USING A BOAT INSTRUMENTATION SYSTEM TO MEASURE AND IMPROVE ELITE ON-WATER SCULLING PERFORMANCE

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A thesis submitted to Auckland University of Technology

in fulfilment of the requirements for the degree of Doctor of Philosophy

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TABLE OF CONTENTS

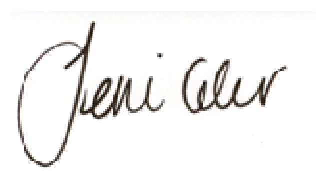
LIST OF FIGURES

LIST OF TABLES

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 has been submitted for the award of any other degree or diploma of a university or other institution of higher learning.

My contribution and the contributions by the various co-authors to each of these papers are outlined in the candidate contribution to co-authored papers table. All co-authors have approved the inclusion of the joint work in this doctoral thesis.



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CANDIDATE CONTRIBUTIONS TO CO-AUTHORED PAPERS

Chapter publication reference	Author %
CHAPTER 2: Coker, J., Hume, P. A., & Nolte, V. (2008). *Evaluating rowing force profiles: Implications from literature.* (Technical Report for Rowing New Zealand). (pp. 1-19). Auckland: Institute of Sport and Recreation Research New Zealand, Auckland University of Technology.	JC = 90% PH = 5% VN = 5%
CHAPTER 3: Coker, J., Hume, P. A., & Nolte, V. (2010). *Quantifying catch technique in elite scullers: A review of literature* (Technical report for Rowing New Zealand). (pp. 1-16). Auckland: Institute of Sport and Recreation Research New Zealand, Auckland University of Technology.	JC = 90% PH = 5% VN = 5%
CHAPTER 4: Coker, J., Hume, P. A., & Nolte, V. (2009, 17-21 August). *Validity of the PowerLine™ Boat Instrumentation System.* Paper presented at the 27th International Conference of Biomechanics in Sports, Limerick, Ireland (pp. 65 – 68).	JC = 92.5% PH = 5% VN = 2.5%
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CHAPTER 6: Coker, J., Nolte, V., & Hume, P. A. (2009). *PowerLine™ biomechanical variables as predictors of sculling performance* (Technical report for Rowing New Zealand). (pp. 1-25). Auckland: Institute of Sport and Recreation Research New Zealand, Auckland University of Technology.	JC = 90% VN = 7.5% PH = 2.5%

CHAPTER 7: Coker, J., Hume, P. A., & Nolte, V. (2010). *Quantifying catch technique in elite scullers: An experimental evaluation of different methodologies* (Technical report for Rowing New Zealand). (pp. 1-18). Auckland: Institute of Sport and Recreation Research New Zealand, Auckland University of Technology.	JC = 90% PH = 5% VN = 5%
CHAPTER 8: Coker, J., Hume, P. A., & Nolte, V. (2010). *The effect of boat class on biomechanical stroke variables in elite scullers* (Technical report for Rowing New Zealand). (pp. 1 - 26). Auckland: Institute of Sport and Recreation Research New Zealand, Auckland University of Technology.	JC = 92.5% PH = 5% VN = 2.5%
CHAPTER 9: Coker, J., Hume, P. A., & Nolte, V. (2010). *The effect of seating order and force synchronisation on performance in elite double sculls* (Technical report for Rowing New Zealand). (pp. 1-12). Auckland: Institute of Sport and Recreation Research New Zealand, Auckland University of Technology.	JC = 92.5 % PH 5% VN 2.5%
APPENDIX 2: Coker, J., Hume, P. A., & Nolte, V. (2008, 13-15 November). *Evaluating rowing force profiles: Implications from literature.* Paper presented at the New Zealand Sports Medicine and Science Conference, Dunedin.	JC = 92.5% PH = 5% VN = 2.5%
APPENDIX 3: Coker, J., Hume, P. A. & Nolte, V., (2010). *Limitations of the uni-directional force measure provided by PowerLine™* (Technical report for Rowing New Zealand). (pp. 1-7). Auckland: Institute of Sport and Recreation Research New Zealand, Auckland University of Technology.	JC = 90% PH = 5% VN = 5%

ACKNOWLEDGEMENTS

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INTELLECTUAL PROPERTY RIGHTS

ETHICS

Ethics for chapters 4 to 9 were approved by the Auckland University of Technology Ethics Committee (AUTEC). The ethics application "08/10 The combined reliability of the PowerLine™ boat instrumentation system and elite rowers and scullers" and the amendment covered the studies on the combined reliability of the PowerLine™ boat instrumentation system and elite scullers (Chapter 5), PowerLine™ biomechanical variables as predictors of sculling performance (Chaper 6), and quantifying catch technique using an experimental evaluation of different methodologies (Chapter 7). The approval letter and the subject information sheet and consent form are included in Appendix 4. The ethics application "08/209 Summary of PowerLine data from 2007/2008 Rowing New Zealand squad members" covered the studies on the effect of sculling boat class on biomechanical stroke variables in elite scullers (Chapter 8) and the effect of seating order and force synchronisation on performance in elite double sculls (Chapter 9). The approval letter and the subject information sheet and consent form are included in Appendix 5.

CONFIDENTIAL MATERIAL

The entirety of this thesis is embargoed by Rowing New Zealand until the embargo agreement is reassessed at the end of 2012. Therefore the thesis must be treated as **confidential**. Research involving national sport organizations if often embargoed to protect the competitive advantage of the teams. These embargoes generally last for one Olympic cycle (four years), while some data are embargoed indefinitely for commercial sensitivity. Publication of papers and conference abstracts resulting from chapters are possible with the written agreement between AUT University and Rowing New Zealand, as has been the case for Chapters 2 and 4. The confidentiality agreement between AUT University and Rowing New Zealand states that the PhD student Jennifer Coker, the project members (supervisors), advisory group members and examiners for the thesis agree that the aims, methods, results, and any details of the project will not be disclosed to any person outside of the project members and advisory group members. This serves to protect the confidentiality of the data, while allowing the PhD student Jennifer Coker to have a small support group for collaborative and advisory purposes for the PhD study. Lisa Holton (lisa@rowingnz.com) from Rowing New Zealand holds the confidentiality agreements signed by Jennifer Coker, her supervisors and several AUT academics and rowing coaches.

ABSTRACT

Sculling performance is largely determined by the magnitude and timing of blade force application, i.e. the size and shape of the sculler's force profile. Discovering specific force profile characteristics that relate strongly with boat velocity in elite scullers, and determining how best to measure them, would allow recommendations for improved performances. The objective of this thesis was to expand knowledge regarding biomechanical measurement of sculling force profiles and to understand how the PowerLine™ boat instrumentation system could be used effectively to measure and improve elite on-water sculling performance.

A literature review showed that effective rowing force profiles are large, smooth, rectangular, and have a peak force in front of the perpendicular oar position. Laboratory validity testing showed that PowerLine™ was valid for use with elite scullers, displaying a standard error of the estimate of less than 0.90 kgF for force and less than 0.5° for angle measures. On-water reliability testing established smallest worthwhile effect sizes for PowerLine™ variables for elite scullers completing 500-m trials, including 0.44% for *stroke power* and 0.5° for angular variables. Scullers in double sculls were more variable than single scullers so consistency in *stroke power* was recommended as a focus for crew scullers. Sculler analyses using PowerLine™ was better when using the average of five strokes rather than single strokes. Step wise linear regression analyses presented models for two elite scullers explaining 84% and 85% of their variation in *boat velocity*. However, the relationships between sculling performance and biomechanical stroke variables, including different measures of catch technique, were not consistent between elite scullers and cannot be generalised.

Analyses of changes in means for four elite scullers showed that biomechanical stroke variables did differ significantly between single, double and quad sculls and therefore training and selection should be boat class specific. In elite double sculls, correlations between change in performance and change in bow versus stroke peak force synchronization indicated that it is likely to be beneficial to performance if the stroke peaks with their force earlier and with the handles further to the stern than the bow

seat. Switching the seating order in these double sculls resulted in mean *boat velocity* changing by up to 5.8% of world record time signifying the importance of seat-specific trialling.

Extensive differences between elite scullers in the strength and direction of relationships between performance and PowerLine™ variables showed that full analyses of all variables must be conducted individually for each sculler. The importance of seating order in double sculls, and the benefits of the stroke seat peaking before the bow, have implications for crew selection, seat allocation, and technical recommendations. Seat trials for crew sculling boats must be seat-specific and include racing in all seating orders. Further research is necessary to verify and explain the synchronisation requirements of crew sculling boats before more scientific seat allocation can be achieved in these boats.

Sculling force profiles from PowerLine™ can be used effectively to measure and improve elite on-water sculling performance.

RESEARCH OUTPUTS RESULTING FROM THIS DOCTORAL THESIS

Conference presentations

Coker, J. (2008, 10-11 October). *The application of biomechanics in rowing.* Paper presented at the AON Rowing New Zealand Coaches Conference, Wellington.

Coker, J., Hume, P. A., & Nolte, V. (2008, 13-15 November). *Evaluating rowing force profiles: Implications from literature.* Paper presented at the New Zealand Sports Medicine and Science Conference, Dunedin.

Coker, J., Hume, P. A., & Nolte, V. (2009, 17-21 August). *Validity of the PowerLine Boat Instrumentation System.* Paper presented at the 27th International Conference of Biomechanics in Sports, Limerick, Ireland.

Technical reports

Coker, J., Hume, P. A., & Nolte, V. (2008). *Evaluating rowing force profiles: Implications from literature.* (Technical Report for Rowing New Zealand). (pp. 1-19). Auckland: Institute of Sport and Recreation Research New Zealand, Auckland University of Technology.

Coker, J., Hume, P. A., & Nolte, V. (2008). *Combined reliability of the PowerLine™ Boat Instrumentation System and elite scullers* (Technical report for Rowing New Zealand). (pp. 1-18). Auckland: Institute of Sport and Recreation Research New Zealand, Auckland University of Technology.

Coker, J., & Maher, W. (2008). *Force and angle data from New Zealand elite and U23 squads: 2007/2008 season* (Technical Report for Rowing New Zealand). (pp. 1-19). Auckland: Institute of Sport and Recreation Research New Zealand, Auckland University of Technology.

Coker, J., Nolte, V., & Hume, P. A. (2009). *PowerLine™ biomechanical variables as predictors of sculling performance* (Technical report for Rowing New Zealand). (pp. 1-25). Auckland: Institute of Sport and Recreation Research New Zealand, Auckland University of Technology.

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ROWING TERMINOLOGY

Blade	The curved spoon end of the oar
Bow (seat)	The sculler or rower seated closest to the bow
Catch position	The furthest reach point of the oar handle towards the stern of the boat
Double scull	A boat designed for two scullers each using two oars
Drive phase	The propulsive phase of the stroke where the blades are moving from the catch position to the finish position and are in the water
Entry	The period of time where then blade moves vertically from being out of the water to being fully covered
Ergometer	A land based rowing machine– with a single central handle that does not differentiate between stroke and bow sides
Feathering	The blades are turned from a position perpendicular to the surface of the water to a position parallel to the water to reduce drag on the oar during the recovery phase
Finish position	The furthest reach point of the oar handle towards the bow of the boat
Foot-stretcher	An angled plate in the boat that the rowing shoes are attached to
Gate	See “oarlock”
Longitudinal axis	The line along the middle of the boat from the bow to the stern

Oar	Entirety of the oar shaft and blade, positioned through the oarlock and used by the rower to propel the boat
Oar excursion	Displacement of the oar (°) during the drive phase of the stroke cycle – also termed *total angle*
Oar shaft	Sometimes termed "loom", the rod-shaped part of the oar that the blade attaches to
Oarlock	Sometimes termed "gate", this is the point of attachment of the oar(s) to the boat
Pair	Two-oared sweep boat with two rowers
Pin	Sometimes termed "swivel", the oarlock(s) rotate around the pin fixed in the rigger(s)
Quad scull	A boat designed for four scullers each using two oars
Recovery phase	The non-propulsive phase of the stroke where the blades are moving from the finish position to the catch position and are not in the water
Release	The period of time where then blade moves vertically from being fully covered to being out of the water
Rigger	Metal attachment to the boat of the boat onto which the oars are attached via the oarlock
Sculling	A class of rowing where a rower holds an oar in each hand
Single scull	A boat designed for one sculler using two oars
Slip	Either at the catch or finish, "slip" refers to oar excursion angles

	that do not contribute to propulsion whilst the blades are moving from the catch position to the finish position
Square off	Position where the oar is perpendicular the longitudinal axis of the boat and the oar angle is zero
Stern	The front of the boat when moving in its intended direction of travel
Stroke (seat)	The rower or sculler seated closest to the stern
Sweep rowing	A class of rowing where each rower holds one oar

ABBREVIATIONS USED THROUGHOUT THIS DOCTORAL THESIS

Abbreviation	Definition
CI	Confidence interval
ES	Effect size
FISA	The International Rowing Federation
kgF	Kilograms of force
ICC	Intra-class correlation coefficient
SD	Standard deviation
spm	Strokes per minute
SPSS	Statistical Package for the Social Sciences
SEE	Standard error of the estimate
TE	Typical error
WRT	World record time

CHAPTER 1 - INTRODUCTION AND RATIONALISATION (PREFACE)

The ultimate metric of sculling performance is the time to complete a set distance, typically 2000 m. This time is dependent solely upon the average boat velocity, determined entirely by the resultant of the drag and propulsive forces acting about the boat (Smith and Loschner, 2002). The size of these forces can be manipulated by aspects of a sculler's technique, principally, the magnitude and timing of blade force application, i.e. the shape and size of their force profile. At the elite level, athletes strive to cut fractions of a second from their performance times, and insight into specific biomechanical characteristics of technique known to relate strongly to performance would therefore be invaluable.

Although athlete testing in a laboratory setting will provide a controlled environment, comparative studies between on-water and ergometer force profiles have highlighted that on-water analysis is the only option for data that truly signifies the sculling competition situation (Dawson, Lockwook, Wilson, & Freeman, 1998; Elliott, Lyttle, & Birkett, 2002; Kleshnev, 2008b; Lamb, 1989; Li, Ho, & Lin, 2007). It is therefore necessary to identify unobtrusive biomechanics instrumentation capable of measuring on-water sculler forces with which to examine predictors of sculling performance that can be presented to coaches and athletes and used in technical interventions.

The central theme of this thesis was to expand knowledge regarding biomechanical measurement of sculling force profiles and to understand how the PowerLine™[1] boat instrumentation system could be used effectively to measure and improve elite on-water sculling performance. This thesis encompasses four overlapping objectives: 1) To review literature concerning sculling force profiles and relationships between characteristics of these profiles and sculling performance; 2) To assess the appropriateness of the PowerLine™ Boat Instrumentation System for use with elite

[1] Peach Innovations Ltd, 27 Grantchester Road, Cambridge CB3 9ED, U.K.

scullers in regard to the validity and reliability of its measures; 3) To investigate the extent to which sculling performance can be quantified using a simplified model of sculling technique based upon one or more of the variables available from PowerLine™ and; 4) To enhance approaches to coaching and crew selection through interventions aimed at improving understanding of sculler force profiles. These objectives were realised through the series of studies that comprise Chapters 2 to 9 of this thesis, and culminate in an overall discussion in Chapter 10, as outlined in Figure 1.

Theme 1: Measuring biomechanical characteristics of rowing - reviews of literature

Two reviews were conducted in this thematic section to gain an understanding of the characteristics of force profiles in rowing and their relationships with boat velocity. Chapter 2 summarises known features of effective force profiles and highlights clear gaps in the literature. This chapter formed the basis of an oral presentation given at the *AON Rowing New Zealand Coaches Conference* (Coker, 2008) and was also presented as a poster at the *New Zealand Sports Medicine and Science Conference* (Coker, Hume, & Nolte, 2008b). These presentations are included in the thesis as Appendices 1 and 2 respectively. A second literature review was developed from discussions with coaches as a result of the presentations from Chapter 2. A resounding need for an unambiguous method for quantifying a sculler's catch technique was identified. Proficiency of technique at the catch was known to be crucial for performance (Richardson, 2005) but there was no universal method agreed for objectively measuring a sculler's effectiveness during this phase. Chapter 3 therefore reviews methods used to analyse catch technique for scullers and investigates whether any previously unpublished methods were appropriate in future experimental studies.

Theme 2: Reliability and validity of sculling biomechanics instrumentation

The high consistency level of elite scullers and the exceptionally small time differences separating finalists at international regattas meant that an extremely high degree of accuracy and reliability was required from any instrumentation used to supply performance measures to these athletes (Baudouin & Hawkins, 2004). Recognising the importance of sculling force profiles, Rowing New Zealand purchased the PowerLine™

Boat Instrumentation System due to the ease of its set-up and calibration, and the ability to synchronise its pin force and oar angle measures with video. However, before this system could be used for regular athlete feedback, the validity and reliability of its measures had to be quantified to ensure that it was appropriate for use with elite scullers. Chapter 4 reports the findings of a laboratory based validation study comparing the force and angle data from PowerLine™ with data from a load cell and inclinometer respectively. This chapter was presented at the *27th International Conference on Biomechanics in Sport* (Coker, Hume, & Nolte, 2009b), where I was fortunate enough to engage in discussions with other rowing biomechanists. These discussions led to questions about the limitations of the unidirectional pin force measured by PowerLine™, specifically whether any non-propulsive force acting parallel to the oar shaft was measured by the system. Appendix 3 reports on a second laboratory based study comparing load cell readings with PowerLine™ measures of a force applied in the direction parallel to the oar shaft. This study also investigated an example of the range of arm relative to oar shaft angles that can be seen in a quad scull and the extent to which PowerLine™ may therefore misrepresent useful force production in scullers.

After substantiating that the PowerLine™ system had a sufficient level of accuracy, it was necessary to determine smallest worthwhile effect sizes for its variables when used with elite scullers. Chapter 5 presents the combined reliability of the PowerLine™ system and six elite scullers. Smallest worthwhile effect sizes were determined allowing the effects for future interventions on performance in elite scullers to be quantified and their relevance to be identified.

Theme 3: Quantifying sculling technique using biomechanics instrumentation

Extraneous variables hinder the reliance on boat velocity as a reliable performance indicator (Nolte, 1991). It was therefore necessary to know with certainty of other variables that could be used to measure performance. Discrepancies existed as to the strength of the relationships between *boat velocity* and some key biomechanical variables, particularly *stroke power* (Baudouin & Hawkins, 2004; Kleshnev, 1999; Smith, Galloway, Patton, & Spinks, 1994). Chapter 6 outlines whether PowerLine™ *stroke* *power*, in association with the other variables that the system could produce, predicted *boat velocity* and whether it could therefore be used as a tool for technique analysis and improvement in two Olympic level single scullers. The study comprising Chapter 7, evolved from the methods of Chapter 6, and the literature reviewed in Chapter 3. This chapter attempted to improve catch technique analysis by determining which method of quantifying catch slip was the best performance predictor for two elite scullers. It also established the strength of any relationships between the different catch slip values in order to allow more comprehensive comparisons between athlete feedback data and previously presented "norms".

Theme 4: Biomechanical interventions to improve approaches to sculling crew selection and coaching

The greater understanding of the PowerLine™ biomechanical stroke variables gleaned from Chapters 4 to 7 led to two final intervention studies. Chapter 8 evolved from questions from the Rowing New Zealand coaches and management who wished to better compare scullers across different boats and to know whether scullers could be better placed into particular crews based on their force profiles. This chapter outlines how the biomechanical stroke variables of four elite scullers, measured by PowerLine™, changed when moving between single, double and quad sculls. This study revealed unexpected patterns in the relative timing of the bow and stroke seat scullers' peak forces in the successful elite double sculls tested. This, together with the gap in the literature identified in Chapter 2 concerning synchronisation of force profiles in symmetrically-rigged crew sculling boats, initiated the final study described in Chapter 9. Four elite scullers completed trials in different seating orders to investigate the effect of synchronisation on performance in elite double sculls in an attempt to enhance seating order selection and understanding of the technique and/or boat set-up required for maximal performance in double sculls.

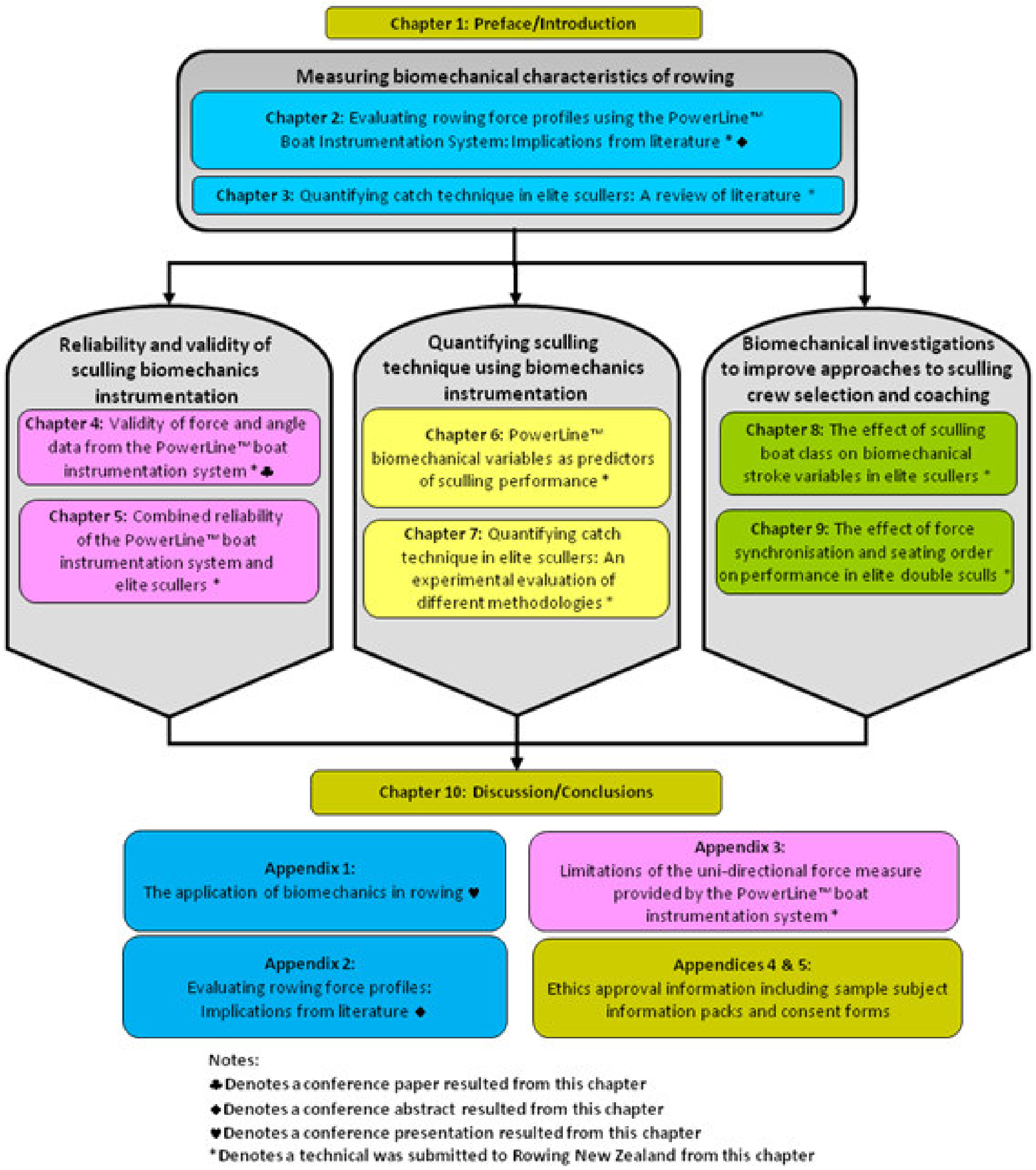


Figure 1: Overview of the thematic sections of the doctoral thesis. The chapters are coloured coded to indicate each theme.

