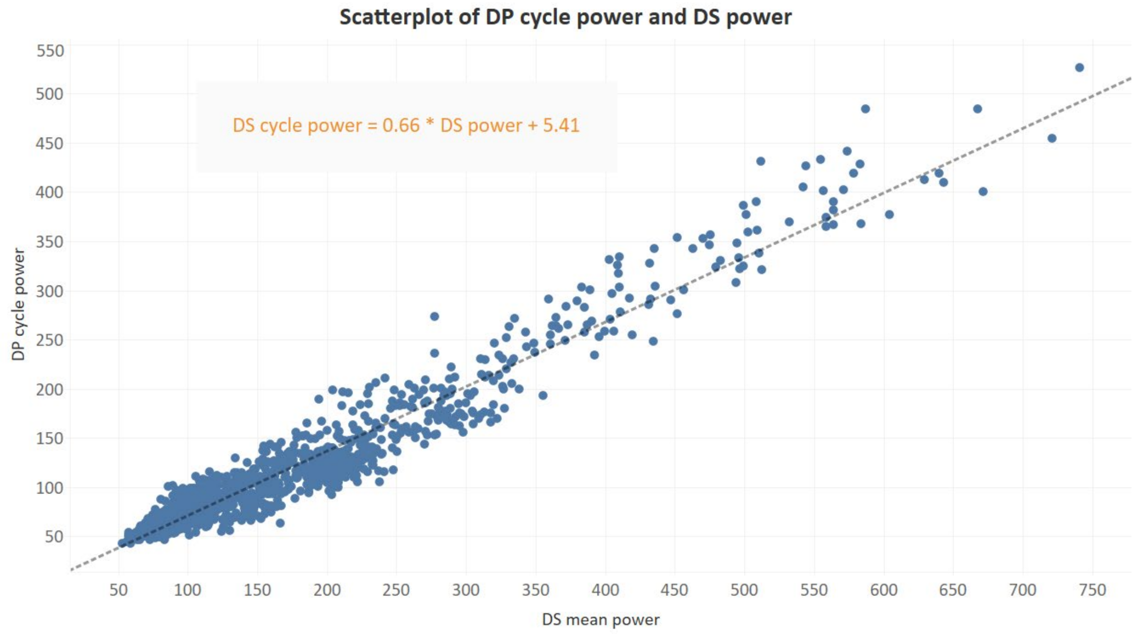

Figure 22. Regression of DP P_{Cycle} to DS P_{Mean}

Scatterplot with linear trendline was fit with $\beta_0 = 5.41 \pm 0.99$, $\beta_1 = 0.66 \pm 0.004$ ($R^2 = 0.93$, SE = 18.86).

Reference Device

The evaluation of the validity and reliability of these systems requires some degree of trust in the objective accuracy of one over another. There is no gold standard reference with which to compare one system against during ergometer paddling. Confirming construct validity is not possible, except perhaps with the comparison of SR with the video data. Conversely, this study has evaluated the criterion (concurrent) validity of three distinct analysis systems. The DS is popular and widely used, although numerous studies have demonstrated its inaccurate measurement of power (Borges et al., 2017; Gore et al., 2013). Furthermore, CRNZ off-water testing does not always rank athletes as they rank in on-water performance, undermining the value of the test itself. Despite this, the popularity of and historical testing data from the DS requires that it be considered the reference device.

The DP system relies on two load cells for measuring torques about the flywheel on the DS; although the load cells are gold standard devices for measuring kinetics, the formulas required for calculating pull forces from torques hinge on complex mathematical calculations unverified in this study. DP also used sub stroke parameter detection (T_{Pull} and T_{Air}) processes which were deemed incorrect after comparison with video and the other two devices. The sum of T_{Pull} and T_{Air} should equal T_{Stroke} but did not in the exported data. However, SR was identical to the DS (d = 0.05 ± 0.16, $\beta_0 = -0.12 \pm 0.22$, $\beta_1 = 1.00 \pm 0.01$, $R^2 = 0.98$, $p < 0.01$), indicating a software issue with the DP. Additionally, misidentified strokes are a significant problem and suggest this system inadequate for kinematic variables. Nonetheless, confirmation of F_{Peak} was possible and immune from the limitations of the DP system.

The SP system uses tested technologies with proprietary algorithms. Regardless, some independent testing and informal validation was previously completed within Goldmine. Calibration processes should be considered the first step in assessing device reliability. Therefore, the question again arises, "which device is most accurate?" Previous literature suggests that the DS systematically underestimates power (Borges et al., 2017), but there is no gold standard criterion device for evaluating it or the SP (whilst paddling). Unfortunately, the hardware malfunction of the SP resulting in null velocity values was a large limitation. It appeared that over half of the sample had incorrect or 0 V_{Blade}. This was directly due to the spinning of the shaft and IMU in the paddler's hands. The athletes probably performed this spinning habitually with the wrist as required with offset blades on-water. Although a primary goal of this study was to compare DS P_{Mean} with SP P_{Mean}, this was not possible. One can speculate that any bias in this comparison might have been due to the methodological difference in velocity calculation between devices. Whereas the DS velocity calculations are derived from the linear rope speed propelling the flywheel, the SP velocity is measured from the tangential linear velocity throughout the stroke. Thus, an accurate comparison of V_{Blade} might be difficult.

Despite the limitation regarding SP V_{Blade} and P_{Mean}, the regression model demonstrates that SP IR was highly correlated with DS power ($r = 0.99$, $SE = 0.04$). Given this high correlation present in the dataset, this study suggests that the SP has comparative equivalent measurement of power or work rate as the DS. Despite the lack of agreement in some stroke phase variables, the strong correlation between these kinetic variables of interest is the most important practical finding. Further studies should assess the correlation of these SP outputs to on-water performance; consequently, results would enhance the understanding of the practical significance of DS power. After such study, conclusions about the practical significance of DS testing for kayak performance can be made with greater confidence.

Chapter 4. Biomechanical Differences Between Ergometer and On-Water Paddling

Preface

This chapter discusses the biomechanical task specificity of ergometer versus on-water paddling. There is a lack of published literature surrounding this topic, so many of the proposed differences are hypothetical. Using the SP device allowed for a comparison of kinematic and kinetic variables across a range of intensities experienced in training and racing.

Abstract

Aims

This study sought to determine if there are biomechanical differences between ergometer and on-water paddling in elite athletes. It was hypothesized that ergometer paddling would differ substantially in both kinematic and kinetic variables, and to a greater magnitude during maximal intensities.

Methods

Four elite male athletes performed a standardised warmup followed by a graduated paddle protocol ranging from 30 – 90 cycles/min on an ergometer fitted with the SP. Later that day, the athletes performed the same warmup and paddle protocol with the SP on-water. Data was analysed using effect sizes, linear regression, and SPM.

Results

Large to very large differences were observed for T_{Pull} (d = 5.9 ± 0.39), T_{Air} (d = 3.7 ± 0.27), F_{Mean} (d = 1.06 ± 0.19), F_{Peak} (d = 1.92 ± 0.22), Impulse (d = 2.62 ± 0.23), and IR (d = 2.10 ± 0.21) between environments. Linear regression models suggested that the differences were incrementally variable across SR. SPM was able to locate areas of significant difference in paddle force-time profiles at each test level.

Discussion

Results suggest that the biomechanical specificity of ergometer paddling is low. SPM results provide visual evidence of force-time profile characteristics unique to each environment. Despite large differences in stroke phase parameters and primary kinetic variables, maximum power output at maximal SR is similar for ergometer and on-water paddling.

Practical Applications

Ergometer paddling is suitable for testing the maximum mechanical properties of athletes, but specific biomechanical differences at all intensities may have unintended consequences and warrant further investigation. Alterations of ergometer design may increase task specificity.

Introduction

Ergometer testing is used extensively in paddle sports to assess and predict sporting performance. The extent to which ergometers match the actual demands of competition, however, is debatable (Nolte, 2005). The use of ergometers for these purposes depends on valid, reliable machines and their task specificity to the sport (Elliott, Lyttle, & Birkett, 2002; Soper & Hume, 2004). Kayak ergometers are suggested to replicate the demands of on-water paddling (von Someren, Phillips, & Palmer, 2000), but some research has proposed notable differences in aerobic, anaerobic, and mechanical demands (Fleming, Donne, Fletcher, et al., 2012; Michael et al., 2008; Villarino-Cabezas, González-Ravé, Santos-Garcia, & Valdivielso, 2013).

The construction of kayak ergometers (as described in Chapter 2) implies fundamental differences with on-water paddling. Air-braked flywheels are used to mimic the “feel” of water, but anecdotally, athletes have reported considerable dissimilarities (Godfrey, Whyte, & Whyte, 2006, p. 40; Shin, Willmott, Mullineaux, & Worsfold, 2017). Indeed, research has suggested that ergometer paddling may have different biomechanical characteristics compared to on-water (Shin et al., 2018). This could be due to muscle activation patterns differences between the two environments (Mickael Begon, Lacouture, & Colloud, 2008). Ergometer paddling has higher measured EMG activity in the anterior deltoid, whereas on-water, the latissimus dorsi muscle appears more active (Fleming, Donne, Fletcher, et al., 2012). Furthermore, ergometer paddling may allow for athletes to achieve a higher SR (Villarino-Cabezas et al., 2013). Fleming, Donne, Fletcher, et al. (2012) found statistically significant differences in rate of force development (RFD) ($p < 0.01$), but not in other variables (F_{Peak}, time to F_{Peak}, impulse, T_{Pull}) when analysing biomechanical differences between ergometer and on-water paddling. This is the only published study examining kinetic differences between the two environments. Despite evidence demonstrating the kinematic similarities of ergometer and on-water paddling (Mickael Begon et al., 2008), there is a gap in the literature and much uncertainty regarding their biomechanical differences. On the other hand, Mickael Begon et al. (2008), identified kinetic similarities between ergometer and on-water paddling. Given the wide range of varying conclusions, further study is required.

Optimising boat performance requires an understanding of how forces generated by the blade propagate through to the kayak seat and footrests. Unlike in rowing, kayaks have fixed seats, so the forces do not necessarily sum to zero. Nevertheless, ergometers may grant insight into these kinetic relationships. In rowing, evidence suggests that ergometers on sliders more accurately replicate the mechanics of on-water performance (Hume, 2017). Others have created a similar mechanism for kayak ergometers, but it has not gained significant popularity (Mickaël Begon et al., 2008).

Presently no studies could be found that examined ergometer and on-water paddling using the same measurement device. This could be due to engineering limitations in paddle instrumentation. It was suggested that this was a critical methodological limitation in previous studies attempting to compare the two or predict on-water performance from ergometer testing. Power and SR are boat performance KPIs and impose constraints during ergometer testing and research. SR is highly correlated to V_{Kayak} (McDonnell, 2013), and it is often manipulated during training to control training zones. The complex relationship between SR, V_{Kayak}, and paddle kinetics further justifies performing research with a single tool so as to reduce predictive error from device differences. In this study, the SP was used to analyse ergometer and on-water paddling and determine biomechanical changes that occur as SR and intensity increase.

Methods

Experimental overview

This study utilised the SP device to compare biomechanical variables between ergometer (ergo) and on-water (H2O) paddling environments.

Participants

Four male elite level kayak sprint athletes were recruited based on predetermined performance criteria. They were all healthy (exclusion criteria, no injuries in the previous two months) and active competitors at the World Junior Championships or above. Athletes were current high performance athletes with Canoe Racing New Zealand during time of testing. All athletes received oral and written information regarding the study's purpose and signed a consent form to participate in the study prior to the testing. Ethical approval for the study was granted from AUTEC 18/151. More information is available in Chapter 3.

Equipment

Smart Paddle

The KZ1/KZ2 smart paddle (SP) device is a custom paddle setup designed and manufactured by Goldmine (HPSNZ, Auckland, NZ). A Jantex carbon shaft (Banka, Slovakia) was equipped with strain gauge arrays (256 Hz) and an IMU (100 Hz). Technical specifications are outlined in appendix ___, and the calibration protocol is described in Chapter 3.

One SP was used for all ergometer testing, and four SPs were used for on-water testing. The SP shaft was measured to 167cm as the same length of the stock DS shaft for ergometer testing. The SP shafts were fitted with the athletes' preferred blades for on-water testing prior to calibration.

Atmospheric Conditions

All on-water testing was done in a single session on Lake Karapiro (Cambridge, New Zealand) under stable environmental conditions (temperature 15 C; humidity 74%; pressure 1343.5 hPa, wind < 0.1 m/s, current < 0.1 m/s)

Procedure

The test protocol and ergometer trials are described in detail in Chapter 3. Approximately 10 hours after the ergometer trials, the on-water trials were performed. All athletes used their usual equipment in addition to the SP. After the standardised warmup, athletes completed the test protocol simultaneously on the training venue. The Windbot device (Igtimi, Dunedin, NZ) was affixed to the coaching boat following the athletes closely. The Tidebot device gathered river current data, though effective current was negligible (< 0.1 m/s). Live SR data from the Rover GPS devices was monitored on the coach boat, with verbal encouragement used to instruct athletes to maintain the prescribed SR. A stopwatch was used to track rest times and stage durations. RPE data was gathered after each stage.

The on-water protocol was performed with rolling starts. The coach gave a verbal cue for the athletes to begin paddling, and they had 15 seconds to reach the prescribed SR. All athletes were able to reach each SR level. Rolling starts were chosen to avoid any effect of standing starts upon fatigue and start technique and maximise adherence to SR zones.

Statistical Analysis

SP data was analysed via HPSNZ logger software (custom MATLAB [MathWorks, Matick, USA]). This software extracted continuous, discrete, and average metrics from raw SP paddling data. Table 6 provides a list of the metrics examined from the SP data.

Table 6. List of biomechanical variables examined by SP on ergo and H2O

Type	Variable	Units	Practical
Kinematic	SR	cycles/min	Stroke rate; measured in R+L cycles/min, equal to $(1/T_{Stroke}) * 60$
	T_{Pull}	Seconds (s)	Pull time a.k.a. water time; time between catch and exit as defined by device)
	T_{Air}	s	Air time; from end of stroke to beginning of contralateral stroke
	T_{Stroke}	s	Stroke time; time elapsed during one stroke cycle from paddle blade entry to entry of contralateral side
	Pull %	%	T_{Pull} / T_{Stroke}
Kinetic	F_{Mean}	N	Mean blade force; mean force perpendicular to paddle shaft during T_{Pull} measured from 1/3 length of blade surface
	F_{Peak}	N	Peak blade force; peak force perpendicular to paddle shaft during T_{Pull} measured from 1/3 length of blade surface
	Impulse	N-s	Sum of net force * T_{Pull}
	IR*	N-s/cycle	Impulse rate; rate of blade impulse transmitted during T_{Stroke}, equal to impulse * SR * constant

Notes. Variables measured by smart paddle (SP) and Rover GPS

** Indicates variable described elsewhere*

All data was exported and stored in Microsoft Excel. Statistical analyses were done using XLSTAT (Addinsoft, Paris, France) and Tableau (Tableau, Seattle, USA), and Stata (Statacorp, College Station, USA). Data were summarised using mean ± SD unless otherwise reported. Cohen's *d* effect sizes and 95% CI were calculated to quantify the standardised mean differences between methods, with threshold values of 0.2, 0.5, 0.8, and 1.3 used to represent small, moderate, large, and very large effects, respectively (Cohen, 1988, p. 40; Rosenthal, 1996). Assumptions of normality and linearity were addressed via examination of the Normal Q-Q plot and scatterplot. Outliers (±1 SD) such as those observed during the first and last two strokes of a trial were discarded.

Since SR was the constrained independent variable, it was important to compare group SR distributions prior to further statistical analysis. The total stroke count for all athletes at each level was considered sufficient for performing analyses on all strokes. Specifically, strokes were considered discrete samples within groups (environments). Mean SR was close to the prescribed value at each test level, though with expected inter and intra-individual variability (Table 7).

Table 7. Collection protocol sample details for ergo and H2O

Test level	N		SR M ± SD		*d*	Rating
	Ergo	H2O	Ergo	H2O		
1	755	496	33.6 ± 1.7	32.6 ± 1.6	0.60 ± 0.11**	Moderate
2	534	543	36.6 ± 1.4	36.2 ± 3.6	0.15 ± 0.12*	Trivial
3	314	299	41.8 ± 2.1	40.7 ± 1.6	0.57 ± 0.16**	Moderate
4	359	347	49.0 ± 2.0	48.1 ± 1.4	0.51 ± 0.15**	Moderate
5	202	183	60.9 ± 3.2	57.7 ± 2.0	1.20 ± 0.22**	Large
6	113	100	80.4 ± 7.3	68.2 ± 3.9	2.06 ± 0.33**	Very large

Notes. Values are M ± SD; SR = stroke rate (cycles/minute); ergo = ergometer environment; H2O = on-water paddling environment, d = Cohens effect size. N strokes describes the total strokes for all four participants performed at each level.

** p<0.05, ** p<0.01.*

Linear and nonlinear regression were used to determine the relationship between test level, SR, and each dependent variable listed in Table 7. Ergometer and on-water groups were compared, controlling for SR. All data were pooled, so each stroke represented an observation where there are multiple observations per person per level. Subjects were treated as a random effect in the regression models to account for the non-independence of the stroke observations. In order to compare linear regression coefficients, data were log-transformed prior to statistical testing. After log-transform most stroke phase parameter variables were fit by linear functions. Residual plots were used to confirm normally-distributed residuals. Scatterplots of nonlinear data were visually examined and presented for practical understanding.

Statistical Parametric Mapping

Statistical parametric mapping (SPM, Friston et al., 2007) was used to determine the existence of statistically significant differences in force-time profiles at each test level. SPM uses random field theory to objectively identify field regions which co-vary significantly with the experimental design (Pataky, Robinson, & Vanrenterghem, 2013, 2016). A SPM two-tailed paired-sample t-test was performed on the time-normalised force data from the SP to determine if a significant difference was present between ergometer and on-water paddling. 1D SPM analyses were implemented in MATLAB as described previously using the open source package located at http://www.spm1d.org/ "RFT1D" (Pataky et al., 2016).

Results

Kinematics

Ergometer and on-water paddling had significant differences in kinematic variables across all intensities. The data was visualised on scatterplots with SR as the independent variable (Figure 23). Table 8 describes the range and relative difference in stroke phase parameters across levels 1-6. T_{Pull} decreased progressively as SR increased for both conditions; however, ergometer paddling had a consistently lower T_{Pull} even when controlling for SR (slope difference = -0.160 ± 0.00, SE = 0.001, z = -152.52, p < 0.01). T_{Air} also decreased as SR increased; in contrast, ergometer paddling had consistently longer T_{Air} compared to on-water paddling (slope difference = 0.42 ± 0.01, SE = 0.003, z = 152.82, p < 0.01).

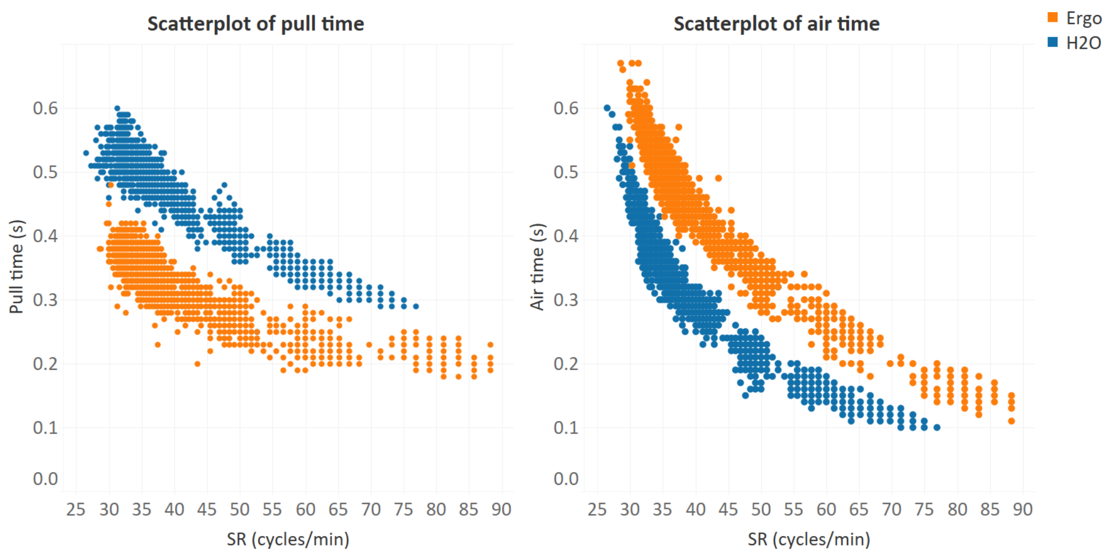

Figure 23. Scatterplots of stroke phase parameters to SR

Scatterplots show nonlinear decreasing trends of stroke phase parameters as SR increases. All strokes for each participant and level are plotted.

Table 8. Descriptive statistics and effect sizes for stroke phase parameters for ergo and H2O

Test level	T_{Pull} (s) M ± SD				T_{Air} (s) M ± SD			
	Ergo	H2O	*d*	Rating	Ergo	H2O	*d*	Rating
1	0.36 ± 0.03	0.52 ± 0.03	5.29 ± 0.24**	Very large	0.54 ± 0.04	0.40 ± 0.05	3.05 ± 0.16**	Very large
2	0.34 ± 0.04	0.50 ± 0.03	4.62 ± 0.23**	Very large	0.48 ± 0.04	0.34 ± 0.03	4.07 ± 0.21**	Very large
3	0.30 ± 0.02	0.46 ± 0.03	6.51 ± 0.40**	Very large	0.42 ± 0.04	0.28 ± 0.02	4.45 ± 0.29**	Very large
4	0.27 ± 0.02	0.41 ± 0.02	6.69 ± 0.38**	Very large	0.35 ± 0.03	0.22 ± 0.02	5.32 ± 0.31**	Very large
5	0.24 ± 0.02	0.36 ± 0.02	6.05 ± 0.47**	Very large	0.26 ± 0.03	0.16 ± 0.02	3.96 ± 0.34**	Very large
6	0.21 ± 0.02	0.32 ± 0.02	6.20 ± 0.65**	Very large	0.17 ± 0.06	0.12 ± 0.02	1.07 ± 0.29**	Large

Notes. Values are M ± SD; T_{Pull} = pull time; T_{Air} = air time; d = Cohens effect size, s = second.

** $p<0.05$, ** $p<0.01$.*

Kinetics

F_{Peak} and F_{Mean} were increasingly different as the intensity level increased. Both variables were most different at maximal intensity (Table 9). Kinetic variables followed a linear relationship as SR increased (Figure 24). The regressions were compared via a mixed models approach controlling for SR and athlete. F_{Peak} differed significantly between the two groups, with the difference increasing at higher intensities (slope difference = 28.72 ± 1.74, SE = 0.89, z = 32.28, $p < 0.01$). There were also significant differences in F_{Mean} between devices, although by a smaller magnitude (slope difference = 8.44 ± 0.92, SE = 0.47, z = 17.95, $p < 0.01$).

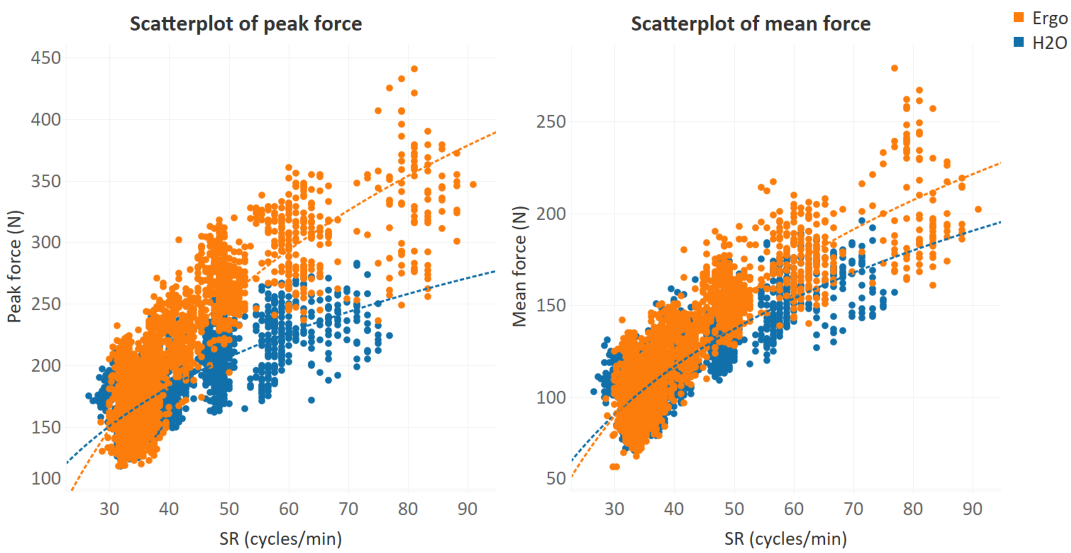

Figure 24. Scatterplots of primary kinetic variables to SR

Scatterplots show nonlinear increasing trends of primary kinetic variables as SR increases. Scatterplot shows increased variability at respective maximal intensities. All strokes for each participant and level are plotted.

Table 9. Descriptive statistics and effect sizes for primary kinetic variables for ergo and H2O

Test level	F_{Mean} (N) M ± SD				F_{Peak} (N) M ± SD			
	Ergo	H2O	*d*	Rating	Ergo	H2O	*d*	Rating
1	99.8 ± 13.8	95.1 ± 12.8	0.35 ± 0.11**	Small	161.9 ± 23.5	154.0 ± 18.5	0.37 ± 0.11**	Small
2	109.2 ± 15.5	102.5 ± 11.2	0.50 ± 0.12**	Moderate	183.6 ± 26.4	164.7 ± 16.8	0.85 ± 0.12**	Large
3	129.8 ± 12.3	118.5 ± 14.5	0.85 ± 0.17**	Large	224.2 ± 21.4	187.8 ± 21.9	1.68 ± 0.18**	Very large
4	153.7 ± 13.1	136.0 ± 13.4	1.34 ± 0.16**	Very large	267.5 ± 22.6	208.3 ± 19.9	2.77 ± 0.21**	Very large
5	175.6 ± 16.4	152.7 ± 15.5	1.44 ± 0.22**	Very large	302.8 ± 27.5	222.8 ± 23.9	3.10 ± 0.30**	Very large
6	204.1 ± 29.0	160.8 ± 14.0	1.87 ± 0.32**	Very large	333.5 ± 45.8	233.9 ± 21.1	2.74 ± 0.37**	Very large

Notes. Values are M ± SD; F_{Mean} = mean force; F_{Peak} = peak force; d = Cohens effect size, N = Newton.

** p<0.05, ** p<0.01*

Impulse and IR were quite different at low-to-mid intensities within the protocol (Table 10). Impulse was consistently lower for ergometer paddling even when controlling for SR (slope difference = -13.78 ± 0.28, SE = 0.15, $z = -95.02$, $p < 0.01$). Despite appearing random, the distribution of impulse and SR had visible significant differences (Figure 25). Impulse was also examined during stroke phase parameters to control for the kinematic differences described earlier. The scatterplot of T_{Pull} and impulse suggests that that on-water paddling still had larger impulse per stroke from 0.3-0.4s, where the distributions overlap (Figure 25). Notably, IR was least different at max intensity ($d = 0.28 \pm 0.27$), though IR was consistently higher across the range of SR (Figure 26).

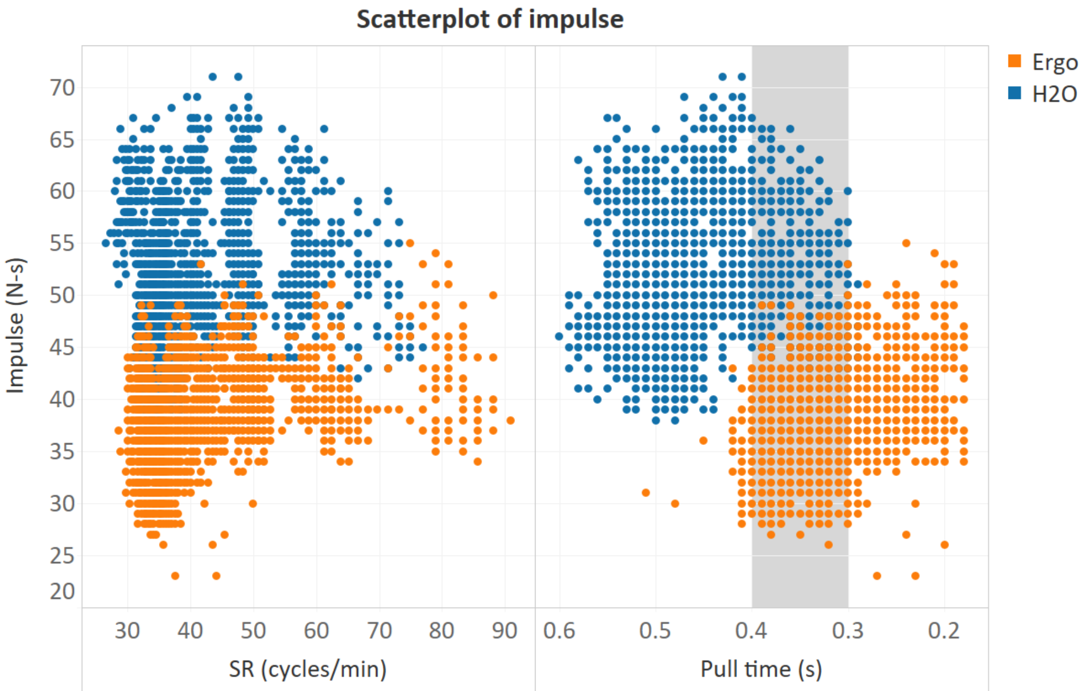

Figure 25. Scatterplots of impulse to SR and T_{Pull}

Note the non-normal distributions but apparent differences in impulse for strokes across SR and at overlapping values of T_{Pull}. All strokes for each participant and level are plotted.

Table 10. Descriptive statistics and effect sizes for impulse and impulse rate for ergo and H2O

Test level	Impulse (N-s) M ± SD				IR (N-s/cycle) M ± SD			
	Ergo	H2O	*d*	Rating	Ergo	H2O	*d*	Rating
1	35.7 ± 4.7	49.6 ± 6.6	2.50 ± 0.15**	Very large	39.7 ± 5.6	53.6 ± 5.9	2.41 ± 0.15**	Very large
2	37.4 ± 6.4	50.7 ± 5.6	2.21 ± 0.15**	Very large	45.5 ± 6.8	61.0 ± 7.2	2.20 ± 0.15**	Very large
3	39.2 ± 3.5	53.7 ± 5.9	3.01 ± 0.23**	Very large	54.5 ± 5.4	73.0 ± 8.3	2.62 ± 0.22**	Very large
4	40.8 ± 3.6	55.2 ± 5.8	3.01 ± 0.22**	Very large	66.4 ± 5.6	88.4 ± 9.5	2.83 ± 0.21**	Very large
5	41.9 ± 3.2	50.9 ± 5.3	3.04 ± 0.29**	Very large	83.5 ± 6.8	104.4 ± 11.4	2.26 ± 0.26**	Very large
6	41.2 ± 4.8	54.3 ± 4.6	1.92 ± 0.32**	Very large	112.0 ± 14.7	116.0 ± 10.5	0.28 ± 0.27**	Trivial

Notes. Values are M ± SD; IR = impulse rate; d = Cohens effect size, s = second, N = newton.

** p<0.05, ** p<0.01.*

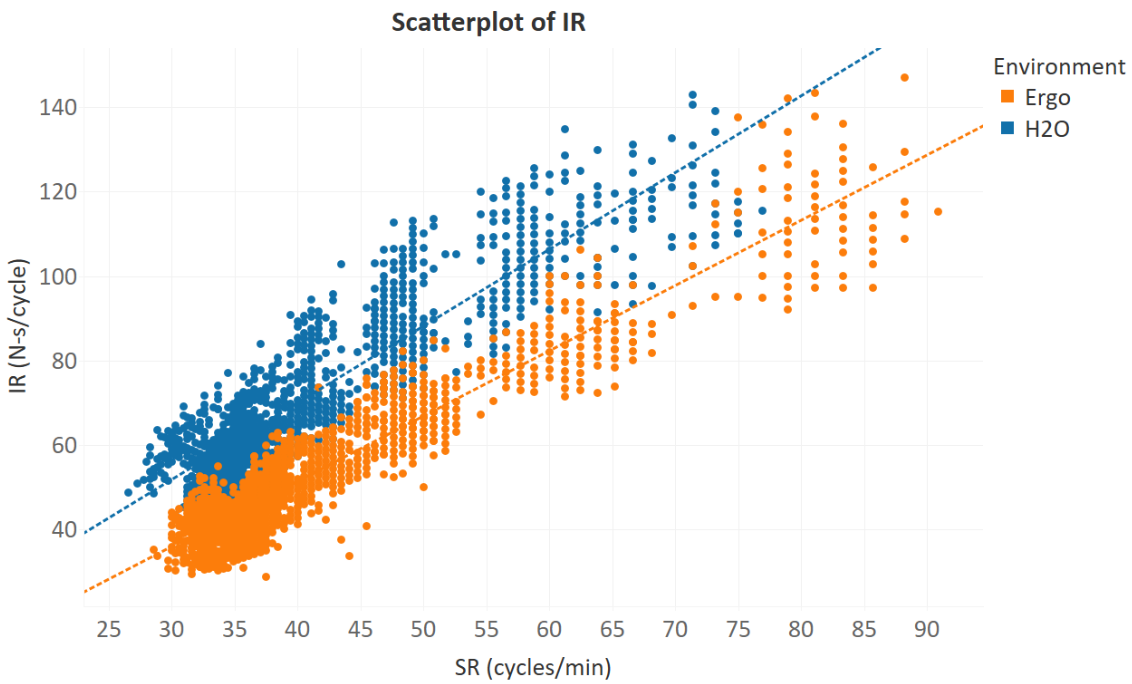

Figure 26. Scatterplot of IR to SR

Scatterplots show linear increasing trend of IR as SR increases. All strokes for each participant and level are plotted.

Statistical Parametric Mapping

Examination of the time normalised averaged force-time profiles reveals clear differences in magnitude and shape across all intensities. Qualitative differences in location of F_{Peak} may be observed and become more pronounced at higher intensities. Visual inspection of Figure 27 shows widening differences from 20-70% of the paddle stroke across levels 1-6. Blade force is significantly higher in the ergometer condition from start to 34% at the lowest intensity level. One supra-threshold cluster (0-34%) exceeded the critical threshold of 2.64 as the force observed during ergometer paddling was significantly higher than on-water paddling ($p < 0.01$). Increasing supra-threshold cluster sizes and magnitudes (t-values) were observed as intensity increased (Table 11).

Table 11. SPM results for difference between ergo and H2O force-time profiles by test level

Level	Range of difference (%)	t	p
1	5-34	2.64	$p < 0.01$
2	5-60, 68-95	2.65	$p < 0.01$
3	5-58, 69-95	2.68	$p < 0.01$
4	5-60, 68-95	2.66	$p < 0.01$
5	15-62, 67-95	2.70	$p < 0.01$
6	17-89	2.77	$p < 0.01$

Notes. t = critical value for detected difference. Range of difference corresponds to the dark grey shaded area in Figure 28.

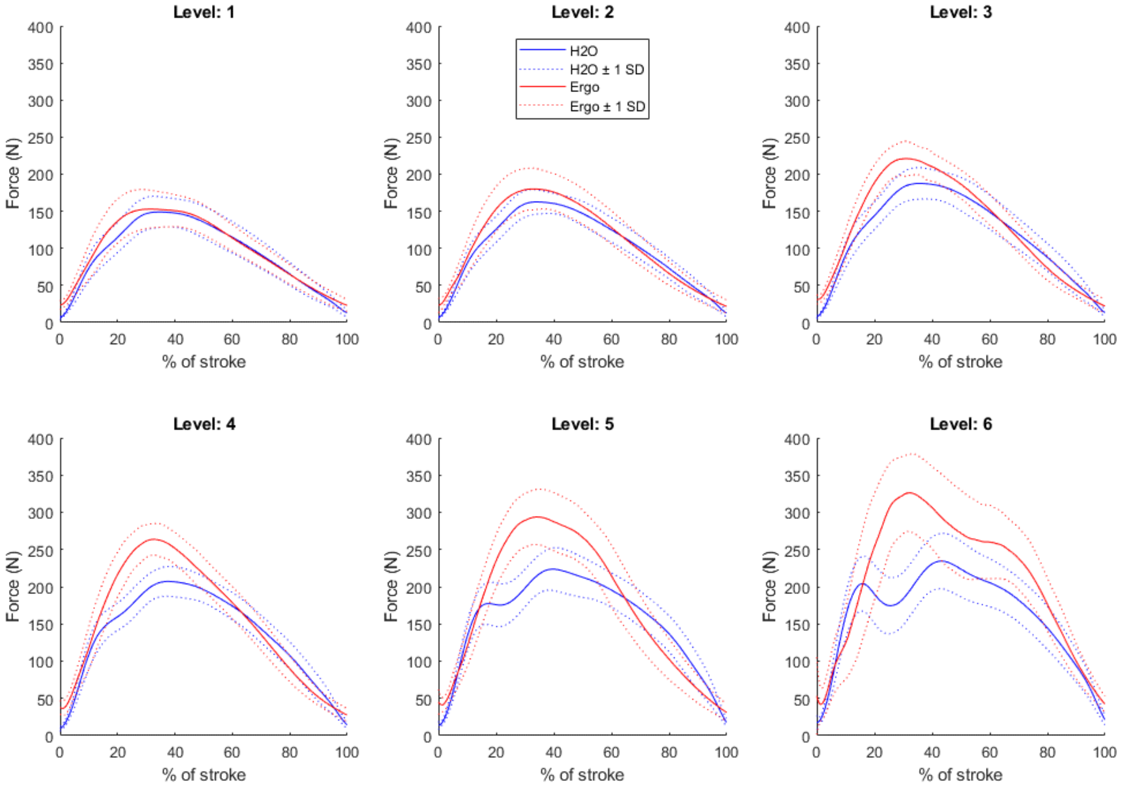

Figure 27. Force-time profiles of ergo and H2O groups across intensities

Mean force-time profiles for all athletes (n = 4) reveal the location of significant differences (non-overlapping SD) between ergometer and on-water paddling for all test levels.

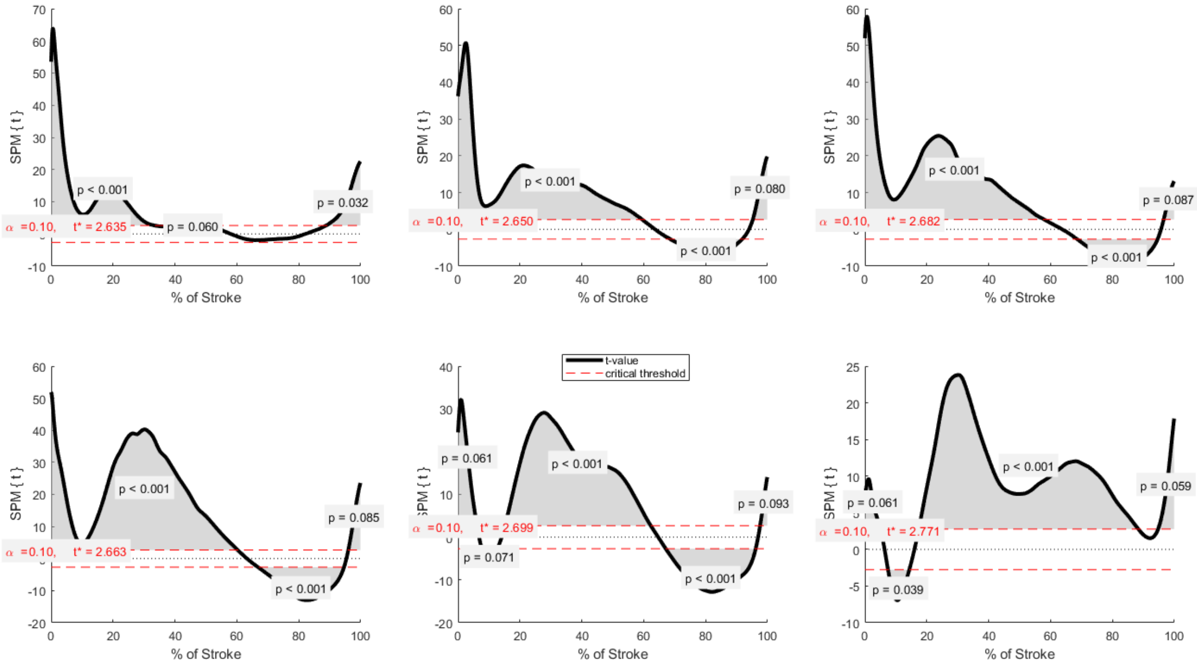

Figure 28. SPM results

Each figure describes the location and magnitude of significant differences between force-time profiles at each test level. Note the larger SPM (t) statistic at higher intensities near 30% of stroke. The results are described in Table 11.

Discussion

The large, significant differences in kinematic and kinetic variables between environments indicate that the biomechanical task specificity of ergometer paddling is low. The regression analyses indicated that differences in T_{Pull}, T_{Air}, F_{Peak}, F_{Mean}, impulse, and IR occur across most tested intensities. The SPM analysis located differences in force-time profiles between groups at all intensities.

Practically, the most relevant comparison for coaches and researchers is between environments at maximal intensity. Although some ergometer testing is performed at submaximal levels, one of the most popular testing protocols is Wingate maximal power testing (Borges et al., 2017; Villarino-Cabezas et al., 2013). Large, significant differences in kinematic and kinetic outputs (e.g., F_{Peak} $d = 2.74 \pm 0.37$, $p < 0.01$) are maximised at the highest intensity levels (Table 12). Athletes were able to achieve higher SRs on the ergometer due to significantly shorter T_{Pull}. Despite the short pull phase, much higher F_{Peak} of the ergometer is of critical importance to researchers and coaches. Ergometer paddling must allow for higher forces either due to the fundamental resistive difference between flywheels and water or altered constraints upon the paddler's force production (such as balance). Although increased forces are seen on the ergometer, the beneficial, or potential detrimental effects have not been investigated. Ultimately, the lack of difference in IR between environments summarises one of the most important conclusions: at maximal intensities, athletes produce somewhat equal work on the ergometer and on-water. Only the way they achieve that work rate differs.

Table 12. Descriptive statistics and effect sizes for biomechanical variables of ergo and H2O paddling at maximal intensity

	SR		T_{Pull}		F_{Peak}		IR	
	Ergo	*H2O*	*Ergo*	*H2O*	*Ergo*	*H2O*	*Ergo*	*H2O*
Mean	80.4	68.2	0.21	0.32	333.5	233.9	112.0	115.6
d	2.06 ± 0.33**		6.20 ± 0.65**		2.74 ± 0.37**		0.28 ± 0.27**	

Notes. Notes. Values are whole-group means; SR = stroke rate (cycles/minute); T_{Pull} = pull time (seconds); T_{Air} = air time (seconds); F_{Peak} = peak force (Newtons); IR = impulse rate (Newton-seconds/cycle); d = Cohens effect size.

** p<0.05, ** p<0.01.*

Descriptive statistics suggested that individual variation was present in the magnitude of difference observed in force variables. Specifically, the distributions showed identical increased divergence at higher intensities, except one athlete (Athlete 3) had more uniform difference (Figure 29). Other scatterplots revealed similar outliers for two other variables (athlete 1, IR, athlete 4, impulse). It is possible that inter-individual technique differences caused these observable trend divergences. If the specificity of ergometer paddling varies by individual, then more research is needed to delineate the exact factors that determine variable responses.

Figure 29. Individual scatterplots of F_{Peak} and SR

Each scatterplot is for one athlete of n = 4. Trend lines demonstrate the variability of individual differences between the two paddle environments.

The SPM analysis helps to visualise the primary differences described above. Visible patterns emerged at higher intensities, particularly in pull % and F_{Peak} (Figure 27 and Figure 31). Not only is F_{Peak} larger, but it also occurs earlier during ergometer paddling. Furthermore, a slight double-peak emerged at levels 5 and 6 (Figure 30). This reflects the "catch" on-water, a brief delay between water entry and maximal force production, that does not appear in ergometer paddling. Alternatively, it could represent blade slip, detrimental posterior displacement of the paddle during T_{Pull}. This is aspect is referred to as "smoothness", which can be quantified by drawing a line between local maxima and calculating the "missed" impulse (Hill, 2002). In other words, increased smoothness would increase propulsive impulse, and have a beneficial impact upon V_{Kayak}. Although smoothness was not quantified for groups or individuals, previous research suggests that this is a disadvantageous force-time profile characteristic (Hill, 2002; Warmenhoven et al., 2018). Visual inspection of force-time profiles does help identify at what intensity this sample and individuals begin to lose smoothness, and, thus, propulsive efficiency. Figure 31 shows qualitative differences in aspects other than FPeak, stroke phase parameters, and smoothness such as shape, squareness (F_{Mean}/F_{Peak}), and intra-group variability.

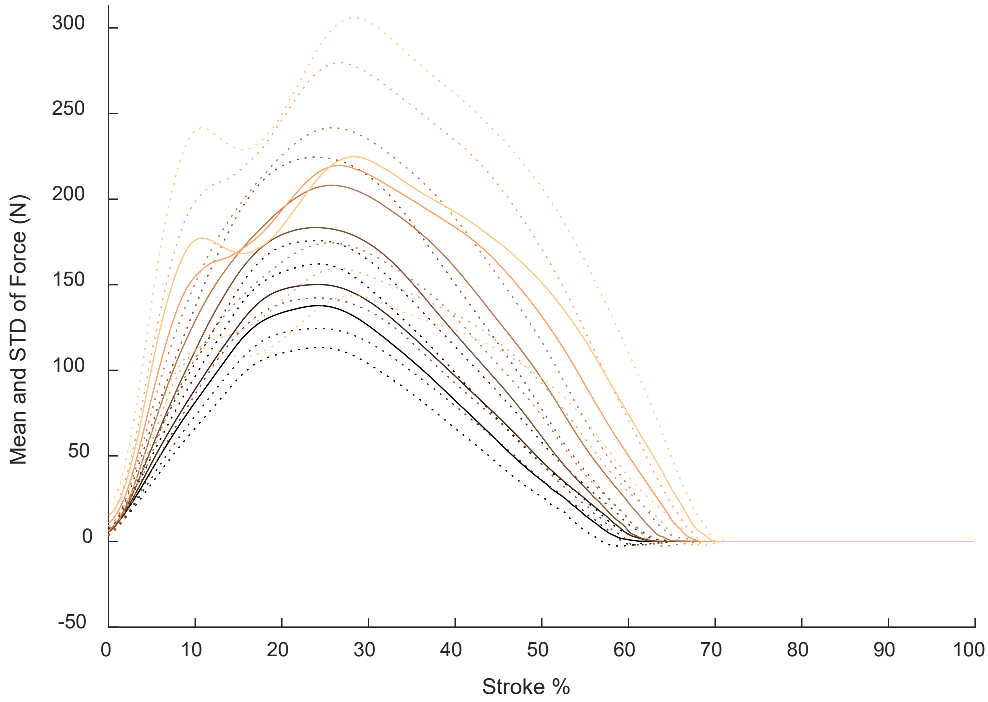

Figure 30. Force-time profiles for one athlete at increasing intensity

Mean force-time profiles for one athlete (n = 1) at levels 1-6 show progressive increase in impulse and increasing lack of profile smoothness.

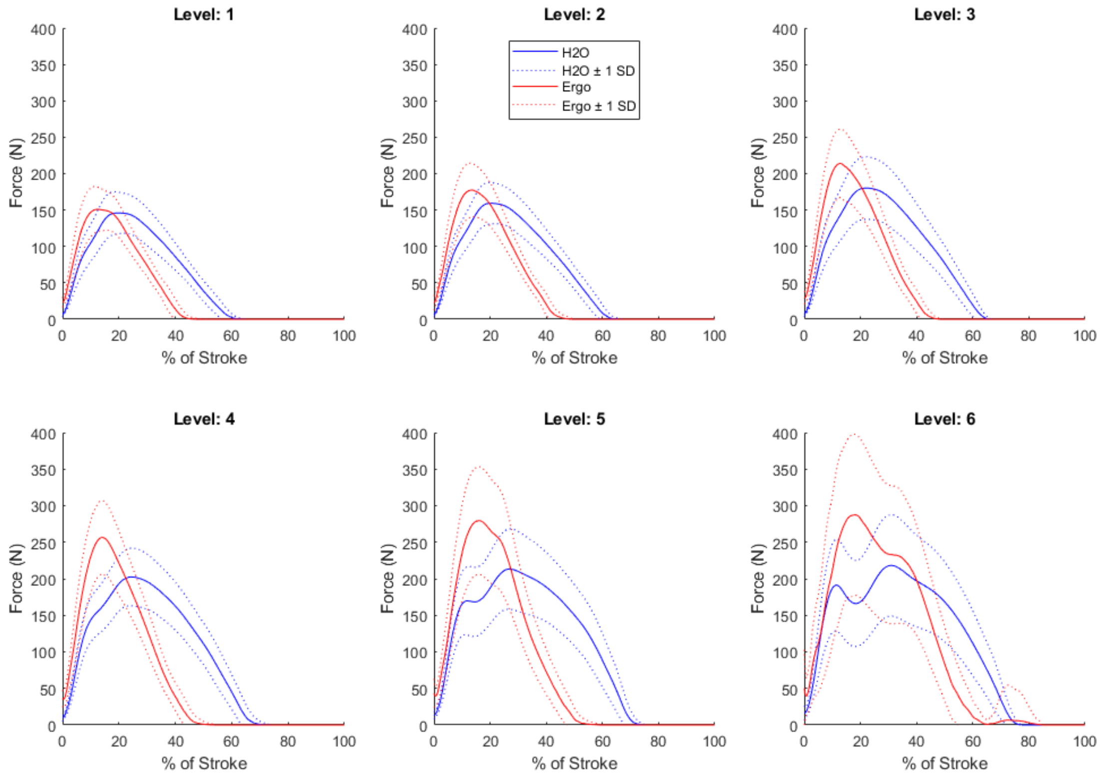

Figure 31. Force-time profiles of ergo and H2O groups for full T_{Stroke}

Mean force-time profiles for all athletes (n = 4) reveal the location of significant differences (non-overlapping SD) between ergometer and on-water paddling for all test levels. Relative stroke *phase parameters differ substantially, as well as force-time profile shape. Note the signature lack of smoothness in the H2O profile at levels 5 and 6.*

High correlation between SR and IR (ergo, $r = 0.92$, $p < 0.01$; H2O, $r = 0.90$, $p < 0.01$) confirms that SR is a good indicator of not only paddling frequency, but also intensity. Due to training requirements, SR was the constrained variable during all testing sessions. At each level, athletes were asked to keep their SR within specific ranges. They were able to adhere to the prescribed SR, except at level 5 ($d = 1.20$, $p < 0.05$) and, as expected, at maximal intensity ($d = 2.08$, $p < 0.01$). These analyses thus not only answer the question, “what happens as athletes paddle faster?” but also “what happens as athletes paddle harder?” The exception occurs at maximal intensity- although SR was significantly different, IR was practically equivalent ($d = 0.28 \pm 0.27$, $p < 0.01$). This study used SR as a determinant of intensity; it was recommended that the data also be analysed using IR as the independent variable. Informal analyses of the data (using IR as the independent variable in linear regression) confirmed similar differences between environments for kinematic and kinetic variables. This is likely due to the high correlation between SR and IR.

The differences in kinematic and kinetic variables suggest that ergometer paddling differs substantially from on-water paddling. These findings build upon the existing literature demonstrating physiological (Michael et al., 2012; Villarino-Cabezas et al., 2013) and kinematic (Mickael Begon et al., 2008; Fleming, Donne, Fletcher, et al., 2012) differences. One study found a statistically significant difference in RFD, but found no difference in T_{Pull}, F_{Peak}, and impulse, differing from the results of this study (Fleming, Donne, Fletcher, et al., 2012). RFD was not examined in this study because it was determined to be an unreliable output from the SP. Nevertheless, large significant differences were observed for T_{Pull}, F_{Peak}, and impulse, and other biomechanical variables.

The quantity of observed differences between devices warrants further investigation into the construction of the DS. In rowing, where similarly observable differences have been reported (Hume, 2017; Kleshnev, 2008; Soper & Hume, 2004), a simple modification of adding sliders underneath the device was seen to drastically minimise the biomechanical differences (Millar, Reid, McDonnell, Lee, & Kim, 2017). A similar invention has been applied to kayak ergometers, although the biomechanical differences from an unmodified device were not reported (Mickaël Begon et al., 2008). Biomechanical differences could also be complicated by the absence of balance as a constraint in ergometer paddling; however, no literature could be found on this topic. More research is needed to determine if ergometer construction could affect paddling biomechanics and better mimic on-water paddling.

As noted by Warmenhoven et al. (2018), there is a lack of research surrounding what aspect of force profiles correlate to performance in paddle sports. Hence, although there are observable differences between environments, proposing that one is superior is only speculation. More research is needed to discover the effect of different force profiles upon performance. Regardless, ergometers are designed to best replicate training and competition activities. The methodology and results contained in this research may provide insight into improving future ergometer specificity.

Chapter 5. Biomechanical Determinants of Kayak Sprint Performance

Preface

This chapter focuses on biomechanical variables of paddling and associated constraints related to boat performance. A study combining SP data and GPS accelerometer data was able to identify numerous kinetic variables with strong associations with boat speed (V_{Kayak}). Allometric scaling is an effective strategy that could be utilized to control for BM differences. More research is needed to quantify the effect of other determinants such as D_F and weather conditions upon performance.

Abstract

Aims

This chapter examines physical variables related to V_{Kayak}. The study itself demonstrates the capabilities of the SP and the relationship between key variables and boat performance. It was proposed that many kinematic and kinetic variables would be strongly correlated with V_{Kayak} and α_{Kayak}, and the strongest predictive relationships might be useful for training prescription. Secondary analyses evaluated the relationship between V_{Kayak} and BM, D_F, and efficiency.

Methods

Ten elite athletes performed a standardised warmup followed by a graduated paddle protocol ranging from 30 – 90 cycles/min on-water under controlled conditions. Data was collected with the SP and Rover GPS. Data was analysed using standardised correlation coefficients, linear and nonlinear regression, R^2, and SE.

Results

Primary kinetic variables had strong correlations with V_{Kayak} (F_{Mean}, $z = 1.49$, $p < 0.01$, F_{Peak}, $z = 1.17$, $p < 0.01$, V_{Blade}, $z = 1.86$, $p < 0.01$). The strongest correlations and predictive power upon V_{Kayak} were with IR ($R^2 = 0.98$, SE = 0.31, $z = 1.86$, $p < 0.01$) and P_{Cycle} ($R^2 = 0.95$, SE = 0.035, $z = 2.08$, $p < 0.01$). Allometric scaling increased the predictive power of most kinetic relationships. Strong correlations were observed between DPS and F_{Peak} ($r = 0.69 \pm 0.10$), F_{Mean} ($r = 0.68 \pm 0.11$), P_{Peak} ($r = 0.72 \pm 0.10$), and impulse ($r = 0.65 \pm 0.18$). e_p was estimated between 0.65-0.75, on average, for all intensities.

Discussion

Results suggest that there are many strong associations between SP variables and V_{Kayak}. These associations enhance our understanding of kayak performance and may be used for future

analysis. A more detailed understanding of D_F, boat motion, and environmental factors are needed to improve predictive capability.

Practical Applications

The predictive capability of kinetic variables upon V_{Kayak} should be evaluated via replication and transformation of this experimental protocol. Allometric scaling improves predictive relationships and should be incorporated into performance testing. Other data, such as boat motion, should be integrated into advanced statistical techniques to quantify their effect on boat performance. IR may be explored as a governing variable for training prescription.

Introduction

Kayak sprint is a physically and technically demanding sport at all levels of competition. Athletes must achieve a delicate balance of power and finesse to gain the slightest advantage against a fellow competitor. For those staff supporting each athlete, the question lingers, how to make a boat go fast.

Previous work has suggested that numerous biomechanical variables have strong correlations with V_{Kayak}. As discussed earlier, on-water kinematic variables such as SR, T_{Pull}, and e_p are all closely tied to V_{Kayak} (Greidanus et al., 2016; McDonnell et al., 2013). Other individual performance characteristics such as anthropometry, muscular strength, and physiological ability are also significant performance predictors (Ackland, Ong, Kerr, & Ridge, 2003; McKean & Burkett, 2014; Steeves et al., 2018; Zouhal et al., 2012). However, the relationship between kinetic variables and V_{Kayak} is unclear, with few published studies examining their correlation on-water. Those studies have proposed propulsive power, F_{Peak}, and stroke phase parameters as variables of interest in kayak performance analysis (Gomes et al., 2015; Macdermid & Fink, 2017). Nevertheless, more research is needed to clarify which kinetic variables are most closely correlated with boat performance.