The findings of all studies are integrated and summarised in Chapter 10. Along with the presentations resulting from Chapters 2 and 4 (Appendices 1 and 2) and the investigation into the limitations of the PowerLine™ system (Appendix 3), the appendices also contain information regarding Auckland University of Technology

Ethics Committee (AUTEC) ethical approval (Appendices 4 and 5). This includes sample subject information packs, consent forms and notifications from AUTEC.

All chapters were submitted to Rowing New Zealand as technical reports, allowing the findings to be applied to the scullers currently competing internationally. A summary of applied work carried out using the PowerLine™ system with New Zealand rowers was also submitted as a technical report and is included in the list of publications resulting from this thesis (Coker & Maher, 2008), but the highly confidential nature of this data prevented this report from being included as an appendix. Where appropriate, findings were also presented at conferences but the majority of this thesis will not be publically available until after the next Olympic Games in 2012 in order to maintain any competitive advantage the findings may give to New Zealand scullers. Although more extensive publication would have been desirable in order to gain constructive feedback on my work from academics, as was so beneficial when I attended the *International Conference on Biomechanics in Sport*, my immersion in the Rowing New Zealand programme enabled me to approach highly relevant and current issues and to gain feedback from elite coaches.

Limitations/delimitations

The obvious limitation faced throughout this thesis is the small number of elite level scullers available in New Zealand. Other international elite scullers could not be involved in the studies due to the conflict of interest between competing nations. A possible solution was to also invite sub-elite scullers to participate in the studies. Two such scullers training with the elite group requested to be involved in the reliability testing for training purposes. Notably lower within and between trial consistencies in these scullers stressed the distinct nature of elites and, substantiated by similar findings from applied testing of a number of additional sub-elite scullers, it was decided that all subjects throughout the thesis must be of an elite level (i.e. winning medals at senior-level, or gold medals at U23-level international regattas). The issue of small subject numbers was overcome as much as possible by increasing the number of strokes recorded and taking a case study approach where appropriate.

CHAPTER 2 – EVALUATING ROWING FORCE PROFILES USING THE POWERLINE™ BOAT INSTRUMENTATION SYSTEM: IMPLICATIONS FROM LITERATURE

This chapter comprises the following technical report submitted to Rowing New Zealand and presented as a poster at the New Zealand Sports Medicine and Science Conference. This chapter also formed the basis of an oral presentation given at the AON Rowing New Zealand Coaches Conference.

Coker, J., Hume, P. A., & Nolte, V. (2008). *Evaluating rowing force profiles: Implications from literature*. (Technical Report for Rowing New Zealand). (pp. 1-19). Auckland: Institute of Sport and Recreation Research New Zealand, Auckland University of Technology.

Coker, J. (2008, 10-11 October 2008). *The application of biomechanics in rowing.* Paper presented at the AON Rowing New Zealand Coaches Conference, Wellington.

Coker, J., Hume, P. A., & Nolte, V. (2008, 13-15 November). *Evaluating rowing force profiles: Implications from literature.* Paper presented at the New Zealand Sports Medicine and Science Conference, Dunedin.

Overview

The aim of this review was to outline current knowledge on rowing force profiles from information in the published literature. Effective force-time and force-angle profiles have a large area under the curve which maximises impulse and work respectively during the drive phase. A more rectangular than triangular shaped curve, comprising a high rate of force development, increases efficiency and drive impulse for the same maximal force output (or maximal force producing capacity of the athlete). Smoother force curves are more effective, potentially due to reduced boat velocity fluctuations and an increased area under the curve. The need for crew coordination is evident but the exact pattern of this synchronisation is not known for different boat types. Disparity exists as to where the peak force should be positioned, but literature incorporating more detailed fluid dynamics recommends that it should occur before the oar is perpendicular to the longitudinal axis of the shell (in front of the "square off") in order to maximise the use of lift forces acting at the blade. Earlier peak positioning will also better utilise the recoil of elastic energy stored in the bend of the oar shaft. More information is required to better match characteristics to specific boat types for effective performance and to understand how precise alterations to technique and set-up can alter rowing force profiles. Limitations of the PowerLine system include the location of the force being measured, and a lack of conclusive evidence that its' automatic variables relate to boat velocity. Ideally blade force rather than pin force would be collected because this is the origin of propulsion and therefore performance, but this is currently not an accessible and realistic variable for regular biomechanical assessment in an elite programme.

Introduction

The cyclic nature of the rowing stroke, comprising the drive (propulsive) and recovery (non-propulsive) phases, results in unavoidable fluctuations in boat velocity occurring within every stroke. During the drive phase, boat velocity will be influenced by the rower(s) coordinating handle and foot-stretcher forces in order to produce blade movement and force that will propel the boat through the water. Boat velocity is also influenced throughout the entire stroke by the transfer of momentum between the boat and the rower(s), who move freely on a sliding seat. Due to these factors, maximal within-stroke boat velocity is known to occur early in the recovery phase, whilst minimum boat velocity occurs at the catch (the blade's entry into the water at the start of the drive phase) (Kleshnev, 2010). Essentially, average boat velocity is determined by the amount of propulsive and drag forces acting about the rowing system (rower(s), shell and blades) (Smith & Loschner, 2002). Blade force is the only source of propulsion, and as such is the key factor that will determine performance

(Baudouin & Hawkins, 2002; Sanderson & Martindale, 1986). A rower's capacity to produce large forces at the handle to be transferred to the blade via the pin, will in part depend upon their physical capacity and the largest, strongest individuals are seen to produce higher boat velocities (Barrett & Manning, 2004). However, it is not always possible to increase physical capacity sufficiently and gains must then be made through the coordination of this force production (i.e., the shape of the force profile), a challenging performance factor to achieve (Anderson, Harrison, & Lyons, 2005; Rekers, 1999).

On-water force profiles are known to differ from those seen on the ergometer and it is therefore vital that force data can be collected on-water (Li et al., 2007). Modern boat instrumentation systems (e.g., PowerLine™), in synchronisation with video data, allow analysis of on-water force profiles. This report will discuss the key characterististics of effective force profiles, as outlined by past rowing literature found by searching the SportDiscus data base of journals using the key words rowing and force.

Force profile characteristics for performance

Throughout this report, two distinct forms of force traces will be referred to; force-time and force-angle profiles. Although they are related and often used interchangeably, when performing further calculations or making comparisons between two or more curves, the correct form should be used. Figure 2 shows the force-angle and force-time profiles for the same stroke.

Area

The area underneath the force-angle curve relates to the amount of work done per stroke whilst the area underneath the force-time curve equates to the impulse added during the drive. Any increase in momentum (and therefore increase in boat velocity, including the reversal of the unavoidable deceleration occuring each stroke) will be determined by the size of this impulse. The area under either curve should therefore be as large as possible. From a coaching perspective, visual comparison can be sufficient to see large differences between the areas of two profiles. However, if quantitative values are required, the force-time curve must be integrated through the drive phase to obtain an impulse value. Hill and Fahrig (2008) proposed a method whereby tangents are drawn from the steepest points of the curve at the catch and finish to the baseline and the area calculated from this modified curve. This method manages the negative areas under the 0 kgF line and also attempts to minimise the addition of inertial forces in these areas of the drive. This would result in more meaningful calculations of rower impulse without the inclusion of these additional unavoidable forces.

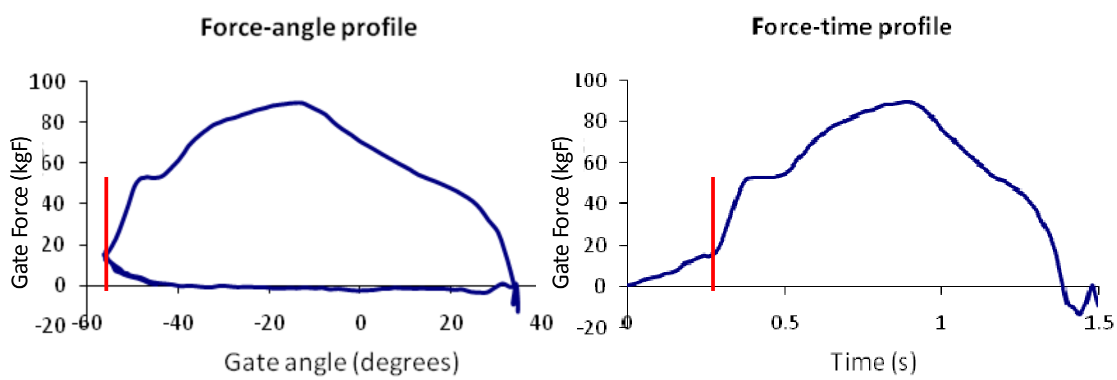


Figure 2: Force-angle profile showing the full stroke, and force-time profile of the same stroke showing time period from minimum to maximum angle. The red line indicates the point where the blade changes direction.

Shape

The area underneath the curve will largely be affected by its shape. Increasing the average force relative to maximal force and achieving a high rate of force development at the beginning of the drive will result in a larger area for the same, or even lower, peak force (Kleshnev, 1999; Kleshnev & Kleshnev, 1998; Millward, 1987). This ratio has been found to be significantly higher in elite than sub-elite rowers (Smith & Draper, 2006). Visually, this will create a more rectangular, rather than triangular shape. Figure 3 presents this idea theoretically, in simplified form. With the same peak force, but increased rate of force development and time at peak, a 50% increase in impulse is seen (B vs. A). Even with a 250 N decrease in peak force, the more rectangular shape of

C in comparison to A results in a 12.5% increase in impulse for C compared to A. This has large potential in enhancing performance without increasing the rower's maximal force-producing capacity.

Smoothness

The smoothness of the force profile has been found to be correlated with rowing level (Rekers, 1999; Smith & Spinks, 1998). This may be due to reduced velocity fluctuations which will increase efficiency (Anderson, Harrison, & Lyons, 2002; Baudouin & Hawkins, 2002, 2004; Smith & Loschner, 2002). Eliminating "dips" will also increase the area under the curve and increase performance accordingly. Although small, the differences in the shape and smoothness of the force profile between experienced rowers are real (Wing & Woodburn, 1995). Individuals will develop a highly repeatable, "signature" force profile through training, allowing rowers to be identified by subtle characteristics in their force profile during the drive phase (Baudouin & Hawkins, 2004; Hill, 2002; Wing & Woodburn, 1995). These characteristics do not appear to change without specialized training so, if alterations are needed, it is necessary to investigate what exactly is causing the undesirable feature and make specific changes accordingly (Hill, 2002).

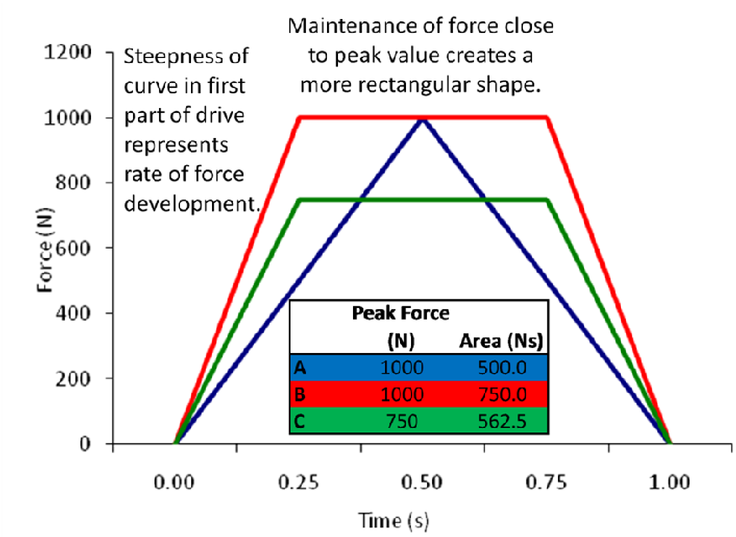


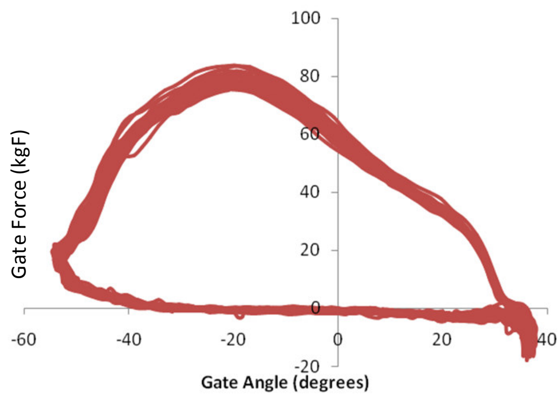
Figure 3: Theoretical illustration of the effect of force-time profile shape on the impulse (area under curve).

Position of peak force

The oar angle at which peak force should occur is a well disputed issue with considerations from mechanics, biomechanics and physiology. Mechanically, it was traditionally thought that the peak force should be applied when the blade is perpendicular to the long axis of the boat. Here the transverse component of the rower's force would be minimal and force would be maximal in the propulsive direction (Celentano, Cortili, di-Prampero, & Cerretelli, 1974; Körner, 1979; Martin & Bernfield, 1980; Smith & Loschner, 2002; Spinks, 1996). Physiologically it was also reported that a rower's metabolism operates at a higher efficiency if they row "middle pressure" strokes as opposed to "hard catch" and "strong finish" strokes (Roth, Schwanitz, Pas, & Bauer, 1993).

Conversely, front-loaded force profiles are thought to be preferable because the resulting power curve is more evenly distributed and will allow for reduced velocity fluctuations and increased mechanical efficiency (Kleshnev, 2006b; Nolte & Morrow, 2002). It is also known that the elastic energy stored in the bend of the oar shaft and later recoiled, is used more effectively if an early peak force is applied (Kleshnev, 2007c). Additionally, rowing literature considering hydrodynamic efficiency and lift forces at the blades argues that a *theoretical* optimal efficiency exists with maximal values at the catch and finish of the stroke (Affeld & Schichl, 1985; Nolte, 1984). This can be explained in the following way; for the same propulsion, the same amount of impulse must be given to the water. This can either be achieved with a small mass and high velocity of the water (blade stalled in the water and boat levered past – as is seen through the mid-drive) or large mass and lower velocity of the water (blade moves through water creating propulsion through lift – as occurs towards the catch and finish) (Young, 1997). Because of the nature of the relationship between kinetic energy and velocity, the stalled blade situation results in more energy lost to the water for the same propulsion. Using lift is therefore more efficient, and if maximal power could be produced by the rower towards the catch and finish, then maximal propulsive forces would be achieved because less rower energy would be lost to the water (Young, 1997).

Although it is not biomechanically possible to create a completely rectangular force profile and instantaneously reach peak force at the catch, by emphasising the start of the drive, not only will lift forces be used more effectively, high local loads on the arms will be avoided, and the body will be positioned to more effectively develop force proportional to strength of the body segments (Schwanitz, 1991). Although arguments for both middle and front loaded force-angle profiles exist most recent literature now confirms that a peak force in front of the perpendicular point is preferable and the reasons for this are presented in Figure 4.



- more evenly distributed power curve reducing boat velocity fluctuations and increasing efficiency
- increased use of lift for propulsion (a more efficient means of propelling the boat)
- enhanced use of the recoil of elastic energy stored with the bend of the oar shaft
- reduced overload on arms
- body better positioned to allow force production proportional to body segment strength

Figure 4: An example of a front-loaded sweep rowing force-angle profile and its advantages based on past literature (Affeld & Schichl, 1985; Kleshnev, 2006b, 2007c; Nolte & Morrow, 2002; Schwanitz, 1991).

Crew synchronisation

Coordination of crew members is generally thought to enhance efficiency because poor synchronisation will create torque about the boat and increase drag (Baudouin & Hawkins, 2002). The most synchronised of crews from the elite German squad was unbeaten in a series of within-squad trials and differences between crew members in the shape of their force profiles were more detrimental to performance than differences in the area (Hill, 2002; Wing & Woodburn, 1995). However, in asymmetrically rigged boats, such as pairs, it is well documented that specific differences between the bow and stroke are vital – the stroke should peak earlier and higher than the bow seat rower (McBride, Sanderson, & Elliot, 2001; Schneider, Angst, & Brandt, 1978; Zatsiorsky & Yakunin, 1991). There is little information on the real drawbacks of having unmatched force patterns within other boat types (Hill, 2002). If sustained maximal force and a rectangular curve is desirable (Kleshnev, 2001b), then in symmetrically rigged boats, hypothetically, there may be potential for success from using force profiles that allow for the crew average force profile to be this shape via staggered individual peaking (see Figure 5). Differences in body size, physical abilities, power application and technique exist between rowers in any crew resulting in variations in blade movement patterns and therefore force profiles (Nolte, 2006). Whether the differences between crew members in oar excursion and force patterns can be reduced via boat set-up alterations, and whether this would be beneficial to boat velocity, is unknown. More detailed understanding of exactly how specific boats classes are propelled and combinations of effective force profiles is therefore necessary.

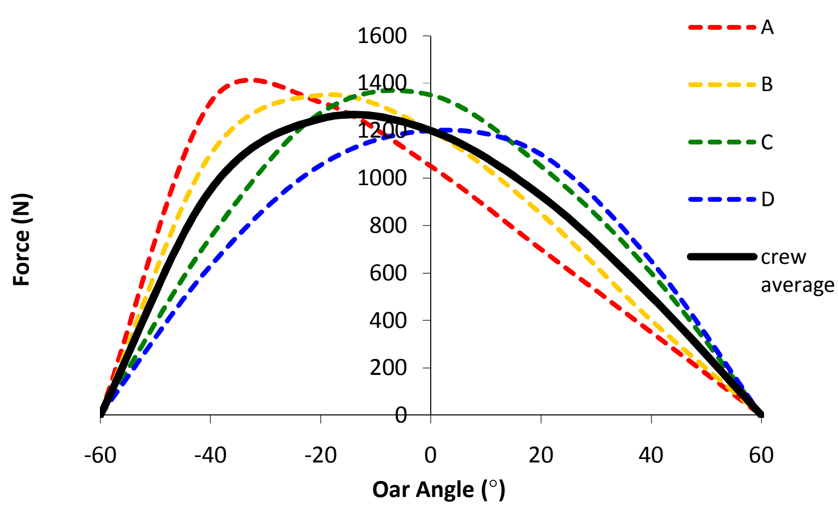


Figure 5: Theoretical graph to show different crew member (A, B, C, D) curve shapes and resultant crew average force during the drive phase.

Graph format

As previously mentioned, it is necessary to use the correct form of the force profile – relative to angle or time. Evaluation of force versus time is a simple method of analysis, useful in conjunction with synchronised video and for examining coordination of timing within a crew (Kleshnev, 2007a). Use of the force-angle curve however, is effective when comparing different stroke rates and is a visual representation of work done per stroke (Kleshnev, 2007a; Spinks, 1996). This form can also be useful when considering crew set-up as it is immediately clear whether a rower is too far forward or back in the boat. If a rower's foot stretcher is further to the bow than other crew members, this rower's force-angle curve will be shifted to the right in comparison to the others (when presented on the same axis and scale) and, if the foot-stretcher is further to the stern, the curve will be shifted to the left.

When making comparisons it is essential that the scale on which the graphs are presented is considered. Ideally they would both be the same but, when not possible, careful evaluation is necessary. Take Figure 6 for example. Which rower would you select? At first glance, "Rower B" appears to have a higher peak force and larger area under the curve whilst "Rower A" seems to work through a larger arch and have a more rectangular shape. In fact, this is exactly the same rower, and exactly the same strokes, merely presented on different scales.

The PowerLine™ Boat Instrumentation System

The PowerLine™ Boat Instrumentation System is comprised of instrumented oarlocks and boat motion sensors that measure pin forces in the direction of the longitudinal axis of the boat, gate angles, boat velocity and boat acceleration, all at 50 Hz. From this, six automatic variables are computed every stroke for each oarlock, along with stroke rate and boat velocity. Similar systems include BioRowTel™[2], which uses the bend in the oar shaft to measure rower force, and WEBA[3] which also uses an instrumented oarlock. The PowerLine™ system was selected by Rowing New Zealand

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[2] BioRow Ltd., www.biorow.com
[3] WEBA Sport und Medical Artikel, Vienna, Austria

due to the simplicity of its set-up and calibration, and its ability to automatically synchronise with video.

Location of force measurement

The main limitation of PowerLine™ is that forces at the pin are presented rather than at the blade. Large forces and angular velocities at the pin will indicate high rower powers despite no knowledge of whether this has been transferred as propulsive force at the blade. At the elite level, where blade work will be skilled, it can be assumed that the pin forces should reflect blade forces well, but force and power data should carefully be compared with boat velocity and video footage to ensure that pin forces and power increases do result in enhanced performance.