A large amount of propulsive impulse generated at the paddle blade is opposed by D_F (Michael et al., 2009). D_F is a major factor in the energetics of paddling, so small changes can result in large changes in performance (Pendergast et al., 2003). Estimations of D_F, though, are complicated by the different contributions of passive (D_P) and active (D_A) drag. D_P is the drag force associated with the boat travelling at a constant velocity V_{Kayak}. It has been estimated (Pendergast et al., 2005) and measured (Gomes et al., 2015) for sprint kayaks and is proportional to V_{Kayak} and system mass. System mass affects total wetted area of the kayak, which causes exponentially-increasing D_P proportional to V_{Kayak}.

Boat movements exclusive of linear horizontal velocity also cause increased D_F; these comprise D_A. Active drag (D_A) describes the drag forces associated with boat motion and resultant inertia changes (Zatsiorsky, 2008). For example, surge (cyclic α_{Kayak} characteristic of paddling) yaw, and pitch have been shown to greatly increase drag forces and decrease propulsive efficiency (Kleshnev, 1999; Pendergast et al., 2005). As with D_P, any movement that causes increased wetted area will increase D_A, summing with D_P to increase D_F. Estimates of D_A are based on valid methods of measuring submaximal oxygen consumption (Pendergast et al., 2005); these have been demonstrated in many aquatic sports (McKenzie & Berglund, 2019). However, robust methods of calculating D_A (such as modeling from 3D boat motion data), or even inclusion of estimated D_A, are not common in the literature.

D_F is proportional to V_{Kayak} squared, and directly proportional to the frontal surface area of the kayak (Gomes et al., 2017). Given the importance of D_F in affecting e_p and performance, it reduction should be a priority for elite kayak sprint athletes and coaches (Greidanus et al., 2016). However, its marked complexity has contributed to a lack of experimental research. Velocity fluctuations, three-dimensional boat movement, and individual movement strategies contribute to its measurement difficulty, but also reveal theoretical D_F reduction strategies (Higgens et al., 2016; Laurent et al., 2013). For example, McDonnell et al. (2013) used shorter intra-stroke deceleration (thus D_F reduction) as a theoretical underpinning for increasing SR to improve performance. Increasing SR usually reduces T_{Air}, so less time during the non-propulsive phase would reduce boat deceleration between strokes. A different perspective to achieve the same result is altering the ratio of stroke phase parameters to increase pull time percentage (pull %). Alternatively, paddlers may be able to improve e_p by producing earlier F_{Peak} during T_{Pull} (Wainwright et al., 2016). It must be noted that drag is not always detrimental; drag at the paddle blade is necessary for horizontal force production. Blade shaft orientation such as pitch or yaw may decrease the drag coefficient, and, thus, propulsive impulse. Other strategies have been proposed to reduce D_F, including equipment design, paddling technique, and reduction of BM (Day, Campbell, Clelland, Doctors, & Cichowicz, 2011; Gomes et al., 2015; Pendergast et al., 2005).

Not only does BM affect D_F, but also bioenergetics and biomechanical demands upon the paddler. In many sports, staff and researchers have experimented with BM scaling for performance data for augmenting analysis. Since the early 1930s, allometric scaling was used to better estimate physiological variables of mammals, and Kleiber's Law stands stating that an animal's metabolic rate scales to the ¾ power of the animal's mass (Kleiber, 1961). Though originally used for metabolic variables, allometric scaling has shown promise for power in controlled lab settings (Suchomel, Nimphius, & Stone, 2018) and in the field, for example, rowing (Pelz & Vergé, 2014). Remarkably, the application of allometric scaling for power and other biomechanical variables in ergometer and field testing has used exponents like that proposed by Kleiber (1961) (0.75). For example, scaling cycle ergometer scores (W) for BM ^ 0.74-0.77 provides the best correlations to male cyclists' performance (Jaafar, 2017), while BM ^ 0.76 is has equivalent significance for female cyclists (Hetzler, Stickley, & Kimura, 2011). Research has suggested scaling exponents from 0.67 for strength exercises (Crewther, McGuigan, & Gill, 2011) to 0.86 in cycle ergometry (Stickley, Hetzler, Wages, Freemyer, & Kimura, 2013). Other studies have explored allometric scaling of team boats (Pelz & Vergé, 2014) and ergometer scores in rowing (Nevill et al., 2010). The quantity of research in this area alludes to its apparent clinical and practical importance. The case for allometric scaling of performance tests is strong and the appraisal by Jaric, Mirkov, and Markovic (2005) gives detailed information on its experimental approach. Hence, this was an important outcome of this study.

Methods

Experimental Overview

This study examined kinematic and kinetic variables of kayak sprint performance across a range of intensities under controlled conditions. Using SP data and GPS data, the predictive capability of kinetic variables upon V_{Kayak} was assessed to understand the biomechanical determinants of boat speed.

The general approach to this analysis was inspired by steps 1-5 of the Applied Research Model for Sport Science (ARMSS) (Bishop, 2008). The full eight-stage model includes:

1. Defining the problem
2. Descriptive research (hypothesis generating)
3. Predictors of performance
4. Experimental testing of predictors
5. Determinants of key performance predictors
6. Efficacy studies (controlled laboratory or field)
7. Barriers to uptake
8. Implementation studies (real sporting setting)

The ARMSS model was proposed to combine exploratory and experimental study designs to maximise transferability (Bernards, Sato, Haff, & Bazyler, 2017). The exploratory component enabled comparison against previous studies and the evaluation of new variables from the SP. Later, causal methods were utilised such as correlation, regression, and confidence intervals (Bernards et al., 2017; Bishop, 2008; Li, 2015).

Participants

Ten (five male, five female) elite level kayak sprint athletes were recruited based on predetermined criteria. They were all active competitors at the World Junior Championships or above, aged 17-26 years, with measured height 181.5 ± 4.0 cm (males), 170.2 ± 6.8 cm (females) and measured body mass 84.9 ± 7.5 kg (males), 76.2 ± 11.5 kg (females). Athletes were all carded high performance athletes with Canoe Racing New Zealand during time of testing. Normal training schedules consisted of 8-12 hours of paddling per week as well as 4-8 hours of resistance training per week. Additionally, study data collection occurred weeks before the athletes left for international competition; thus, they were engaged in a heavy training block. All athletes received oral and written information regarding the study's purpose and signed a consent form to participate in the study prior to the testing. Ethical approval for the study was granted from AUTEC 18/151.

Equipment

Smart Paddle

Four SP devices were used for this study. They were calibrated via the process described in Chapter 3. Then, they were fitted with the blades used by each athlete.

Rover GPS

The Rover GPS units are an in-house boat tracking device designed by Goldmine (HPSNZ, Auckland, New Zealand) for paddle sports. They consist of a high-frequency GPS receiver (10 Hz) and a six DoF (three linear accelerometers and three gyroscopes) IMU (100 Hz). The sensors can calculate cadence, DPS, V_{Kayak}, and more. Then the Rovers send live feedback to a compatible device via ANT+™ protocol.

Environmental Conditions

On-water testing was done on Lake Karapiro (Cambridge, New Zealand) and Lake Pupuke (Auckland, New Zealand) under stable environmental conditions (Karapiro, temperature 15 C, humidity 74%, pressure 1343.5 hPa; Pupuke, temperature 11 C, humidity 82%, pressure 1026 hPa). A Windbot device (Igtimi, Dunedin, NZ) was affixed to the coaching boat following the athletes closely to monitor real-time wind velocity and direction in close proximity to the athletes. For the females athletes' trial, the Windobt was positioned on the dock as close as possible to the testing area. Average parallel wind velocity was 0.33 ± 0.74 m/s on Lake Karapiro and 1.87 ± 0.64 m/s on Lake Pupuke during the testing session. River current data was gathered using the Tidebot (Igtimi, Dunedin, NZ), though effective current was negligible (<.1 m/s).

Procedure

Data collection occurred on two separate days in order to accommodate the different training venues for the men's and women's squads. All athletes used their usual equipment in addition to the SP. After the standardised warmup, athlete squads completed the test protocol (as described in Chapters 3 & 4) simultaneously on the training venue. The on-water protocol was performed with rolling starts. The coach gave a verbal cue for the athletes to begin paddling, and they had 15 seconds to reach the prescribed SR. All athletes were able to reach each SR level. Rolling starts were chosen to avoid any effect of standing starts upon fatigue and start technique and maximise adherence to SR zones.

Live SR data from the Rover GPS devices was monitored on the coach boat, with verbal encouragement used to instruct athletes to maintain the prescribed SR. A stopwatch was used to track rest times and stage durations. RPE data was gathered after each stage.

Statistical Analysis

Stroke Detection

In order to combine Rover and SP data, it was necessary to evaluate comparative reliability of the two devices for common outputs. Stroke detection was compared via discrete counts to confirm that the two devices detected all strokes within a trial. SR was assessed via Passing-Bablock regression and Bland-Altman plots for method comparison and determination of any bias.

Data Selection

SP data was collected and trimmed with the HPSNZ logger software. Rover data was collected and trimmed with the HPSNZ performance metrics software. The Rover and SP discrete stroke data were then manually time-matched according to the timestamp and right/left stroke designation. Only data during the constant velocity phase was used (Figure 32)

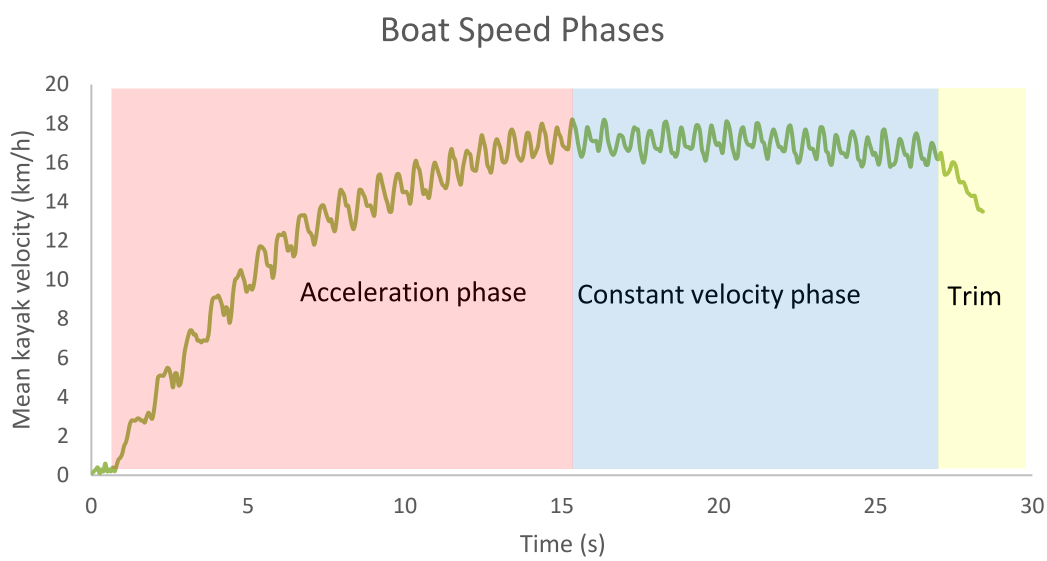

Figure 32. Boat speed phases

Rover data during one experimental trial. Blue shaded area indicates boat running speed phase after peak.

Only data after peak V_{Kayak} was used. The acceleration phase data from start to peak speed was separated, as the kinetic-kinematic relationships are substantially different. This is due to the system acceleration characteristics and drag relationships, which are discussed later in Chapter 6. Constant velocity phase includes all strokes from peak V_{Kayak} until end of paddling. Overall, the athletes are slightly decelerating, but the deceleration is not purposeful; it is due to fatigue and other factors.

Sample Preparation

All data was exported and stored in Microsoft Excel. Statistical analyses were done using XLSTAT (Addinsoft, Paris, France) and Tableau (Tableau, Seattle, USA). Data were summarised using mean ± SD unless otherwise reported. Assumptions of normality and linearity were addressed via examination of the Normal Q-Q plot and scatterplot. Comparison of SR between Rover and SP was assessed with Bland-Altman plots and Passing-Bablock regression. Outliers (±1 SD) such as those observed during the last two strokes of a trial were discarded. Analyses were performed at the group and individual level.

Variables Explored

The HPSNZ software described earlier was used to generate all data. This software extracted continuous, discrete, and average metrics from Rover GPS and SP. Those metrics were determined via previous consultation with experts, coaches, and staff as outlined by Oldham and Millar (2018). Stroke phase parameters were determined in accordance with those reported by

McDonnell, Hume, and Nolte (2012a). Tableau was used to create various derived metrics that were not exportable by HPSNZ logger. The variables examined in this study are listed below (Table 13).

Table 13. List of biomechanical variables examined during on-water paddling by Rover GPS and SP

	Variable	Units	Practical
Kinematic	SR	cycles/min	Stroke rate; measured in R+L cycles/min, equal to $(1/T_{Stroke}) * 60$
	DPS	m	Distance per stroke; horizontal boat displacement during T_{Stroke}
	V_{Kayak}	km/h	Kayak velocity (km/h); mean horizontal boat velocity during one stroke cycle T_{Stroke}
	α_{Kayak}	m/s^2	Mean positive acceleration during T_{Stroke}
	Speed surge	km/h	ΔV_{Kayak} from minimum V_{Kayak} to maximum V_{Kayak} during T_{Stroke}
	T_{Pull}	Seconds (s)	Pull time; time elapsed from blade entry to exit
	T_{Air}	s	Air time; time elapsed from blade exit to entry of contralateral side
	T_{Stroke}	s	Stroke time; time elapsed during one stroke cycle from paddle blade entry to entry of contralateral side
	Pull %	%	T_{Pull} / T_{Stroke}
	V_{Blade}	m/s	Mean linear blade velocity during pull (tangential velocity)
Kinetic	F_{Mean}	N	Mean blade force; mean force perpendicular to paddle shaft during T_{Pull} measured from 1/3 length of blade surface
	F_{Peak}	N	Peak blade force; peak force perpendicular to paddle shaft during T_{Pull} measured from 1/3 length of blade surface
	Impulse	N-s	Sum of net force * T_{Pull}
	P_{Mean}	W	Mean blade power; product of $F_{Mean} * V_{Blade}$
	P_{Peak}	W	Peak blade power; product of F_{Peak} * peak V_{Blade}
	P_{Cycle*}	W/cycle	Cycle power; P_{Mean} averaged across T_{Stroke}, equal to $(P_{Mean} * T_{Pull}) / T_{Stroke}$
	IR*	N-s/cycle	Impulse rate; rate of blade impulse transmitted during T_{Stroke}, equal to impulse * SR * constant (Equation 4)
	F_{Mean}/F_{Peak}*		Ratio of mean force and peak force
	EWS *	(W-s)	Effective work per stroke, $P_{Mean} * T_{Stroke}$ (Equation 7)

*Notes. * denotes derived variable described elsewhere*

In addition to expert consultation, previous literature influenced the creation of several derived variables. IR and P_{Cycle} were examined as described in Chapters 3 and 4. As suggested by Gomes et al. (2015), the F_{Mean}/F_{Peak} ratio was calculated for each stroke. Various symmetry index (SI) were calculated to quantify the differences between right and left for kinematic and kinetic variables (Equation 6) (Bishop, Read, Chavda, & Turner, 2016; Fohanno, Nordez, Smith, & Colloud, 2015; Glassbrook, Fuller, Alderson, Wills, & Doyle, 2018). Effective work per stroke (EWS) was calculated for each stroke as well (Equation 7), inspired by its strong positive correlations with boat velocity in other paddle sports (Baudouin & Hawkins, 2002; Kleshnev, 2006).

Equation 6. Calculation of peak power symmetry index

$$P_{Peak}\text{SI} = (P_{Peak}Right - P_{Peak}Left)/([P_{Peak}Right - P_{Peak}Left]/2) * 100$$

Equation 7. Calculation of effective work per stroke

$$\text{EWS} = P_{Mean} * T_{Stroke}$$

In order to confirm research direction, a correlation matrix was created. Spearman's rank correlation coefficients were transformed via Fisher's z-transformation for normality (Bernards et al., 2017). This was to account for non-normal, positively skewed distributions. Variables with strong correlations to V_{Kayak} or other kinematic variables (DPS, SR) were prioritised. Primary kinetic measures F_{Peak}, F_{Mean}, and V_{Blade} were examined first. Further emphasis was placed upon variables with the potential for live feedback on HPSNZ software (SR, impulse).

Predictive Modelling

The priority metric of interest was V_{Kayak}, mean boat velocity during one stroke cycle. A variety of statistical approaches were used to evaluate causal relationships: correlation, scatterplots, regression, and confidence intervals. Correlation coefficients were compared to assess significant relationships across the dataset. Standard linear regression was used to systematically assess the impact of discrete kinetic and derived metrics upon V_{Kayak}. First, data were examined as one sample containing all strokes for all individuals. Then, the same comparisons were made within individuals and for mean values at each test level. This was to observe if using all strokes caused overinflated regression results. Normality of V_{Kayak} at each level was appraised via the Q-Q plot and scatterplots. Despite heteroscedasticity at high intensities and autocorrelation of V_{Kayak} to the previous sample, data was lognormally distributed. The data was log-transformed according to the exponential growth of D_F as velocity increases (Greidanus et al., 2016; Pendergast et al., 2005). Residual plots were used to examine normally-distributed residuals. Variables were systemically added and removed in order to minimise the standard error of the regression (SE) and presented with adjusted R^2.

Equation 8. Linear regression formula for log-transformed variables

$$\ln(V_{Kayak}) = \beta_0 + \beta_1 \ln(X)$$

Intra-stroke Kayak Velocity

During the exploratory phase, consultation with experts inspired this study to examine not just V_{Kayak}, but also intra-stroke kayak velocity. Unfortunately, current accelerometer technology is not considered accurate enough to measure α_{Boat} (Cardinale & Varley, 2016; Janssen & Sachlikidis, 2010; Nagahara et al., 2017; Robinson et al., 2011; Varley et al., 2012). Therefore, the researchers sought to investigate other kayak kinematic variables. Because V_{Kayak} = SR * DPS, DPS was proposed to be a variable of interest. The Rover GPS units were considered accurate enough to estimate DPS. As suggested by Kleshnev (2006), although DPS fundamentally declines as SR increases (Figure 33), theoretically, maintenance of DPS during increased SR is a desirable performance indicator. It is known that SR is a oft-manipulated training variable, and is highly associated with elevated physiological activation (Baudouin & Hawkins, 2002). However, SR may have a ceiling where stroke technique capitulates (McDonnell et al., 2013). The correlation between SR and V_{Kayak} is strong and well-established (McDonnell et al., 2013), but that of DPS and V_{Kayak} is less clear (Michael et al., 2009). As the other primary determinant to speed, DPS may be the more modifiable performance variable. Currently, the relationship between paddle kinetics, boat acceleration characteristics, and DPS is unknown. Therefore, DPS was examined as a representation of substroke boat performance. Additionally, this investigation was warranted by the need to inspect strokes as discrete samples; V_{Kayak} is highly autocorrelated from stroke to stroke. Thus, while overall speed may be the goal in kayak sprint performance, DPS may be a primary determinant in V_{Race}.

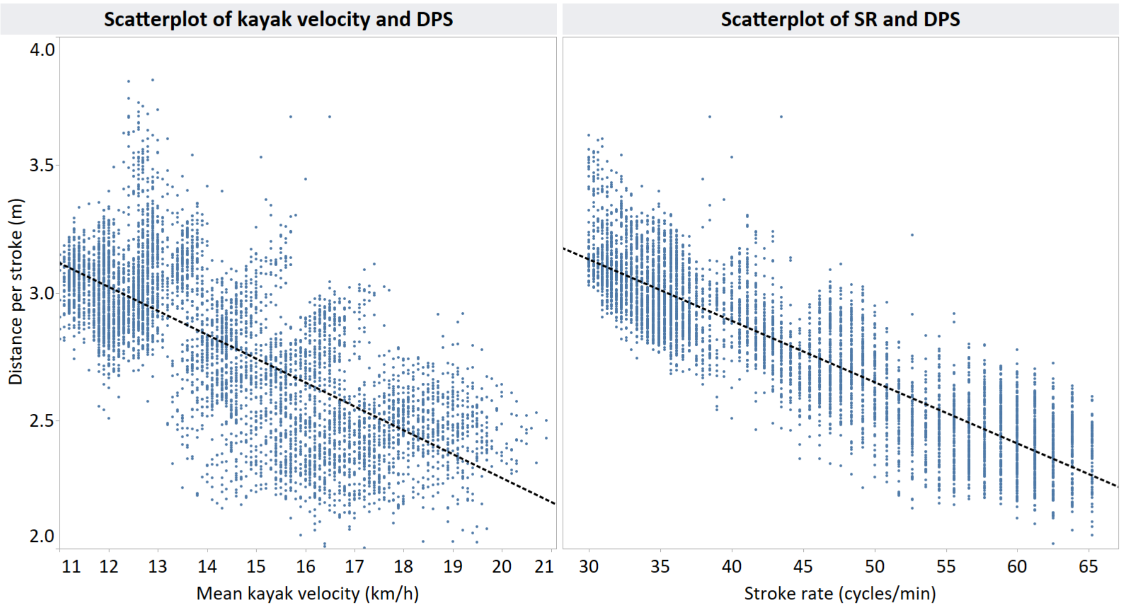

Figure 33. Scatterplots of DPS to V_{Kayak} and SR

Linear trend lines show negative correlation as intensity increases. All strokes for each participant and level are plotted.

Several kinetic and kinematic variables were examined to determine associations and correlations with DPS and α_{Boat}. DPS was used as the dependent variable in correlation and regression analyses; independent variables examined included F_{Peak}, P_{Mean}, P_{Peak}, impulse, IR, and the aforementioned scaled to BM. Due to the documented (r = -0.19 to -0.88) (Hay & Yanai, 1996; McDonnell et al., 2013) and observed (r = -0.71) negative correlation between SR and DPS, SR groupings were created in order to control for confounding effects. Groupings allowed the creation of subsamples with all strokes within a range of SR ± 1.5 cycles/min (e.g., 30-33, 33-36). The size of SR groupings was chosen to control for SR whilst maximising statistical power (strokes per group, 217-1204). After creating subsamples, strong relationships were observed between V_{Kayak} and DPS (Figure 34).

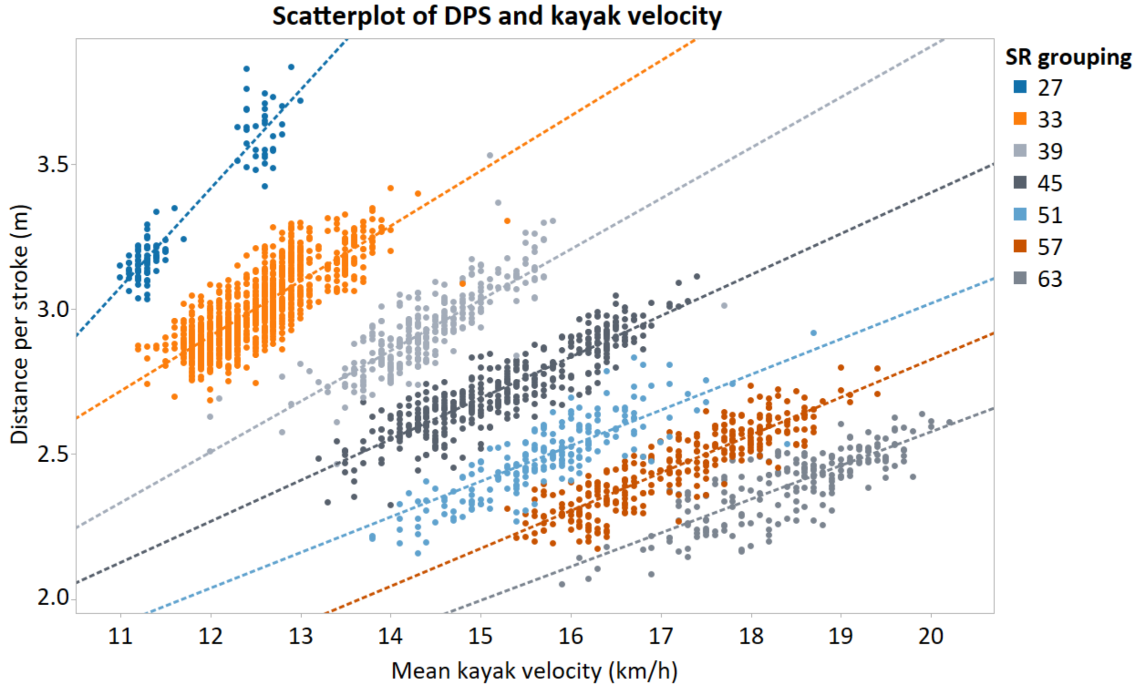

Figure 34. Scatterplot of DPS to V_{Kayak} with SR groups

Linear trendlines show positive relationships within subsamples. Only a random selection of 7/12 SR groupings analysed are shown for emphasis.

In addition to investigating DPS, a stroke efficiency index proposed by Pyne and Trewin (2001) was used in correlational analyses. As discussed earlier, higher DPS may be a desirable outcome across all intensities; thus, the index should positively correlate to improved performance. This dimensionless index "I" (m^2/s) has been used in rowing (Kleshnev, 2006) and is calculated as such:

Equation 9. Calculation of stroke efficiency

$$I = Kayak\ velocity * DPS$$

Allometric Scaling

The proposed power exponents were based on previously published experimental results of body mass scaling in sport (Crewther et al., 2011; Hetzler et al., 2011; Jaafar, 2017; Nevill et al., 2010; Stickley et al., 2013). Allometric scaling exponents were derived by plotting the product of performance variable and BM versus V_{Kayak} on a log-log scale (Jaric et al., 2005; Nevill, Ramsbottom, & Williams, 1992). The slope of the linear regression line was used as the scaling exponent for body mass. Assumptions of normally-distributed residuals and linearity and homogeneity of residuals were confirmed in order to produce a mass-independent performance variable (Suchomel et al., 2018). A fitted allometric model was developed to produce a derived exponent fitted to the sample in this study (e.g., P_{Mean}/BM^0.59) (Atkins, 2004; Crewther et al., 2011). The exponents were further refined by curve fitting adjustment in Tableau. Separate exponents were derived for the female (0.62) and male (0.51) groups.

Ratio Scaling

An exponent of 1.0 was used for ratio scaling so that each kinetic variable was scaled to body mass (Jaric et al., 2005).

Drag Estimation

In attempts to understand the interaction of external forces with paddle kinetics, an estimation of D_F was performed for a subsample of the data. The equations reported by Gomes et al. (2015) were used to calculate the net passive drag (D_P) upon the boat. Five athletes (two male, three female) had BM and boat sizes that corresponded to existing formulas for calculation of D_P within this sample.

The results of the D_P estimation allowed for an integration of drag force into a predictive model. The regression equation was fit via a polynomial relationship:

Equation 10. Linear regression formula inclusive of drag

$$\ln(V_{Kayak}) = \beta_0 + \beta_1 \ln(Cycle\ power * BW^{0.59}) + \beta_3 D_P$$

Fundamentally, constant V_{Kayak} occurs when D_F is opposed by propulsive forces equal and opposite in magnitude (McKenzie & Berglund, 2019, p. 20). It was theorised that net force should be near zero during constant velocity paddling; a negative value would indicate deceleration, and positive, acceleration (Baker, 2012). Thus, D_A was calculated for each individual in this subsample from net force inclusive of blade force and D_P.

Equation 11. Calculation of net kayak force at constant V_{Kayak}

$$F_{Net} = \left(\frac{[F_{Mean} * T_{Pull}]}{T_{Stroke}}\right) * -(D_A * T_{Stroke}) - (D_P * T_{Stroke})$$

This can be rewritten as

$$F_{Net} = IR - D_A - D_P$$

Because $F_{Net} = 0$ at constant velocity,

$$D_A = IR - D_P$$

Although e_p has been discussed in the literature, there are no published calculations of it. Because D_P is proportional to V_{Kayak}, the remaining D_F (D_A) is explained by technique, boat motion, and blade slip. Therefore, it was proposed that e_p could be estimated from the ratio of D_A and propulsive impulse.

Equation 12. Calculation of paddling efficiency

$$e_p = \left(1 - \frac{D_A}{IR}\right) * 100$$

Results

A summary of the step protocol is visualised with the histograms (Figure 35) The spread of P_{Mean} (females, 147-333 W, males, 210-518 W) highlights the variability and range of the sample collected in this study.