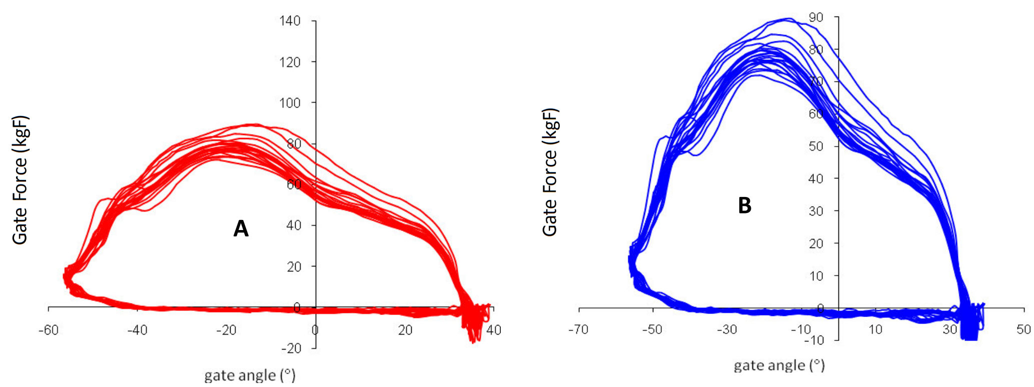


Figure 6: Identical force-angle data presented on two different scales.

Past studies have used forms of rower power as key variables for determining rowing performance (Baudouin & Hawkins, 2002, 2004; Caplan & Gardner, 2005; Kleshnev, 1999; Kleshnev & Kleshnev, 1998; Smith et al., 1994; Smith & Spinks, 1988, 1995) but as yet, it is not clear whether power calculated from pin force, as provided by PowerLine™, is an effective tool for on-water ranking of rowers within an elite group. Although blade force and power would be the ideal measures since the blade is the origin of propulsion, this is not at present, an accessible variable for regular biomechanical feedback in elites. The PowerLine™ system has been purchased by

Rowing New Zealand, is easily installed, and results in minimal or no alteration to the feel of the boat for the athlete. Thus, it would be beneficial if this form of power was directly related to boat velocity, but this requires testing. Impulse and work done, available from force-time and force-angle curve respectively, are possible alternative tools for this purpose.

Automatic values presented by PowerLine™

The PowerLine™ software automatically presents certain values which must be approached with a certain degree of scrutiny. PowerLine™ catch and finish "slips" represent the angles after the catch and before the finish through which the blade moves whilst less than a pre-determined threshold force value is being produced. Using this definition, reduced "slip" (often considered a favourable alteration because more stroke length is used for propulsion) will be seen if the blade is "rowed in" with force applied to the pin before the blade is in the water – not something to aspire to. Inertial blade forces, created as the blade changes direction at the catch will add to the gate force reading as well (Ishiko, 1971; Kleshnev, 2002b). These inertial forces are shown as all force to the left of the red line in the force-time profile in Figure 2. In a single scull they were found to represent almost 100% of the handle force at the catch and finish (between 70 and 80 N – approximately 7-8 kgF as presented by PowerLine™) (Kleshnev, 2002b). Forces from the blade being pressed against the gate by the rower as they approach the catch will also be included in the gate force reading.

Kleshnev and Baker defined "slip" as the angle through which the blade moves between its change in direction (at the catch or finish) and the point where the blade is fully covered – available from synchronised video and angle data (Kleshnev & Baker, 2007a). With this definition, forces on the pin whilst the blade is out of the water, are not considered. Zero "slip" of this meaning can only really be achieved with a stationary boat and would create large braking forces if attempted during rowing. This is because the blade would have to be placed and removed when it was moving slower than the water relative to the boat. Looking at Figure 7, you can see that the "slip" as defined by Kleshnev and Baker (2007), is in fact the angles that the blade moves through during the entry and the release. It may then, be better to rename "catch slip”, “entry degrees” and replace the term “finish slip” with “release degrees” (Kleshnev & Baker, 2007a). The degree to which the PowerLine™ values represent Kleshnev’s values from video analysis is a key area for future investigation.

Regardless of definition, we know that the aim should not be a value of zero, but what should the value be for effective rowing? The balance is between increasing propulsive stroke angle (by minimising slip) and reducing braking forces during the entry and release (by increasing slip). Kleshnev and Baker (2007b) proposed that the blade entry should be timed so that the blade matches the water speed when it is approximately 50% covered, that the hands should be raised 0.1 s before the catch, and that upwards force should be applied to the handle to achieve as fast an entry as possible at this time. In order to prevent back splash and the negative forces associated with it, Macrossan and Macrossan (2006) suggested a minimum angular velocity of the blade at the moment of catch (blade first touching the water) to be $(v_b \sin\theta)/L$, where v_b is the boat velocity, L is the outboard and θ, the angle the oar shaft makes with the hull. This would result in the blade tip velocity relative to the water being parallel to the oar shaft, avoiding front or back splash, and thus minimizing the negative effects of early or late entry.

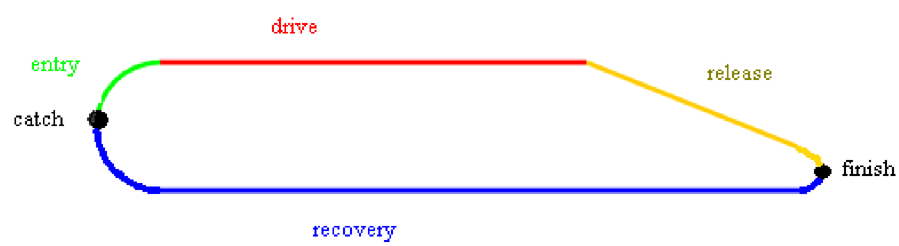


Figure 7: Representation of handle path showing time phases (drive, release, recovery and entry) and time points (catch and finish) of the rowing stroke, adapted from Nolte (2007).

Reliability/validity

Feedback from the instrumentation systems is only useful if it can be proved to be reliable (always reporting the same value if the same force/angle is occurring) and valid (reporting the actual force/angle that occurs). If there is a 4° inaccuracy, for example, and a 5° increase in catch angle is reported after a period of training, it cannot be concluded that a full 5° gain has indeed occurred. The PowerLine™ manufacturers claim accuracy of "better than 0.5°" for the angle measures and, for the force, to "2% of full scale" (4 kgF) (Peach Innovations). Results of validity and reliability testing conducted for Rowing New Zealand will be reported as soon as available.

Conclusions

Although highly disputable areas still exist, the literature highlights characteristics within force profiles that can be used to assess performance. Effective force profiles have as large an area as possible under the force-time curve, have a more rectangular than triangular shape (comprising of a high rate of force development and maintenance of force as close to peak as possible for as long as possible), are as smooth as possible, display coordination of crew members (precision depends on boat-type with notable differences between seats in a pair, but it is generally thought that crew members should synchronise force profiles, particularly in shape), and are generally believed to have a peak force in front of the perpendicular.

CHAPTER 3 – QUANTIFYING CATCH TECHNIQUE: A REVIEW OF LITERATURE

This chapter comprises the following paper presented as a technical report to Rowing New Zealand.

Coker, J., Hume, P. A., & Nolte, V. (2010). *Quantifying catch technique in elite scullers: A review of literature* (Technical report for Rowing New Zealand). (pp. 1-16). Auckland: Institute of Sport and Recreation Research New Zealand, Auckland University of Technology.

Overview

There are various methods of quantifying sculling catch technique, but the pros and cons of each method and their relationship with performance (as measured by boat velocity) are unclear. The aim of this report was to review methods of quantifying catch slip technique for scullers. Peer-reviewed journals, books, theses, and conference proceedings published since 1960 were searched using SportsDiscus, ISI Web of Knowledge, and Google Scholar data bases resulting in 35 references being reviewed. Keywords searched included 'rowing and biomechanics' and 'rowing technique'. Three alternative methods for quantifying catch technique to the familiarly used video analysis technique are presented. These are angular displacement and time from the minimum angle to: 1) 20 kgF; 2) 30% of peak force and; 3) positive boat acceleration. Advantages and disadvantages for each method are discussed and it is shown that, to some extent, each method measures a different aspect of catch technique. A novel approach using polar plots for giving feedback on these data to athletes is also outlined. There are clear limitations to all of the presented methods of quantifying catch technique and so clarification is needed regarding how the variables resulting from each method relate to the performance criterion, boat velocity. Future studies should therefore aim to quantify this relationship and investigate how to best relay these objective data to athletes for effective technique improvement.

Introduction

Possibly the most challenging part of the sculling stroke cycle to master, the catch is the blade's entry into the water, forming the transition between the recovery and drive phases of the stroke (Richardson, 2005). Technique at the catch will affect the forces acting on the boat and blade during the entry and early drive phases, and poor technique will cause the boat to decelerate and decrease the run of the boat, reducing sculler effectiveness (Richardson, 2005). A sculler's catch technique will also influence how much of their overall reach (or total angle) contributes to propulsion of the rower-boat-blade system.

When tracking athlete improvements and/or coaching effectiveness it is crucial that any changes in technique can be identified and quantified and that objective information feedback can be given (Spinks & Smith, 1994). The angle through which a blade moves towards the stern of the boat after the catch position whilst it is not propelling the system has been used for this purpose when focusing on catch technique, and in past literature has been called "catch slip", or "wasted catch angle". We will refer to this concept as catch slip in this paper. Ambiguity then lies in the definition of when the blade starts to propel the system and as a result, various methodologies using time and/or angular displacement of the blade to a certain force value, vertical blade angle, or visual blade position have been used to quantify the catch slip values (Kleshnev, 1999, 2002a; Kleshnev & Baker, 2007a, 2007b; Smith et al., 1994).

The aim of this literature review was to review methods of quantifying catch slip previously used to analyse catch technique for scullers and investigate whether any previously unpublished methods may be more appropriate in future experimental studies.

Methods

Peer-reviewed journals, books, theses, and conference proceedings published since 1960 were searched using SportsDiscus, ISI Web of Knowledge, and Google Scholar data bases. Keywords searched included 'rowing and biomechanics' and 'rowing technique'.   Originally 500 articles were found. Articles were then excluded if they did not have at least an English abstract, or if they did not include analyses of on-water catch technique. Thirty five references were included in the final review in total.

Findings

1. Why is catch technique important?

1.1 Maximising stroke length

Boat velocity is the product of the distance that the boat travels per stroke (stroke distance) and the stroke frequency (stroke rate) and the most effective way to increase boat velocity is to increase stroke distance whilst maintaining a sufficient stroke rate, particularly in sculling boats (Kleshnev, 2001c; Martin & Bernfield, 1980; Smith & Loschner, 2002). Energy given to the boat during the stroke is the product of the forces acting on the pin and the distance over which they occur, therefore more energy will be given to the boat each stroke at the same average force if the arch through which the oar is displaced whilst it is in the water is increased ("effective stroke length"). Stroke distance and boat velocity will therefore be related to effective stroke length. In past literature a longer stroke has been associated with increased performance whilst long wasted catch angles were seen to be key parameters in distinguishing lower performance level rowers (McBride, 1998; Nolte, 1991; Richardson, 2005; Smith et al., 1994). It is consequently crucial that rowers aim to minimise their wasted catch angles and utilise the full length to which they can reach, maximising propulsive drive length.

1.2 Maximising blade lift forces

The phases of the drive where the blade is furthest from the perpendicular point are also particularly important in taking full advantage of lift forces occurring at the blade. To appreciate this idea we must understand how the blade creates propulsion. In the early and latter stages of the drive, the blade is known to act as a hydrofoil as it moves forward through the water, creating a lifting force with a large component in the direction of boat movement (Caplan & Gardner, 2007b; Nolte, 1993). During the mid-drive however, lift contributes less to propulsion, but increased drag force at the blade allows the boat to be propelled (Affeld, Schichl, & Ziemann, 1993; Pulman, 2004). Therefore, to use the rower's energy more effectively, high lift forces should be achieved at the start and end of the drive (dependent upon the angle of attack and velocity of the blade relative to the water) and high drag forces on the blade in the mid-drive (Caplan & Gardner, 2007a; Pulman, 2004). A theoretical optimal efficiency exists during the drive with maximal values at the catch and finish of the stroke, and even when presenting measured as opposed to theoretical efficiency values, the peak occurs not at the perpendicular point, but earlier in the drive, as shown in Figure 8 (Affeld & Schichl, 1985).

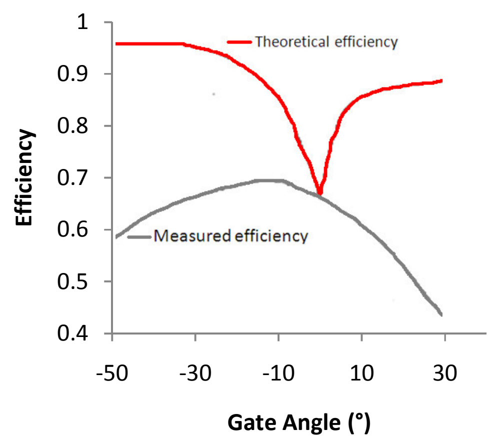


Figure 8: Theoretical efficiency at different oar angles during the drive phase and measured efficiency from a Macon blade. The oar position perpendicular to the boat is at 0° (adapted from Affeld and Schichl (1985)).

The existence of higher efficiency values in the early and latter phases of the drive can explained in the following way; for the same propulsion, the same amount of impulse must be given to the water which can either be achieved with a small mass of water at a high velocity or a large mass of water at a lower velocity (Young, 1997). Because kinetic energy is a quadratic function of velocity, the small mass, high velocity situation (stalled blade) results in more kinetic energy being transferred to the water for the same impulse. Using lift to propel the boat, as opposed to resistance against a stalled blade, therefore increases hydrodynamic efficiency (Young, 1997). The highly efficient early phase of the drive should therefore not be wasted by poor technique at the catch.

1.3 Minimising braking forces

Late entry will result in a long wasted catch angle, reducing effective stroke length. However, "wasted" catch angle can never be zero - at the catch the blade has zero horizontal velocity relative to the boat and in a moving boat would thus create stopping forces if already in the water (Kleshnev & Baker, 2007a, 2007b). Equation 1 has been presented as an expression for the minimum angular velocity of the blade at the moment of catch (blade first touching the water) in order to avoid backsplash and negative forces on the blade (Macrossan & Macrossan, 2006).

Equation 1: $\dot{\boldsymbol{\beta}} = (\boldsymbol{V_b}\ \boldsymbol{sin\,\beta})/\boldsymbol{L}$

L is the outboard length, $\mathrm{V_b}$ is boat velocity, and β is the angle the oar shaft makes with the hull. This theoretical model is based on the fact that to minimise wasted catch angle whilst avoiding back splash, the blade must enter the water just as the angle of attack on the blade would be 0°. This means that at this moment the vector of water velocity relative to the tip of the blade is parallel to the shaft. The velocity of the tip of the blade is the sum of the vectors for boat velocity and tangential velocity of the blade relative to the boat (see Figure 9). It can be seen in Figure 9 that in order for the blade tip velocity to be parallel to the oar shaft the rower must be precise with the horizontal angular oar velocity that they create – if this velocity is too high, the resultant blade tip velocity does not act parallel to the oar shaft and would cause "front splash", wasting length at the catch and reducing efficiency by giving energy to the water. In order to calculate the desired horizontal angular oar velocity we can, rearrange Equation 1 to result in Equation 2.

Equation 2: $\boldsymbol{V_b}\ \boldsymbol{sin\,\beta} = \dot{\boldsymbol{\beta}}\boldsymbol{L}$

It will, however, take a period of time for the blade to move vertically to the fully-covered position. Equation 2 can be satisfied throughout the blade entry with substitution of instantaneous oar angle instead of catch angle for β but it is questionable whether this high level of precision is achievable. Elite rowers have been observed to compromise by moving the blade vertically as quickly as possible during entry, and satisfying Equation 2 when the blade is 50% buried, matching the velocity of the water relative to the boat at this point (Kleshnev & Baker, 2007b).

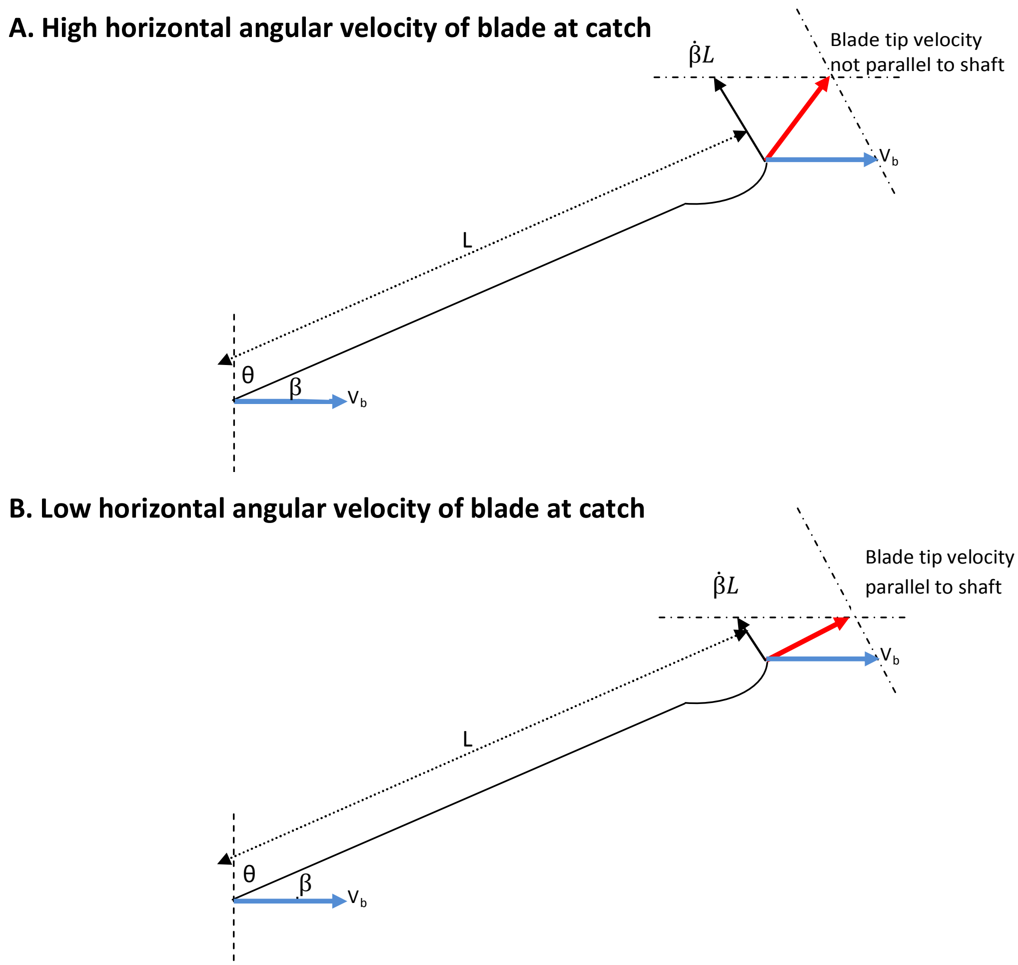


Figure 9: Instantaneous velocity of the tip of the blade (red line) is the vector sum of boat velocity (V_b), and tangential velocity of the blade tip relative to the boat ($\dot{\beta}L$). For the same boat velocity and oar angle (θ) it is shown that with a lower angular velocity (in B versus A), the blade tip velocity is parallel to the oar shaft (adapted from Macrossan (2006) and Nolte (1984)).

2. How can catch technique be quantified?

2.1. Angular displacement/time of blade entry

Catch slip has been defined as the angle through which the blade moves between its change in direction and the point where it is fully covered (Kleshnev & Baker, 2007a). This method is commonly used by coaches in semi-quantitative visual analysis, counting the number of frames between the apparent catch position and the point where the blade is covered. Values of this variable (termed catch slip) using measured rather than apparent catch position have been presented relating to good and very good performers (Kleshnev, 2007a). These data could ideally be compared to current scullers' performances but a number of limitations are associated with this method. Firstly, the blade need not be fully covered for it to be propelling the boat and this method for quantifying catch slip discards the potential for effective work during the entry phase. Also, the accuracy of this method using standard 25 Hz video cameras, as in the work of Kleshnev (2007), is limited due to significant displacement of the blade occurring between frames. Finally, the visual version of this method is more time consuming for coaches to perform than obtaining variables available automatically from systems such as PowerLine™. For Rowing New Zealand, ideally, the relationship between the commonly used and documented video analysis version of catch slip and the automatic PowerLine™ catch slip should be known.

2.2. Angular displacement to a force threshold

PowerLine™ is the biomechanics feedback tool used by Rowing New Zealand. It automatically presents a catch slip angle calculated as the angle that the blade moves through whilst less than a pre-set threshold force is applied to the pin in the direction of the longitudinal axis of the boat. For sculling, 20 kgF (196 N) is the pre-set catch force threshold. The automatic nature of this process using the PowerLine™ system enables minimal delay between task and feedback with potential for coaches to conveniently utilise the values without post-event analysis of force or video data. PowerLine™ catch slip values to some extent actually present the rate of force development and, although this is important for depicting the shape of, and area underneath, the force-time curve, they do not indicate how long the blade is out of the water whilst moving sternward. Using PowerLine™ methodology, reduced slip will be seen if the blade is “rowed in” with non-effective force applied to the pin before the blade is in the water due to the inertia of the rowing oar. Inertial blade forces, created as the blade changes direction at the catch are also included in the pin force reading (Ishiko, 1971; Kleshnev, 2002b). In a single scull inertial blade forces can represent almost 100% of the handle force seen at the catch and finish (between 70 and 80 N) (Kleshnev, 2002b) which would equate to 7.1 to 8.2 kgF as presented by PowerLine™. Forces from the blade being pressed against the gate by the rower may also increase the force reading, especially around the catch. Positive forces can be seen in Figure 10 to the left of the blue vertical line for approximately 0.28 s before the blade was seen to first enter the water on synchronised video footage.

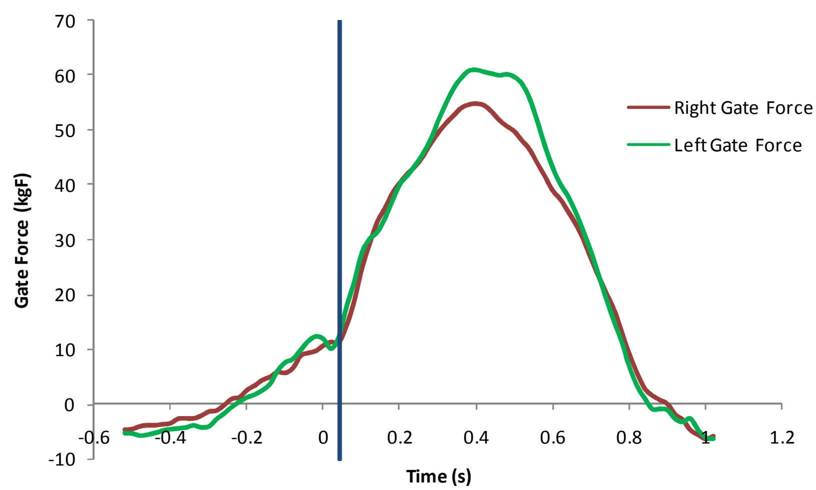


Figure 10: Force-time profile for an elite sculler from one stroke. The blue vertical line indicates the time of the video picture where the blade was first seen in contact with the water from synchronised video footage. Time, 0 seconds, represents the point where both blades were at the minimum angle for that stroke according to PowerLine™.

A study utilising a similar methodology but substituting 30% of the peak handle force as the threshold value has shown that a decrease in the resulting slip angles is related to increased blade efficiency (Kleshnev, 1999). With claimed potential performance gains of up to 5% from enhancing blade efficiency this is clearly not an area to be ignored (Kleshnev, 1999). The same issues with "rogue" force production not resulting from blade-water interaction occur with this method and post-collection analysis is required to compute where 30% of peak force occurred for each stroke. Using past testing of the same athlete to input an approximation of 30% based on their previous average peak force as the threshold is possible but accuracy will be lost. This is not acceptable with elite scullers.

2.3. Angular displacement/time to positive boat acceleration

In past research, more successful crews were seen to have no loop in the boat acceleration versus oar angle curve around the catch (Kleshnev, 1999). The loop represents reversal of oar direction at the catch before minimum boat acceleration has occurred which signifies poor coordination of stretcher and handle forces (Kleshnev, 1999). An example of one stroke from a less experienced sculler showing the loop in the acceleration versus gate angle profile around the catch is shown in Figure 11. The minimum boat acceleration of the best rowers (world champions versus national championship finalists) is also known to be larger at the same stroke rate (-10.1 m/s^2 versus -6.9 m/s^2) but with a shorter time period, meaning that the better rowers accelerate their body more effectively around the catch (Kleshnev, 2002a).

Advantages and disadvantages exist for all previously presented methods and the relationships between the variables resulting from each method and performance (as measured by boat velocity) are unclear. Based upon these findings, a final method for calculating catch slip is proposed by our rowing research group as the angular displacement and time taken between the minimum angle and positive acceleration of the boat being achieved. At this point the rower is not merely overcoming the unavoidable deceleration of the boat that occurs at the end of the recovery and the beginning of the drive, but actually increasing the boat velocity due to a technical aspect around the catch. The relationship between this value and average stroke velocity is unknown, but it would be anticipated that, if positive acceleration can be achieved earlier in the drive, a longer period of positive acceleration will occur, and high boat velocity will result. It may be that by delaying the onset of acceleration a higher peak and average acceleration can occur during the stroke, hence the need for investigation.

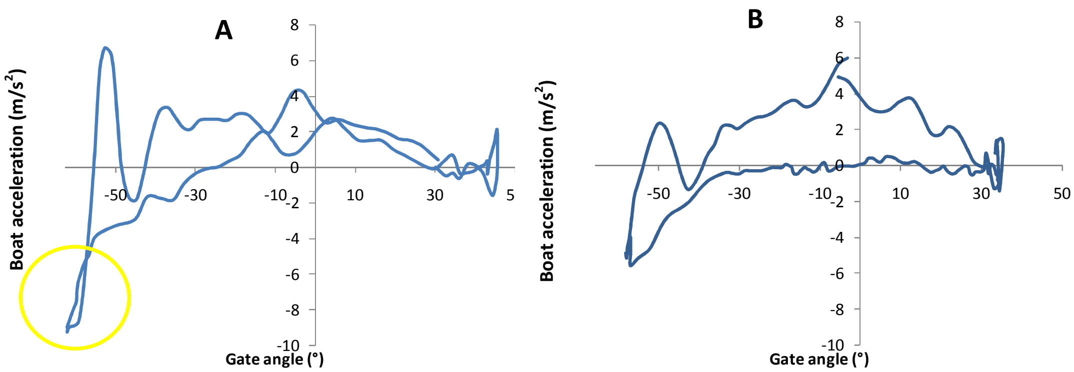


Figure 11: Example of one stroke from a less experienced rower (A) showing the loop in the acceleration versus gate angle profile around the catch (highlighted by the yellow circle), and one stroke from a more experienced rower (B) without the loop.

3. Athlete feedback of catch technique

Although it is agreed that catch technique is crucial for performance, it is clear from the literature that there is no definitive way to give feedback to athletes concerning the proficiency and effectiveness of their technique in this phase. Regardless of whether the methodology for calculating the relevant variable(s) can be substantiated, the reality of what any number of degrees of catch slip actually looks or feels like to the majority of rowers, through personal experience working with elite New Zealand rowers, is unfamiliar. Typical force-angle profiles presented automatically by many boat instrumentation systems such as PowerLine™, show a relatively flat area on the profile during the catch phase (as shown in the red circle in Figure 12).

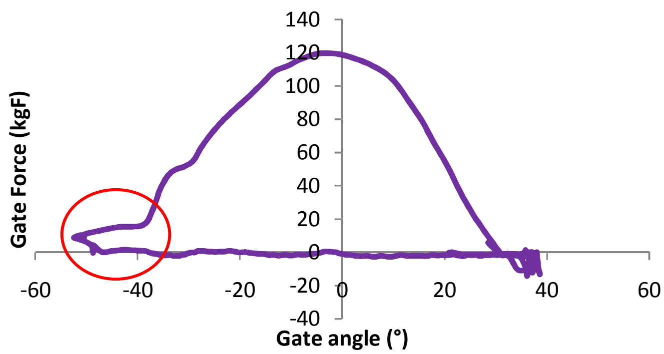
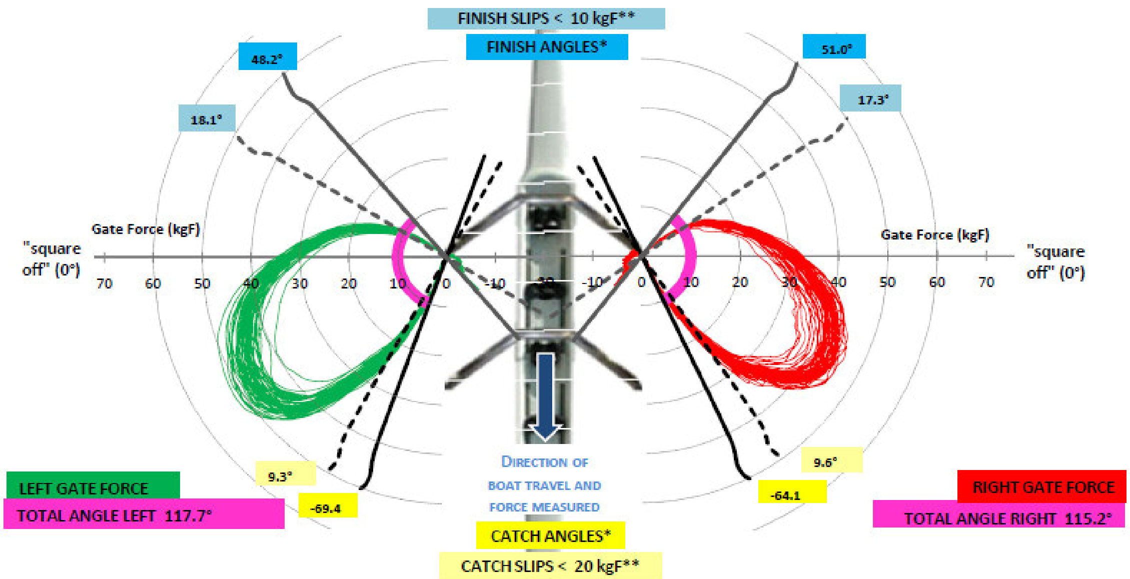


Figure 12: Typical force-angle profile presented by boat instrumentation systems for one stroke showing an extreme example of "catch slip" in the red circle (when referring to angular oar displacement to a threshold force values).

Although plots in the format shown in Figure 12 give a visual representation of the accompanying catch slip value, many scullers cannot not easily relate the figure to what is actually occurring on the water. In response to personal communication with elite scullers, the graphical presentation as shown in Figure 13 has been developed using Excel[4] to show polar plots of PowerLine™ periodic (50 Hz) gate angles and gate forces and automatic catch slip values (angular oar displacements to 20 kgF). Although developed for the PowerLine™ catch slip values, any one of the previously mentioned methodologies for quantifying catch slip could be substituted. This plot forms a realistic visual presentation of how much oar movement is occurring during the catch

[4] Microsoft, Washington, WA 98052, USA

phase (both at the handle and blade tip) as a clear proportion of the total stroke length and as such is now the preferred feedback template for a large number of rowers. Despite it being the preferred format for many of the Rowing NZ elite rowers and coaches, experimental research is still required to quantify its effectiveness at implementing changes in catch technique.



*catch and finish angles are the angles made between the oar shaft and the "square off" position at the maximum and minimum reach points.

**catch and finish slips are the angles through which the blade moves whilst less than a threshold force is being applied to the pin.

Figure 13: Alternative presentation of sculling force-time profiles and blade excursions using polar plots for an elite sculler completing an 8 km piece at 30 spm.

Conclusions

We have presented three alternative methods for quantifying catch technique to the familiarly used video analysis technique and one novel approach for giving feedback on these data to athletes. The alternative methods are angular displacement and time from the minimum angle to: 1) 20 kgF; 2) 30% of peak force and; 3) positive boat acceleration. All the methods have their limitations and, to some extent measure different aspects of catch technique. The most convenient (and therefore "coach-friendly") method would be to use pre-set threshold forces without the need for time intensive manual analysis, as is the case with the PowerLine™ system. However, clarification is needed because as yet, there has been limited investigation of how the variables resulting from each method relate to boat velocity, the ultimate performance criterion, or to how they relate to each other. Future studies should aim to quantify the relationship between each of these variables and boat velocity in order to justify their use in elite on-water sculling analysis. It may be that it is necessary to measure all versions of catch slip in order to develop a full analysis of an individuals' catch technique throughout this stroke phase. Understanding of the interaction between each of these variables would also be beneficial in order to compare scullers analysed previously using different methodologies. Finally, the new approach to feedback using polar plots is proving to be popular with New Zealand coaches and athletes, but an evaluation of its effectiveness in implementing changes to catch technique would be valuable.

CHAPTER 4 – VALIDITY OF FORCE AND ANGLE DATA FROM THE POWERLINE™ BOAT INSTRUMENTATION SYSTEM

This chapter comprises the following paper presented at the International Society of Biomechanics in Sport conference.

> Coker, J., Hume, P., & Nolte, V. (2009, 17-21 August). *Validity of the PowerLine™ Boat Instrumentation System.* Paper presented at the 27th International Conference of Biomechanics in Sports, Limerick, Ireland (pp. 65 – 68).

Overview

The PowerLine™ Boat Instrumentation System is comprised of instrumented oarlocks capable of measuring pin forces in the direction of boat travel and oarlock angles. The aim of this study was to determine the reliability and validity of the force and angle data from the PowerLine™ Boat Instrumentation System in a laboratory setting. Data were collected with the sculling oarlocks affixed to a horizontally aligned, stabilised wing rigger. For force analysis, signals were collected at 50 Hz from both the PowerLine™ system and a 1 kN load cell[5] during 10 repetitions at a rate of approximately 30 repetitions per minute. For angular analysis, whilst recording with PowerLine™, oarlocks were repositioned for a minimum of two seconds at known angles in a random order using an inclinometer accurate to one tenth of a degree over a range of -80° to +60°, in 20° increments. Linear regression analysis through the origin was used to compare the PowerLine™ values with known values from the load cell and the inclinometer. Laboratory testing proved the force and angle sensors to be valid

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[5] Applied Measurement Australia, P.O. Box 159, Oakleigh, Victoria 3166, Australia

throughout the testing range (0 N to 554.8 ± 20.4 N, and -80° to +60° respectively) when fully functioning. The PowerLine™ Boat Instrumentation System appears to be appropriate for measuring biomechanical variables in an elite sculling programme. On-water reliability testing is still required to fully evaluate their application in quantifying the effect of interventions made to technique or boat set-up.

Introduction

The role of an applied rowing biomechanist is to supply coaches with the information they need to analyse rowing technique and boat speed (McBride, 2005). At the elite level, coaches and athletes strive to cut tenths of a second from performance times, thus a high degree of accuracy and reliability is required from any instrumentation used to supply such measures (Baudouin & Hawkins, 2004). Although athlete testing in a laboratory setting will provide a more controlled environment, it will not represent the task as it would be performed in competition (Baca, 2006; Williams & Kendall, 2007). Comparative studies between on-water and ergometer force profiles have highlighted that on-water analysis is the only option for data that truly signifies the rowing performance situation (Dawson et al., 1998; Elliott et al., 2002; Kleshnev, 2008a; Lamb, 1989; Li et al., 2007). In providing highly applicable measures, it is also vital that the instrumentation does not interfere with the normal operation of the boat and the sculler (Müller, Benko, Raschner, & Schwameder, 2000; Smith & Spinks, 1989).

The PowerLine™ Boat Instrumentation System represents a means of providing relevant, on-water data without noticeable change to the athlete set-up. The manufacturers claim accuracy in the force measures of up to two percent of its full scale (an error of up to 40 N) and 0.5° in the angle measures, but independently tested validity of its measures have not previously been documented (Peach Innovations). The aim of this study was to provide independent validity measures for the instrumented sculling oarlocks.

Methods

To avoid damage to Rowing New Zealand equipment and to control for movement of the pin, all validation was carried out in a laboratory setting. For all procedures, the oarlocks were fixed to a pin, horizontally oriented in a wing rigger as shown in Figure 14. Eight sculling oarlocks were tested in total. Only dynamic force validation could be performed due to an auto-zeroing function built into the oarlocks - the system assumes any force application that remains static is zero and automatic calibration occurs. This was not considered limiting as static forces are not seen in the normal rowing situation.

Figure 14: Laboratory set-up for all validation procedures.

Using an inclinometer (SmartTool™ Level[6]) the PowerLine™ logger zeroing function was used to set 0° as the position where the oarlock would be parallel to the midline of the boat – horizontal orientation of the working face of the oarlock in the validation set-up. Dynamic linearity and validity of the force measure was determined by recording sample data whilst a dynamic linear force was manually applied by pulling downwards on a bar hanging from the oarlock with a 1.0 kN load cell suspended in series. At a rate of 30 ± 2 repetitions per minute, 10 repetitions were recorded at 50 Hz from both the PowerLine™ system and the load cell in a range of 0.0 N to 554.8 ± 20.4 N. This range was selected because it exceeded the range of forces previously seen in national level scullers (0 to 441 N) by more than 25% (Elliott et al., 2002). Outputs from

[6] M-D Building Products, OKC Plant, 4041 N. Santa Fe, Oklahoma City, OK 73118, USA

the load cell were recorded using Labview[7] and output from the logger was downloaded later. The two entire data sets from the 10 repetitions were collated in Excel and analysed, synchronising the data using the first local maximum force reading.

Although all effort was made to apply the force in the vertical direction, some deviation occurred and, because the load value presented by PowerLine™ is the actual force, resolved in the vertical direction, Equation 3 was used to calculate the actual load.

Equation 3 : $L = \frac{L_{vert}}{\cos\alpha}$

where L is the actual force applied, α is the oarlock angle, and L_{vert} is the resolved vertical force presented by the PowerLine™ software. Linear regression analyses through the origin were computed in SPSS[8] where the "dependent variable" was the oarlock reading and the "independent variable" was the load cell reading.

For angle validation, the oarlocks were repositioned for a minimum of two seconds at known angles in a random order using an inclinometer (SmartTool™ Level) accurate to 0.1° (MD BuildingProducts, 2007). A range -80° to +60° was used in 20° increments. PowerLine™ data were downloaded and linear regression analyses through the origin were computed in SPSS using the average value from each two second increment in comparison with the known angles.

Results

Table 1 shows the results of the linear regression through the origin of the oarlock reading with the load cell for each of the eight oarlocks. The standard error of the estimate (SEE) was at most 8.9 N for all oarlocks except oarlock #1408 which displayed an SEE of 11.7 N. The R^2 values were all 1.00, except oarlock #1408 that displayed an R^2 value of 0.99. Oarlocks 1401 to 1407 showed a range of 15.5 N to 45.6 N in the maximal error of the estimate for each oarlock whilst oarlock 1408 had a maximal

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[7] National Instruments, 11500 N Mopac Expwy, Austin, Texas 78759-3504, USA
[8] SPSS Inc. Headquarters, 233 S. Wacker Drive, 11th floor, Chicago, Illinois 60606

error of 81.5 N. Results of the regression analyses for oarlock angle versus inclinometer angle are presented in Table 2. The SEE was 0.9° or less for all oarlocks except for oarlock #1408 which had an error of 3.1°. R^2 was 1.00 for all oarlocks. Oarlocks 1401 to 1407 showed a range of 0.5° to 1.4° in the maximal error of the estimate for each oarlock.

Table 1: Dynamic linearity statistics for the force measures from the sculling oarlocks in the range of 0 N to 554.8 ± 20.4 N compared with force measures from the load cell. Linear regression was computed through the origin.

Oarlock number	Slope	R^2	Standard error of the estimate (N)	Max error (N)
1401	1.01	1.00	8.9	44.5
1402	1.04	1.00	5.1	30.6
1403	0.99	1.00	8.0	39.3
1404	1.04	1.00	7.4	21.2
1405	1.00	1.00	4.3	15.5
1406	1.05	1.00	7.7	45.6
1407	1.01	1.00	4.2	20.3
1408	0.93	0.99	11.7	81.5

Table 2: Static linearity statistics for the angle measures from the sculling oarlocks in the range - 80° to 60° compared with the angle measure from the inclinometer. Linear regression was computed through the origin.

Oarlock number	Slope	R^2	Standard error of the estimate (°)	Max error (°)
1401	1.00	1.00	0.9	1.1
1402	1.01	1.00	0.2	0.7
1403	1.00	1.00	0.4	0.6
1404	1.00	1.00	0.7	1.0
1405	1.00	1.00	0.9	1.4
1406	1.00	1.00	0.3	0.5
1407	1.00	1.00	0.7	1.1
1408	0.98	1.00	3.1	8.2

Discussion

Apart from sculling oarlock #1408 (which has since been replaced), the force and angle measures proved to have an acceptable level of validity in the range tested in a laboratory setting. In previous repeated short on-water bursts, elite scullers showed typical expected variation between trials of 1.2% in stroke length and 4.9% in peak propulsive force (Soper, Hume, & Tonks, 2003). This would equate to 1.1° in a sculler with a total arch of 95°, and 29.4 N in a sculler with a peak propulsive force of 600 N.

For oarlocks #1401 to #1407, SEE in force was at most 8.9 N, and 0.9° for the angle measure therefore a greater percentage of variation in the overall values will come from the scullers themselves rather than the instrumentation system. For oarlocks #1401 to #1407, the SEE for the force measures falls below the manufacturers' claimed accuracy level of 40 N but the SEE of the angle measure exceeded 0.5° (claimed angle measure error) in four of these oarlocks. The maximal errors are also higher than the manufacturers' error values in some oarlocks. The non-automatic synchronisation method used in this study may account for this higher than anticipated, and potentially over-estimated, maximal error and SEE. Subjective feedback from the scullers who have used the testing system over the past 16 months has shown that there is no alteration to the feel of the boat set-up as long as the pitch of the scullers' usual oarlocks is the same as the instrumented oarlocks.

Conclusion

The force and angle measures from the laboratory testing of the PowerLine™ Boat Instrumentation System for sculling proved to have an acceptable level of validity represented by a standard error of the estimate of 8.9 N or less for force, 0.9° or less for angle, and an R^2 of 1.00 for both variables in all functioning oarlocks over the testing range. Malfunction in one sculling oarlock highlighted the need for regular validity testing. Further investigation is required to determine the on-water reliability of the output variables from the PowerLine™ Boat Instrumentation System when used by elite scullers.

CHAPTER 5 – COMBINED RELIABILITY OF THE POWERLINE™ BOAT INSTRUMENTATION SYSTEM AND ELITE SCULLERS

This chapter comprises the following technical report submitted to Rowing New Zealand.

Coker, J., Hume, P. A., & Nolte, V. (2008). *Combined reliability of the PowerLine™ Boat Instrumentation System and elite scullers* (Technical report for Rowing New Zealand). (pp. 1-18). Auckland: Institute of Sport and Recreation Research New Zealand, Auckland University of Technology.

Overview

The effect of an intervention on key performance-determining biomechanical parameters can only be judged once the reliability of such measures has been quantified to identify the smallest worthwhile effect. To date, no research has reported the variation in force and angle variables available from the PowerLine™ Boat Instrumentation System alone, or in combination with elite scullers. This study determined the expected normal variation in the biomechanical variables provided by the system when six Olympic level scullers completed three 500-m trials of on-water sculling at a self-selected rate and pace that represented the constant pace used throughout the middle 1000 m of a 2000-m race. *Stroke power, catch angle, finish angle, finish slip, catch slip, drive start, stroke rate* and *boat velocity* were collected for the middle 40 strokes of each of the three trials of 500 m. Within-trial consistency was evaluated using the mean, standard deviation (SD), slope and standard error of the estimate of all variables. Within-subject reliability between trials was analysed via the averaged individual typical error and intra-class correlation coefficients between pairs of trials for each variable. Grouped reliability between trials was investigated using the typical error and intra-class correlation coefficient for grouped individual means between trials. Lower than expected within-trial consistency was seen in *boat velocity* and *stroke rate* (SD of at least 1.0% for *boat velocity* and 1.5% for *stroke rate*) considering constant rate and pace were stipulated. However, both variables showed high reliability both within and between subjects (typical error less than 1.0% for *boat velocity* and less than the precision level of 0.5 strokes per minute of the rate meter for *stroke rate*). Angular variables were highly consistent and reliable showing less than 1° for both within-trial variation and between-trial typical error within and between subjects. Consistency and reliability in *drive start* were underestimated compared with values calculated as a percentage of total stroke time which were of a more acceptable level (SD less than 1.2% and typical error less than 1.0%). *Stroke power* showed substantially lower consistency and reliability (SD at least 4.7% within trials and typical error between trials at least 4.1% within subject, and up to 2.2% when subjects were grouped) than *boat velocity*. Low intra-class correlation coefficients were seen within and between subjects due to the high similarity in subject performance level and stroke-to-stroke matching not being exact. Smallest worthwhile effect sizes were 0.13% for *boat velocity*, 0.16% for *stroke rate*, 0.44% for *stroke power*, and 0.5° for angular variables. High reliability in most variables promotes the use of the PowerLine™ Boat Instrumentation System for biomechanical analysis in elite scullers. High variation within and between trials in *stroke power* compared to *boat velocity* highlights the need for future research into the use of *stroke power* as a performance predictor variable. Large differences between subjects in individual typical errors between trials support the need for a personalised approach to analysis at the elite performance level. Specifically the higher stroke-to-stroke and between-trial variability in *stroke power* seen in double versus single scullers may highlight the need for a training focus on consistency of individual scullers' biomechanical variables when in crew boats.