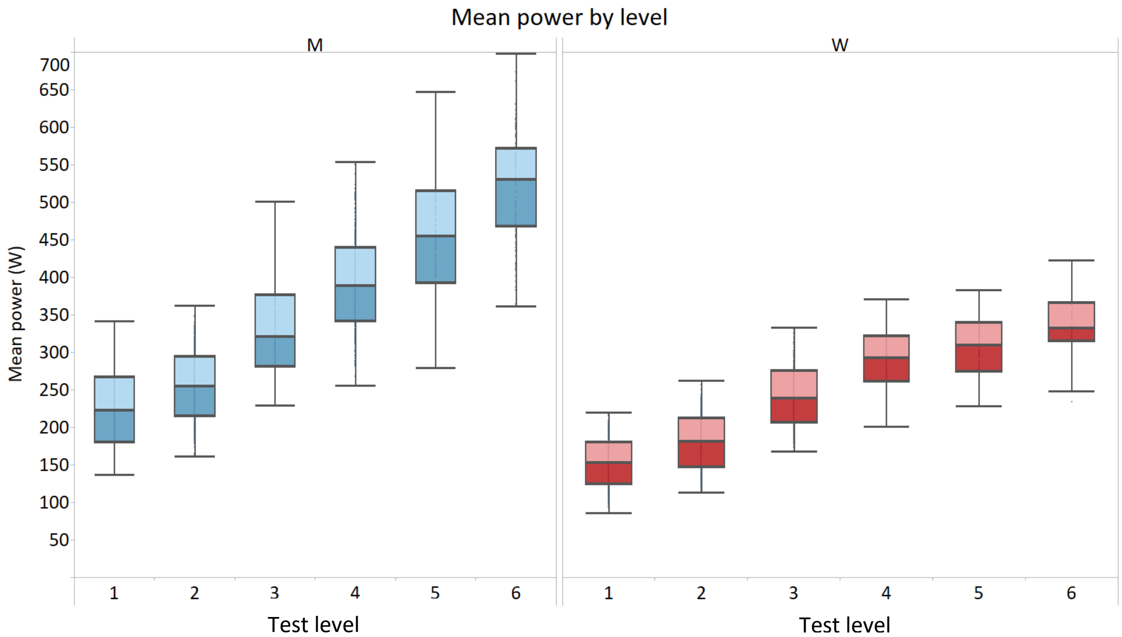

Figure 35. Box-and-whisker plot of P_{Mean} at each test level

M = males, W = females

The two collection devices were compared for SR measurement. The Passing-Bablock regression model indicated linearity and good agreement ($\beta_0 = 0.00 \pm 0.01$, $\beta_1 = 1.00 \pm 0.01$, $R^2 = 0.99$, $p < 0.01$) (Figure 36). Bland-Altman plots confirmed that the measure SR identically (limits of agreement = 0.01 ± 0.015, α=0.05) (Figure 37). Therefore, despite expected device measurement error, the differences in measured SR were considered equivocal. For all combined/derived metrics that used SR, SP SR was used.

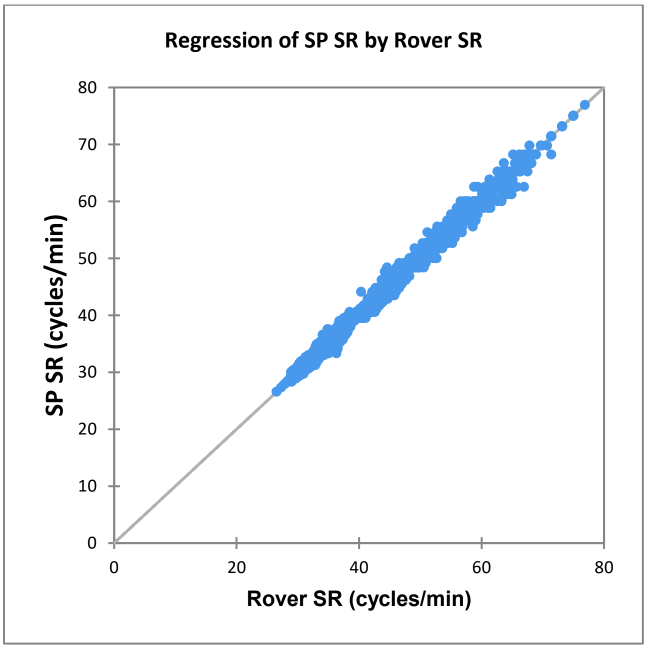

Figure 36. Passing-Bablock regression analysis of Rover GPS and SP SR

N = 5754, SR range 23-77, Pearson correlation coefficient r = 0.99, p < 0.01. Regression line equation y = 0.00 + 1.00 x; 95% CI for intercept 0.000 to 0.001 and for slope 1.00 to 1.01 indicates good agreement. Cusum test for linearity indicates no significant deviation from linearity (p > 0.05).

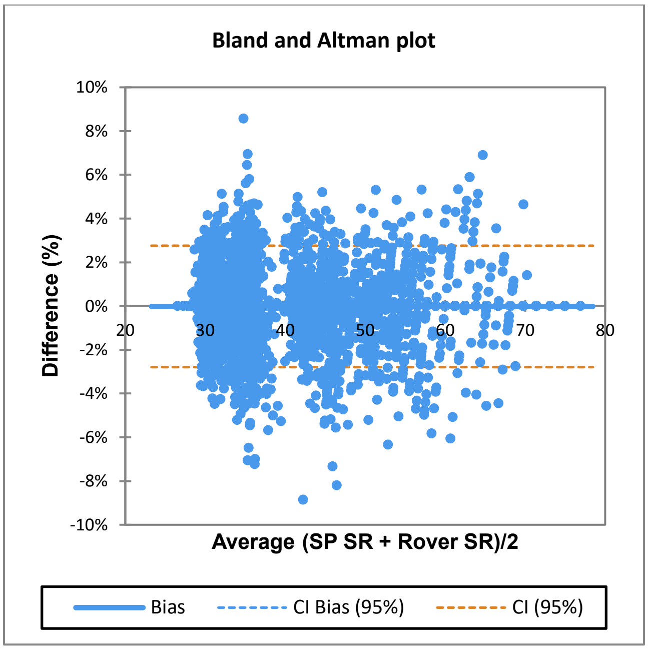

Figure 37. Bland-Altman plot of the relation between Rover GPS and SP SR

Bias = 0.02 ± 1.4%; limits of agreement= 2.79 to 2.76 %.

Predictive Modelling

A variety of strong correlations were measured between kinetic and kinematic variables (Table 14). Primary kinetic variables (F_{Mean} and F_{Peak}) and V_{Blade} had strong correlations with V_{Kayak} (F_{Mean}, $z = 1.49$, $p < 0.01$, F_{Peak}, $z = 1.17$, $p < 0.01$, V_{Blade}, $z = 1.86$, $p < 0.01$). P_{Mean} had a strong relationship with V_{Kayak} ($z = 1.73$, $p < 0.01$), but derived metrics P_{Cycle} and IR were the strongest (P_{Cycle}, $z = 2.08$, $p < 0.01$; IR, $z = 1.86$, $p < 0.01$). Linear regression models of the primary SP measures revealed positive predictive relationships for all variables (F_{Mean}, , $\beta_1 = 0.58 \pm 0.01$, $R^2 = 0.80$, SE = 0.07, $p < 0.01$ [Figure 38]; F_{Peak}, $\beta_1 = 0.55 \pm 0.01$, $R^2 = 0.66$, SE = 0.09, $p < 0.01$; V_{Blade}, $\beta_1 = 6.1 \pm 0.02$, $R^2 = 0.93$, SE = 0.09, $p < 0.01$). P_{Mean} also had a strong predictive relationship with V_{Kayak} ($\beta_1 = 0.40 \pm 0.002$, $R^2 = 0.88$, SE = 0.06, $p < 0.01$) (Figure 39)

Table 14. Correlations between kayak kinematics and SP variables during on-water paddling

Variable	V_{Kayak}	DPS	SR	Speed surge	α_{Kayak}
V_{Kayak}		-0.92	1.78	-0.12	0.44
DPS	-0.92		-1.40	0.43	-0.22
SR	**1.78**	**-1.40**		-0.25	0.38
Speed surge	-0.12	0.43	-0.25		0.78
α_{Kayak}	0.44	-0.22	0.38	0.78	
Accel integral +ve	-0.22	0.38	-0.30	**1.53**	0.90
Accel integral -ve	-0.36	-0.12	-0.18	-0.55	-0.25
Accel duration	**-1.61**	**1.09**	**-1.69**	0.18	-0.51
Decel duration	**-1.58**	**1.52**	**-2.27**	0.29	-0.30
Accel/decel ratio	0.97	**-1.21**	**1.19**	-0.39	0.10
F_{Mean}	**1.49**	-0.58	**1.07**	-0.02	0.43
F_{Peak}	**1.17**	-0.40	0.83	0.11	0.48
V_{Blade}	**1.86**	-0.91	**1.55**	-0.14	0.45
Impulse	0.52	0.04	0.28	0.21	0.23
T_{Pull}	**-1.51**	**1.24**	**-1.82**	0.19	-0.46
T_{Air}	**-1.59**	**1.35**	**-2.19**	0.31	-0.29
P_{Mean}	**1.73**	-0.67	**1.23**	-0.04	0.47
P_{Peak}	**1.45**	-0.53	**1.03**	0.05	0.51
P_{Cycle}	**2.08**	-0.86	**1.54**	-0.13	0.43
IR	**1.86**	-0.79	**1.40**	-0.12	0.38
EWS	**1.16**	-0.39	0.81	0.04	0.41
Stroke efficiency	0.90	-0.06	0.52	0.25	0.44

*Notes. V_{Kayak} = mean kayak velocity (kilometers per hour); DPS = distance per stroke (meters); SR = stroke rate (cycles/minute); α_{Kayak} = kayak acceleration (meters^2/second); accel = acceleration; decel = deceleration; +ve = integral of positive acceleration; -ve = integral of negative acceleration; F_{Mean} = mean force; F_{Peak} = peak force; T_{Pull} = pull time; T_{Air} = air time; P_{Mean} = mean power (watts); P_{Peak} = peak power (watts); P_{Cycle} = cycle power (watts/cycle); IR = impulse rate (Newton-seconds/cycle); EWS = effective work per stroke (W-s); Stroke efficiency = V_{Kayak} * DPS. Values are Z-scores of transformed Spearman's rank correlation coefficients. Significant ($p < 0.01$) correlation z-scores highlighted in **bold** are above +1 and examined further.*

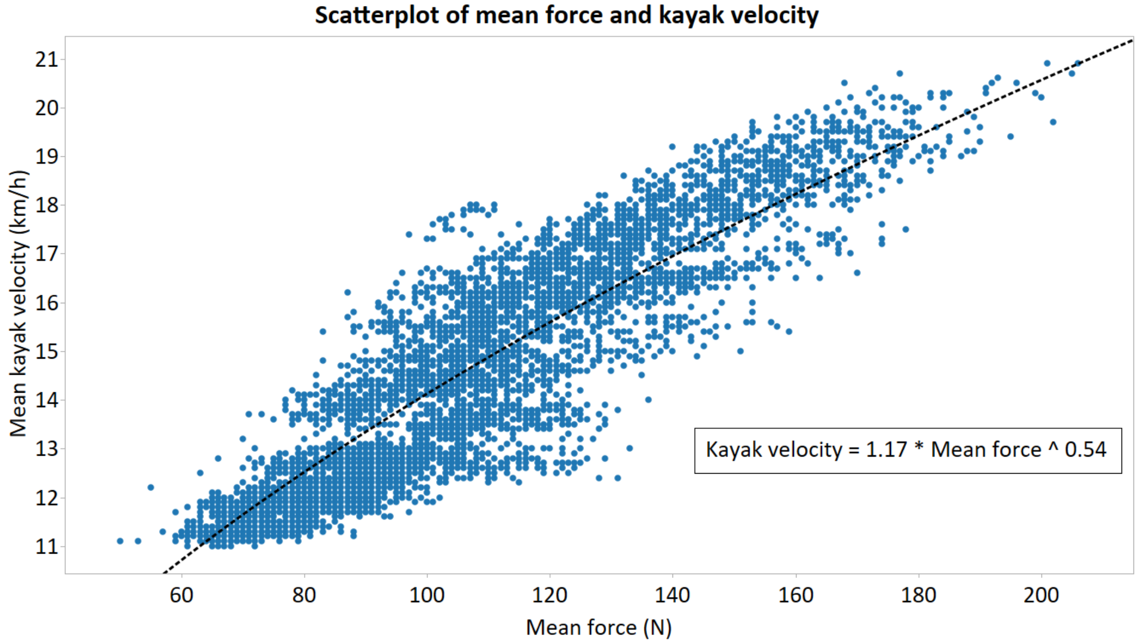

Figure 38. Scatterplot of F_{Mean} to V_{Kayak}

Trend line equation noted.

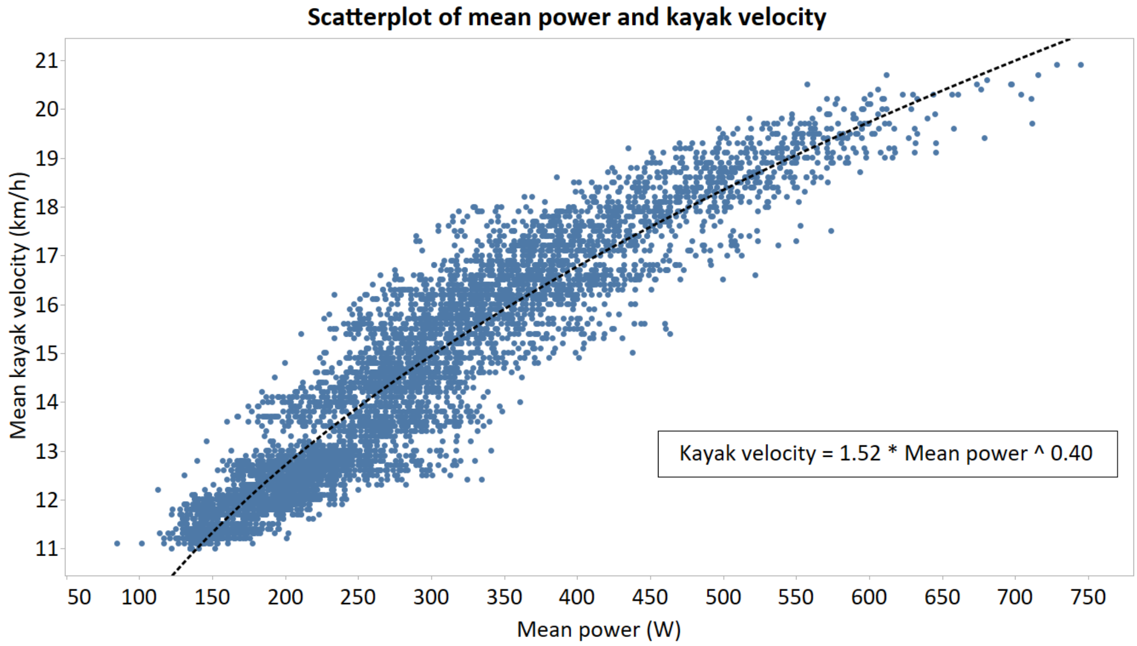

Figure 39. Scatterplot of P_{Mean} to V_{Kayak}

Trend line equation noted.

Allometric Scaling

In order to obtain the optimal predictive model for V_{Kayak}, the variable with the strongest correlation (P_{Cycle}, r = 0.98) was plotted against speed. The BM scale factor for the full sample was included ($BM^{0.59}$) in a linear regression model $\ln[V_{Kayak}]=0.35*\ln[P_{Cycle} / BM] + 1.16$ (R^2 = 0.95, SE = 0.035, $p < 0.01$). IR had a similarly strong correlation with V_{Kayak}, so it was examined via linear regression. Log-transformed data was regressed against V_{Kayak} (R^2 = 0.90, SE = 0.05, $p < 0.01$), and the BM scale factor ($BM^{0.59}$) was added to create a final model with R^2 = 0.95 and SE = 0.036 ($\ln[V_{Kayak}] = 0.53 * \ln[IR / BM] + 1.81$, $p < 0.01$) (Figure 40).

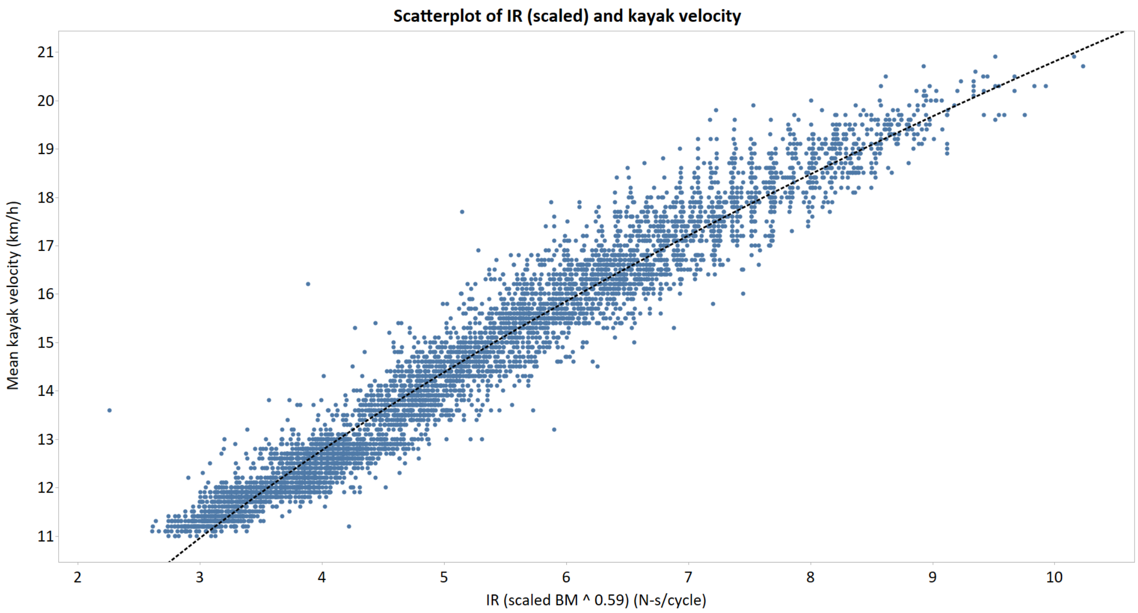

Figure 40. Scatterplot of IR (scaled) to V_{Kayak}

Trend line equation $V_{Kayak} = 6.10 * IR\ (scaled)^{0.53}$

Previous literature suggested that different BM scale factors be used for female and male cohorts (Folland, Mc Cauley, & Williams, 2008; Hazir & Kosar, 2007). New allometric scale factors were derived for each cohort as described earlier. The men's sample (n = 3757 strokes) was separated and regressed against V_{Kayak} to produce a model ($\ln[V_{Kayak}] = 0.36*\ln[P_{Cycle} / BM] + 1.02$) that improved from R^2 = 0.97 to R^2 = 0.98 (SE = 0.025, $p < 0.01$) with a BM scale factor of $BM^{0.51}$ (Figure 41b). The model for the female athlete data (n = 1725 strokes) ($\ln[V_{Kayak}] = 0.35*\ln[P_{Cycle} / BM] + 1.22$) was improved from R^2 = 0.94 to R^2 = 0.97 (SE = 0.020, $p < 0.01$) with a scale factor of $BM^{0.62}$ (Figure 41a). These scale factors were used in the following analyses.

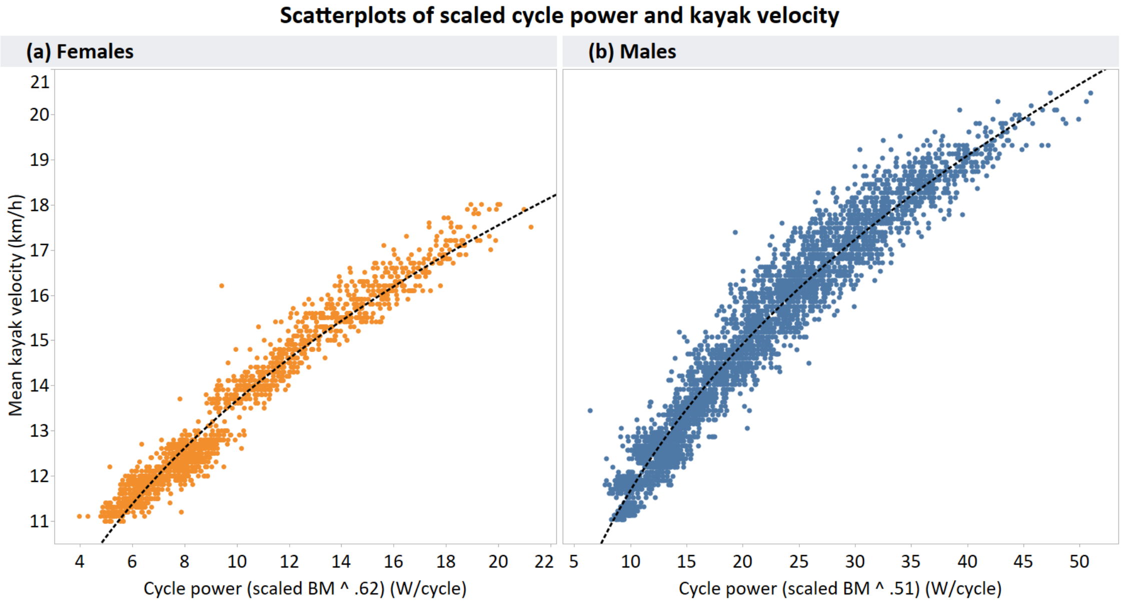

Figure 41. Scatterplots of P_{Cycle} (scaled) to V_{Kayak} by sex

Nonlinear trend lines specify the velocity increase for a given increase in P_{Cycle} (scaled) (a) females, $V_{Kayak} = 3.40 * P_{Cycle}\ [scaled]^{0.35}$; (b) males, $V_{Kayak} = 2.76 * P_{Cycle}\ [scaled]^{0.36}$). Note the difference in trend line slope.

P_{Cycle} and V_{Kayak} were strongly correlated even when analysing the mean values for each test level ($R^2 = 0.94$, SE = 0.58, $p < 0.01$) (Figure 42b). Individual trend lines for each athlete demonstrate the strength of the relationship ($R^2 > 0.98$ for all) and the inter-individual variability of their respective trends (Figure 42a). The variability between individuals decreases when normalised for BM ($R^2 = 0.97$, SE = 0.39, $p < 0.01$).

IR and boat velocity had a similar strong correlation ($r = 0.98 \pm 0.01$). Individual relationships had better predictive relationships ($R^2 > 0.98$ for each) (Figure 43a) and group variability decreased when normalised for bodyweight ($R^2 = 0.94 \pm 0.03$, SE = 0.46 ± 0.24, $p < 0.01$) (Figure 43b).

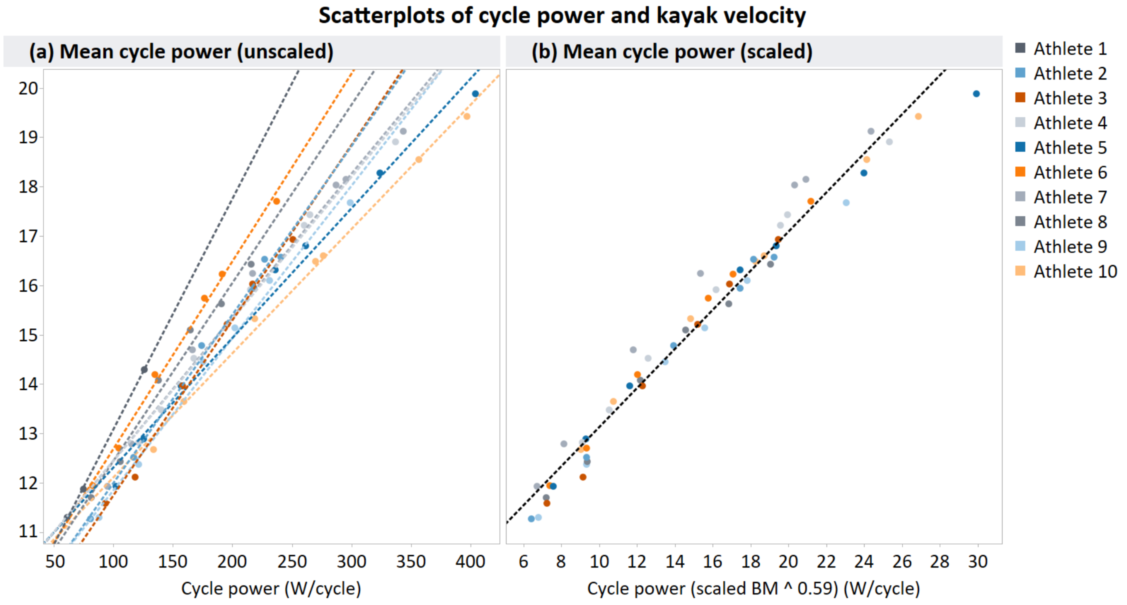

Figure 42. Scatterplots of mean P_{Cycle} to V_{Kayak} by test level

Each point represents mean P_{Cycle} for one athlete during one test level. (a) Linear trendlines for each athlete show different individual kinetic demands for travelling at a given V_{Kayak}. (b) Allometrically scaled P_{Cycle} shows much narrower margins for kinetic demands of V_{Kayak} (R^2 = 0.97, SE = 0.39, $p < 0.01$).

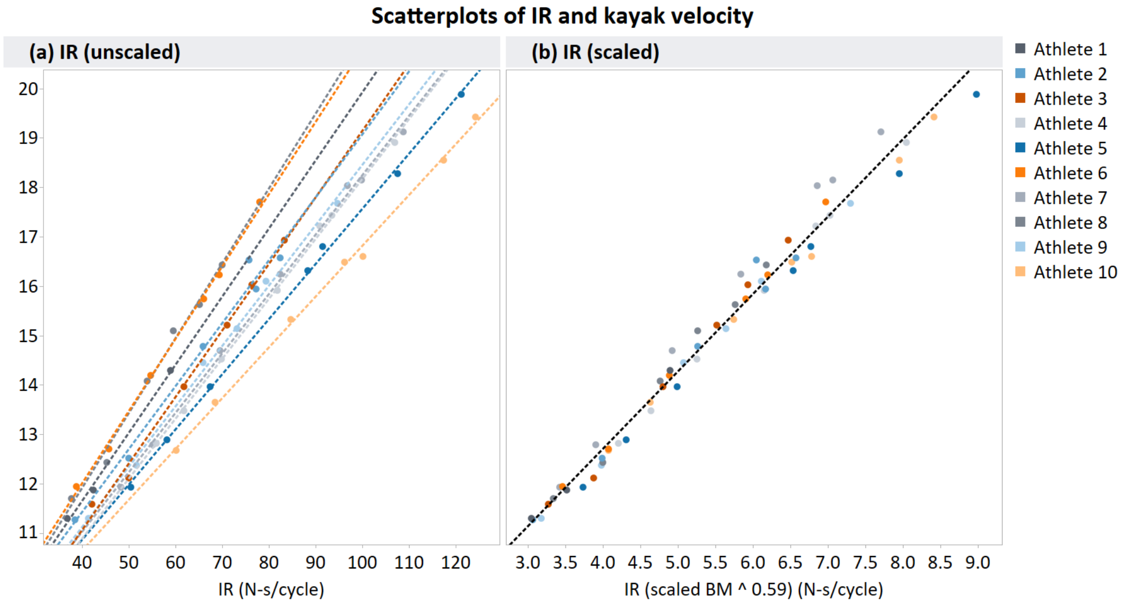

Figure 43. Scatterplots of mean IR and kayak velocity by test level

Each point represents mean IR for one athlete during one test level. (a) Linear trendlines for each athlete show different individual kinetic demands for traveling at a given constant boat velocity. (b) Allometrically scaled IR shows much narrower margins for kinetic demands of constant boat velocity (R^2 = 0.98, SE = 0.31, $p < 0.01$).

Derived Variables

EWS had a moderately strong positive correlation with V_{Kayak} across all intensities (β_1 = 0.92, R^2 = 0.51, $p < 0.01$). It was strongly correlated with V_{Kayak} within each test level (R^2 = 0.51 ± 0.14), for each athlete (R^2 = 0.67 ± 0.12), and moderately with SR for each athlete (R^2 = 0.67 ± 0.12). Figure 44 shows the variability amongst the athletes across intensities, while Figure 45 reveals more clear individual trends.