Introduction

Biomechanical measures are used to monitor performance in elite rowers. At this level of proficiency, small changes are considered important thus a high degree of reliability is required from the instrumentation used to supply biomechanical measures

(Baudouin & Hawkins, 2004). For repeated trials under the same conditions, a reliable measure has small changes in the mean, small within-subject variation and a high test-retest correlation, as measured by the intra-class correlation coefficient (ICC) (Hopkins, Schabort, & Hawley, 2001; Schabort, Hawley, Hopkins, & Blum, 1999). Once the reliability of a measure has been quantified, the smallest worthwhile effect can be calculated. The smallest worthwhile effect, equating to 0.2 times the normal variation in a measure (Cohen, 1988), can be used to determine whether an intervention has been successful in altering that measure. The expected variation between performances in an elite athlete is 1% (Hopkins, Hawley, & Burke, 1999), so for biomechanical variables to be appropriate for use in this population, typical error between trials must be 1.0% or less.

As yet there is no published work outlining the reliability of the PowerLine™ Boat Instrumentation System. A reliability study of two male and nine female elite scullers during six short maximal bursts using the RowBot System showed a typical error of 1.2% (95% CI = 0.08 – 2.2) for stroke length and 4.9% (95% CI = 6.7 – 17.8) for peak propulsive force (Soper et al., 2003). The PowerLine™ system is intended to be used regularly for biomechanical analysis to monitor and improve performance as part of the elite Rowing New Zealand programme. Therefore, a study to determine the reliability of the PowerLine™ variables for elite rowers was required to allow valid conclusions to be drawn from subsequent research and athlete feedback data on performance. The system's default force thresholds (in sculling, 20 kgF for the catch and 10 kgF for the finish) were used as these would be used by coaches without specialist assistance from a biomechanist. Specifically, the aim of this study was to determine within-trial consistency, within-subject reliability between trials, and between-subject reliability normally seen in the force and angle data presented by PowerLine™ when used by elite scullers at race pace.

Methods

The Auckland University of Technology Ethics Committee approved the study and, as required, all participants were informed of the testing procedures and each gave written informed consent. On-water testing occurred between January and February 2008.

Participants

Six Olympic level scullers (one heavyweight women's double scull, one lightweight men's double scull, one heavyweight women's single scull and one heavyweight men's single scull) from the Rowing New Zealand elite squad were selected based on their availability and fitness on the given testing dates.

Procedures

In single and double sculls equipped with PowerLine™ and Nielsen-Kellerman Speed Coach[9] rate meters, athletes performed three 500 m trials from a flying start at race pace (the self-selected constant stroke rate and level of exertion normally applied throughout the middle 1000 m of a 2000-m race). Rest time was given that would allow a small rigging change and the return to the start (more than five minutes). Trials were carried out using the lane and distance markers in a pre-measured 2000 m rowing course. Trial times were recorded using a stop watch from a motor boat running parallel to the crew (as is standard Rowing New Zealand practice). This monitoring was necessary because it was the intention to complete additional trials if large variations in trial times had been seen during data collection, but this was not required. Although familiarisation trials are recommended (Hopkins & Hewson, 2001), it was hoped that these additional trials could be avoided, if possible, in order to minimise fatigue and disruption to the training schedule of these elite athletes. The PowerLine™ logger unit recorded pin force, oar angle and boat velocity data at 50 Hz throughout each trial and software computed the stroke variables bilaterally for each rower. The pin force collected was resolved automatically in the direction of the longitudinal axis of the boat (or boat travel). Video was taken to allow identification of any anomalies and to aid with the identification of start and finish points.

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[9] Nielsen-Kellerman, Boothwyn, PA 19061.

Statistical analyses

The middle 40 strokes from each trial were used for analysis based upon the following stroke-to-stroke variables:

- *Stroke rate* (spm) – strokes per minute.
- *Stroke power* (W) – average stroke power calculated automatically as the product of the handle force and handle velocity components in the x-direction (direction of the longitudinal axis of the boat), and only included in the averaged *stroke power* when positive. The handle force was calculated as pin force * outboard / oar length, and the handle velocity calculated as ω.r.cosθ, where ω is angular oar velocity, r is inboard length and θ is oar angle.
- *Catch angle* (°) – minimum angle reached during the stroke (because the angle where the oar would be perpendicular to the longitudinal axis of the boat is set to be 0°, the catch angle has a negative value and is therefore the minimum angle).
- *Finish angle (°)* – maximal angle reached during stroke (see above – the finish angle therefore has a positive value and is the maximum angle).
- *Catch slip (°)* – angular displacement from the minimum gate angle to the point at which the pin force value exceeded 196 N (20 kgF displayed by PowerLine™) in the direction of the longitudinal axis of the boat during that stroke.
- *Finish slip (°)* – angular displacement from the point where the pin force value fell below 98 N (10 kgF), to the maximum angle.
- *Boat velocity* (m/s) – it should be noted that this value is not calibrated therefore can only represent change in velocity from stroke to stroke rather than an absolute value[10].

[10] Calibration has not been carried out because Nielsen-Kellerman units are used as standard for velocity analysis on a daily basis in the Rowing New Zealand programme. The athlete time required for calibration of the PowerLine™ system for every crew is not deemed advantageous for use with this squad.

- *Drive start* (arbitrary units*0.02 seconds) – this value is given as the number of data points that occur between the catch threshold force being exceeded and the blade moving 10° away from the maximal angle value and gives a very approximate estimation of drive time. PowerLine™ collects at 50 Hz therefore data points are 0.02 seconds apart, hence the multiplication factor.

Any non-angular variables were analysed via the log transformed value to stabilise variance. For each trial, *stroke rate* and *boat velocity* had only four "subjects" (one for each boat) whilst all other variables had two "subjects" per sculler (one for each oar, a total of 12).

Within-trial consistency

Within-trial consistency was calculated from individual subject standard deviations, averaged for each trial of 40 strokes. It was noticed that certain variables increased or decreased throughout trials in some subjects so linear regression analyses were computed using Excel, and averaged slopes and standard error of the estimates (SEE) presented. The SEE[11] is a measure of the stroke to stroke variation once the slope has been taken into consideration. Stroke number was normalised in each trial to allow "slope" to represent a change through the entire trial.

Within-subject reliability between trials

Within-subject reliability between the three trials was investigated via the typical error (TE) and intra-class correlation coefficient (ICC) using a reliability spreadsheet (Hopkins, 2000b). The TE represents the typical variation seen between trials after changes in mean have been taken into account, whilst the ICC indicates the extent to which the ranking in the measures has altered between trials (ranging from 0.00 to 1.00, where 1.00 would mean perfect agreement between tests) (Hopkins, 2000a). The level for confidence limits was set at 90%. Between-trial values were computed for

[11] $\mathrm{SEE} = \sqrt{\frac{\Sigma(Y - \acute{Y})^2}{N}}$ where Y is an actual score, Ý is a predicted score based on the slope, and N is the number of pairs of scores.

each pair of trials for each subject separately using all strokes then averaged for each pair of trials for all subjects and the range displayed.

Grouped reliability between trials

Using grouped mean values for each subject, between-trial reliability was calculated for each pair of trials. The same spreadsheet and confidence limits were used as for within-subject reliability between trials.

Results and discussion

Within-trial consistency

Stroke-to stroke consistency (SD) has been linked to rowing performance level (Smith & Spinks, 1995) and elite variation between performances is reported to be 1% or less (Hopkins et al., 1999). Although stroke-to-stroke consistency and between trial variation are not necessarily linked, the benefits of consistency are known, and a constant *stroke rate* and pace were stipulated, so 1% has been taken as an acceptable level of variation within a trial. Table 3 presents the within-trial consistency for all variables averaged for all Olympic scullers (n=4 crews for *boat velocity* and *stroke rate*, n=12 oars for all other variables).

Stroke-to-stroke consistency than anticipated considering constant *stroke rate* and pace were stipulated. Averaged for all scullers, SD in *boat velocity* was lowest in trial 3 (1.1%) and SD in *stroke rate* was lowest in both trial 1 and trial 3 (1.5%). However, these scullers are dependent upon their Nielsen-Kellerman Speed Coach units, which show a value to the nearest 0.5 strokes per minute (spm), to match a specified *stroke rate*. At a rating of 33 spm, 2.1% equates to 0.7 spm whilst the anticipated 1.0% variation would equate to 0.3 spm - a difficult expectation in accuracy from the scullers given the 0.5 spm precision of the Nielsen-Kellerman units. On average there was a decrease over the 40 strokes in all trials for *boat velocity* (reduction of 3% in trial 1, and 2% in both trials 2 and 3) and *stroke rate* (reduction of 3% in trials 1 and 3, and 4% in trial 2). This was not however universal, with three crews increasing their *stroke rate* and *boat velocity* in trial 3 and their *stroke rate* in trial 2, one crew increasing their *boat velocity* in trial 1, and another in trial 2. The SEE was smaller than the SD (1.2% versus 2.1% for *stroke rate,* and 0.94% versus 1.2% for *boat velocity* on average in Trial 2), but when *stroke rate* and *boat velocity* should be constant throughout the trial it is SD that is important. The high SD values within and between trials for the scullers show either a fatiguing effect or a lack of ability or desire to maintain constant *stroke rate* and *boat velocity* when stipulated, even in these highly experienced, elite scullers.

Stroke power showed low stroke-to-stroke consistency with an average SD greater than 4.7% in each trial. One sculler showed a SD as high as 8.8%. This is low consistency considering the substantially lower variability seen in *boat velocity*. The actual relationship between these two variables therefore requires investigation to determine whether *stroke power* can be used as a performance predictor. Averaged for all subjects, *stroke power* decreased through each trial (greatest decrease of 5.2% in trial 3). However a high range existed in the slope value across the group showing individual preferences in the pattern of effort through the 500 m. Averaged SEE for *stroke power* was lower than SD for all trials, but the smallest averaged SEE for a trial was still 4.2% (trial 2) - low consistency within-trial, even when pacing through the exertion was taken into consideration. The issue with *stroke power* is that each oar has a *stroke power* value but there is only one *boat velocity* value per crew. Therefore variation in one oar may be offset by variation in the opposite direction in another crew member. Averaging the SD in *stroke power* for the two single scullers resulted in 3.2%, 3.2% and 3.3% for trials 1 to 3 whilst the double scullers had higher averaged SDs of 5.8%, 5.5% and 6.1% in each trial. This is despite SD in *boat velocity* being equal for singles versus doubles in trials 2 and 3. In trial 1, the SD in *boat velocity* for double sculls was 0.6% higher than for the single sculls but one of the doubles was a relatively newly-formed crew and this trial can be classed as a familiarisation trial.

Table 3: Individual mean, standard deviation (SD), slope, and standard error of the estimate (SEE) for stroke variables from each trial (n=40 strokes per trial for each variable), averaged for all Olympic scullers (n=4 crews for *boat velocity* and *stroke rate*, n=12 oars for all other variables).

		Olympic (6 rowers in 2 doubles & 2 singles)		
	Trial	**1**	**2**	**3**
Boat velocity (m/s)	Mean	5.10	5.13	5.13
	SD (range) (%)	1.5 (1.1 – 2.1)	1.2 (1.0 – 1.4)	1.1 (0.66 – 1.5)
	Slope (range) (%)	0.97 (0.96 – 0.99)	0.98 (0.97 – 0.98)	0.98 (0.96 – 1.00)
	SEE (range) (%)	1.2 (0.77– 1.6)	0.94 (0.83 – 1.1)	0.84 (0.67 – 1.1)
Stroke rate (spm)	Mean	32.9	33.0	33.1
	SD (range) (%)	1.5 (1.1 – 1.9)	2.1 (1.5 – 2.6)	1.5 (1.1 – 2.1)
	Slope (range) (%)	0.97 (0.96 – 0.98)	0.96 (0.93 – 1.03)	0.97 (0.94 – 1.01)
	SEE (range) (%)	1.1 (1.0 – 1.3)	1.2 (1.1 – 1.4)	1.1 (1.0 – 1.1)
Stroke power (W)	Mean	167	171	171
	SD (range) (%)	4.9 (2.8 – 8.8)	4.7 (2.9 – 7.6)	5.2 (2.7 – 8.8)
	Slope (range) (%)	0.94 (0.84 – 1.08)	0.96 (0.88 – 1.04)	0.95 (0.85 – 1.04)
	SEE (range) (%)	4.3 (2.3 – 6.8)	4.2 (2.4 – 7.6)	4.5 (2.0 – 7.4)
Drive Start	Mean	53	53	53
	SD (range) (%)	2.1 (1.4 – 6.2)	2.0 (1.4 – 2.6)	1.7 (1.3 – 2.6)
	Slope (range) (%)	1.02 (0.95 - 1.04)	1.03 (0.98 – 1.07)	1.02 (1.00 – 1.04)
	SEE (range) (%)	1.9 (1.2 – 6.1)	1.6 (1.1 – 2.5)	1.5 (1.2 – 2.5)
Catch Angle (°)	Mean	-68.9	-68.8	-68.8
	SD (range)	0.7 (0.5 – 1.0)	0.8 (0.4 – 1.1)	0.7 (0.4 – 1.4)
	Slope (range)	0.0 (-0.7 – 0.8)	-0.7 (-2.4 – 1.4)	-0.5 (-2.4 – 1.0)
	SEE (range)	0.7 (0.4 – 1.0)	0.7 (0.4 – 1.0)	0.6 (0.4 – 1.2)
Finish Angle (°)	Mean	47.2	47.3	47.3
	SD (range)	0.8 (0.6 – 1.5)	0.8 (0.6 – 1.3)	0.8 (0.5 – 1.3)
	Slope (range)	0.7 (-0.6 – 1.9)	1.2 (-1.1 – 2.7)	0.7 (-0.7 – 1.9)
	SEE (range)	0.8 (0.5 – 1.5)	0.7 (0.5 – 1.3)	0.8 (0.5 – 1.3)
Catch Slip (°)	Mean	8.6	8.5	8.5
	SD (range)	0.8 (0.3 – 2.1)	0.8 (0.4 – 1.9)	0.7 (0.3 – 1.4)
	Slope (range)	0.6 (-1.1 – 3.3)	0.7 (-0.4 – 2.3)	0.4 (-1.0 – 1.5)
	SEE (range)	0.7 (0.2 – 1.8)	0.7 (0.3 – 1.9)	0.7 (0.3 – 1.4)
Finish Slip (°)	Mean	14.1	13.5	13.6
	SD (range)	1.0 (0.7 – 1.6)	0.9 (0.7 – 1.4)	1.0 (0.7 – 1.2)
	Slope (range)	0.2 (-3.0 – 1.9)	0.5 (-1.5 – 2.2)	0.3 (-2.0 – 2.5)
	SEE (range)	1.0 (0.7 – 1.5)	0.9 (0.6 – 1.3)	0.9 (0.5 – 1.2)

Range is given in brackets for SD, slope and SEE. Slope is given as a factor change over the 40 strokes for non-angular variables and as a change in degrees for angular variables.

Consistency in the *drive start* measure improved with trial number and appeared to have high variability (SD of 2.1%, 2.0% and 1.7% for trials 1, 2 and 3 respectively). However, *drive start* is a measure of how much time is spent on a particular phase of the stroke. This phase takes approximately half of the total stroke time. For example, in trial 2 at a *stroke rate* of 32.1 spm, the measured 2.0% SD in the mean *drive start* time of 55*0.02 seconds equated to 1.2% of the total stroke time. The standard deviations presented in Table 3 therefore overestimate the variation in the variable when it is considered as a percentage of total stroke time. The angular variables showed high consistency in general with averaged SD, slope and SEE being 1.2° maximum (trial 2, slope, *finish angle*). Taking an average overall stroke length of 116.1°, 1.2° equates to 1.0% which is acceptable variation in these technique-based variables. However, the range indicates that some individuals showed higher variability (maximum of 2.1° - trial 1, *catch slip*) suggesting an individual approach to recommendations is required.

Within-subject reliability between trials

Table 4 presents the within-subject reliability between trials via the typical error (TE) and intra-class correlation coefficient (ICC), averaged from individual analysis. For all variables low ICCs were seen (maximum of 0.55). However, it would not be expected (or necessarily important) that stroke-to-stroke matching would occur precisely. The middle 40 strokes were taken from each 500-m piece. Each 500-m piece did not necessarily have the same number of strokes therefore, although the first strokes analysed from trials 2 and 3 would be from almost the same place within the 500-m stretch, they may not match exactly. Therefore ICCs will not be discussed further in this section.

Elite athletes are expected to vary between performances by no more than 1% (i.e. a typical error of less than 1% indicates an acceptable level of reliability) (Hopkins et al., 1999). Averaged individual TE between trials was 1.0% or less for *boat velocity*, the performance criterion, as anticipated. Maximal averaged individual TE for *stroke rate* was 2.1% which represents high reliability when considering the accuracy presented by the stroke rate meter display. *Stroke power* had low within-subject reliability between trials with an averaged TE of 4.3% for trial 1 versus 2, 4.4% for trial 3 versus 2 and 4.1% for trial 3 versus 1, and TE as high as 7.9% when individual values for *stroke power* were inspected. When the individual TE values were averaged separately for single and double sculls, *stroke power* was still unreliable with TE greater than 1.0%. However, the singles had TE of 2.6%, 2.5% and 2.7% for the three trial pairings whilst the double sculls showed TE of on average 5.2%, 5.3% and 4.8% - around twice the TE of the singles. This shows that, not only does sculling with another crew member allow the sculler to be less consistent from stroke to stroke whilst maintaining fairly constant *boat velocity*, it also allows each crew member to vary more in *stroke power* from trial to trial. *Drive start* varied on average between trials by 1.6% signifying high reliability when considering this as a percentage of total stroke time. All angular variables displayed TE of, on average, less than 1° indicating high reliability under these conditions.

Grouped reliability between trials

Table 5 presents the grouped, between-trial reliability. Large confidence intervals in the values (e.g. ICC for *stroke rate* in each pair of trials) can be explained by the small number of degrees of freedom and the high similarity between subjects. We have not been able to increase the number of subjects as we wanted to maintain specificity to Olympic scullers and conflict of interest would occur if Olympic scullers from other nationalities were included. Greater reliability may also be achieved by increasing the number of strokes analysed, but this would depend upon the training schedule of the athletes because repeated longer maximal exertions cannot be easily incorporated into training. If longer exertions were used, they may have to be spread over a number of days which, due to weather conditions, could increase variability further. Reliability values are only relevant to future studies using the same protocol (rest time, interval between trials), therefore this would have to be considered when designing future studies based on the resulting reliability values.

At the 90% confidence level, *boat velocity* showed high reliability with the highest TE being 0.63% (90% CI: 0.39 – 1.9%), and the lowest ICC being 1.00 (90% CI: 0.90 – 1.00) between trial 3 versus 2. The upper confidence limit in TE is however, almost twice the 1% expected variation between trials in elite athletes (Hopkins et al., 1999). Increasing the number of subjects should reduce the size of the confidence limits but as discussed, this is problematic. This study did show higher reliability between trials in *boat velocity* than previous literature with similar subjects that showed a percent standard error of measurement of 4.6% (95% CI = 3.6 – 5.7%) (Soper, 2004). Choppy water in the earlier study and different instrumentation could explain these discrepancies. The TE found in our study is similar to the 0.6% seen with high school rowers in repeated 2000-m tests on a Concept 2 ergometer (Schabort et al., 1999). It makes sense that elite on-water reliability over 500 m would be consistent with school level off-water reliability over 2000 m. An ergometer creates a more stable (reliable) environment than on-water, a 2000-m exertion tends to give higher reliability than 500 m, but elite scullers should be more reliable than school rowers (Soper & Hume, 2004). Typical error in *stroke rate* is highest between trial 3 versus 1 with a value of 1.4% (90% CL: 0.87 – 4.2). The gradual increase in mean *stroke rate* with increased trial number (see Table 3) explains this and may highlight the need for a familiarisation trial before interventions are made in future studies. The inclusion of a familiarisation trial is supported by previous findings that state that the variation between the first two trials is 1.3 times greater that between any subsequent trials (Hopkins & Hewson, 2001).

Stroke power had low group reliability between trials with a TE of 2.2% (90% CL: 1.6 – 3.4%) for trial 3 versus 2 and trial 3 versus 1, especially considering the highly reliable nature of the performance variable, *boat velocity*. However, this does closely match the findings of Soper and Hume (2004) who reported that a 2.0% change in mean power equated to a 0.7% change in velocity using a previously devised formula (Hopkins et al., 2001). As seen with stroke-to-stroke consistency and within-subject reliability between trials, the technique based variables of *drive start, catch angle, finish angle, catch slip* and *finish slip* showed high reliability between-subjects. *Drive start* had a TE of 0.78% (90% CL: 0.59 – 1.2%) and an ICC of 0.97 (0.91 – 0.99) between trial 3 and 1, the lowest reliability pair, whilst the TE for all pairs of trials in all angular variables was less than 0.5°. This is not only less than 1% of stroke length, but also less than the maximum error claimed by the manufacturer (Peach Innovations), highlighting the highly reliable and consistent nature of technique in elite scullers despite higher variability in the effort-based variable, *stroke power*.

Table 4: Individual intra-class correlation coefficients and typical error from each pair of trials, averaged for all subjects (n=40 strokes per trial for each subject for each variable), for all scullers (n=4 crews for *boat velocity* and *stroke rate*, n=12 oars for all other variables).

	Value (range)	Olympic rowers, averaged (6 rowers in 2 doubles & 2 singles)		
		Trial 1 vs. Trial 2	**Trial 3 vs. Trial 2**	**Trial 3 vs. Trial 1**
Boat velocity	Typical error (%)	1.0 (0.83 – 1.3)	0.78 (0.63 – 0.89)	1.0 (0.86 – 1.2)
	Intra-class R	*0.46 (0.41 – 0.57)*	*0.50 (0.14 – 0.65)*	*0.35 (-0.05 – 0.57)*
Stroke rate	Typical error (%)	1.3 (1.2 – 1.5)	1.2 (0.92 – 1.5)	1.1 (0.80 – 1.2)
	Intra-class R	*0.36 (-0.23 – 0.65)*	*0.55 (0.21 – 0.77)*	*0.41 (-0.13 – 0.64)*
Stroke power	Typical error (%)	4.3 (2.0 – 7.9)	4.4 (2.4 – 7.6)	4.1 (2.6 – 6.7)
	Intra-class R	*0.21 (-0.08 – 0.58)*	*0.22 (-0.13 – 0.54)*	*0.31 (0.02 – 0.69)*
Drive Start	Typical error (%)	1.7 (1.0 -4.5)	1.5 (1.0 – 2.4)	1.6 (1.0 – 4.8)
	Intra-class R	*0.34 (-0.10 – 0.65)*	*0.27 (-0.26 – 0.65)*	*0.33 (-0.02 – 0.63)*
Catch Angle	Typical error (°)	0.7 (0.4 – 1.1)	0.6 (0.4 – 1.0)	0.7 (0.3 – 1.2)
	Intra-class R	*0.04 (-0.26 – 0.21)*	*0.25 (-0.15 – 0.52)*	*0.08 (-0.16 – 0.39)*
Finish Angle	Typical error (°)	0.8 (0.6 – 1.4)	0.7 (0.5 – 1.3)	0.8 (0.5 – 1.4)
	Intra-class R	*0.13 (-0.35 – 0.51)*	*0.19 (-0.19 – 0.57)*	*0.13 (-0.14 – 0.46)*
Catch Slip	Typical error (°)	0.7 (0.2 – 2.0)	0.7 (0.3 – 1.6)	0.7 (0.2 – 1.9)
	Intra-class R	*0.12 (-0.27 – 045)*	*0.07 (-0.37 – 0.41)*	*0.07 (-0.25 – 0.33)*
Finish Slip	Typical error (°)	1.0 (0.8 – 1,5)	0.9 (0.7 – 1.3)	1.0 (0.6 – 1.5)
	Intra-class R	*0.05 (-0.22 – 0.46)*	*0.18 (-0.07- 0.41)*	*0.08 (-0.24 – 0.38)*

Typical error is presented as a coefficient of variation (%) for non-angular variables, and as degrees for angular variables. The range of each variable is given.

Smallest worthwhile effect sizes

Treating trial 1 as a familiarisation trial and considering the typical error between trials 2 versus 3 as the normal variation in performance, the smallest worthwhile effect following future interventions would be 0.2 times that variation (Cohen, 1988). If case studies on these specific athletes are to be carried out, their individual reliability values should be used, but if a group of elite scullers are to be investigated the smallest worthwhile effect in *boat velocity* is 0.13%, in *stroke rate* is 0.16%, and in *stroke power* is 0.44%. The smallest worthwhile effect sizes calculated for angular variables and for *drive start* are smaller than the systems' accuracy level (0.5°) therefore any change seen above this in these variables is worthwhile. The high range in the individual between-trial typical error emphasises that an individualistic approach to recommendations is preferable in an elite group.

Table 5: Grouped intra-class correlation coefficients and typical error from each trial (n=40 strokes per trial for each variable), for all scullers (n=4 crews for *boat velocity* and *stroke rate*, n=12 oars for all other variables).

	Value (90% CI) given	Olympic rowers, grouped (6 rowers in 2 doubles & 2 singles)		
		Trial 1 vs. Trial 2	**Trial 3 vs. Trial 2**	**Trial 3 vs. Trial 1**
Boat velocity	Typical error (%)	0.55 (0.34 – 1.6)	0.63 (0.39 – 1.9)	0.60 (0.40 – 1.3)
	Intra-class R	*1.00 (0.92 – 1.00)*	*1.00 (0.90 – 1.00)*	*1.00 (0.97 – 1.00)*
Stroke rate	Typical error (%)	0.70 (0.44 – 2.1)	0.81 (0.50 – 2.4)	1.4 (0.87 – 4.2)
	Intra-class R	*0.93 (0.02 – 1.00)*	*0.87 (-0.32 – 1.00)*	*0.71 (-0.64 – 0.99)*
Stroke power	Typical error (%)	1.3 (0.94 – 2.0)	2.2 (1.6 – 3.4)	2.2 (1.6 – 3.4)
	Intra-class R	*1.00 (0.99 – 1.00)*	*0.99 (0.97 – 1.00)*	*0.99 (0.97 – 1.00)*
Drive Start	Typical error (%)	0.41 (0.31 – 0.64)	0.43 (0.32 – 0.66)	0.78 (0.59 – 1.2)
	Intra-class R	*0.99 (0.98 – 1.00)*	*0.99 (0.97 – 1.00)*	*0.97 (0.91 – 0.99)*
Catch Angle	Typical error (°)	0.2 (0.1 – 0.3)	0.4 (0.3 – 0.6)	0.4 (0.3 – 0.7)
	Intra-class R	*0.99 (0.98 – 1.00)*	*0.98 (0.93 – 0.99)*	*0.97 (0.91 – 0.99)*
Finish Angle	Typical error (°)	0.2 (0.2 – 0.4)	0.3 (0.2 – 0.4)	0.4 (0.3 – 0.6)
	Intra-class R	*0.99 (0.97 – 1.00)*	*0.99 (0.97 – 1.00)*	*0.98 (0.93 – 0.99)*
Catch Slip	Typical error (°)	0.2 (0.2 – 0.3)	0.2 (0.1 – 0.3)	0.3 (0.2 – 0.4)
	Intra-class R	*0.99 (0.98 – 1.00)*	*1.00 (0.99 -1.00)*	*0.99 (0.97 – 1.00)*
Finish Slip	Typical error (°)	0.3 (0.2 – 0.4)	0.2 (0.2 – 0.5)	0.4 (0.3 – 0.6)
	Intra-class R	*0.99 (0.96 – 1.00)*	*0.98 (0.94 – 0.99)*	*0.97 (0.92 – 0.99)*

Typical error is presented as a coefficient of variation (%) for non-angular variables, and as degrees for angular variables. The 90% confidence interval is given for each value.

Summary

Higher reliability between trials in *boat velocity* and the technique-based variables than in previous research promotes the use of PowerLine™ for biomechanical feedback in elite scullers. The expected variation between performances in an elite athlete is 1.0% (Hopkins et al., 1999). All athletes showed typical error in *boat velocity* (i.e. performance) less than 1% for trials 2 versus 3 (treating trial 1 as a familiarisation trial) but higher typical errors were seen in *stroke rate*, *stroke power* and *drive start*. Higher *Stroke rate* errors can be explained by the dependence of the scullers on the Nielsen-

Kellerman rate meter and its low display accuracy, and *drive start* variability is overestimated compared to when considered as a percentage of stroke time. However, the low reliability in *stroke power* causes concern and directs future investigation into its relationship with *boat velocity*. Variation in PowerLine™ *stroke power* (measured at the pin, in the direction of boat movement) may not be strongly correlated with actual stroke to stroke *boat velocity* and its use as a performance predictor may be questionable. It is known that the relationship between *boat velocity* and rower power (measured via the bend in the oar shaft) varies with boat type and the same increase in power results in larger velocity gains in larger boats (Kleshnev, 1999). As we only investigated relatively small boats in this article, the low *boat velocity* variation in the present results despite high *stroke power* (at the pin) variation may therefore be understandable. The higher variability seen from stroke-to-stroke and from trial-to-trial in double versus single scullers could potentially have influence on training methods. Higher stroke-to-stroke consistency is related to better performance level and higher efficiency (Kleshnev, 1996; Smith & Spinks, 1995) so if both scullers within a double could become as consistent as the singles scullers, performance gains may be found. Higher reliability may be seen if the number of subjects or strokes was increased, but this is problematic whilst maintaining specificity to Olympic sculling crews and not being detrimental to training regimes. The large range in individual typical error between trials supports the need for an individual approach to analysis at the elite performance level.

CHAPTER 6 – POWERLINE™ BIOMECHANICAL VARIABLES AS PREDICTORS OF SCULLING PERFORMANCE

This chapter comprises the following technical report submitted to Rowing New Zealand.

> Coker, J., Nolte, V., & Hume, P. A. (2009). *PowerLine™ biomechanical variables as predictors of sculling performance* (Technical report for Rowing New Zealand). (pp. 1-25). Auckland: Institute of Sport and Recreation Research New Zealand, Auckland University of Technology.

Overview

Boat velocity is the ultimate sculling performance measure, but is highly affected by environmental conditions and gives limited understanding of why a performance level is achieved. A need exists for a set of biomechanical stroke variables capable of accurately predicting boat velocity. Theoretically, stroke power is related to boat velocity, but past findings are mixed and no data are available for the specific power measure from the PowerLine™ Boat Instrumentation System. The aim of this study was to determine whether the PowerLine™ *stroke power* value, in association with other variables from the PowerLine™, was significantly related to *boat velocity*. Six automatic and nine computed biomechanical stroke variables were collected from PowerLine™ data for 120 strokes each from two elite single scullers at race rate and pace. Stepwise linear regression analyses were computed to predict *boat velocity* from these variables. *Stroke power* was significantly correlated with *boat velocity* for both scullers (R = 0.44, 90% CI: 0.31 to 0.55; and R = 0.67, 90% CI: 0.58 to 0.75) for stroke by stroke analysis. The strength of the correlation increased to 0.60 (90% CI: 0.49 to 0.69) and 0.88 (90% CI: 0.84 to 0.91) for five stroke average analyses. Stepwise linear regression models based on PowerLine™ automatic variables explained 24% and 49% of the

variation in *boat velocity* for the two scullers with slight increases in variance explained when adding computed variables and the previous stroke's velocity to the model. The strongest predictive models for *boat velocity* explained 84% and 85% of the variance for the two scullers when five stroke averages were used. PowerLine™ *stroke power* was a predictor of sculling performance, but the strength of its relationship with *boat velocity* was not consistent; this study reiterates the necessity for individualisation of elite sculler biomechanical analysis. A combination of the stroke variables available from PowerLine™ can explain a large percentage of the variance in *boat velocity*, but in future research alternative variables and/or instrumentation may increase the percentage of *boat velocity* variation that can be explained. Sculler analyses averaging variables over five strokes were more meaningful than stroke by stroke analysis and this approach is recommended.

Introduction

The ultimate measure of sculling performance is the time taken to complete a set distance on-water (i.e., boat velocity). Extraneous variables such as wind and water flow-rate affect the reliability of this performance indicator, and knowledge purely of the result gives limited indication of why the outcome has occurred (Maestu, Jurimae, & Jurimae, 2005). It is therefore necessary to use other measurable stroke variables to monitor performance. Performance changes can then be more confidently identified, and the potential to repeat gains through similar technical alterations or physiological adaptations is increased. The relationship between these stroke variables and sculling performance (*boat velocity* for the purpose of this article) is quantifiable by statistical analysis and the more direct the relationship, the more valuable the testing will be (Maestu et al., 2005). Power is the standard performance predictor used by Rowing New Zealand in their off-water (ergometer) testing[12]. Ideally, on-water PowerLine™ *stroke power* would be related to off-water power and on-water performance, and would be a useful and comparable variable.

[12] The Concept2 uses power to calculate time so the two are interchangeable for ergometer testing

Sculling performance depends on the sculler(s) producing as high a force as possible, over as long a distance as possible, as quickly as possible (Nolte, 1991) (i.e., producing high stroke power). Theoretically, PowerLine™ *stroke power* should show strong positive correlations with *boat velocity*. However, past literature has reported mixed findings on how rower power is related to on-water performance (Baudouin & Hawkins, 2004; Kleshnev, 1999; Smith et al., 1994). Studies that have reported significant correlations have used bend in the oar shaft to calculate power, but the PowerLine™ Boat Instrumentation System (PowerLine™) used by Rowing New Zealand uses force applied to the pin in the direction of the longitudinal axis of the boat to give its *stroke power* variable. PowerLine™ is preferable for use by Rowing New Zealand as it does not interfere with the scullers' techniques and it is quick and easy to install. As well as *stroke power,* a number of other biomechanical stroke variables can be produced by PowerLine™ automatically, and calculated for example, using Excel templates or macros. Ideally, the quickly and easily produced automatic variables would predict *boat velocity* well and therefore coaches could use PowerLine™ to monitor on-water rowing performance without the need for additional data processing. If these automatic variables alone are not sufficient, alternative stroke variables computed from these data may need to be added to a mathematical model of rowing performance to allow such monitoring.

No past literature is available indicating whether the biomechanical stroke variables measured via the methodology used by PowerLine™ relate to boat velocity. The aim of this study was to determine whether PowerLine™ *stroke power*, in association with the other automatic and/or computed variables produced by PowerLine™, were significantly related to *boat velocity*. Recommendations for training and conclusions from interventions can then be made soundly based on collection of relevant variables.

Methods

Participants

Two Olympic-level heavy-weight single scullers (male: 101.7 kg, 2.00 m, 29 years; female: 77.3 kg, 1.81 m, 20 years) volunteered for the study. Both participants were informed of the procedures and gave written consent.

Procedures

Single sculls were equipped with PowerLine™ to record pin force, oar angle and boat velocity at 50 Hz throughout each trial. The two scullers performed three 500-m trials from a flying start at the self-selected constant rate and pace normally exerted in the middle 1000 m of a 2000-m race. Rest time of more than five minutes was given between 500-m trials to allow the scullers to perform at race pace without overly fatigued technique throughout the 120 strokes that were analysed (middle 40 strokes of each 500-m piece for each sculler). Trials were carried out on the final 500 m of a pre-measured 2000-m rowing course with 500-m markers.

The following variables were collected for each of the 120 strokes:

1. Automatic

- *Stroke power (W)* – average sculler power for the stroke phase (sum of left and right sides). Power is calculated as the product of the handle force and handle velocity components in the x-direction (direction of the longitudinal axis of the boat), and only included in the averaged *stroke power* when positive. The handle force was calculated as pin force * outboard / oar length.
- *Catch angle (°)* – minimum angle reached during the stroke (average of left and right sides)
- *Finish angle (°)* – maximum angle reached during the stroke (average of left and right sides)
- *Catch slip (°)* – angular displacement from the minimum gate angle to the point at which the force value exceeded 196 N (20 kgF displayed by

PowerLine™) in the direction of the longitudinal axis of the boat during that stroke (average of left and right sides)

- *Finish slip (°)* – angular displacement from the point where the force value falls below 98 N (10 kgF), to the maximum angle (average of left and right sides)
- *Stroke rate (spm)* - number of strokes/minute

2. Computed

The following variables were also computed for each stroke on request from the Rowing NZ elite coaches after initial athlete testing using the PowerLine™ system had displayed apparent differences between athletes in these variables;

- *Peak force (N)* – average of left and right sides of one stroke
- *Total angle (°)* – catch angle subtracted from the finish angle (average of left and right sides)
- *Total slip (°)* – the sum of the catch and finish slips for that stroke (average of left and right sides)
- *Working angle (°)* – total angle minus the total slip (average of left and right sides)
- *Power difference (W)* – absolute difference between the left and right sides in stroke power
- *Catch angle difference (°)* – absolute difference between the left and right sides in catch angle
- *Finish angle difference (°)* – absolute difference between the left and right sides in finish angle
- *Catch slip difference (°)* – absolute difference between the left and right sides in *catch slip* (°)
- *Finish slip difference (°)* – absolute difference between the left and right sides in *finish slip (°)*

- *Previous stroke boat velocity (m/s)* – mean boat velocity from the previous stroke.

Statistical analyses

Pearson correlations were computed using SPSS for each independent variable against *boat velocity* ad R and p values presented. Scatter plots were generated in Excel for these relationships and the curve estimation function used to determine any non-linear trends. Using SPSS, stepwise linear regression analyses were computed separately for each sculler with the dependent variable, *boat velocity* and the predictor variables; *stroke power, catch angle, finish angle, catch slip, finish slip* and *stroke rate*. The stepping method criteria were set as $p \leq 0.05$ for entry, and ≥ 0.15 for removal (Hopkins, 2000c). The process was repeated adding the computed independent variables; *peak force, total angle, total slip, working angle, power difference, catch angle difference, finish angle difference, catch slip difference,* and *finish slip difference*. *Previous stroke boat velocity* was then added as an input variable to compute a third linear model for each sculler. Finally, five stroke moving averages were computed for all variables and stepwise linear regression analyses again computed to predict *boat velocity*. R and p values were recorded for each model, and a pre-formatted spreadsheet was used to obtain the 90% confidence interval for the correlation coefficients (Hopkins, 2007a). Analyses were performed via the log-transformed variables for all except *power difference* and angular variables. Correlations were taken as significant when $p \leq 0.05$.

Results

From visual inspection, all correlations were linear (e.g., *boat velocity* versus *stroke power* plots shown in Figure 15). Table 6 presents mean ±SD for all PowerLine™ variables for each sculler. Similar stroke to stroke variation (reported as SD) was seen in both scullers for most variables except *stroke rate* and *power difference*. Sculler B showed variation in *stroke rate* double that of Sculler A (1.3% versus 2.6%). For *power difference* Sculler B showed a lower mean and variation than Sculler A (33 ±10 W versus 5 ±3 W). Pearson correlation coefficients (R values) with 90% confidence intervals are also presented in Table 6.

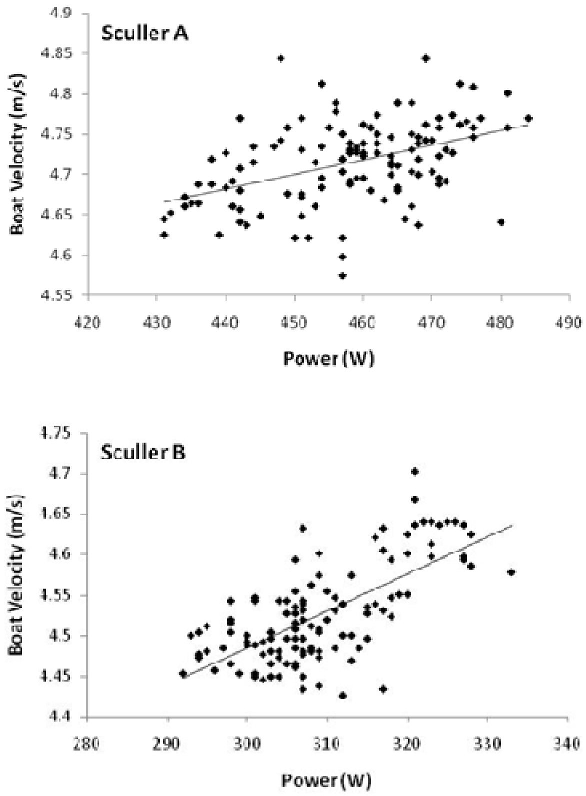

Figure 15: Scatter plots for *boat velocity* versus *stroke power* for Sculler A and Sculler B including the linear regression trend-lines.

For single stroke analyses, both scullers displayed significant positive correlations between *stroke power* and *boat velocity*. Significant correlations were also displayed between *catch angle* and *boat velocity*, but Sculler A showed a negative correlation (R = -0.32, 90% CI: -0.45 to -0.18) and Sculler B, a positive correlation (R = 0.43, 90% CI: 0.30 to 0.55). Due to the negative nature of the *catch angle* values, negative correlations signified that *boat velocity* increased as the *catch angle* became more negative (i.e., longer). For Sculler A, significant correlations were additionally seen between *boat velocity* and *peak force* (R = 0.73, 90% CI: 0.52 to 0.86) *total angle* (R = 0.47, 90% CI: 0.15 to 0.70) and *working angle* (R = 0.42, 90% CI: 0.09 to 0.67). For Sculler B significant correlations were seen between *boat velocity* and all of the automatic variables, and between *boat velocity* and *peak force*, *total angle, working angle,* and *power difference*. *Previous stroke boat velocity* had a significant influence on seven of the stroke variables for Sculler A, and on 11 of the stroke variables for Sculler B (see Table 7). Scatter plots for change in *boat velocity* from the previous stroke versus *stroke power* are presented in Figure 16.

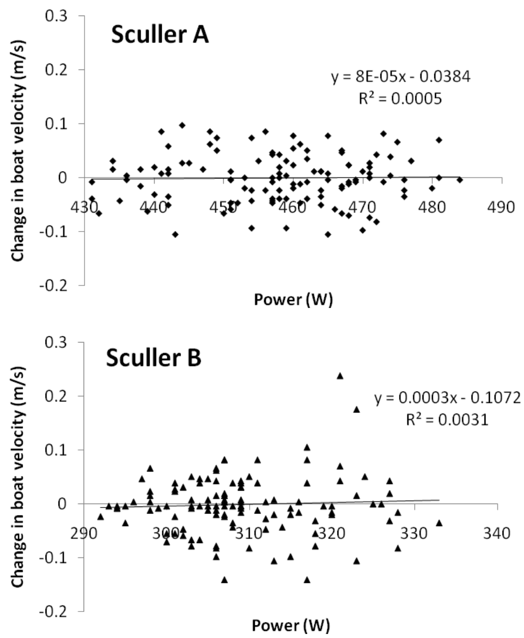

Figure 16: Scatter plots for change in *boat velocity* from the previous stroke versus *stroke power* for Sculler A and Sculler B including the linear regression trend-lines, R^2 values and equations.

Table 6: Mean ±SD for PowerLine™ variables from n = 120, and Pearson correlation coefficients with 90% confidence intervals (90% CI) for automatic and computed PowerLine™ variables versus *boat velocity* using single stroke (n = 120) and five-stroke average analyses (n = 116).