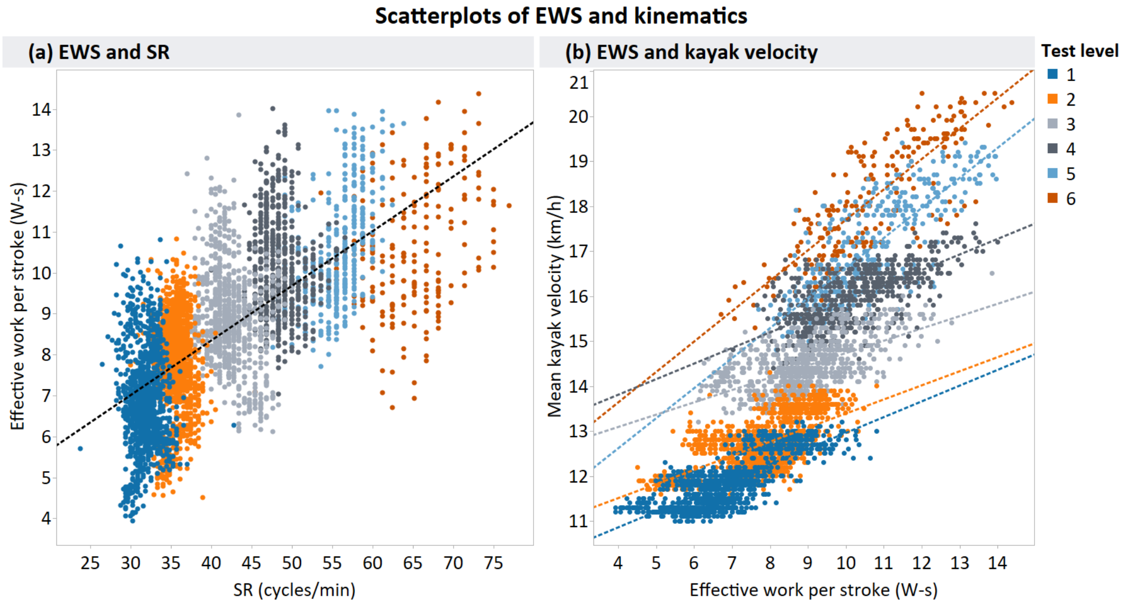

Figure 44. Scatterplots of EWS to SR and V_{Kayak} by test level

(a) Scatterplot of EWS and SR shows a positive trend (β_1 = 0.11, R^2 = 0.47), but less clear relationships within each test level (R^2 = 0.00 ± 0.01). (b) Scatterplot of EWS and V_{Kayak} shows moderately positive relationships (R^2 = 0.51 ± 0.14) at each test level and increasing trend slope (from β_1 = 0.34 to 0.68)

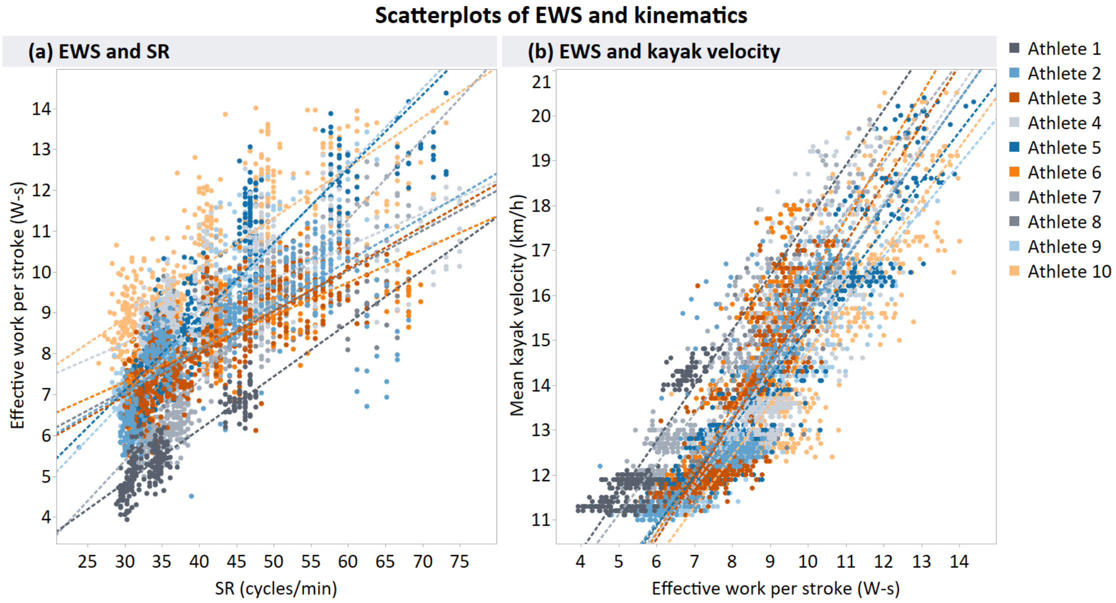

Figure 45. Scatterplots of EWS to SR and V_{Kayak} by athlete

(a) Scatterplot of EWS and SR shows better trendline fit when drawn for each athlete ($R^2 = 0.67 \pm 0.12$) (b) Scatterplot of EWS and V_{Kayak} show strong positive relationships ($R^2 = 0.77 \pm 0.09$) for each individual.

The scatterplot of F_{Mean}/F_{Peak} ratio and V_{Kayak} showed significant variability around the mean (Figure 46). When analysing mean F_{Mean}/F_{Peak} per level for each athlete, stronger correlations were observed ($r = 0.92 \pm 0.06$, $p < 0.05$). No significant relationships were found with DPS or other acceleration characteristics.

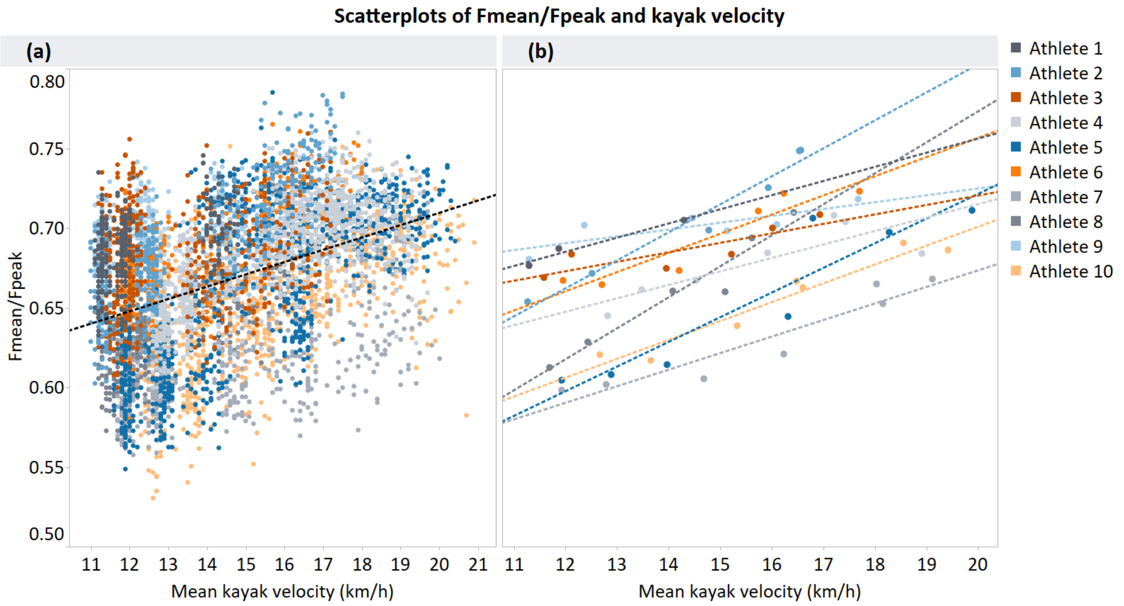

Figure 46. Scatterplots of F_{Mean}/F_{Peak} ratio to V_{Kayak}

(a) Scatterplot of all strokes demonstrates significant variability across individuals and intensities. (b) Mean values per level for each athlete show stronger relationships ($R^2 = 0.85 \pm 0.12$, $SE = 0.12 \pm 0.10$, $p < 0.05$).

Drag Estimation

With the addition of D_F, the model was improved from $R^2 = 0.98$ to 0.99 and SE = 0.033 to 0.019. The process was replicated for the sample with real-time wind data. This addition resulted in a statistically insignificant, practically negligible improvement in the predictive model. Although it was within the researcher's aim the inclusion of wind and D_F data for all individuals, limitations (discussed later) prevented statistically valid methods of doing so.

The D_F calculations did allow for the estimation of D_A for the subsample of paddlers with applicable D_P equations (Table 15). D_A was 20.8 ± 5.41 N, on average, for athletes at each test level, ranging from 8.3 – 30.6 N. e_p was 0.70 ± 0.05 % for all athletes across intensities.

Table 15. Estimated drag forces and paddling efficiency for athlete subsample

Test level	V_{Kayak}	SR	D_P	D_A	e_p (%)
1	11.8 ± 0.6	31.9 ± 1.5	30.0 ± 3.5	15.3 ± 5.3	67.2 ± 6.7
2	12.6 ± 0.6	35.2 ± 1.4	34.3 ± 3.5	18.7 ± 4.7	65.3 ± 5.2
3	14.3 ± 0.5	43.0 ± 3.0	44.7 ± 2.9	20.2 ± 4.7	69.2 ± 5.3
4	15.9 ± 0.5	48.5 ± 2.5	56.5 ± 4.4	24.9 ± 4.4	69.6 ± 3.2
5	17.1 ± 0.9	56.4 ± 2.4	66.0 ± 8.1	23.7 ± 6.8	73.9 ± 5.7
6	18.2 ± 1.4	66.5 ± 5.6	74.1 ± 15.0	24.5 ± 6.4	75.3 ± 5.8

Notes. M ± SD for five athletes (n = 5); V_{Kayak} = mean kayak velocity (kilometers per hour); SR = stroke rate (cycles/minute); D_P *= passive drag force (Newtons);* D_A *= passive drag force (Newtons); e_p = paddling efficiency (%)*

Determinants of Intra-stroke Kayak Velocity

Within each test level, V_{Kayak} and DPS were moderately correlated ($r = 0.52 \pm 0.13$, $p < 0.01$). Amongst subsamples with SR groupings between 30-63, strong correlations existed between V_{Kayak} and DPS ($r = 0.78 \pm 0.10$, $p < 0.01$) (Figure 34). Furthermore, moderate to strong correlations were observed between DPS and F_{Peak} ($r = 0.69 \pm 0.10$, $p < 0.01$) (Figure 47), F_{Mean} ($r = 0.68 \pm 0.11$, $p < 0.01$), P_{Peak} ($r = 0.72 \pm 0.10$, $p < 0.01$), and impulse ($r = 0.65 \pm 0.18$, $p < 0.05$). Notably, all values with ratio scaling had slightly weaker correlations to DPS compared to absolute values (mean difference = -8.2 ± 5.1%, $d = 0.13 \pm 0.06$)

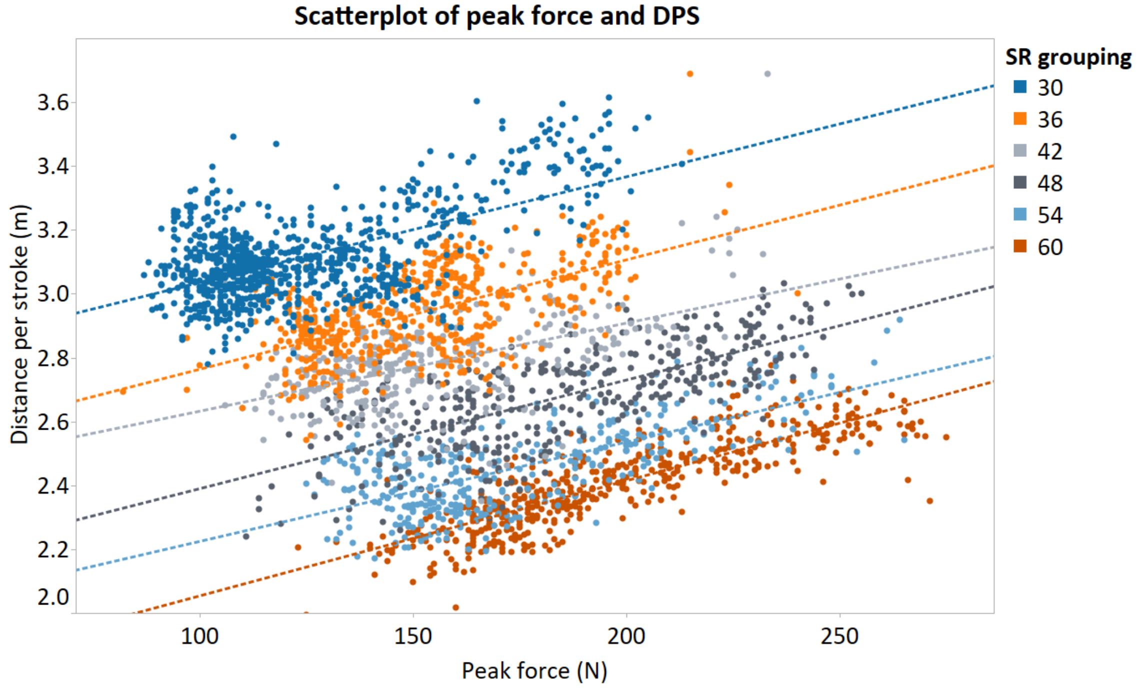

Figure 47. Scatterplot of DPS to F_{Peak}

Linear trendlines show positive relationships within subsamples. 6/12 SR groupings analysed are shown for emphasis

Stroke efficiency and V_{Kayak} were moderately correlated across all intensities ($r = 0.75$, $p < 0.01$). Like the relationships between kinetic variables and DPS, more clear associations were visible when the data were separated by test level ($r = 0.85 \pm 0.05$, SE = 0.35 ± 0.11, $p < 0.01$) (Figure 48). Many kinetic variables such as F_{Peak}, P_{Mean}, and EWS showed strong positive correlations with stroke efficiency across all intensities ($R^2 = 0.69 \pm 0.04$, SE = 2.50 ± 0.16, $p < 0.01$) (Figure 49).

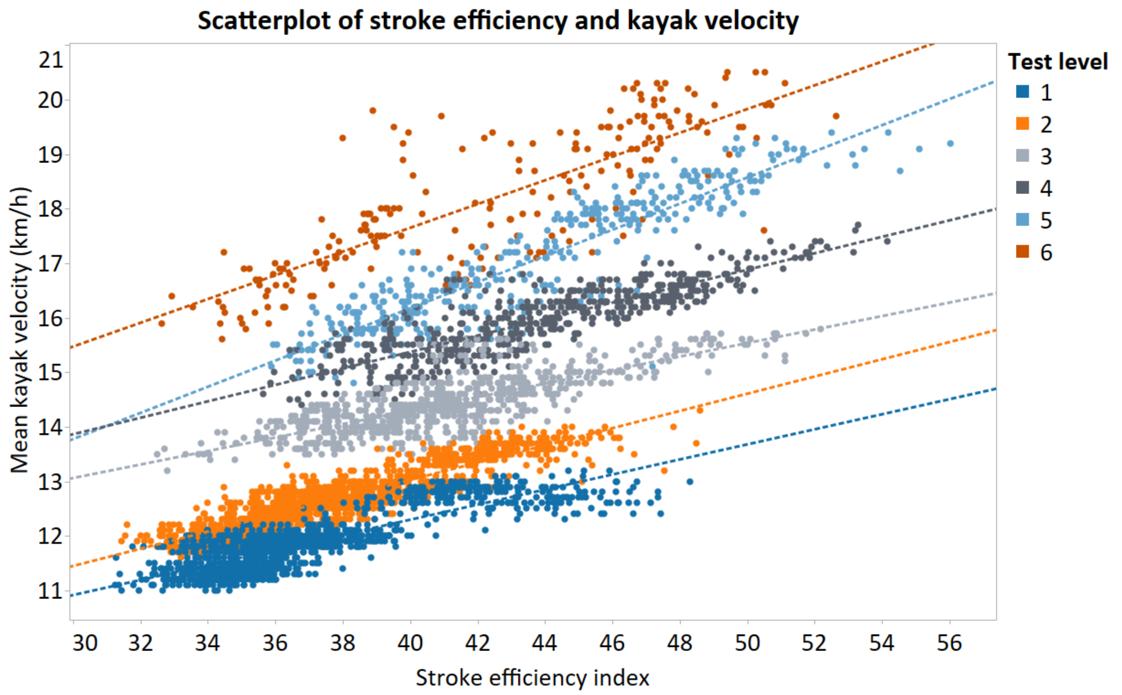

Figure 48. Scatterplot of V_{Kayak} to stroke efficiency index by test level

Linear trendlines show positive correlations at each test level. Linear regression revealed strong predictive relationships ($R^2 = 0.73 \pm 0.08$, $p < 0.01$).

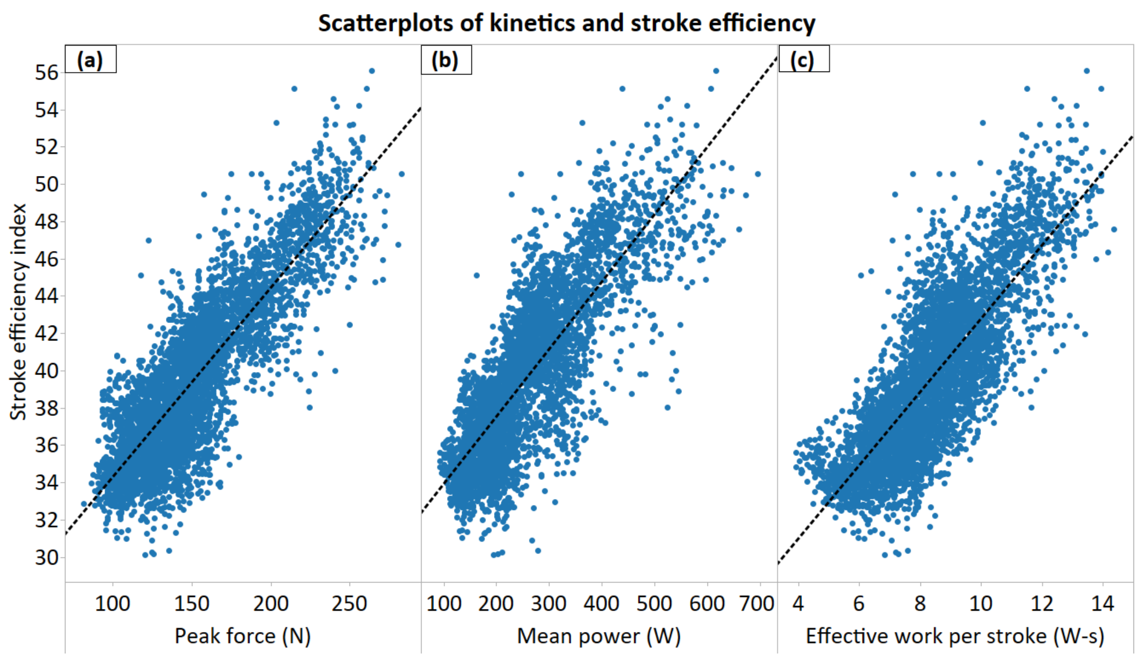

Figure 49. Scatterplots of stroke efficiency index to F_{Peak}, P_{Mean}, and EWS

(a) Linear trendlines show moderate-to-strong positive relationships between stroke efficiency and (a) F_{Peak} ($\beta_1 = 0.10$, $R^2 = 0.73$, $SE = 2.31$, $p < 0.01$) ,(b) P_{Mean} ($\beta_1 = 0.04$, $R^2 = 0.68$, $SE= 2.52$, $p < 0.01$), and (c) EWS ($\beta_1 = 1.97$, $R^2 = 0.65$, $SE= 2.63$, $p < 0.01$).

Various kinetic symmetry measures were examined for their relationship with DPS. It was theorised that kinetic assymetries would correspond to greater DPS on that side. The variables with the strongest correlations to DPS were examined. No significant relationships were observed when comparing neither F_{Peak} nor P_{Peak} SI with DPS SI within each test level ($r < 0.50$, $p > 0.05$) (Figure 50).

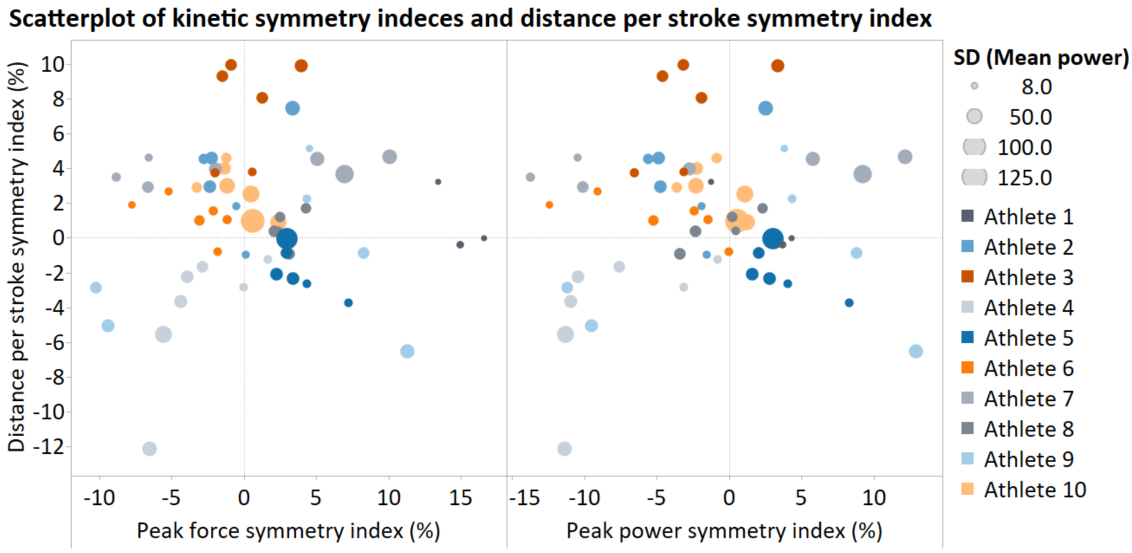

Figure 50. Scatterplots of DPS SI to F_{Peak} and P_{Peak} SI by level

Each point represents the mean value for an individual during one test level. Positive values correspond to greater value for the right paddle side. SD = standard deviation. Example of SI calculation in Equation 6.

Discussion

These results posit that kinematic and kinetic variables have specific linear and nonlinear relationships with V_{Kayak}. The study was an attempt to understand how to make a boat go fast; causal relationships and transferable findings were evaluated via the ARMSS approach. Expert, sport-specific expert opinion and partial correlation coefficients were used for the hypothesis-generating exploratory phase. Next, linear and nonlinear regression analysis determined the degree of association between predictor variables and V_{Kayak}. The analysis allowed for the experimental replication of previous deterministic models and the addition of new data. Whether analysing all strokes, each test level, or individual athletes, numerous strong, positive predictive relationships were established between performance variables and V_{Kayak}

After assessing various deterministic relationships (Table 14), derived variables were applied to BM scaling techniques. First, P_{Cycle} was plotted with V_{Kayak} to obtain the best model fit (Figure 41). Combined with the BM scale factor, the final regression results intimate a strong nonlinear relationship and provide basis for scaling other kinetic variables. Rather, the results shed light on these athletes' specific biomechanical demands of paddling a kayak (Figure 42). Similar to the work of Kleiber (1961) regarding allometric scaling of bioenergetic variables (VO2, basal metabolic rate), these results demonstrate that scaling biomechanical variables is a transferable, viable performance analysis technique.

Despite providing substantive grounds for answering the primary research question, this research cannot answer entirely how to make a boat faster. Instead, any significant relationships only confirm their association to speed. For example, the strong correlation ($r = 0.66\text{-}0.86$) between SR and V_{Kayak} has been studied (Hay & Yanai, 1996; McDonnell et al., 2013; Mononen & Viitasalo, 1995; Wainwright et al., 2016) and re-examined here ($r = 0.89$). Subsequently, researchers have implied that increasing SR is a viable means to increase V_{Kayak}. The paddler must move the paddle faster than the water moving beside the boat in order to generate propulsive impulse. Thus, SR and V_{Kayak} are fundamentally and inextricably related. Therefore, causal inference must be made with caution.

As outlined by McDonnell et al. (2012b), V_{Kayak} is resultant of SR and DPS. SR has been used in other research designs (Gomes et al., 2011; Michael et al., 2009; Shin et al., 2018) as well as this one for as a control or constraint during paddling study collection protocols. On the other hand, DPS is less understood; informal conversations with coaches for this study frequently insisted upon its importance despite little published research supporting it. In comparison with SR, DPS has a fundamental negative correlation with V_{Kayak} noted in these results ($r = -0.71$, $p < 0.01$) as well as those of McDonnell et al. (2013) ($r = -0.19$, $p = 0.62$). Despite the negative association, DPS will decrease proportionally to SR only when travelling at constant V_{Kayak}. If a paddler can minimise the fundamental decrease of DPS at increasing SR, it would have a beneficial impact of performance. It is possible that the paddle kinetics drive the intra-stroke boat kinematics such as DPS and its subfactors. Hence, whereas previous models framed speed by resultant kinematics, the main factors that cause their variation occur at the paddle and other points of boat-athlete-water interface. For this study, controlling for SR (by grouping in subsamples) was the step that revealed key relationships between kinetic variables and DPS. With evidence of these associations, it expands upon the research question with solutions for positively affecting DPS and V_{Kayak}. These are discussed later in Chapter 6.

DPS was used as a surrogate measure for intra-stroke boat velocity not only because of its universal importance among coaches, but also because it was considered one of the more reliable measures of the Rover GPS units. As noted by Janssen and Sachlikidis (2010), GPS accelerometers have inadequate accuracy for derivation of detailed boat kinematics such as surge, and α_{Kayak}. Although this was a limitation for the analysis, DPS is possibly a more valuable metric to examine for the broader kayak sprint community. Since DPS is the focus of many coaching programmes and performance analysis projects, the results presented here could be of tremendous value for those wishing to evaluate and improve it. The strong relationships between primary and derived variables (EWS, stroke efficiency) and V_{Kayak} must be investigated further through replication and experimental means. Future research should evaluate these relationships in a robust manner such as that described by Bishop (2008).

The lack of clear positive associations between V_{Kayak}, DPS, F_{Mean}/F_{Peak} ratio, and kinetic SI are contrary to reported data and suggested links (Gomes et al., 2015; Limonta et al., 2010). The only significant relationship (between F_{Mean}/F_{Peak} and V_{Kayak} [Figure 46]) emerged when the data was averaged by level and athlete. This comparison was affected most by inter-individual variability; individual constraints and technique differences may explain the large variability observed among these elite paddlers. Or technology limitations could fail to detect the detail needed to reveal stronger significant correlations. Regardless, asymmetries and individual force production strategies do not necessarily harm or benefit performance (Wietrzyński et al., 2013). This topic requires more study.

These data demonstrate inarguable idiosyncrasy amongst this cohort. The inter-individual variation in F_{Peak} visualised in Figure 50 highlights different force-producing abilities as SR increases during on-water paddling. This is pertinent information for coaches using SR during training. Knowledge of individual SR-kinetic relationships may indicate specific training needs: some athletes may need to increase SR, while others need to improve kinetic output around a certain SR. To advance this understanding, a plot such as Figure 51 may be beneficial. Since P_{Cycle} and V_{Kayak} are strongly correlated ($z = 2.08$, $p < 0.01$), indicating the exact SR zones where an athlete deviates from their individual trend or squad trend illuminates that athlete's strengths and weaknesses. For example, Athlete 2 (noted) appears unable to produce increasing P_{Cycle} at SR zones above 60. Coaching interventions to address this weakness could examine improving the components of P_{Cycle} (F_{Mean}, V_{Blade}, pull %) to affect V_{Kayak} above SR 60. Despite the potentially confounding effects of constraining SR to investigate boat kinematics and paddle kinetics (discussed earlier and later), practically relevant conclusions may be drawn from this protocol and individual SR plots.