		Mean ±SD (n = 120)		R (90% CI) vs. boat velocity using single strokes (n = 120)		R (90% CI) vs. boat velocity using 5 stroke averages (n = 116)	
		Sculler A	**Sculler B**	**Sculler A**	**Sculler B**	**Sculler A**	**Sculler B**
AUTOMATIC	*Boat velocity (m/s)***	4.71 ±1.1%	4.53 ±1.3%	-	-	-	-
	Stroke power (W)	458 ±2.7%	309 ±2.9%	0.44 (0.31 to 0.55)*	0.67 (0.58 to 0.75)*	0.60 (0.49 to 0.69)*	0.88 (0.84 to 0.91)*
	Stroke rate (spm)	34.3 ±1.3%	32.3 ±2.6%	-0.02 (-0.17 to 0.13)	0.51 (0.39 to 0.61)*	0.02 (-0.13 to 0.17)	0.61 (0.50 to 0.70)*
	Catch angle (°)	-67.8 ±0.7	-66.1 ±0.8	-0.32 (-0.45 to -0.18)*	0.43 (0.30 to 0.55)*	-0.50 (-0.61 to -0.38)*	0.50 (0.38 to 0.61)*
	Finish angle (°)	51.3 ±0.6	47.6 ±0.6	0.15 (0.00 to 0.29)	-0.31 (-0.44 to -0.17)*	0.40 (0.26 to 0.52)*	-0.52 (-0.62 to -0.40)*
	Catch slip (°)	5.5 ±0.3	7.2 ±0.3	-0.02 (-0.17 to 0.13)	-0.35 (-0.48 to -0.21)*	0.11 (-0.04 to 0.26)	-0.60 (-0.69 to -0.49)*
	Finish slip (°)	15.4 ±0.6	14.2 ±0.8	-0.10 (-0.25 to 0.05)	0.26 (0.13 to 0.41)*	0.03 (-0.12 to 0.18)	0.49 (0.36 to 0.760)*
COMPUTED	*Peak force (kgF)*	60.7 ±2.4%	49.2 ±2.2%	0.49 (0.37 to 0.60)*	0.54 (0.42 to 0.64)*	0.71 (0.62 to 0.78)*	0.68 (0.59 to 0.75)*
	Total angle (°)	119.0 ±1.0	113.7 ±1.1	0.32 (0.18 to 0.45)*	-0.48 (-0.59 to -0.35)*	0.58 (0.47 to 0.67)*	-0.59 (-0.68 to -0.48)*
	Total slip (°)	21.0 ±0.7	21.4 ±0.8	-0.09 (-0.24 to 0.06)	0.10 (-0.05 to 0.25)	0.06 (-0.09 to 0.21)	0.28 (0.13 to 0.42)*
	Working angle (°)	98.0 ±1.1	92.3 ±1.2	0.37 (0.23 to 0.49)*	-0.51 (-0.61 to -0.39)*	0.44 (0.31 to 0.56)*	-0.60 (-0.69 to -0.49)*
	Power difference (W)	33 ±10	5 ±3	-0.03 (-0.18 to 0.12)	0.16 (0.01 to 0.30)	-0.03 (-0.18 to 0.12)	0.25 (0.10 to 0.39)*
	Catch angle difference (°)	0.9 ±0.6	0.5 ±0.3	0.01 (-0.14 to 0.16)	0.02 (-0.13 to 0.17)	0.11 (-0.04 to 0.26)	0.11 (-0.04 to 0.26)
	Catch slip difference (°)	1.5 ±0.6	1.7 ±0.5	-0.11 (-0.26 to 0.04)	0.02 (-0.13 to 0.17)	-0.22 (-0.36 to -0.07)*	-0.12 (-0.27 to 0.03)
	Finish angle difference (°)	3.2 ±1.8	1.4 ±0.9	0.05 (-0.10 to 0.20)	0.03 (-0.12 to 0.18)	0.29 (0.14 to 0.42)*	0.04 (-0.11 to 0.19)
	Finish slip difference (°)	1.6 ±1.1	2.0 ±1.0	-0.07 (-0.22 to 0.08)	0.14 (-0.01 to 0.28)	-0.40 (-0.52 to -0.26)*	0.27 0.12 to 0.41)*

**Correlation is significant at the 0.05 level*

Using moving five stroke averages for all variables increased the strength of all significant correlations (see Table 6). Using this approach, the correlation between *boat velocity* and *stroke power* resulted in R values of 0.60 (90% CI: 0.49 to 0.69) and 0.88 (90% CI: 0.84 to 0.91) for Scullers A and B respectively. In both scullers, *finish slip difference* showed a non-significant correlation with *boat velocity* using single stroke analysis. However, when five stroke analysis was adopted, significant correlations were seen (R = -0.40 (90% CI: -0.52 to -0.46) for Sculler A and 0.34 (90% CI: 0.12 to 0.41) for Sculler B). Using single and five stroke analysis, neither sculler showed significant correlations between *boat velocity* and *catch angle difference*. Only Sculler A showed significant correlations between *boat velocity* and *finish angle difference* (R = 0.29, 90% CI: 0.14 to 0.42), and *catch slip difference* (R = -0.22, 90% CI: -0.36 to -0.07).

Table 7: Pearson correlation coefficients with 90% confidence intervals (90% CI) for automatic and computed PowerLine™ variables versus *previous stroke boat velocity.*

	R (90% CI) versus *previous stroke boat velocity* (n = 120)	
	Sculler A	**Sculler B**
Boat velocity (m/s)	0.60 (0.49 to 0.69)*	0.58 (0.47 to 0.67)*
Stroke power (W)	0.40 (0.27 to 0.52)*	0.61 (0.51 to 0.70)*
Stroke rate (spm)	0.13 (-0.02 to 0.28)	0.48 (0.35 to 0.59)*
Catch angle (°)	-0.22 (-0.36 to -0.07)*	0.28 (0.13 to 0.41)*
Finish angle (°)	0.11 (-0.04 to 0.26)	-0.26 (-0.40 to -0.11)*
Catch slip (°)	0.11 (-0.04 to 0.26)	-0.38 (-0.50 to -0.24)*
Finish slip (°)	-0.01 (-0.16 to 0.14)	0.37 (0.23 to 0.49)*
Peak force (kgF)	0.50 (0.38 to 0.61)*	0.45 (0.37 to 0.60)*
Total angle (°)	0.23 (0.08 to 0.37)*	-0.34 (-0.47 to -0.20)*
Total slip (°)	0.04 (-0.11 to 0.19)	0.21 (0.06 to 0.35)*
Working angle (°)	0.19 (0.04 to 0.33)*	-0.45 (-0.56 to -0.32)*
Power difference (W)	-0.01 (-0.16 to 0.14)	0.06 (-0.09 to 0.21)
Catch angle difference (°)	0.03 (-0.12 to 0.18)	0.02 (-0.13 to 0.17)
Catch slip difference (°)	-0.03 (-0.18 to 0.12)	-0.04 (-0.19 to 0.11)
Finish angle difference (°)	0.07 (-0.08 to 0.22)	0.06 (-0.09 to 0.21)
Finish slip difference (°)	-0.20 (-0.34 to -0.05)*	0.12 (-0.03 to 0.27)

**Correlation is significant at the 0.05 level*

Stepwise linear regression analyses

Presented in Table 8 are the results from the stepwise linear regression analyses. Using single stroke analysis, with just the automatic stroke variables, both scullers presented a model including *stroke power* and a measure of reach at either the catch (Sculler A) or the finish (Sculler B). Only 24% of the variance in *boat velocity* for Sculler A was explained by the model from just automatic variables whilst 49% of the variance in *boat velocity* was explained for Sculler B. For the analyses including both automatic and computed variables for Sculler A, *stroke power* was replaced with *peak force,* whilst in Sculler B *stroke power* was still included as a predictor but *finish angle* was replaced with *total angle.* Again, *boat velocity* for Sculler B was better explained than for Sculler A (50% versus 28% respectively). When *previous stroke boat velocity* was also added to the model input, 43% of variation in *boat velocity* was explained for Sculler A by *previous stroke boat velocity* and *working angle,* and 55% was explained for Sculler B by *stroke power, total angle, previous stroke boat velocity,* and *power difference.* For Sculler A, *boat velocity* was increased by a higher *previous stroke boat velocity* (R = 0.60, 90% CI: 0.49 to 0.69) and increased *working angle*. For Sculler B, *boat velocity* was increased through increased *stroke power*, decreased *total angle*, a higher *previous stroke boat velocity* (R = 0.58, 90% CI: 0.47 to 0.67) and increased *power difference.* Using the moving average over five strokes as the input for the model resulted in 84% of *boat velocity* variance being explained for Sculler A via *peak force, catch angle, stroke rate, catch slip, finish angle, stroke power, finish slip difference* and *working angle.* The same analysis resulted in 85% of *boat velocity* variance being explained for Sculler B via *stroke power, finish slip difference, catch angle* and *power difference.*

Table 8: Summary of stepwise linear regression analyses between *boat velocity* and biomechanical stroke variables obtained from PowerLine™ data.

Independent variables Input	**Variables included in model**		**R (90% CI)**		
	Sculler A	Sculler B	Sculler A	Sculler B	n
Automatic	*Stroke power* *Catch angle*	*Stroke power* *Finish angle*	0.49 (0.36 to 0.60)*	0.70 (0.62 to 0.77)*	120
Automatic AND Computed	*Peak force* *Catch angle*	*Stroke power* *Total angle*	0.53 (0.41 to 0.63)*	0.71 (0.62 to 0.78)*	120
Automatic, Computed, AND *previous stroke boat velocity*	*Previous stroke boat velocity* *Working angle*	*Stroke power* *Total angle* *Previous stroke boat velocity* *Power difference*	0.66 (0.56 to 0.74)*	0.74 (0.66 to 0.80)*	119
Automatic AND Computed, using 5-stroke averages	*Peak force* *Catch angle* *Stroke rate* *Catch slip* *Finish angle* *Stroke power* *Finish slip difference* *Working angle*	*Stroke power* *Finish slip difference* *Catch angle* *Power difference*	0.92 (0.89 to 0.94)*	0.92 (0.89 to 0.94)*	116

**correlation is significant at the 0.05 level.*

Discussion

The two elite scullers in our study were more elite and/or heavy in nature than scullers/rowers reported in published studies (Elliott et al., 2002; Hofmijster, Landman, Smith, & Van Soest, 2007; Kleshnev, 1999), so mean biomechanical stroke data were as expected. For example, compared to 458 W ±2.7% and 309 W ±2.9% respectively for mean ±SD *stroke power* for the male and female scullers in this study, Kleshnev (1999) found a mean *stroke power* of 325 W for men and 247 W for women. However, both heavyweight and lightweight scullers were involved in Kleshnev's study, therefore a lower mean *stroke power* would be expected. Similarly, Elliott et al. (2002), found peak force values of 441 N for men and 356 N for women at a stroke rate of 28 spm (compared to 596 N ±2.4% and 483 N ±2.2% for Scullers A and B respectively) – understandably lower than our data as the scullers were U23 level and the *stroke rate* was on average 5.3 spm lower. It must also be noted that direct comparisons are not possible as all of these past studies used a measure of the bend in the oar shaft, rather than longitudinal force at the pin to calculate *stroke power* (as produced by PowerLine™). *Catch angles* and *finish angles* for Scullers A and B sit within the higher end of the range presented from scullers over 3.5 years of data collected at the Australian Institute of Sport (Kleshnev, 2001a).

The lower consistency level in *stroke rate* seen in Sculler B compared to Sculler A (SD of 2.6% and 1.3% respectively) can be explained by the slightly lower performance and experience level of Sculler B, potentially accounting for the difference between scullers in the correlation coefficients for *boat velocity* and *stroke rate*. Although Sculler B exhibited a significant positive correlation between *stroke rate* and *boat velocity*, in agreement with past studies (Kleshnev, 1996; Martin & Bernfield, 1980), the smaller variation in *stroke rate* in Sculler A may not be enough to exhibit large enough changes in *boat velocity* for a correlation to be identified.

Bi-variate correlations with boat velocity

Single stroke analysis

The significant positive correlations between *boat velocity* and *stroke power* found for both Scullers A and B were expected (R = 0.44, 90% CI: 0.31 to 0.55 and R = 0.67, 90% CI: 0.58 to 0.75 respectively). During each stroke, impulse must be given to the rower-boat system either to increase mean *boat velocity*, or to maintain mean *boat velocity* by overcoming the unavoidable decrease during the stroke cycle due to drag forces. Impulse can be increased either by lengthening the time through which propulsive force is exerted, or by increasing the mean stroke force. *Boat velocity* is the definitive measure of performance, and in increasing *boat velocity*, the blade must travel faster through its fixed range of motion (i.e., reducing the drive time) whilst maintaining the same, or as high as possible, impulse development during the drive phase. Thus rate of impulse development (i.e., power) becomes vital and it would therefore be expected that *stroke power* would be correlated with *boat velocity*. Although impulse could be calculated directly, *stroke power* was chosen due to its accessibility to the Rowing New Zealand coaches directly from PowerLine™.

It cannot be anticipated that *boat velocity* variation would be explained entirely by *stroke power*, as measured by the methodologies used in this study. *Stroke power* is measured at the pin whereas propulsion occurs at the blade so discrepancies will exist between measured *stroke power* and actual power or energy used for generating *boat velocity*. Propulsion in water can only be achieved by giving water some momentum therefore energy will always be lost to the water (Van Ingen Schenau & Cavanagh, 1990). The amount of energy that is lost will depend on sculler technique and blade design, and is a measure of efficiency (Affeld et al., 1993). For example, it is likely that some scullers pull with greater inclination and bury the blade deeper resulting in a greater area of the loom moving through the water, increasing drag production and reducing *boat velocity* for the same *stroke power* (Celentano et al., 1974). It was believed that between one third and one quarter of energy was lost to the flow of water around the blade (Affeld et al., 1993), but later experimental studies reported better efficiency values for oars of 75-85%, or a total of about 20% lost as a result of water movement at the blade (Hofmijster et al., 2007; Kleshnev, 1999; Nolte, 1984). Finally, a direct linear relationship between *stroke power* and *boat velocity* would not necessarily be anticipated because drag force increases disproportionally with velocity and power is proportional to the third power of velocity (Hill & Fahrig, 2008). Data from 21 crews resulted in correlation coefficients between actual and trend data in the range of 0.8 to 0.9 for the power-velocity equation $P = k*v^3$ (Kleshnev, 1999). However, using our data, correlations between *stroke power* and *boat velocity* cubed resulted in no change to the correlation (R value) for either sculler compared to the initial linear regression analysis.

Theoretically, *stroke power* could relate better to change in *boat velocity* over the stroke. If a very low *boat velocity* occurs in the previous stroke, a below mean *boat velocity* may be recorded in the next stroke despite a high *stroke power* and boat acceleration being achieved. This was not the case in our two scullers at the fixed rate – *stroke power* was not correlated with change in *boat velocity* compared to the previous stroke (see Figure 16). Despite power in the past having been determined as the main factor affecting rowing performance, increasing power at the same stroke rate does not always increase velocity (Kleshnev, 1999). The relationship between *stroke rate*, *stroke power*, and *boat velocity* for each crew or single sculler is therefore expected to be different and requires individual assessment. High correlation coefficients have been seen between stroke power and rowing performance for between-subject effects but there is limited within-subject, fixed rate data (Baudouin & Hawkins, 2004; Smith et al., 1994). As with *stroke power*, both scullers showed significant positive correlations between *peak force* and *boat velocity*. Average force would be expected to relate well to *boat velocity* due to the increased impulse or power that could be achieved during the drive phase (for a fixed drive time or handle velocity respectively) and it is recommended that this variables be calculated in future research. However, if *peak force* increases without a matched increase in average force, a more triangular than rectangular curve shape results, reducing efficiency and decreasing *boat velocity* (Kleshnev, 1999). Given both scullers showed significant correlations between *peak force* and *boat velocity* points towards a high level of consistency in curve shape regardless of *peak force* in these scullers.

A long stroke is necessary for a high level of performance in sculling and a long outboard arch (*total angle*) creates large reaction forces at the blade, aiding boat propulsion (Nolte, 1991). The longer the arch through which the oar travels each stroke, the more work can be done, and the further the boat will travel per stroke, increasing *boat velocity*. Longer angles at the catch will also enable easier entry of the blade without negative forces and “backsplash” because it is easier to match the blade velocity relative to the water with the boat velocity relative to the water in the longitudinal direction (Macrossan & Macrossan, 2006; Nolte, 1984). Past research reported that rower forces exerted in the early and latter phases of the drive are inefficient due to wasted energy from high transverse forces not aiding propulsion (Celentano et al., 1974; Körner, 1979; Martin & Bernfield, 1980; Smith & Loschner, 2002; Spinks, 1996). It has now been argued that long catch angles do not waste energy because power is the scalar product of force and velocity, and the scalar product of any force perpendicular to the direction of boat travel is zero, so longer catch angles merely increase the gearing (Kleshnev, 1999). Additionally, lift forces act in the early and latter phases of the drive and create highly efficient boat propulsion (Affeld & Schichl, 1985; Caplan & Gardner, 2007b; Nolte, 1984).

At the 2000 Olympic Games, anthropometric data were recorded for 273 rowing competitors (Kerr et al., 2007). Compared to the general population, heavyweight elite level rowers were significantly taller, had longer segment lengths, had arm spans longer than their height, and shorter sitting height relative to their overall height (i.e. relatively longer legs). The best placed rowers from this competition were significantly taller than the rest. These athletes would be able to achieve longer stroke lengths, which supports the idea that success in sculling should be related to *total angle*. Long angles, particularly catch angles, which facilitate the benefits of a peak force occurring before the square off position, should therefore be correlated with increased boat velocity (Kleshnev, 2006b, 2007c; Nolte & Morrow, 2002; Schwanitz, 1991).

Both scullers showed significant correlations between *boat velocity* and *catch angle* but in opposite directions. Sculler A displayed the anticipated relationship whereby a longer *catch angle* related to increased *boat velocity*, whilst for Sculler B a longer *catch angle* must have been achieved at the detriment of one or more other performance related factor(s). One such factor was *stroke rate* in this sculler - *catch angle* was shorter as *stroke rate* increased (R = 0.72, 90% CI: 0.64 to 0.79) and *stroke rate* was significantly positively related to *boat velocity* (see Table 6). Although in general scullers would be advised to achieve as long a *catch angle* as their flexibility will allow, over reaching at the catch in an unstable body position may result in reduced coordination and/or rate of blade entry and force production, at the detriment to performance.

Similarly, Sculler A showed increased performance from a longer *total angle* whilst Sculler B displayed reduced performance (see Table 6). The non-significant relationship between *finish angle* and *boat velocity* for Sculler A, and the match in magnitude of the correlation values between *boat velocity* and *catch angle*, and between *boat velocity* and *total angle*, means that variation in *boat velocity* due to change in *total angle* is from variation in *catch angle*. Performance in this sculler is therefore unaffected by their length at the finish. Longer *finish angles* and *catch angles* were both related to decreased *boat velocity* for Sculler B. Variation in *total angle* resulting in altered performance may therefore be a result of variation in length at either end of the stroke for this sculler. Increasing the *finish angle* beyond effective reach whilst maintaining the same *stroke rate* could result in disruption to the stability of the boat and increase negative pin forces, increasing drag forces and reducing mean *boat velocity* for Sculler B. *Working angle* was related to *boat velocity* for both scullers due to its strong positive relationship with *total angle* (R = 0.75 and 0.77 for Scullers A and B respectively), and more so for its interaction with *total slip* (R = 0.32 and 0.22).

Catch slip and *finish slip* values quantify the blade displacement that occurs whilst pin force is lower than set thresholds, supposedly describing the period of the drive phase where the sculler is not contributing to boat propulsion. Slips values should therefore be negatively related to *boat velocity* provided the methodology for calculating these variables is correct, the thresholds are set properly, and no detrimental side effects of short slip values occur. The pre-set thresholds for PowerLine™ for sculling boats were 20 kgF (196 N) at the catch, and 10 kgF (98 N) at the finish. Sculler B displayed the anticipated negative correlation with *boat velocity* for *catch slip* (R = -0.35, 90% CI: -0.48 to -0.21), but showed a positive relationship between *finish slip* and *boat velocity* (R = 0.26, 90% CI: 0.13 to 0.41), potentially due to a smoother release of the blade from the water, reducing negative forces during this phase. Sculler A exhibited no significant correlations between either of the slip values and *boat velocity*. Clearly a need for further investigation into the use of these variables and the methods used to calculate them is necessary.

A technical discrepancy between the two scullers is displayed in the *power difference* values and in the scullers' force profiles (see Figure 17 as an example). Sculler A had a higher *stroke power* on the left than right side (a *power difference of* 33 ±10 W) whereas Sculler B was more even on both sides in *stroke power* (a *power difference* of 5 ±3 W). A high *power difference* should decrease *boat velocity* in the measured direction due to unmatched moments acting on the centre of mass of the rower-boat system resulting in deviation of the direction of boat velocity from the desired path, increasing drag forces. Sculler B displayed an unexpected weak but significant positive relationship between *power difference* and *boat velocity* (R = 0.16, 90% CI: 0.01 to 0.30) and Sculler A did not display any relationship between these variables. Based on data collection from elite scullers over the past 18 months in New Zealand, it has been seen that scullers with unmatched timing at the catch between the left and right blade entry learn to compensate for the resulting initial rotation of the boat by increasing the power on the alternate side (Coker, 2009). If this is the case for Sculler A, and *power difference* is related to catch timing to allow a direct average path of boat travel during the stroke, it may not correlate with *boat velocity* in the short term. However, it cannot be concluded that in the long term, reduction in *power difference* in either sculler would not affect performance. More detailed testing with video analysis of the technique of Sculler A in particular or information on the boat pitch, yaw and roll, is needed to determine the reason for the high *power difference*. Although not a performance related issue in the short term, bilateral imbalance will also need addressing for injury prevention.

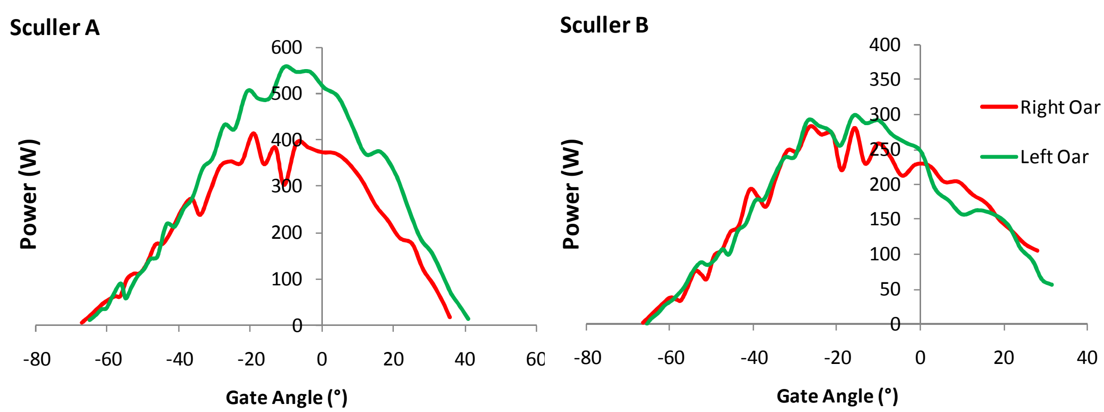

Figure 17: Raw power versus gate angle data from a typical stroke for each sculler.