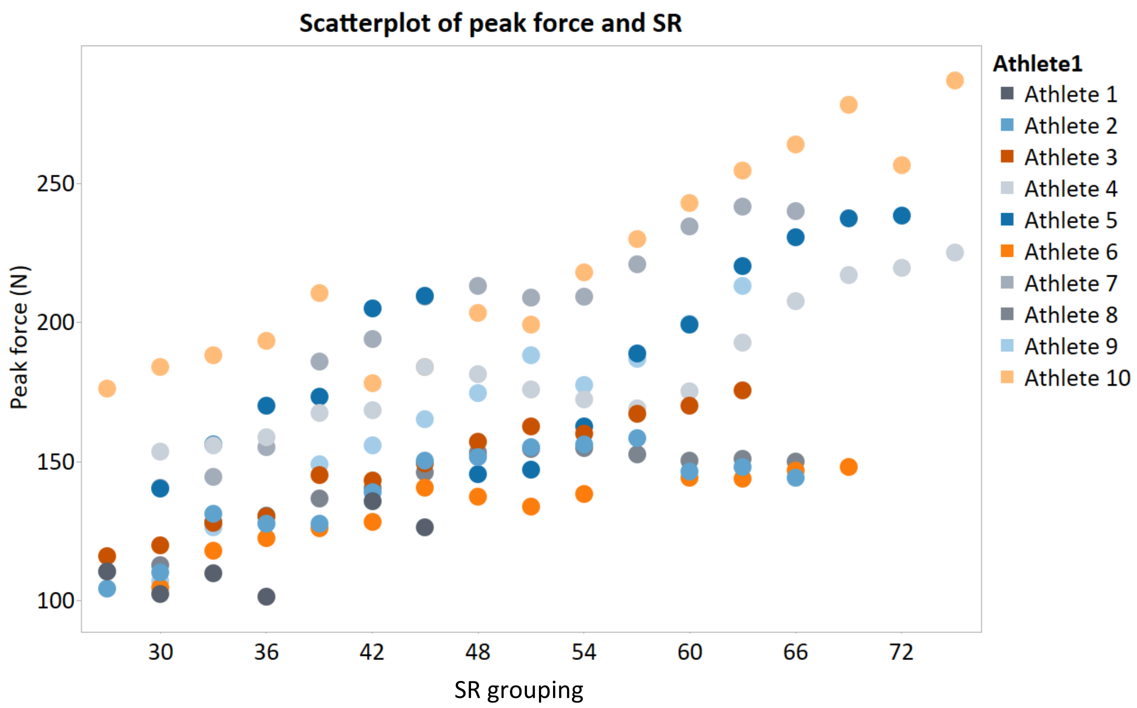

Figure 51. Scatterplot of F_{Peak} to SR by athlete

One point represents mean F_{Peak} within SR grouping for each individual.

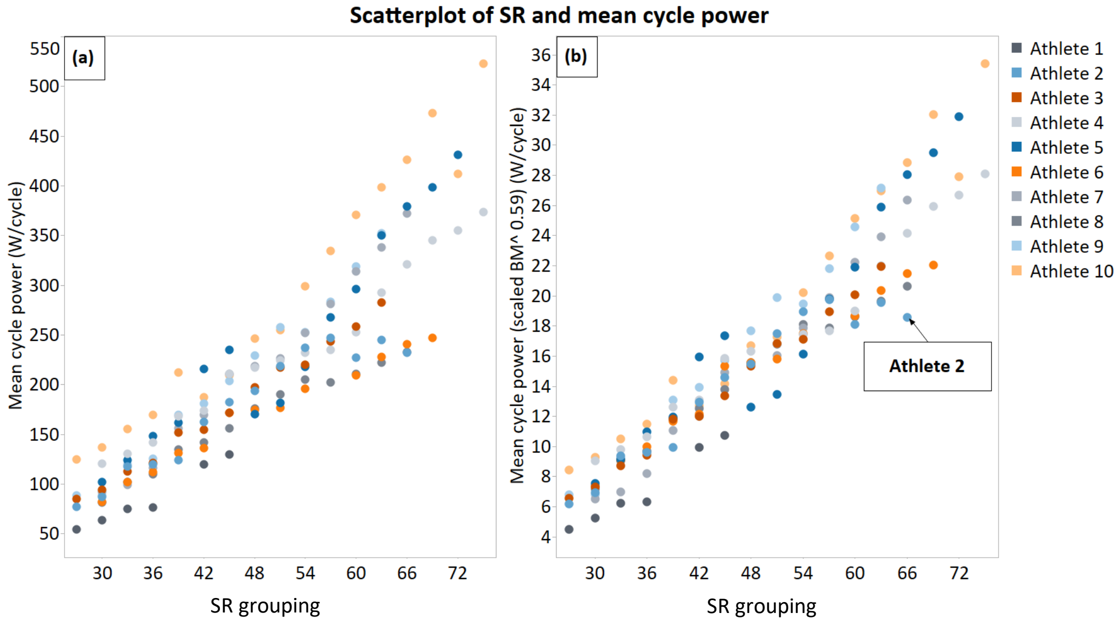

Figure 52. Scatterplots of P_{Cycle} to SR by athlete

One point represents mean (a) P_{Cycle} and (b) P_{Cycle} (scaled) within SR grouping for each individual

Although paddle kinetics may have demonstrably positive relationships with boat kinematics, there are other immutable factors affecting performance. This study attempted to analyse the effect of environmental conditions upon V_{Kayak} and paddler biomechanics; unfortunately, the wind and current were negligible in magnitude during data collection. Had more variable data been collected in combination with this data, it could inform upon the magnitude of effect and implications for different boat sizes or system masses (e.g., K1 or team boats). Despite the homogeneity in these peripheral variables, their triviality enabled greater confidence in assessing kinetic variables' predictive potential.

The calculation of D_F for this dataset is meant to inspire further exploration in paddle sports. Although the estimation of D_A and D_P contains inherent error, it provides a basis for measurement in the field. Theoretically, average net force during constant velocity paddling should equal zero. However, net force proved difficult to analyse due to inherent mathematical error in the collection devices and formulas from Pendergast et al. (2005) deemed inaccurate. Specifically, the calculation of D_A resulted in values significantly larger than the measured blade force occurring within a test level. It is possible that the SP is underestimating blade force, but the results from Chapter 3 and the magnitude of difference with modelled formulas suggests otherwise. Conversely, the formulas for estimating D_P from (Gomes et al., 2015) appear to be valid. The availability of formulas for only 5 of 10 athletes was a limitation to interpreting the values. Estimated D_P accounted for approximately 69.7% of D_F if equal to IR as proposed in formula __. This is contrary to studies suggesting that D_A is greater than D_P during kayaking

(Ackland et al., 2003). Of course, there are other factors that affect boat performance and paddling efficiency, such as boat motion and blade slip, but these should be included in the estimation of D_A. The effect of boat motion upon drag has not yet been measured in published research, and there is no consensus upon the best way to measure D_A. Accurate calculation could open new doors in performance analysis of kayak sprint. Future studies should continue exploring total D_F estimation and build upon the research of Gomes et al. (2017) by modelling various boat sizes, masses, and shapes for thorough analysis.

This study provides an estimation of e_p derived from IR, D_A, and D_P. The range of 67-75% is in agreement with values proposed by Brooks, Abbott, and Wilson (1986, pp. 50-66) and Pendergast et al. (2003). e_p is of critical importance to coaches and researchers due to its influence upon boat performance and athlete energy expenditure. A proposed future study could examine e_p and physiological variables to adequately determine its affect upon performance and relation to paddle mechanics.

This study is one of few to examine the paddle kinetics of elite athletes during real-world conditions. It demonstrates the remarkable value of a tool such as the SP and the plethora of possible relevant analyses. The next step is to evaluate specific biomechanical determinants in an experimental manner to advance the knowledge of technique and how to make a boat travel faster.

Chapter 6. General Discussion and Applications

Introduction

This study is one of the first to examine an instrumented kayak paddle and its potential in situ. Each experimental chapter features its own results and discussion, so this section serves to summarise main findings and extract global practical conclusions. First, it was necessary to examine the validity and reliability of the SP compared to a reference device. Though, as expected, there were significant differences, the consistency amongst SR and kinetic measures was considered sufficient to use the SP for the other planned studies. The comparison of ergometer and on-water paddling with the SP is the first study of its kind, according to extensive literature review. The study of on-water kinetics is also quite unique, providing a valuable cross-section of elite paddlers in their normal training environment. The experimental protocol and quality of SP hardware and software enabled data collection that is considered both specific and relevant.

The partnership with HPSNZ and CRNZ was critical in the development of the research protocol and technology support of the SP and associated software. It is the research team's belief that the protocol developed not only allowed for the transference of results across environments, but also ensured the practical relevance for the athletes and coaches for future use. Many practical applications gleaned from these studies concern application to individual athletes' performance analysis. Though analysing data for the full sample of elite paddlers was essential for statistical power, the most relevant findings for coaches and support staff were the identification and quantification of individual performance.

Practical Applications

Previously, training intensities were categorised by SR; despite the demonstrated strong correlation between SR and V_{Kayak} ($z = 1.78$), these results suggest that a kinetic variable such as IR or P_{Cycle} is a better method of quantifying training intensity. The use of power for training prescription and performance analysis is accepted in other cyclic anaerobic power sports such as cycling (Martin, Davidson, & Pardyjak, 2007), and rowing (Hofmijster et al., 2007; Lintmeijer, Hofmijster, Schulte Fischedick, Zijlstra, & Van Soest, 2018). Whereas prescribing training via HR or SR has a physiological (mostly aerobic) basis, training with power quantifies the neuromuscular demands of the activity. HR-based training is sensitive to the effects of fatigue, environment, and even hydration (Allen & Coggan, 2012, p. 18), while SR-based training is affected by individual paddling technique, currents, and accurate feedback (Higgens et al., 2016; Michael et al., 2009). Furthermore, neither of these methods may accurately assess the neuromuscular fatigue associated with high-intensity, short-interval sessions (von Someren et al., 2000; Zamparo et al., 2006). Power-based training may avoid many of those pitfalls, thus providing a more valid basis of training prescription and performance evaluation (Baca, 2006;

Paquette, Bieuzen, & Billaut, 2018). Given the strong predictive relationship between IR ($R^2 = 0.94$, SE = 0.46, $p < 0.01$), P_{Cycle} ($R^2 = 0.98$, SE = 0.02, $p < 0.01$) and V_{Kayak}, these variables could be valid methods of training prescription. IR may be especially valuable given its quick calculation from existing metrics. P_{Cycle} has a slightly stronger correlation but requires more intensive calculation from the SP software. Practical implementation of this training style would require live data feedback from the SP to a wireless device on the kayak visible to the athlete. Coaches also need live feedback on their wireless device for monitoring on the coach boat during training. Modification of training plans would require baseline measurement of athlete power output and physiological response via a similar protocol as used here (Denham, Scott-Hamilton, Hagstrom, & Gray, 2017). To maximise the efficacy of this approach, allometric scaling techniques must be used. The approach applied in Chapter 5 is the most strongly supported method of adjustment. This entails plotting the product of a performance variable and BM versus V_{Kayak} on a log-log scale (Jaric et al., 2005; Nevill et al., 1992). The slope of the linear regression line is used as the scaling exponent. The results presented here suggest that this is an easily employed strategy to be calculated for each athlete. Repetition of the scaling process every 6-12 months would be most effective to ensure measurement accuracy.

The kinetic data made available by the SP could also be immensely valuable for force-velocity (F-v) profiling. This process allows for detailed profiling of the maximal mechanical abilities of individual athletes' performance, and more personalised training from its insights (Morin & Samozino, 2016). The protocol used in these studies was not designed for F-v profiling; on-water maximal testing from a static start would be needed. However, it is possible that with the SP and rover data, a similar process could be performed. F-v profiling in kayak has not been reported in the literature, and thorough reliability testing of the GPS units must be performed, otherwise more valid and reliable methods, such as radar, are superior (Simperingham, Cronin, Pearson, & Ross, 2019).

With the observed differences between ergometer and on-water paddling, SR does not appear to be a valid constraint for ergometer testing. As shown in Figure 24 and Figure 25, kinetic variables differ significantly across most of the prescribed SR levels. Therefore, during submaximal testing, athletes constrained to a specific SR may be performing at a different physiological intensity than desired or than occurs at that SR on-water. This problem invites further discussion regarding the purpose of ergometer testing and the impact of these large differences upon the paddler. For example, does heightened F_{Peak} during ergometer paddling increase injury risk, or provide a greater neuromuscular training stimulus? Regardless, despite demonstrated differences in primary variables between environments, the similarity of IR at maximal intensity ($d = 0.31$, $p < 0.01$) suggests that the ergometer is a valid method of performance evaluation at maximal intensities. This is supported by the results of Chapter 5 confirming IR is a strong mechanical predictor of V_{Kayak} (Figure 40). Because athletes produce comparable IR at max between environments (Table 12), ergometer testing is a valid method of examining maximal mechanical capabilities. Furthermore, these data support the use of DS power for testing prescription instead of SR. Since DS power and SP IR are closely associated ($R^2 = 0.98$, $p < 0.01$) (Figure 20), and IR is similar between environments at max, DS power should be used for DS testing zones. It is unclear whether physiological variables are similar between environments, though, even at similar mechanical output (IR). This may be examined via similar research approach with IR as the controlled independent variable against physiological variables such as VO2 or lactate concentration. This would illuminate the validity of ergometer testing for the physiological demands of kayak sprint.

Despite the similarities between environments, it could be desirable to convert DS testing outcomes using the formulas presented earlier (Figure 20). This would allow for the comparison of DS ergometer data against on-water SP data. A more efficient approach would be to use the SP for all ergometer testing. This has numerous advantages; not only could testing data from both environments be compared, but also any intra-device differences and calibration drift would be irrelevant. Moreover, the SP provides useful outputs that the DS does not (impulse, F_{Peak}, F_{Mean}, P_{Peak}). The SP hardware error described in Chapter 3 should be addressed before this approach is implemented. Another advantage to using the SP for all testing is to quantify the difference between environments for each individual. It is possible that, due to a less-constrained system (unaffected by BM, wind, current, balance), athletes would perform differently on the ergometer at any given intensity. This is supported by the results presented in Chapter 4. Evaluating the difference between environments for kinematic and kinetic outputs for an individual generates a form of "performance potential" index where coaches and staff could extrapolate athlete potential. This concept has not been examined in previously published literature.

This study found tremendous value in the comparison of full force-time profiles. When presented the results of the SPM analysis, CRNZ coaches and HPSNZ staff expressed strong interest in further discussion of these data. It would be quantifiably estimable to have the option of exporting these data directly from the logger software already used to analyse SP data. Then, the SPM analysis used to compare performance between environments could be repeated. The most important insights were seen when comparing ergometer and on-water stroke profiles at test levels 5 and 6. A proposed method of obtaining similar results would be a single step test with progressively increasing SR; then, the exact SR where the force-time profile loses smoothness (Figure 30) could be identified for individuals. Although smoothness was not measured here, it is a variable of interest given its association with boat speed in rowing (Hill, 2002).

Considering the variety of practical applications resulting from this study, the researchers believe it would be prudent and powerful to use this protocol for squad evaluation at least every six months. Not only would it provide the same cross-sectional data, but also establish longitudinal benchmarking for both the squad and individuals. Furthermore, inter-individual analysis would enable objective evaluation of training interventions and progress tracking. This feedback/feed-forward loop would only become stronger as the pool of normative data and chronological data points grow for both squad and individual. Most importantly, the protocol was designed to be simple, quick, and non-fatiguing, so that it may be added into a training block without impacting training and easily moved to a day with calm environmental conditions.

These results highlighted several strong relationships between biomechanical variables and boat performance. The strength of the correlation observed between V_{Kayak}, T_{Stroke}, T_{Pull}, T_{Air}, pull %, and F_{Peak} aligns with those proposed by Michael et al. (2009), McDonnell et al. (2013), and evaluated by Gomes et al. (2015). These data also suggest an association between V_{Kayak}, propulsive impulse, reduced BM, force-time profile smoothness, and squareness (F_{Mean}/F_{Peak}). Based on these findings, we conclude that these are viable methods of increasing V_{Kayak}. At least, they are specific mechanisms that warrant further exploration via experimental investigation. However, these aspects of paddling are undeniably interrelated, and one could expect them to change concurrently. A visual representation of each proposed factor is described in Figure 52.

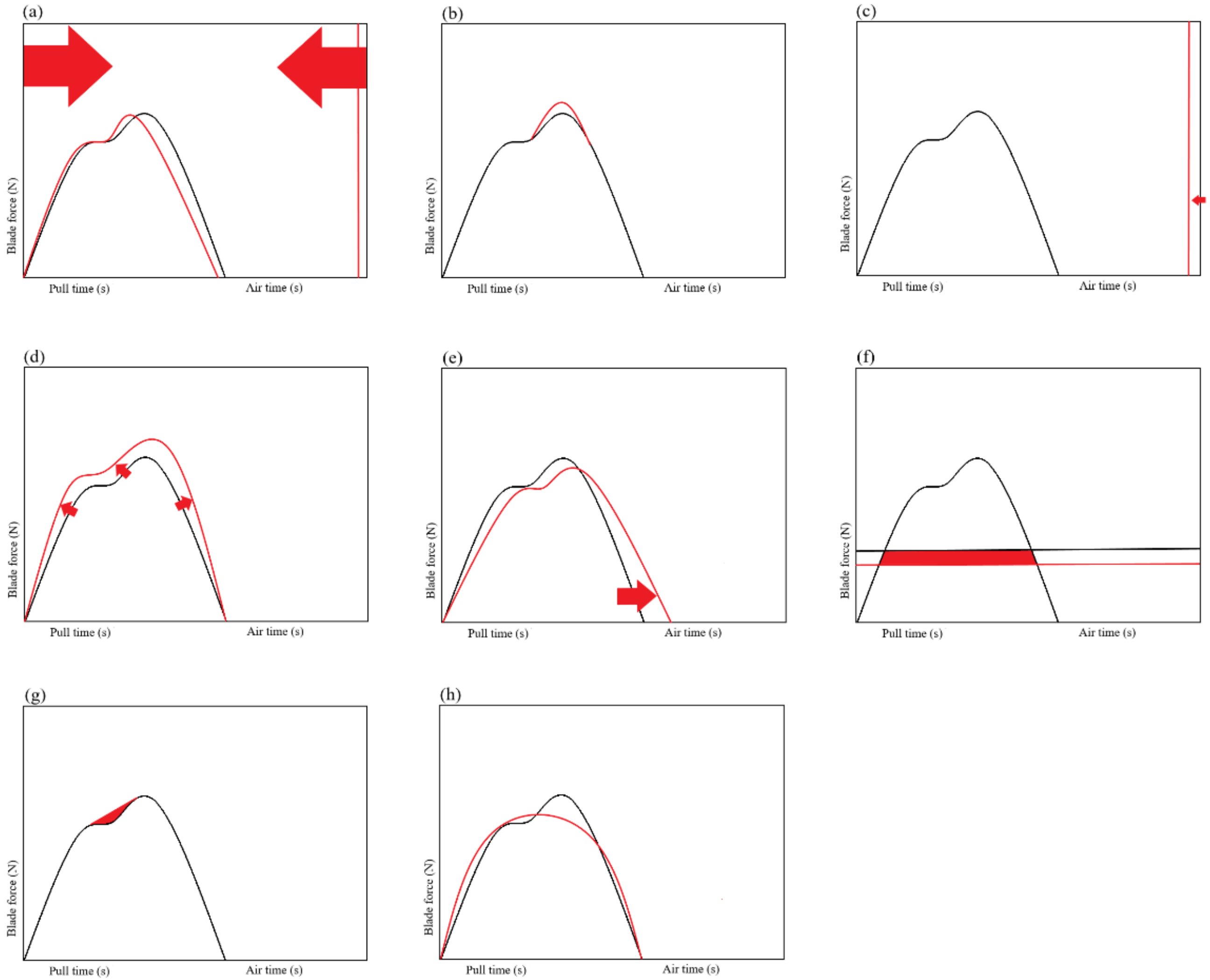

Figure 53. Proposed effective strategies to increase V_{Kayak} *and* V_{Race}*.*

(a) Reduce T_{Stroke}. Even with a proportional decrease in propulsive impulse, increased SR improves e_{p}.

*(b) Increase F_{Peak}. Potential increase in DPS (*Figure 47*) and stroke efficiency (*Figure 49*) at constant V_{Kayak}.*

(c) Reduce T_{Air}. Smaller non-propulsive phase reduces deceleration due to D_{P}, increasing e_{p}.

(d) Increase stroke impulse. Expansion of force-time profile in any direction (arrows) corresponds to greater propulsive force.

(e) Increase pull %. Assuming equal propulsive impulse, reduced time in non-propulsive T_{Air} reduces deceleration due to D_{P}, increasing e_{p}.

(f) Reduce D_{P}. Examples include reduced BM or improved equipment, resulting in smaller magnitude of D_{F} (from black to red horizontal line, shaded red) counteracting propulsive impulse, and thus increased e_{p}.

*(g) Increase force profile smoothness. Reduced "double-peak" characteristic increases propulsive impulse (*Figure 7*).*

(h) Increase force profile squareness. Assuming equal propulsive impulse, greater F_{Mean}/F_{Peak} ratio improves e_{p}.

Limitations

Despite attempts to perform a comprehensive, robust examination of kayak paddling kinetics, several limitations must be considered when interpreting thesis results. This project was a Master's level thesis; other research aims were discussed, but left unpursued due to time constraints.

The researchers chose to only examine paddling kinetics during steady state paddling, known as the constant velocity phase (Figure 32). Preliminary results suggested that the kinematic and kinetic relationships occurring during the acceleration phase were dramatically different to that seen during the constant velocity phase. Several factors contribute to the observed differences, including system mass-acceleration characteristics, technique, technological limitations, and sample size constraints. These were factored into the research design, and rolling starts were used in place of standing starts.

The use of SR as the independent variable in the experimental protocol must be considered when interpreting the results. As discussed earlier, constraining SR causes sample clustering at each level (Table 7). In Chapter 4, results are slightly different when comparing environments at a given SR versus test level. This is especially true at maximal intensity because athletes could perform higher SR on the ergometer (Table 12). Constraining SR does not account for individual movement strategies, which are shown to vary inter-individual (Warmenhoven et al., 2017). Specifically, athletes may achieve V_{Kayak} differently, which could explain the variability in some analyses (Figure 42 and Figure 51). However, as noted, SR and IR are strongly correlated for both ergometer and on-water paddling, so SR is a good indicator of not only paddling frequency but also paddling intensity under many conditions. A cyclical derived kinetic variable may be better for understanding intensity, as it considers propulsive force and SR (Equation 4). Regardless, there are nuanced differences observable whether examining the data as a whole, by SR, test level, or individual athlete. As test levels corresponded to SR ranges used by CRNZ in training, it was thought that this protocol would provide the most practically-relevant results for coaches and support staff.

What this protocol does not examine is paddling biomechanics during race conditions. Although the test levels examined here do include the range of SR and velocities observed during all ICF competition distances (200, 500, and 1000m), different relationships may be observed between, for example, F_{Mean} and V_{Kayak} when accounting for the fatigue and pacing strategy of true race conditions. Other methods of experimental design for biomechanical analysis of kayak are proposed by Warmenhoven et al. (2018) (Figure 53). Research approach framework for exploring constraints and their effect upon performance. to control for individual, environmental, and task constraints. These variables are not fully accounted for in these studies' experimental protocol.

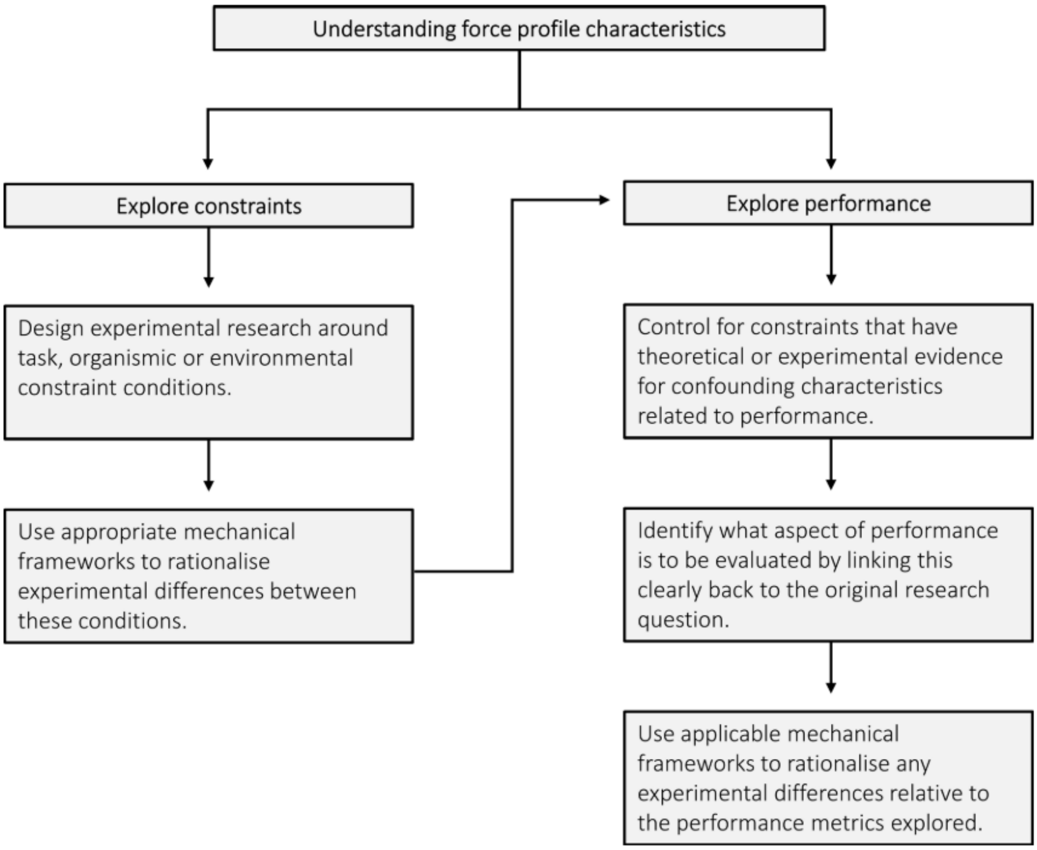

Figure 54. Research approach framework for exploring constraints and their effect upon performance.

Adapted from "Over 50 years of researching force profiles in rowing: What do we know," by Warmenhoven, J., Cobley, S., Draper, C., & Smith, R. (2018), Sports Medicine, 1-12.

Although methods of estimating D_F are established, a robust calculation of D_P and D_A for each athlete was not performed. Rather, its estimation was meant to provide normative data and inspire future study. The D_P formulas proposed by Gomes et al. (2015) were only available for three body masses and three boat sizes. Thus, the estimation of total D_F in Chapter 5 was limited to a subsample and warrants further investigation to account for all body masses, boat sizes, and to confirm validity. It is well-established that magnitude of boat roll, yaw, and pitch affects D_A substantially (McKenzie & Berglund, 2019, p. 21; Pendergast et al., 2005; Vadai & Gingl, 2016). Although the rover devices were able to measure boat motion in all axes, only horizontal α_{Kayak} was analysed. This is due to data analysis time constraints. D_A was estimated based on hypothetical assumptions of the system acceleration characteristics at constant velocity. Since all forces should sum to zero, the difference between IR and D_P is equal to D_A and propulsive impulse lost to blade slip. Therefore, although the its calculation here may overestimate D_A, the calculation of e_p may be accurate as it captures propulsive efficiency (blade slip) and D_A.

Modern advanced statistical techniques such as machine learning, neural models, and waveform analysis could provide more thorough analysis of the kinetic data gathered across all studies. Only in Chapter 4 were force-time profiles assessed via SPM; it is possible that advanced statistical techniques can recognise other important patterns in paddling profiles (Fothergill, Harle, & Holden, 2008; Gløersen, Myklebust, Hallén, & Federolf, 2018). For example, there could be value in analysing force-angle or V_{Blade} profiles (Caplan, 2009; Federolf, Reid, Gilgien, Haugen, & Smith, 2014). Moreover, a strategy such as principal component analysis (PCA) could identify "force signatures": unique patterns of interest to coaches seeking detailed technique feedback (Warmenhoven et al., 2017). Another effective statistical tool for force signatures is discrete point analysis, which appears very promising in other paddle sports (Warmenhoven et al., 2018).

Kinetic measurements at all points of contact between athlete and boat should be performed for a complete understanding of paddler biomechanics. Nilsson and Rosdahl (2016) and M. B. Brown et al. (2010) have reported strong, significant correlations between seat forces, foot forces, and boat performance. Evaluating the balance of these forces inside the kayak-athlete-paddle system (Figure 9) could explain the magnitude of difference between environments in Chapter 4, or the variability in many of the blade kinetics-V_{Kayak} relationships reported in Chapter 5. Another missing element is that of equipment setup, which could impact the interplay of the system forces. Aspects such as seat-to-footbar distance, seat type, paddle length, and paddle angle offset could affect performance, but have not been experimentally evaluated in the literature (Table 2).

Weather conditions were near perfect during both on-water data collections. Despite using the Yachtbot and Tidebot devices in the study design, measured wind and current were negligible (wind, < 2 m/s; current, < 0.1 m/s). Ideal weather conditions ensured robust data collection, so are not a limitation *per se*. However, it was the researchers' intention to quantify weather conditions to demonstrate a statistically valid method of weather conditions inclusion in performance prediction. Using the Yachtbot and Tidebot consistently for future studies could provide a basis for weather conditions correction such as that proposed by Higgens et al. (2016). Although outside of the scope of this thesis, it would provide comparative power for results across environmental conditions and help to predict results for important upcoming competitions.

The One Giant Leap power paddle was introduced as a commercially-available product during this thesis project (One Giant Leap, Nelson, NZ). Although there is not currently enough documentation to compare it to the SP studied in this thesis, the One Giant Leap paddle could be a viable solution that might provide similar data for less cost and overhead. Alternatively, the company may have resources or interest in addressing some of the limitations addressed here. It would be prudent to contact the company with the results of these studies to discuss if collaboration or partnership could be beneficial.

Future Research Direction

1) Evaluate the biomechanical determinants of the acceleration phase of kayak sprint (Figure 32).
2) Investigate the paddling biomechanics of team (K2, K4) boats.
3) Integrate boat motion data into boat drag estimation (Figure 1).
4) Explore paddling biomechanics data via advanced statistical techniques such as machine learning, principal component analysis (PCA), or discrete point analysis.
5) Measure all associated forces in the kayak-athlete-paddle system (Figure 9) and compare with V_{Kayak}.
6) Track environmental data for inclusion into performance prediction processes.
7) Experimental evaluation of different equipment setup parameters (e.g., footbar distance, paddle length) and their effect upon performance (Table 2).

Recommendations for CRNZ

1) Implementation of IR or P_{Cycle} as a real-time feedback metric for on-water training
2) Use the experimental paddle protocol with SP and rover data at least every six months for performance evaluation of the high performance squad.
3) Use the SP for all ergometer testing.
4) Use the SP to compare ergometer and on-water paddling for all high performance athletes annually.

Conclusions

This thesis presents a substantial contribution to the body of knowledge surrounding kayak performance and the potential for a tool such as the SP. It did achieve its aims in proving the utility of the SP and enriching the knowledge of kayak paddling biomechanics in various contexts. The combination of several factors (including technical support, CRNZ and athlete buy-in, AUT-HPSNZ partnership) permitted the execution of quality and robust studies with valuable and immediately actionable insights.

References

Ackland, T. R., Ong, K. B., Kerr, D. A., & Ridge, B. (2003). Morphological characteristics of olympic sprint canoe and kayak paddlers. *Journal of Science and Medicine in Sport, 6*(3), 285-294.

Aitken, D., & Neal, R. (1992). An on-water analysis system for quantifying stroke force characteristics during kayak events. *International Journal of Sport Biomechanics, 8*(2), 165-173.

Allen, H., & Coggan, A. (2012). *Training and racing with a power meter*: VeloPress.

Atkins, S. J. (2004). Normalizing expressions of strength in elite rugby league players. *Journal of Strength and Conditioning Research, 18*(1), 53-58.

Baca, A. (2006). Innovative diagnostic methods in elite sport. *International Journal of Performance Analysis in Sport, 6*(2), 148-156.

Baker, J. (2012). Biomechanics of paddling. *ISBS-Conference Proceedings Archive, 1*(1).

Baker, J., Rath, D., Sanders, R., & Kelly, B. (1999). A three-dimensional analysis of male and female elite sprint kayak paddlers. *ISBS-Conference Proceedings Archive, 1*(1).

Baudouin, A., & Hawkins, D. (2002). A biomechanical review of factors affecting rowing performance. *British Journal of Sports Medicine, 36*(6), 396-402.

Begon, M., Colloud, F., & Lacouture, P. (2008). Measurement of contact forces on a kayak ergometer with a sliding footrest–seat complex. *Sports Engineering, 11*(2), 67-73. https://doi.org/10.1007/s12283-008-0011-2

Begon, M., Lacouture, P., & Colloud, F. (2008). 3D kinematic comparison between on-water and on ergometer kayaking. *ISBS-Conference Proceedings Archive, 1*(1).

Begon, M., Mourasse, O., & Lacouture, P. (2009). A method of providing accurate velocity feedback of performance on an instrumented kayak ergometer. *Sports Engineering, 11*(2), 57.

Bernards, J. R., Sato, K., Haff, G. G., & Bazyler, C. D. (2017). Current research and statistical practices in sport science and a need for change. *Sports, 5*(4), 87.

Bifaretti, S., Bonaiuto, V., Federici, L., Gabrieli, M., & Lanotte, N. (2016). E-kayak: A wireless DAQ system for real time performance analysis. *Procedia Engineering, 147*, 776-780. https://doi.org/10.1016/j.proeng.2016.06.319

Bilic-Zulle, L. (2011). Comparison of methods: Passing and bablok regression. *Biochemia Medica: Biochemia Medica, 21*(1), 49-52.

Bini, R. R., & Diefenthaeler, F. (2009). Mechanical work and coordinative pattern of cycling: A literature review. *Kinesiology, 41*(1), 25-39.

Bishop, C., Read, P., Chavda, S., & Turner, A. (2016). Asymmetries of the lower limb: The calculation conundrum in strength training and conditioning. *Strength & Conditioning Journal, 38*(6), 27-32.

Bishop, D. (2008). An applied research model for the sport sciences. *Sports Medicine, 38*(3), 253-263.

Bishop, D., Bonetti, D., & Dawson, B. (2002). The influence of pacing strategy on VO2 and supramaximal kayak performance. *Medicine & Science in Sports & Exercise, 34*(6), 1041-1047.

Bjerkefors, A., Rosen, J., Tarassova, O., & Arndt, A. (2018). Three-dimensional kinematics and power output in elite para-kayakers and elite able-bodied flat-water kayakers. *Journal of Applied Biomechanics*, 1-8. https://doi.org/10.1123/jab.2017-0102

Bjerkefors, A., Tarassova, O., Rosen, J. S., Zakaria, P., & Arndt, A. (2018). Three-dimensional kinematic analysis and power output of elite flat-water kayakers. *Sports Biomechanics, 17*(3), 414-427. https://doi.org/10.1080/14763141.2017.1359330

Bjerkefors, A., Tarassova, O., Rosén, J. S., Zakaria, P., & Arndt, A. (2017). Three-dimensional kinematic analysis and power output of elite flat-water kayakers. *Sports Biomechanics*, 1-14.

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

Bonetti, D. L., & Hopkins, W. G. (2010). Variation in performance times of elite flat-water canoeists from race to race. *International Journal of Sports Physiology and Performance, 5*(2), 210-217.

Borges, T. O., Bullock, N., Aitken, D., & Coutts, A. J. (2017). Accuracy and validity of commercially available kayak ergometers. *International Journal of Sports Physiology and Performance, 12*(9), 1267-1270.

Bourgois, J., Vrijens, J., Verstuyft, J., Zinzen, E., & Clarijs, J. (1998). Physiological studies; specificity in the evaluation of performance capacity in kayak. In *Science and Practice of Canoe/Kayak High-Performance Training* (pp. 93-105)

Brooks, A., Abbott, A., & Wilson, D. (1986). Human-powered watercraft. *Scientific American, 255*(6), 120-131.

Brown, Lauder, & Dyson. (2011). Notational analysis of sprint kayaking: Differentiating between ability levels. *International Journal of Performance Analysis in Sport, 11*(1), 171-183.

Brown, M. B., Lauder, M., & Dyson, R. (2010). Activation and contribution of trunk and leg musculature to force production during on-water sprint kayak performance. *ISBS-Conference Proceedings Archive, 28*, 1-4.

Cabrera, D., Ruina, A., & Kleshnev, V. (2006). A simple 1+ dimensional model of rowing mimics observed forces and motions. *Human Movement Science, 25*(2), 192-220.

Campagna, P., Brien, D., Holt, L., Alexander, A., & Greenberger, H. (1982). A biomechanical comparison of olympic flatwater kayaking and a dry-land kayak ergometer. *Canadian Journal of Applied Sport Sciences, 7*, 242.

Caplan, N. (2009). The influence of paddle orientation on boat velocity in canoeing. *International Journal of Sport Science and Engineering, 3*(3), 131-139.

Cardinale, M., & Varley, M. C. (2016). Wearable training-monitoring technology: Applications, challenges, and opportunities. *International Journal of Sports Physiology and Performance, 12*(Suppl 2), S2-55-S52-62. https://doi.org/10.1123/ijspp.2016-0423

Cohen, J. (1988). The effect size index: D. *Statistical Power Analysis for the Behavioral Sciences, 2*, 284-288.

Coker, J., Hume, P., & Nolte, V. (2009). Validity of the powerline boat instrumentation system. *ISBS-Conference Proceedings Archive, 1*(1).

Crewther, B. T., McGuigan, M. R., & Gill, N. D. (2011). The ratio and allometric scaling of speed, power, and strength in elite male rugby union players. *The Journal of Strength & Conditioning Research, 25*(7), 1968-1975.

Day, A., Campbell, I., Clelland, D., Doctors, L. J., & Cichowicz, J. (2011). Realistic evaluation of hull performance for rowing shells, canoes, and kayaks in unsteady flow. *Journal of Sports Sciences, 29*(10), 1059-1069.

Denham, J., Scott-Hamilton, J., Hagstrom, A. D., & Gray, A. J. (2017). Cycling power outputs predict functional threshold power and maximum oxygen uptake. *Journal of Strength and Conditioning Research*.

Elliott, B., Lyttle, A., & Birkett, O. (2002). Rowing: The Rowperfect ergometer: A training aid for on-water single scull rowing. *Sports Biomechanics, 1*(2), 123-134.

Federolf, P., Reid, R., Gilgien, M., Haugen, P., & Smith, G. (2014). The application of principal component analysis to quantify technique in sports. *Scandinavian Journal of Medicine & Science in Sports, 24*(3), 491-499.

Fernandez-Nieves, A., & De Las Nieves, F. (1998). About the propulsion system of a kayak and of basiliscus basiliscus. *European Journal of Physics, 19*(5), 425.

Fleming, N., Donne, B., & Fletcher, D. (2012). Effect of kayak ergometer elastic tension on upper limb EMG activity and 3D kinematics. *Journal of Sports Science & Medicine, 11*(3), 430.

Fleming, N., Donne, B., Fletcher, D., & Mahony, N. (2012). A biomechanical assessment of ergometer task specificity in elite flatwater kayakers. *Journal of Sports Science & Medicine, 11*(1), 16.

Fohanno, V., Nordez, A., Smith, R., & Colloud, F. (2015). Asymmetry in elite rowers: Effect of ergometer design and stroke rate. *Sports Biomechanics, 14*(3), 310-322.

Folland, J. P., Mc Cauley, T. M., & Williams, A. G. (2008). Allometric scaling of strength measurements to body size. *European Journal of Applied Physiology, 102*(6), 739-745.

Fothergill, S., Harle, R., & Holden, S. (2008). Modeling the model athlete: Automatic coaching of rowing technique. *Structural, Syntactic, and Statistical Pattern Recognition*, 372-381.

Giavarina, D. (2015). Understanding Bland Altman analysis. *Biochemia Medica: Biochemia Medica, 25*(2), 141-151.

Glassbrook, D. J., Fuller, J. T., Alderson, J. A., Wills, J. A., & Doyle, T. L. (2018). The symmetry angle identifies less clinically relevant inter-limb asymmetries than the symmetry index in healthy adults. *ISBS-Conference Proceedings Archive, 36*(1), 622.

Gløersen, Ø., Myklebust, H., Hallén, J., & Federolf, P. (2018). Technique analysis in elite athletes using principal component analysis. *Journal of Sports Sciences, 36*(2), 229-237.

Godfrey, R., Whyte, G., & Whyte, G. (2006). Training specificity. *The Physiology of Training. London: Churchill Livingstone Elsevier*, 23-43.

Gomes, B., Viriato, N., Sanders, R., Conceição, F., Vilas-Boas, J. P., & Vaz, M. (2011). Analysis of the on-water paddling force profile of an elite kayaker. *ISBS-Conference Proceedings Archive, 1*(1).

Gomes, B. B., Conceição, F. A., Pendergast, D. R., Sanders, R. H., Vaz, M. A., & Vilas-Boas, J. P. (2015). Is passive drag dependent on the interaction of kayak design and paddler weight in flat-water kayaking? *Sports Biomechanics, 14*(4), 394-403.

Gomes, B. B., Machado, L., Ramos, N. V., Conceição, F. A., Sanders, R. H., Vaz, M. A., . . . Pendergast, D. R. (2017). Effect of wetted surface area on friction, pressure, wave and total drag of a kayak. *Sports Biomechanics*, 1-9.

Gomes, B. B., Ramos, N. V., Conceição, F. A. V., Sanders, R. H., Vaz, M. A. P., & Vilas-Boas, J. P. (2015). Paddling force profiles at different stroke rates in elite sprint kayaking. *Journal of Applied Biomechanics, 31*(4), 258-263.

Gore, C., Tanner, R., Fuller, K., & Stanef, F. (2013). Determination of maximal oxygen consumption (VO2max). *Physiological Tests for Elite Athletes*, 103-122.

Greidanus, A., Delfos, R., & Westerweel, J. (2016). Drag and power-loss in rowing due to velocity fluctuations. *Procedia Engineering, 147*, 317-323.

Gullstrand, L., Lindberg, T., Cardinale, D., Tarassova, O., & Bjerkefors, A. (2013). Validation of a kayak ergometer power output Symposium conducted at the meeting of the 18th Annual Congress of the European College of Sport Science

Harfield, P., Halkon, B., Mitchell, S., Phillips, I., & May, A. (2014). A novel, real-time biomechanical feedback system for use in rowing. *Procedia Engineering, 72*, 126-131. https://doi.org/10.1016/j.proeng.2014.06.004

Hay, J., & Yanai, T. (1996). Evaluating the techniques of elite us kayakers *A Report to Us Olympic Committee and Us Canoe and Kayak Team. Iowa City, Ia: University of Iowa*.

Hazir, T., & Kosar, N. S. (2007). Assessment of gender differences in maximal anaerobic power by ratio scaling and allometric scaling. *Isokinetics and Exercise Science, 15*(4), 253-261.

Helmer, R., Farouil, A., Baker, J., & Blanchonette, I. (2011). Instrumentation of a kayak paddle to investigate blade/water interactions. *Procedia Engineering, 13*, 501-506.

Hetzler, R. K., Stickley, C. D., & Kimura, I. F. (2011). Allometric scaling of wingate anaerobic power test scores in women. *Research Quarterly for Exercise and Sport, 82*(1), 70-78.

Higgens, A., Conway, L., Banks, J., Taunton, D., Hudson, D., & Turnock, S. (2016). Development of a kayak race prediction including environmental and athlete effects. *Procedia Engineering, 147*, 305-310. https://doi.org/http://dx.doi.org/10.1016/j.proeng.2016.06.296

Hill, H. (2002). Dynamics of coordination within elite rowing crews: Evidence from force pattern analysis. *Journal of Sports Sciences, 20*(2), 101-117.

Hofmijster, M. J., Landman, E. H. J., Smith, R. M., & Van Soest, A. J. K. (2007). Effect of stroke rate on the distribution of net mechanical power in rowing. *Journal of Sports Sciences, 25*(4), 403-411.

Hume, P. A. (2017). Movement analysis of scull and oar rowing. In B. Müller, S. I. Wolf, G.-P. Brueggemann, Z. Deng, A. McIntosh, F. Miller, & W. S. Selbie (Eds.), *Handbook of Human Motion* (pp. 1-21). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-30808-1_133-1

Jaafar, H. (2017). Allometric scaling of power-force-velocity ergometry profiles in men. *Annals of Human Biology, 44*(7), 648-651.
Jackson, P. (1995). Performance prediction for olympic kayaks. *Journal of Sports Sciences, 13*(3), 239-245.
Jackson, P., Locke, N., & Brown, P. (1992). The hydrodynamics of paddle propulsion Symposium conducted at the meeting of the 11th Australasian Fluid Mechanics Conference
Janssen, I., & Sachlikidis, A. (2010). Validity and reliability of intra-stroke kayak velocity and acceleration using a GPS-based accelerometer. *Sports Biomechanics, 9*(1), 47-56.
Jaric, S., Mirkov, D., & Markovic, G. (2005). Normalizing physical performance tests for body size: A proposal for standardization. *Journal of Strength & Conditioning Research, 19*(2), 467-474.
Johns, D. A., Irwin, G. J., & Sung, Y. K. (2014). An early sophisticated east polynesian voyaging canoe discovered on new zealand's coast. *Proceedings of the National Academy of Sciences, 111*(41), 14728-14733.
Kendal, S., & Sanders, R. (1992). The technique of elite flatwater kayak paddlers using the wing paddle. *International Journal of Sport Biomechanics, 8*(3), 233-250.
Kleiber, M. (1961). The fire of life. An introduction to animal energetics. *The Fire of Life. An Introduction to Animal Energetics.*
Kleshnev, V. (1999). Propulsive efficiency of rowing. *ISBS-Conference Proceedings Archive, 1*(1).
Kleshnev, V. (2006). Method of analysis of speed, stroke rate and stroke distance in aquatic loco-motions. *ISBS-Conference Proceedings Archive, 1*(1).
Kleshnev, V. (2008). Comparison of on-water rowing with its simulation on Concept2 and Rowperfect machines. *ISBS-Conference Proceedings Archive, 1*(1).
Klitgaard, K. K., de Zee, M., & Hansen, J. (2018). A new device for measuring forces in the footrest and seat during sprint kayaking. *ISBS-Conference Proceedings Archive, 1*(1).
Larsen, J., Modest, R., Serup, B., & Secher, N. (1988). A new kayak ergometer based on wind resistance. *Ergonomics, 31*(11), 1701-1707. https://doi.org/10.1080/00140138808966820
Laschowski, B., & Nolte, V. (2016). Statistical analyses of unidirectional static forces on instrumented rowing oarlocks. *Procedia Engineering, 147*, 765-769. https://doi.org/https://doi.org/10.1016/j.proeng.2016.06.322
Laurent, A., Rouard, A., Mantha, V. R., Marinho, D. A., Silva, A. J., & Rouboa, A. I. (2013). The computational fluid dynamics study of orientation effects of oar blade. *Journal of Applied Biomechanics, 29*(1), 23-32.
Li, J. (2015). Statistical methods of causal inference in sports science research. *Open Cybernetics & Systemics Journal, 9*, 2070-2074.
Li, M. (2017). The progress of biomechanical researches in kayaking. *Yangtze Medicine, 1*(01), 30.
Limonta, E., Squadrone, R., Rodano, R., Marzegan, A., Veicsteinas, A., Merati, G., & Sacchi, M. (2010). Tridimensional kinematic analysis on a kayaking simulator: Key factors to successful performance. *Sport Sciences for Health, 6*(1), 27-34.
Lintmeijer, L. L., Hofmijster, M. J., Schulte Fischedick, G. A., Zijlstra, P. J., & Van Soest, A. J. K. (2018). Improved determination of mechanical power output in rowing: Experimental results. *Journal of Sports Sciences, 36*(18), 2138-2146. https://doi.org/10.1080/02640414.2017.1367821
Lok, Y. L. (2013). Biomechanics study in sprint kayaking using simulator and on-water measurement instrumentation: An overview Symposium conducted at the meeting of the Third Malaysian Postgraduate Conference
López López, C., & Ribas Serna, J. (2011). Quantitative analysis of kayak paddling technique: Definition of an optimal stroke profile. *Revista Andaluza De Medicina Del Deporte, 4*(3).
Macdermid, P. W., & Fink, P. W. (2017). The validation of a paddle power meter for slalom kayaking. *Sports Medicine International Open, 1*(02), 50-57.
Malm, T. (1995). Excavating submerged stone age sites in denmark-the tybrind vig example. *Oxbow Monograph*, 385-396.

Mann, R., & Kearney, J. (1980). A biomechanical analysis of the olympic-style flatwater kayak stroke. *Medicine and Science in Sports and Exercise, 12*(3), 183-188.
Martin, J. C., Davidson, C. J., & Pardyjak, E. R. (2007). Understanding sprint-cycling performance: The integration of muscle power, resistance, and modeling. *International Journal of Sports Physiology & Performance, 2*(1), 5-21.
McDonnell, L. (2013). *The effect of stroke rate on performance in flat-water sprint kayaking*. Auckland University of Technology. Retrieved from http://ezproxy.aut.ac.nz/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=ir00946a&AN=auck.10292.6028&site=eds-live
McDonnell, L., Hume, P., & Nolte, V. (2012a). An observational model for biomechanical assessment of sprint kayaking technique. *Sports Biomechanics, 11*(4), 507-523.
McDonnell, L., Hume, P., & Nolte, V. (2012b). Sprint kayaking stroke rate reliability, variability and validity of the Digitrainer accelerometer compared to Gopro video measurement. *ISBS-Conference Proceedings Archive, 1*(1).
McDonnell, L., Hume, P., & Nolte, V. (2013). A deterministic model based on evidence for the associations between kinematic variables and sprint kayak performance. *Sports Biomechanics, 12*(3), 205-220.
McDonnell, L. K., Hume, P. A., & Nolte, V. (2013). A deterministic model based on evidence for the associations between kinematic variables and sprint kayak performance. *Sports Biomechanics, 12*(3), 205-220.
McKean, M. R., & Burkett, B. J. (2014). The influence of upper-body strength on flat-water sprint kayak performance in elite athletes. *International Journal of Sports Physiology and Performance, 9*(4), 707-714.
McKenzie, D., & Berglund, B. (2019). *Canoeing*: International Canoe Federation.
Michael, J. S., Smith, R., & Rooney, K. (2010). Physiological responses to kayaking with a swivel seat. *International Journal of Sports Medicine, 31*(08), 555-560.
Michael, J. S., Rooney, K. B., & Smith, R. (2008). The metabolic demands of kayaking: A review. *Journal of Sports Science & Medicine, 7*(1), 1-7.
Michael, J. S., Rooney, K. B., & Smith, R. M. (2012). The dynamics of elite paddling on a kayak simulator. *Journal of Sports Sciences, 30*(7), 661-668.
Michael, J. S., Smith, R., & Rooney, K. B. (2009). Determinants of kayak paddling performance. *Sports Biomechanics, 8*(2), 167-179. https://doi.org/10.1080/14763140902745019
Millar, S.-K., Reid, D., McDonnell, L., Lee, J., & Kim, S. (2017). Elite rowers apply different forces between stationary and sliding ergometers, & on-water rowing. *ISBS-Conference Proceedings Archive, 35*(1), 4.
Mononen, H., & Viitasalo, J. (1995). Stroke parameters and kayak speed during 200 m kayaking. *ISBS-Conference Proceedings Archive, 1*(1), 632-633.
Morgoch, D., Galipeau, C., & Tullis, S. (2016). Sprint canoe blade hydrodynamics - modeling and on-water measurement. *Procedia Engineering, 147*, 299-304. https://doi.org/http://dx.doi.org/10.1016/j.proeng.2016.06.295
Morin, J.-B., & Samozino, P. (2016). Interpreting power-force-velocity profiles for individualized and specific training. *International Journal of Sports Physiology and Performance, 11*(2), 267-272.
Nagahara, R., Botter, A., Rejc, E., Koido, M., Shimizu, T., Samozino, P., & Morin, J. B. (2017). Concurrent validity of GPS for deriving mechanical properties of sprint acceleration. *Int Journal of Sports Physiology and Performance, 12*(1), 129-132. https://doi.org/10.1123/ijspp.2015-0566
Nakashima, M., Ito, S., & Nakagaki, K. (2019). Simulation of sprint canoe paddling. *Sports Engineering, 22*(1), 1.
Nakashima, M., Kitazawa, A., Nakagaki, K., & Onoto, N. (2017). Simulation to clarify the effect of paddling motion on the hull behavior of a single kayak in a sprint race. *Sports Engineering, 20*(2), 133-139. https://doi.org/10.1007/s12283-016-0222-x
Nates, F. M., & Colloud, F. (2016). A 6-component paddle sensor to estimate kayaker's performance: Preliminary results. *ISBS-Conference Proceedings Archive, 33*(1).

Nevill, A. M., Beech, C., Holder, R. L., & Wyon, M. (2010). Scaling concept ii rowing ergometer performance for differences in body mass to better reflect rowing in water. *Scandinavian Journal of Medicine & Science in Sports, 20*(1), 122-127.
Nevill, A. M., Ramsbottom, R., & Williams, C. (1992). Scaling physiological measurements for individuals of different body size. *European Journal of Applied Physiology and Occupational Physiology, 65*(2), 110-117.
Nevill, A. M., & Whyte, G. (2005). Are there limits to running world records? *Medicine & Science in Sports & Exercise, 37*(10), 1785-1788.
Nilsson, J. E., & Rosdahl, H. G. (2016). Contribution of leg-muscle forces to paddle force and kayak speed during maximal-effort flat-water paddling. *International Journal of Sports Physiology & Performance, 11*(1), 22-27.
Niu, L., Chen, L. H., Tou, Z. Q., Tay, C. S., Lin, Y. F., Kong, P. W., . . . Chan, C. C. (2018). Kayaking paddle blade compression load distribution sensing system based on optical fiber with a polydimethylsiloxane membrane. *Applied Optics, 57*(6), 1387-1392. https://doi.org/10.1364/AO.57.001387
Nolan, G., & Bates, B. (1982). A biomechanical analysis of the effects of two paddle types on performance in north american canoe racing. *Research Quarterly for Exercise and Sport, 53*(1), 50-57.
Nolte, V. (2005). *Rowing faster*: Human Kinetics.
O'Malley, V. (2013). *The Meeting Place: Maori and Pakeha Encounters, 1642-1840*: Auckland University Press.
Oldham, T., & Millar, S. K. (2018). Using expert knowledge to inform multivariate analyses. *ISBS-Conference Proceedings Archive, 36*(1), 1028.
Paquette, M., Bieuzen, F., & Billaut, F. (2018). Muscle oxygenation rather than VO2max as a strong predictor of performance in sprint canoe–kayak. *International Journal of Sports Physiology and Performance, 13*(10), 1299-1307.
Pataky, T. C., Robinson, M. A., & Vanrenterghem, J. (2013). Vector field statistical analysis of kinematic and force trajectories. *Journal of Biomechanics, 46*(14), 2394-2401.
Pataky, T. C., Robinson, M. A., & Vanrenterghem, J. (2016). Region-of-interest analyses of one-dimensional biomechanical trajectories: Bridging 0d and 1d theory, augmenting statistical power. *Peerj, 4*, e2652.
Paton, C., & Hopkins, W. (2006). Ergometer error and biological variation in power output in a performance test with three cycle ergometers. *International Journal of Sports Medicine, 27*(06), 444-447.
Pelz, P. F., & Vergé, A. (2014). Validated biomechanical model for efficiency and speed of rowing. *Journal of Biomechanics, 47*(13), 3415-3422.
Pendergast, D., Mollendorf, J., Zamparo, P., Termin 2nd, A., Bushnell, D., & Paschke, D. (2005). The influence of drag on human locomotion in water. *European Journal of Applied Physiology, 94*(2), 122-127.
Pendergast, D., Zamparo, P., Di Prampero, P., Capelli, C., Cerretelli, P., Termin, A., . . . Mollendorf, J. (2003). Energy balance of human locomotion in water. *European Journal of Applied Physiology, 90*(3-4), 377-386.
Pyne, D., & Trewin, C. (2001). Analysis of stroke rates in freestyle events at 2000 olympics. *Swimming in Australia, 17*(1), 1-3.
Qiu, Y., Wei, W., Liu, A., & Cao, J. (2008). Comparative research on the stroke rhythm of men and women kayakers in the international competition. *ISBS-Conference Proceedings Archive, 1*(1).
Ridge, B., Pyke, F., & Roberts, A. (1976). Responses to kayak ergometer performance after kayak and bicycle ergometer training. *Medicine and Science in Sports and Exercise, 8*(1), 18-22.
Robinson, M. G., Holt, L. E., Pelham, T. W., & Furneaux, K. (2011). Accelerometry measurements of sprint kayaks: The coaches' new tool. *International Journal of Coaching Science, 5*(1).
Rosenthal, J. A. (1996). Qualitative descriptors of strength of association and effect size. *Journal of Social Service Research, 21*(4), 37-59.
Shephard, R. (1987). Science and medicine of canoeing and kayaking. *Sports Medicine, 4*(1), 19-33.

Shin, C., Willmott, A. P., Mullineaux, D. R., & Worsfold, P. (2017). The effect of bungee tension on power profiling in kayak ergometry. *ISBS-Conference Proceedings Archive, 35*(1), 7.

Shin, C., Willmott, S., & Mullineaux, D. (2018). Does isoinertial ergometry profiling represent on-water sprint capacity in kayakers? *ISBS-Conference Proceedings Archive, 36*(1), 342.

Simperingham, K. D., Cronin, J. B., Pearson, S. N., & Ross, A. (2019). Reliability of horizontal force–velocity–power profiling during short sprint-running accelerations using radar technology. *Sports Biomechanics, 18*(1), 88-99.

Soper, C., & Hume, P. A. (2004). Rowing: Reliability of power output during rowing changes with ergometer type and race distance. *Sports Biomechanics, 3*(2), 237-248.

Sperlich, J., & Baker, J. (2002). Biomechanical testing in elite canoeing. *ISBS-Conference Proceedings Archive, 1*(1).

Steeves, D., Thornley, L. J., Goreham, J. A., Jordan, M., Landry, S. C., & Fowles, J. R. (2018). Reliability and validity of a novel trunk strength assessment for high performance sprint flatwater kayakers. *International Journal of Sports Physiology and Performance*, 1-27.

Stickley, C. D., Hetzler, R. K., Wages, J. J., Freemyer, B. G., & Kimura, I. F. (2013). Allometric scaling of wingate anaerobic power test scores in men. *The Journal of Strength & Conditioning Research, 27*(9), 2603-2611.

Sturm, D., Parida, V., Larsson, T., & Isaksson, O. (2011). Design of user-centred wireless sensor technology in sports: An empirical study of elite kayak athletes Symposium conducted at the meeting of the International Conference on Research into Design.

Sturm, D., Yousaf, K., Brodin, L.-Å., & Halvorsen, K. (2013). Wireless kayak on-water ergometry–part 1: Paddle blade force. *Sports Technology, 6*(1), 29-42.

Sturm, D., Yousaf, K., & Eriksson, M. (2010, 7-9 June 2010). A wireless, unobtrusive kayak sensor network enabling feedback solutions Symposium conducted at the meeting of the 2010 International Conference on Body Sensor Networks https://doi.org/10.1109/BSN.2010.24

Suchomel, T. J., Nimphius, S., & Stone, M. H. (2018). Scaling isometric mid-thigh pull maximum strength in division i athletes: Are we meeting the assumptions? *Sports Biomechanics*, 1-15.

Toro, A. (1986). *Canoeing: An olympic sport*: Printed in the US by Olympian Graphics.

Tullis, S., Galipeau, C., & Morgoch, D. (2018). Detailed on-water measurements of blade forces and stroke efficiencies in sprint canoe. *Multidisciplinary Digital Publishing Institute Proceedings, 2*(6), 306.

Ualí, I., Herrero, A. J., Garatachea, N., Marín, P. J., Alvear-Ordenes, I., & García-López, D. (2012). Maximal strength on different resistance training rowing exercises predicts start phase performance in elite kayakers. *The Journal of Strength & Conditioning Research, 26*(4), 941-946.

Vadai, G., & Gingl, Z. (2016). Can the fluctuations of motion be used to estimate the performance of kayak paddlers? *Journal of Statistical Mechanics: Theory and Experiment, 2016*(5), 054040.

Vadai, G., Makan, G., Gingl, Z., Mingesz, R., Mellár, J., Szépe, T., & Csamangó, A. (2013). On-water measurement and analysis system for estimating kayak paddlers' performance Symposium conducted at the meeting of the 36th International Convention on Information & Communication Technology Electronics & Microelectronics

van Someren, K., & Palmer, G. S. (2003). Prediction of 200-m sprint kayaking performance. *Canadian Journal of Applied Physiology, 28*(4), 505-517. https://doi.org/10.1139/h03-039

van Someren, K. A., & Howatson, G. (2008). Prediction of flatwater kayaking performance. *International Journal of Sports Physiology and Performance, 3*(2), 207-218.

Varley, M. C., Fairweather, I. H., & Aughey1, Robert J. (2012). Validity and reliability of GPS for measuring instantaneous velocity during acceleration, deceleration, and constant motion. *Journal of Sports Sciences, 30*(2), 121-127.

Villarino-Cabezas, S., González-Ravé, J. M., Santos-Garcia, D. J., & Valdivielso, F. N. (2013). Comparison between a laboratory test in kayak-ergometer and continuous and interval

exercises on open water in well-trained young kayakers. *International Sportmed Journal, 14*(4), 196-204.
von Someren, K. A., Phillips, G. R. W., & Palmer, G. S. (2000). Comparison of physiological responses to open water kayaking and kayak ergometry. *International Journal of Sports Medicine, 21*(03), 200-204. https://doi.org/10.1055/s-2000-8877
Wainwright, B., Cooke, C., & Low, C. (2016). Performance related technique factors in olympic sprint kayaking. *ISBS-Conference Proceedings Archive, 33*(1).
Wang, Z., Wang, J., Zhao, H., Yang, N., & Fortino, G. (2016). Canoesense: Monitoring canoe sprint motion using wearable sensors Symposium conducted at the meeting of the International Conference on Systems, Man, and Cybernetics.
Warmenhoven, J., Cobley, S., Draper, C., Harrison, A., Bargary, N., & Smith, R. (2017). Considerations for the use of functional principal components analysis in sports biomechanics: Examples from on-water rowing. *Sports Biomechanics*, 1-25.
Warmenhoven, J., Cobley, S., Draper, C., & Smith, R. (2018). Over 50 years of researching force profiles in rowing: What do we know? *Sports Medicine*, 1-12.
Wietrzyński, M., Mazur-Różycka, J., Gajewski, J., Michalski, R., Różycki, S., & Buśko, K. (2013). The assessment of muscle strength symmetry in kayakers and canoeists. *Biomedical Human Kinetics, 5*(1).
Zamparo, P., Tomadini, S., Didone, F., Grazzina, F., Rejc, E., & Capelli, C. (2006). Bioenergetics of a slalom kayak (k1) competition. *International Journal of Sports Medicine, 27*(07), 546-552.
Zatsiorsky, V. (2008). *Biomechanics in sport: Performance enhancement and injury prevention* (Vol. 9): John Wiley & Sons.
Zouhal, H., Lahaye, S. L. D., Abderrahaman, A. B., Minter, G., Herbez, R., & Castagna, C. (2012). Energy system contribution to olympic distances in flat water kayaking (500 and 1,000 m) in highly trained subjects. *Journal of Strength & Conditioning Research, 26*(3), 825-831.

Appendices

Appendix 1. Ethics approval and amendment form

AUTEC Secretariat

Auckland University of Technology

D-88, WU406 Level 4 WU Building City Campus

T: +64 9 921 9999 ext. 8316

E: ethics@aut.ac.nz

www.aut.ac.nz/researchethics

30 April 2018

Jonathon Neville

Faculty of Health and Environmental Sciences

Dear Jonathon,

Ethics Application: 18/151 Kinetic determinants of kayak sprint performance

Thank you for submitting your application for ethical review. I am pleased to advise that the Auckland University of Technology Ethics Committee (AUTEC) approved your ethics application at their meeting on 23 April 2018, subject to the following conditions:

1. Clarification of the involvement of Jessica Bush in the research;

2. Clarification of whether the questionnaire referred to in section B.12 of the application is the '4 scales' included with application. If yes, provide some guide lines for athletes about what to do with it;

3. Clarification of why there is a menstrual cycle questionnaire;

4. Clarification of why only the 'men's elite athletes' will be reimbursed for travel;

5. Amendment of the Information Sheet as follows:

a. Inclusion in the section on discomforts and risks the dual role of the researcher and the potential for a conflict of interest and provide details of how these will be mitigated;

b. Inclusion of details about the travel reimbursement referred to in section K.4.3 of the application.

Please provide me with a response to the points raised in these conditions, indicating either how you have satisfied these points or proposing an alternative approach. AUTEC also requires copies of any altered documents, such as Information Sheets, surveys etc. You are not required to resubmit the application form again. Any changes to responses in the form required by the committee in their conditions may be included in a supporting memorandum.

Please note that the Committee is always willing to discuss with applicants the points that have been made. There may be information that has not been made available to the Committee, or aspects of the research may not have been fully understood.

Once your response is received and confirmed as satisfying the Committee's points, you will be notified of the full approval of your ethics application. Full approval is not effective until all the conditions have been met. Data collection may not commence until full approval has been confirmed. If these conditions are not met within six months, your application may be closed and a new application will be required if you wish to continue with this research.

To enable us to provide you with efficient service, we ask that you use the application number and study title in all correspondence with us. If you have any enquiries about this application, or anything else, please do contact us at ethics@aut.ac.nz.

I look forward to hearing from you,

Yours sincerely

Kate O'Connor

Executive Manager

Auckland University of Technology Ethics Committee

Cc: ericharbour@gmail.com; plews@plewsandprof.com

Auckland University of Technology Ethics Committee (AUTEC)

Auckland University of Technology
D-88, Private Bag 92006, Auckland 1142, NZ
T: +64 9 921 9999 ext. 8316
E: ethics@aut.ac.nz
www.aut.ac.nz/researchethics

4 December 2018

Jonathon Neville
Faculty of Health and Environmental Sciences

Dear Jonathon

Re Ethics Application: **18/151 Kinetic determinants of kayak sprint performance**

Thank you for providing evidence as requested, which satisfies the points raised by the Auckland University of Technology Ethics Committee (AUTEC).

Your ethics application has been approved for three years until 4 December 2021.

Standard Conditions of Approval

1. A progress report is due annually on the anniversary of the approval date, using form EA2, which is available online through http://www.aut.ac.nz/research/researchethics.
2. A final report is due at the expiration of the approval period, or, upon completion of project, using form EA3, which is available online through http://www.aut.ac.nz/research/researchethics.
3. Any amendments to the project must be approved by AUTEC prior to being implemented. Amendments can be requested using the EA2 form: http://www.aut.ac.nz/research/researchethics.
4. Any serious or unexpected adverse events must be reported to AUTEC Secretariat as a matter of priority.
5. Any unforeseen events that might affect continued ethical acceptability of the project should also be reported to the AUTEC Secretariat as a matter of priority.

Please quote the application number and title on all future correspondence related to this project.

AUTEC grants ethical approval only. If you require management approval for access for your research from another institution or organisation, then you are responsible for obtaining it. You are reminded that it is your responsibility to ensure that the spelling and grammar of documents being provided to participants or external organisations is of a high standard.

For any enquiries, please contact ethics@aut.ac.nz

Yours sincerely,

Kate O’Connor

Executive Manager

Auckland University of Technology Ethics Committee

Cc: ericharbour@gmail.com; plews@plewsandprof.com

Appendix 2. Participant information sheet

14/6/2018

Project Title: Kinetic determinants of kayak sprint performance

An Invitation

Hi, my name is Eric Harbour and I am a MSc student at AUT, as well as a Performance Analyst Intern for High Performance Sport New Zealand (HPSNZ). Along with Dr. Jono Neville and Dr. Paul McAlpine, I invite you to help with a project that examines the accuracy of the KZ2 instrumented paddle system.

What is the purpose of this research?

Kayak sprint performance is dependent on a number of variables including endurance, weather, and power. With new innovations such as the KZ2 paddle system (Goldmine, HPSNZ), on-water power production may be measurable as a variable of interest to performance analysis. However, before a tool such as this may be used to guide analysis or technique changes, it must be evaluated for validity and reliability.

Therefore, we propose to determine the accuracy of this tool via an off-water and on-water testing protocol. This study will utilise the KZ2 in comparison with other devices to ascertain its suitability for future research and application.

How was I identified and why am I being invited to participate in this research?

You have been identified as a potential participant for this research based on your having previously represented New Zealand at international competitions as a Canoe Racing New Zealand (CRNZ) athlete.

As an athlete who has competed at the international level, CRNZ has contacted you with an advertisement and an information sheet relating to this study; both contain my contact details as the primary researcher (Eric Harbour). Should you wish to follow up in response to the advertisement and information sheet by contacting me, then only at that time will I have access to your contact details as a researcher. Otherwise your contact information will remain solely with CRNZ

However, you will not be able to partake in the study if you currently have any illness or injury that would inhibit your ability to perform the training sessions or assessments, or which may put you at risk of further injury.

How do I agree to participate in this research?

Your participation in this research is voluntary (it is your choice) and whether or not you choose to participate will neither advantage nor disadvantage you as a CRNZ athlete. Should you choose to participate, you will need to read through this information sheet, and then respond to me via email (Erictharbour@gmail.com). After that, I will send you an informed consent form, which you will need to sign, and return to me prior to participating. You are able to withdraw from the study at any time. If you choose to withdraw from the study, then you will be offered the choice between having any data that is identifiable as belonging to you removed or allowing it to continue to be used. However, once the findings have been produced, removal of your data may not be possible.

What will happen in this research?

Your involvement in this research will require you to attend 2 separate testing sessions. The first session will be an off-water step test at various intensities performed on the Dansprint ergometer at the AUT Millennium SPRINZ labs (or alternatively at the CRNZ high performance centre Lake Karapiro). The same day you will complete an identical on-water test before your normal scheduled training. This will be done at your respective on-water training centre.

All data collection will be performed at the on-water training environment, or SPRINZ labs at AUT Millennium. You will need to perform regular kayak training activities and fill out questionnaires (sRPE, menstrual cycle [if female]). We would also ask that you refrain from any abnormal training/strenuous exercise 24h before any session (outside of scheduled training), alcohol for 12h, and caffeine within 3h. Any further questions, please don’t hesitate to ask.

What are the discomforts and risks?

There are no anticipated discomfort or risks from participating in this research, as the training sessions and testing involved are not out of the ordinary from your routine training and monitoring as part of being a CRNZ athlete. As I have a dual role as researcher and performance analyst for the team, there is a potential conflict of interest regarding your inclusion into the study and transparency of results. Your decision whether or not to participate, and performance across the study will not affect your status as a CRNZ athlete or be shared with your coach if you choose. Any questions or concerns may be mediated by AUT staff Jono Neville (Jneville@aut.ac.nz) for consultation.

What are the benefits?

You will have the opportunity to learn about your physical capacity during kayaking at various intensities. Also, CRNZ will be able to use the KZ2 for future training and feedback should the research validate its use as a reliable and accurate tool. The research may inform future technological innovation and research within paddle sports and beyond. It may enhance understanding of athlete biomechanics during paddling to improve coaching, competition, performance, or injury prevention. Furthermore, this study will form part of my Masters thesis, and may also form part of academic presentations, or publications.

What compensation is available for injury or negligence?

In the unlikely event of a physical injury as a result of your participation in this study, rehabilitation and compensation for injury by accident may be available from the Accident Compensation Corporation, providing the incident details satisfy the requirements of the law and the Corporation's regulations.

How will my privacy be protected?

During the collection of data for this study, all information will remain confidential to the researchers involved, no names will be made public, and no statements will be made about specific inclusion of athletes within this research. If the findings are to be published in the public domain, it will be presented in aggregated statistical format (describing group means), and will be de-identified if any individual results are discussed. However, given the inclusion criteria, this study is being conducted on a relatively small population base (highly trained kayakers) and thus only limited confidentiality can be offered based on you being a known member of that elite group.

What are the costs of participating in this research?

Including pre-testing, training sessions, and follow up recovery data collection you will be required to give approximately 3-5 hours of your time to this project throughout the period of one week.

If data collection requires you to travel greater than 20 kilometers from your training location, travel reimbursement in the form of fuel or transport vouchers will be provided. Please indicate this request ASAP upon reply to this study.

What opportunity do I have to consider this invitation?

2 weeks.

Will I receive feedback on the results of this research?

At the end of the study you will receive a written summary of the findings, highlighting your own individual paddling profile. Your personal results will be shared with your coach, should you grant us permission.

What do I do if I have concerns about this research?

Any concerns regarding the nature of this project should be notified in the first instance to the Project Supervisor: Dr. Jono Neville, Jneville@aut.ac.nz, 020 4104 8486

Concerns regarding the conduct of the research should be notified to the Executive Secretary of AUTEC, Kate O'Connor, *ethics@aut.ac.nz* , 921 9999 ext 6038.

Whom do I contact for further information about this research?

Please keep this Information Sheet and a copy of the Consent Form for your future reference. You are also able to contact the research team as follows:

Researcher contact details:

Name: Eric Harbour

Email: Erictharbour@gmail.com

Project supervisor contact details:

Name: Jono Neville

Email: Jneville@aut.ac.nz

Approved by the Auckland University of Technology Ethics Committee on *30/4/2018*, AUTEC Reference number *18/151*.

Appendix 3. Consent form

TE WĀNANGA ARONUI O TĀMAKI MAKAU RAU

Project title:

Kinetic determinants of kayak sprint performance

Project Supervisor: *Dr. Jono Neville, Dr. Paul McAlpine*

Researcher: ***Eric Harbour***

- ○ I have read and understood the information provided about this research project (Information Sheet dated 14/06/2018)
- ○ I have had an opportunity to ask questions and to have them answered.
- ○ I understand that taking part in this study is voluntary (my choice) and that I may withdraw from the study at any time without being disadvantaged in any way.
- ○ I understand that if I withdraw from the study then I will be offered the choice between having any data that is identifiable as belonging to me removed or allowing it to continue to be used. However, once the findings have been produced, removal of my data may not be possible.
- ○ I understand that all data collected will be de-identified when presented for research purposes, and allow for its use in journal publications, a post-graduate thesis and academic presentations
- ○ I agree to allow my collected data to be stored in High Performance Sport New Zealand (HPSNZ) athlete database, to enhance future understanding of Canoe Racing New Zealand (CRNZ) athlete training adaptations
- ○ I am not suffering from heart disease, high blood pressure, any respiratory condition (mild asthma excluded), any illness, injury or infection that impairs my physical performance, or could be worsened by participation in this study.
- ○ I wish to receive a summary of the research findings

  (please tick one): Yes○ No○
- ○ I wish to have a summary of my data shared with my CRNZ coach

  (please tick one): Yes○ No○
- ○ I agree to take part in this research.

○ Any further comments, or cultural preferences that the researchers should be made aware of?

Participant's signature: ....

Participant's name: ....

Email contact: ....

Date: ....

Approved by the Auckland University of Technology Ethics Committee on 30/04/2018 AUTEC Reference number 18/151

Note: The Participant should retain a copy of this form.

Appendix 4. Ergometer trial checklist

Date:________________ Time: ________________ Location:_________________

Name: __________________ Weight (kg): ___________ Height (cm): ____________

Pressure: ______________ Altitude: _______________ Temp: ________________

1. Confirm pre-trial diet, caffeine intake
2. Obtain consent, show participant info sheet
3. Dansprint setup
   - ☐ Calibrate Dansprint (to athlete's weight & desired resistance)
   - ☐ Zero load cells (no tension on ropes)
   - ☐ Do not zero wheels
   - ☐ Set "near" load cells
   - ☐ Set "far" load cells
   - ☐ Check seat/footrest

☐ Men's warmup
- Roll and Stretch 10'
- Bike: L2: 10' - 2' off
- Ergometer: L2 : 02:00/01:00 off | VO2 max: 00:20/01:40 off

☐ Video

Level	SR	Duration	Dansprint collect	Instrumented Dansprint collect	Load cells if changed
Paddle L2	32	03:00			
Rest		01:00			
Paddle L3	36	02:00			
Rest		01:00			
Paddle L4	40	01:00			
Rest		02:00			
Paddle L5	48	01:00			
Rest		02:00			
Paddle RP	60	00:30			
Rest		03:00			
Paddle max		00:15			

Appendix 5. On-water trial checklist

Date:______________ Time: __________________ Location:__________________

Pressure: _____________ Altitude: ______________Temp: ______________

1. Confirm pre-trial diet, caffeine intake
2. Obtain consent, show participant info sheet
3. K1 setup
    a. Apply Rover 2s; power on
    b. Distribute KZ smart paddle; record names, power on
    c. Check seat/footrest
4. Yachtbot setup
    a. Tiedown securely to front of boat
    b. Power on
    c. Look for 3 green lights (GPS lock)

Athlete	Rover	Paddle
Taris		
Kurtis		
Ashton		
Max		

☐ Video

Level	SR	Duration	
Paddle L2	32	03:00	
Rest		01:00	
Paddle L3	36	02:00	
Rest		01:00	
Paddle L4	40	01:00	
Rest		02:00	
Paddle L5	48	01:00	
Rest		02:00	
Paddle RP	60	00:30	
Rest		03:00	
Paddle max		00:15	

- [ ] Tidebot
    - Secure antenna
    - Remove from case
    - Power on; look for green light (GPS lock)
    - Let float for >02:00 and >5m

Appendix 6. Instrumented ergometer information

Aim:

1) To measure right and left side paddling kinematics (stoke rate, stroke length, stroke velocity) and kinetics (force and power) of Kayaking on an indoor kayak ergometer (Dansprint).

2) To provide real-time continuous data as well as stoke-by-stoke average and peak values for the right and left stroke kinematics and kinetics when kayaking of an indoor ergometer.

3) To not interfere with athlete's kayaking performance and allow uninhibited paddling at maximal paddling speeds and forces.

Purpose:

To enable a greater understanding of the right and left side paddling mechanics and paddling technique during kayaking on and indoor kayak ergometer. To provide a detailed analysis of right and left paddle position, velocity, force and power generation.

Benefits:

To provide a detailed quantitative analysis of kayaking technique.
To improve kayak performance by identifying strengths and weaknesses and support training decisions related to strength, conditioning and technique.
To enable direct comparisons of performance metrics between kayakers and comparisons to elite.

Design:

The first novel aspect to the design is that pull force on the right and left ropes are measured by two load cells mounted in-between the main body of the ergometer and the fly wheel unit at the front of the kayak. The load cells are placed on the right and left sides of the ergometer and measure the respective right and left compression and tension forces transmitted between the body of the ergometer and the flywheel. The load cells are pre-mounted between two metal plates, forming a load cell sandwich. After removing the flywheel from the ergometer, the load cell sandwich bolts directly to the end of the ergometer body and the flywheel then bolts directly to the outer side of the load cell sandwich.

Knowing the force on each load cell (positive or negative) the distance between the two load cells, the distance between the two bungee/tension ropes running from the ergometer to the flywheel, the tension exerted by the bungee system on these ropes and the distance from the centre of the load cells to the flywheel pulleys allows the summation of moment about the centre of the load cells. Knowing the forces on each load cell, bungee tension and moment arms off applied forces the rope tension in the right and left paddles can be calculated. The results includes pull force and angle of pull.

Validation of right and left pull force was achieved by: 1) attaching a third load cell the centre of the paddle and recording total pull force as the entire paddle as moved forward and back. Both right and left paddle rope forces are approximately equal and compared to calculated rope force based on load cell readings, paddle position and bungie tension; 2) attaching a third load cell to the right and then left paddle rope and recording pull force at varying angles and force during the paddling cycle. Again comparing each measured rope force to that calculated rope force based on load cell readings, paddle position and bungie tension.

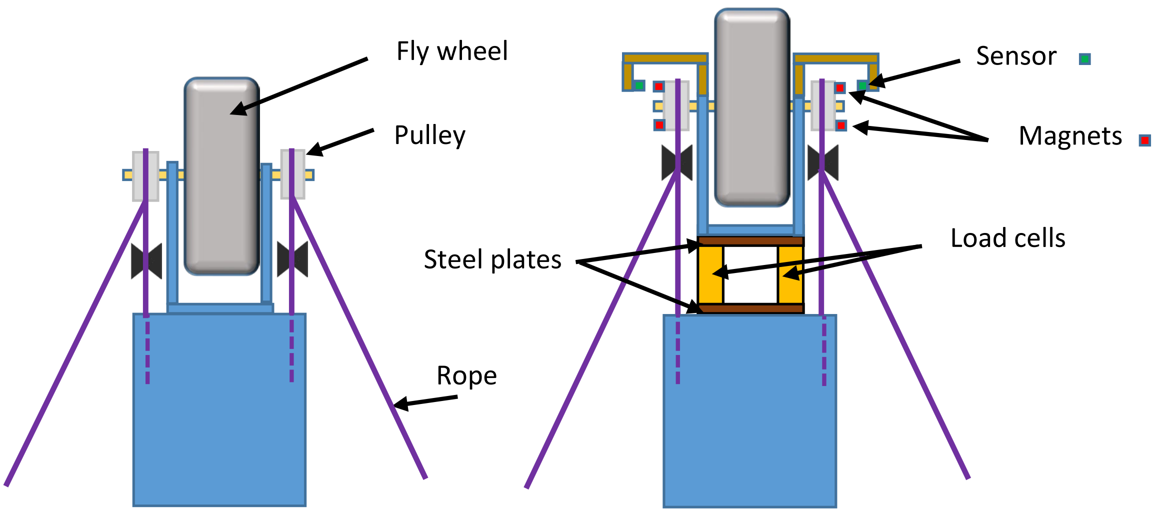

Figure 1. Kayak ergometer with load cells and wheel sensors

Right and left paddle position, beginning and end of stroke, as well as stroke velocity is obtained using two small magnets and a hall affect (magnetic) sensor on each of the right and left pulleys which the rope from each paddle passes around to drive the flywheel. A magnetic hall-effect sensor fixed to a wheel to give wheel speed is not new.

A second novel aspect of the design is combining the right and left load cell (force) data with the right and left position and velocity data obtained from the flywheel to give the direction of pull and right and left power as well as stroke-by-stroke data.

A third novel aspect is measuring right and left rope tension and including this in the calculations of pull and recovery forces in the rope. The magnitude of the right and left rope tension can be changed by adjusting the bungee cords at the rear of the ergometer. A calibration procedure establishes the rope tension as a function of stroke length. As the pull stoke progresses the bungee attached to the rope stretches and the tension it provides increases. The bungee produces a small additional resistance to that of the flywheel, but is important in retracting or pulling the rope back into the ergometer during the recovery phase of the stroke cycle. By recording the load cell forces when the paddle is placed statically at the foot rest and then at the rear of the seat, a near and far tension in the ropes can be calculated. When determining pull force and recovery tension in the rope this calibration data and paddle position is used to provide the resistance produced by the bungee on the right and left sides.

An additional benefit of the design is that static tension in the ropes can be measured and balanced between right and left sides of the ergometer prior to kayaking. It also allows individual preferences to rope tension to be measured and repeated on different days.

Right and left stroke position and velocity is obtained independently from the encoders on the respective flywheels. The direction of travel of the right and left sides of the paddle is determined from the right and left force data. The flywheel data (position and velocity) and load cell data (forces) are combined to give right and left power and to derive stroke-by-stoke means and peaks of kinematic and kinetic data.

Implementation was through National Instrument LabView and a NI6009 USB 8 channel A/D device sampling at 1000Hz. A custom LabView application (VI) was written to collect the 4 analogue channels; two channels of force data and two channels from the Hall Effect sensors. The software allowed calibration of bungee tension to paddle position, and during rowing the calculation of right and left stoke position and velocity, right and left pull force, and calculation of right and left stroke power.

Traditional approach

The traditional approach to measuring pull force is to place a small light weight force transducers or load cell in-line with the rope near to the attachment with the paddle. This has several known disadvantages:

1) A mass at the end of the right and left ends of the paddle. Interference with stroke kinematics that increases with increasing stroke rate
2) It is loose and flaps around producing inaccuracies and noise if force recordings. Increases with increasing stoke rate.
3) Cabling is needed to power the transducer and return the output signal. Additional interference with stroke kinematics.

Position and velocity data may be recorded to two ways

1) Similar to the present using either a magnet or light encoder attached to the flywheel.

2) Using a video based system, either 2D or 3D, that tracks the end points of the right and left sides of the paddle. Position and velocity is reconstructed for each stroke. It is not intrusive on the athlete but can be expensive depending on camera system used and requires additional space to position the cameras on either side of kayak ergometer. There is also a need to integrate the outputs from the video system with the force measurements. This takes time and so precludes real-time data display and feedback, unless you using an expensive 3D system that can capture and analyse video and analogue data real time, such as Vicon or Motion Analysis.

Prepared by Dr. Allan Carman