It was interesting that *previous stroke boat velocity* was not more highly correlated with *boat velocity* (R = 0.60, 90% CI: 0.49 to 0.69 and R = 0.58, 90% CI: 0.47 to 0.67, for Sculler A and Sculler B respectively) despite stroke to stroke consistency being a predictor of performance level in sculling (Smith et al., 1994). It is, however, the scullers' high within-trial consistency level itself (SD = 1.1 % and 1.3 % for the two scullers) that results in this weaker than anticipated correlation. The stroke to stroke variation in *boat velocity* is small enough to mean that stroke to stroke *boat velocity* fluctuations are negligible compared to lower performance level scullers, even if consecutive strokes are at different ends of the range of *boat velocity* experienced during a trial (which would result in a weak correlation between *previous stroke boat velocity* and *boat velocity*).

Five-stroke average analyses

Five stroke average analyses increased the strength of the correlations between *boat velocity* and the variables compared to single stroke analysis (see Table 6). *Stroke power*, being of particular interest, explained 36% and 77% (Scullers A and B respectively) of the variation in *boat velocity* when five stroke analysis was used compared to 19% and 45% from single stroke analysis. This is explained in the way by which PowerLine™ separates strokes. The start of a new stroke is taken as the point where the oar moves 10° from its finish position (i.e., on the early recovery phase). This means that the majority of the recovery phase and boat run resulting from the previous drive phase and its stroke variables, is not included in the *boat velocity* of that stroke, but is instead, added to the following stroke. Therefore, when five strokes are taken and averaged instead of one, the correlations between *boat velocity* and relevant stroke variables improve in strength because recovery phases associated with the drive phases recorded are included in that comparison. The correlation between *finish slip difference* and *boat velocity* was greatly impacted by increasing the number of strokes over which the analysis was performed. For single stroke analysis neither sculler showed a significant correlation, but using five stroke analysis, significant negative (R = -0.40, 90% CI: -0.52 to -0.26) and positive (R = 0.27, 90% CI: 0.12 to 0.41) correlations were seen for Scullers A and B respectively. The negative correlation for Sculler A would be expected as increased yaw of the boat and drag forces would be anticipated if force was maintained further on one side than the other. The positive correlation for Sculler B is surprising and indicates that technical change(s) resulting in an increase in *finish slip difference* also positively influences other performance predicting variables. For example, an increased *finish slip difference* was related to a decrease in *finish angle* (R = -0.35, 90% CI: -0.48 to -0.21, for five stroke analysis) and a decrease in *finish angle* resulted in an increase in *boat velocity* for this sculler (R = -0.52, 90% CI: -0.62 to 0.40, for five stroke analysis). Only Sculler A showed significant correlations between *boat velocity* and *catch slip difference* (R = -0.22, 90% CI: -0.36 to -0.07), and *finish angle difference* (R = 0.29, 90% CI: 0.14 to 0.42). The negative relationship with *catch slip* difference is understandable since unbalanced forces occurring between the left and right sides at the catch will result in yaw, increasing drag. The positive relationship with *finish angle difference* was not anticipated since it was expected that yaw would be influenced by this variable in the same way as *catch slip difference*. However, this variable showed significant positive correlations with both *stroke power* (R = 0.38, 90% CI: 0.24 to 0.50) and *peak force* (R = 0.50, 90% CI: 0.38 to 0.61) both of which are positively correlated with *boat velocity* (see Table 6). Neither single stroke nor five-stroke average analyses resulted in significant correlations between *boat velocity* and c*atch angle difference.* Although this variable was not related to performance for either sculler it should still be calculated because the different catch angles will result in different gearing and therefore load occurring on the left and right sides in the early drive (Kleshnev, 2006b), potentially leading to imbalance and therefore injury (Knapick, Bauman, Jones, Harris, & Vaugh, 1990).

Stepwise linear regression

Based on the results and theory from the bi-variate correlation analyses with *boat velocity*, it is understandable that the linear models resulting from the stepwise linear regression analyses all included a measure of physical capacity (*stroke power* and/or *peak force*) and an angular measure of reach (see Table 8). The additional 4% and 1% of variance explained for Scullers A and B respectively from the addition of the computed variables into the model may not seem worth the additional time and expense of computing the extra variables. However, in elite scullers, where small performance gains are considered vital, the potential for advancement from this supplementary data is desirable. Additionally, the added benefit of possible injury risk identification from the lateral imbalance information could be crucial and it is therefore recommended that the entire set of biomechanical stroke variables is computed given the data derivation can be semi-automated.

Previous stroke boat velocity will affect the water speed relative to the boat when the blade enters the water altering the handle velocity which will impact *stroke power* both directly (because *stroke power* is proportional to handle velocity) and indirectly, by altering the muscular contraction velocities and therefore the amount of force that the sculler is capable of achieving in the early drive (Hamilton & Luttgens, 2002). Adding *previous stroke boat velocity* to the stepwise linear regression input improved the strength of the model for both scullers (43% of variance in *boat velocity* explained for Sculler A and 55% for Sculler B). However, this information is not easily applied to improving sculling performance – to say to a coach that in order to improve boat velocity in one stroke, the previous stroke velocity should be increased is not helpful. However, the knowledge of how the previous stroke's boat velocity significantly affects performance predictors may have implications for under-speed or over-speed training (e.g., training in a faster or slower boat type, or with added resistance from bungy cords, or speed assistance from a motor boat) in order to influence stroke variables. For example, both scullers achieved higher *stroke power* with increased velocity in the previous stroke (see Table 7) therefore, training in slower boat types or with a bungy cord, where it would be more difficult to achieve a high *stroke power* may challenge the scullers to improve their power producing capacity in a more difficult environment.

Taking the average of each variable every five strokes instead of taking each stroke separately greatly improved the predictive strength of PowerLine™ stroke variables due to the stroke cut off point that PowerLine™ uses. The stepwise linear regression using five stroke averages resulted in 84% and 85% of the variance in *boat velocity* being explained for the two scullers. This indicates that elite sculler analysis using PowerLine™ should use this method rather than a stroke by stroke approach.

The models presented leave a percentage of variance in *boat velocity* unexplained. The potential limitations of the methodology that could lead to this include insufficient data being collected to describe stroke to stroke changes in environmental conditions or detailed rower kinematics. The measurement of force solely in the direction longitudinal to the boat may also overlook certain key parameters, along with the limitations of measuring force at the pin rather than the centre of pressure of the blade where propulsion actually occurs (a movable and currently unmeasured point). Finally, there is potential for more insight to be gained into the effect of specific details of catch (and finish) technique that may allow for better description of *boat velocity* based on biomechanical stroke variables. This may include blade entry details, alteration of catch and finish slip thresholds, or measurement of foot stretcher forces to better understand the impact of the interaction between handle and stretcher forces on performance.

Summary

- *Stroke power* was a predictor of sculling performance for the elite scullers tested, but its relationship with *boat velocity* was not direct and cannot be generalised to all scullers at a fixed race rate.
- The length to which a sculler reaches is an important performance predictor, but the exact relationship between *catch* and *finish angles* and *boat velocity* will depend on the individual sculler.
- Sculler analysis using PowerLine™ is better performed using the average of each five strokes rather than single strokes. Using this approach, models were presented for the two scullers explaining 84% and 85% of their variation in boat velocity.
- Some variation in *boat velocity* was left unexplained by the stroke variables presented in this study. The percentage of variation explained may be improved by alternative methodologies for quantifying catch and/or finish technique, by enhanced environmental modelling, by involving rower kinematic analysis, or by the development of instrumentation capable of measuring forces at other locations on the boat-blade system.

- The numerous differences between the two scullers tested reiterated the need for an individualised approach for elite sculler analysis and it is therefore suggested that all automatic variables and computed variables discussed in this study are presented for future elite sculler analysis despite certain parameters not relating to performance in these particular scullers.

CHAPTER 7 - QUANTIFYING CATCH TECHNIQUE: AN EXPERIMENTAL EVALUATION OF DIFFERENT METHODOLOGIES

This chapter comprises the following technical report submitted to Rowing New Zealand.

Coker, J., Hume, P. A., & Nolte, V. (2010). *Quantifying catch technique in elite scullers: An experimental evaluation of different methodologies* (Technical report for Rowing New Zealand). (pp. 1-18). Auckland: Institute of Sport and Recreation Research New Zealand, Auckland University of Technology.

Overview

Methods of quantifying sculling catch technique have been presented in past literature, but relationships between the resulting values themselves and also with performance (as measured by *boat velocity*) are unclear. The aim of this study was to determine which method of quantifying catch slip technique was the best performance predictor for two elite scullers, and to establish the strength of any relationships between the catch slip values to allow more comprehensive comparisons between athlete feedback data and previously presented "norms". Pin force in the direction of boat travel, gate angle, boat velocity and boat acceleration were collected at 50 Hz using PowerLine™ for 120 strokes from two Olympic level scullers at race pace, synchronised with video footage where possible. Catch slip values were computed using four different methods: angular displacement and time taken from the minimum angle to 196 N of pin force (*PowerLine-Angle and PowerLine-Time*), 30% of the peak force for the stroke (*30% peak-Angle* and *30% peak-Time*), to the blade being covered (*Buried-Angle* and *Buried-Time*), and to positive boat acceleration (*Acceleration-Angle* and *Acceleration-Time*). Linear regression analyses were used to determine relationships between catch slip values and also with *boat velocity*. Mechanistic inferences were calculated using a spreadsheet provided by Hopkins (2007a). Correlation values with 90% confidence intervals (90% CI) and p values are presented. Sculler A showed significant positive correlations between *boat velocity* and *Acceleration-Time, 30% peak-Angle* and *30% peak-Time* (R = 0.20, 0.42 and 0.29 respectively, $p \leq 0.05$), whilst Sculler B showed significant negative relationships between *boat velocity* and *PowerLine-Angle, PowerLine-Time, Acceleration-Time, 30% peak-Angle* and *30% peak-Time* (R = -0.60, - 0.48, -0.22, -0.28 and -0.35 respectively, $p \leq 0.05$). All relationships between the angle and time versions of each slip version (*PowerLine, 30% peak, Buried* and *Acceleration*) were significant. PowerLine™ slip values can relate to *boat velocity,* but can be inconsistent for different elite scullers. The velocity at which the blade is buried and the rate of force development in the early drive appear to be key performance predictors and can increase or decrease *boat velocity* depending on the individual sculler. PowerLine™ slip values and 30% of peak force slip values in our scullers seem consistent with values presented in past research. Elite scullers should be analysed as individuals given the variation shown in our two elite scullers. Given data for only two scullers have been presented, more data are required to confirm the findings.

Introduction

Possibly the most challenging part of the sculling stroke cycle to master, the catch is the blade's entry into the water, forming the transition between the recovery and drive phases of the stroke (Richardson, 2005). Technique at the catch will affect the forces acting on the boat and blade during the entry and early drive phases, and poor technique will cause the boat to decelerate and decrease the run of the boat, reducing sculler effectiveness (Richardson, 2005).

A sculler's catch technique will also influence how much of their overall reach (or total angle) contributes to propulsion of the rower-boat-blade system. The angle through which a blade moves towards the stern of the boat after the catch position whilst it is not propelling the system, has in past literature been called "catch slip". Most commonly, catch slip has been defined as the angle through which the blade moves between its change in direction and the point where it is fully covered (Kleshnev & Baker, 2007a). This method is commonly used by coaches in semi-quantitative visual analysis, counting the number of frames between the apparent catch position and the point where the blade is covered. Values of this variable using measured rather than apparent catch position have been presented relating to good and very good performers (Kleshnev, 2007a). However, there are a number of limitations to this method. Firstly, the blade need not be fully covered for it to be propelling the boat, and this method for quantifying catch slip discards the potential for effective work during the entry phase. Also, the accuracy of this method using standard 25 Hz video cameras, as in the work of Kleshnev (2007), is limited due to significant displacement of the blade occurring between frames.

PowerLine™ is the biomechanics feedback tool used by Rowing New Zealand. It automatically presents a catch slip angle calculated as the angle that the blade moves through whilst less than a pre-set threshold force is applied to the pin in the direction of the longitudinal axis of the boat. For sculling, 20 kgF (196 N) is the pre-set catch force threshold. Using this method enables minimal delay between task and feedback with potential for coaches to conveniently utilise the values without post-event analysis of force or video data. PowerLine™ catch slip values to some extent actually present the rate of force development and, although this is important for depicting the shape of, and area underneath, the force-time curve, they do not indicate how long the blade is out of the water whilst moving sternward. Using PowerLine™ methodology, reduced slip will be seen if the blade is "rowed in" with non-effective force applied to the pin before the blade is in the water due to the inertia of the rowing oar. Inertial blade forces, created as the blade changes direction at the catch are also included in the pin force reading (Ishiko, 1971; Kleshnev, 2002b). In a single scull inertial blade forces can represent almost 100% of the handle force seen at the catch and finish (between 70 and 80 N) (Kleshnev, 2002b) which would equate to 7.1 to 8.2 kgF as presented by PowerLine™. Forces from the blade being pressed against the gate by the rower may also increase the force reading, especially around the catch.

A study utilising a similar methodology, but substituting 30% of the peak handle force as the threshold value, has shown that a decrease in the resulting slip angles is related to increased blade efficiency (Kleshnev, 1999). With claimed potential performance gains of up to 5% from enhancing blade efficiency this is clearly not an area to be ignored (Kleshnev, 1999). The same issues with "rogue" force production not resulting from blade-water interaction occur with this method and post-collection analysis is required to compute where 30% of peak force occurred for each stroke. Using past testing of the same athlete to input an approximation of 30% based on their previous average peak force as the threshold is possible, but accuracy will be lost. This is not acceptable with elite scullers.

In past research, more successful crews were seen to have no loop in the boat acceleration versus oar angle curve around the catch (Kleshnev, 1999). The loop represents reversal of oar direction at the catch before minimum boat acceleration has occurred which signifies poor coordination of stretcher and handle forces (Kleshnev, 1999). The minimum boat acceleration of the best rowers (world champions versus national championship finalists) is also known to be larger at the same stroke rate (-10.1 m/s^2 versus -6.9 m/s^2) but with a shorter time period, meaning that the better rowers accelerate their body more effectively around the catch (Kleshnev, 2002a). Based upon these findings, a final method for calculating catch slip is proposed by our rowing research group as the angular displacement and time taken between the minimum angle and positive acceleration of the boat being achieved. At this point the rower is not merely overcoming the unavoidable deceleration of the boat that occurs at the end of the recovery and the beginning of the drive, but actually increasing the boat velocity due to a technical aspect around the catch.

Three alternative methods for quantifying catch technique to the familiarly used video analysis technique have been discussed. These are angular displacement and time from the minimum angle to: 1) 20 kgF; 2) 30% of peak force and; 3) positive boat acceleration. All the methods have their limitations and, to some extent measure different aspects of catch technique.

Aims

The aims of this study were to determine which method of quantifying catch slip technique was the best performance predictor for two elite scullers, and to establish the strength of any relationships between the catch slip values to allow more comprehensive comparisons between athlete feedback data and previously presented “norms”. This will enable coaches and athletes to use the most appropriate values for analysis and technical focus and to compare their own values with those from a larger data pool where different methods may have been used.

Methods

Participants

Two Olympic-level heavy-weight single scullers (male: 101.7 kg, 2.00 m, 29 years; female: 77.3 kg, 1.81 m, 20 years) volunteered for the study. Both participants were informed of the procedures and gave written consent.

Procedures

Single sculls were equipped with PowerLine™ to record pin force, oar angle and boat velocity at 50 Hz throughout each trial. The two scullers performed three 500-m trials from a flying start at the self-selected constant rate and pace normally exerted in the middle 1000 m of a 2000-m race. Rest time of more than five minutes was given between 500-m trials to allow the scullers to perform at race pace without overly fatigued technique throughout the 120 strokes that were analysed (middle 40 strokes of each 500-m piece for each sculler). Trials were carried out on the final 500 m of a pre-measured 2000-m rowing course with 500-m markers.

The PowerLine™ logger unit recorded pin force, oarlock angle, boat velocity, and boat acceleration data at 50 Hz throughout each trial. Video footage from a speed boat running along side the sculler was recorded at 25 Hz from the sagittal view where possible and automatically synchronised with PowerLine™ data. Because stopwatch timing occurred from the same speed boat, at certain points video was not possible, therefore n = 29 for Sculler A and n = 36 for Sculler B for analyses of *buried-angle* and *buried-time* (see below). The middle 40 strokes from each 500-m piece were extracted and four different versions of catch slip were computed for each stroke, each version having an angle and a time value as follows:

- *PowerLine-Angle (°)* – angular displacement from the minimum gate angle to the point at which the force value exceeded 196 N (20 kgF as displayed by the system) in the direction of the longitudinal axis of the boat in that stroke.
- *PowerLine-Time (s)* – time taken from when the minimum gate angle was reached to the point at which the PowerLine™ force value exceeded 196 N (20 kgF as displayed by PowerLine™) in the direction of the longitudinal axis of the boat in that stroke.
- *30% peak-Angle (°)* – angular displacement from the minimum gate angle to the point at which the PowerLine™ force value exceeded 30% of the peak pin force achieved in the direction of the longitudinal axis of the boat in that stroke.
- *30% peak-Time (s)* – from PowerLine™ data, the time taken from when the minimum gate angle was reached to the point at which the PowerLine™ force value exceeded 30% of the peak pin force achieved in the direction of the longitudinal axis of the boat in that stroke.
- *Acceleration-Angle (°)* – from PowerLine™ data, the angular displacement from the minimum gate angle to the point where positive boat acceleration was achieved (shown as the displacement, A, in Figure 18).
- *Acceleration-Time (s)* – the time taken from when the minimum gate angle was reached to the point when positive boat acceleration was achieved.
- *Buried-Angle (°)* - from synchronised video footage and PowerLine™ angle data, the angular displacement from the minimum gate angle to the point at which the blade was first seen to be fully buried (no blade visible above the water).
- *Buried-Time (s)* – from synchronised video footage and PowerLine™ angle data, the time taken from when the minimum gate angle was reached to the point at

which the blade was first seen to be fully buried (no blade visible above the water).

The bilateral average was taken for each value except for *Buried-Angle* and *Buried-Time* values which were only available from the side being videoed.

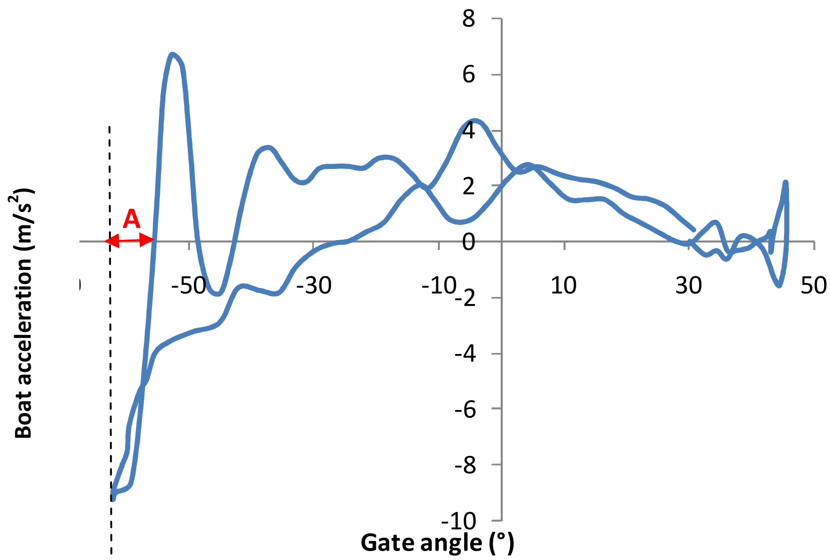

Figure 18: Example of one stroke, showing *acceleration-angle,* A, as the angular displacement between the minimum angle reached during the stroke and the point at which boat acceleration reaches zero m/s^2.

Statistical analyses

Pearson correlations were carried out to determine R values with 90% confidence intervals (90% CI) and p values for the relationships between *boat velocity* and *PowerLine-Angle, PowerLine-Time, 30% peak-Angle, 30% peak-Time, Acceleration-Angle*, *Acceleration-Time, Buried-Angle* and *Buried-Time.* For these analyses, five stroke moving averages were used in accordance with past research showing that PowerLine™ stroke variables related better with *boat velocity* due to the stroke position at which PowerLine™ separates strokes (Coker, Nolte, & Hume, 2009). Single stroke analyses were then used to determine R and p values for the correlations between all slip values[13]. Analyses were performed via the log-transformed variable for non-angular variables. SPSS[14] was used to compute the R and p values, and a pre-formatted spreadsheet was used to obtain the 90% confidence interval and mechanistic inference (Hopkins, 2007a). Correlations were taken to be significant when $p \leq 0.05$.

Results

Table 9 presents the mean ±SD for all stroke variables for both scullers. Both scullers presented similar stroke-to-stroke variation in *boat velocity* (SD = 1.1% and 1.3% for Scullers A and B respectively). However, Sculler A had higher consistency in *stroke rate* than Sculler B (SD = 1.2% and 2.5% respectively). The relationship between *stroke rate* and *boat velocity* was unclear for Sculler A whilst Sculler B displayed a significant positive relationship at the 90% CI with R = 0.63 (0.36 to 0.80), as shown in Table 10. Sculler A showed significant positive correlations between *boat velocity* and *Acceleration-Time, 30% peak-Angle* and *30% peak-Time* (R = 0.20, 0.42 and 0.29 respectively), whilst Sculler B showed significant negative relationships between *boat velocity* and *PowerLine-Angle, PowerLine-Time, Acceleration-Time, 30% peak-Angle* and *30% peak-Time* (R = -0.60, - 0.48, -0.22, -0.28 and -0.35 respectively). As shown in Table 11 both scullers showed significant positive correlations between degree and time slips of the same type (e.g. *PowerLine-Angle* and *PowerLine-Time*). The largest R value was 0.89 (Sculler B, *Buried-Time* versus *Buried-Angle)* and the lowest R value was 0.28 (Sculler A, *PowerLine-Time* versus *PowerLine-Angle)*. With the exception of *Acceleration-Angle* and *Acceleration-Time,* Sculler B displayed higher R values between time and degree slips of the same type than Sculler A; particularly for *30% peak-Angle* and *30% peak-Time* where R = 0.81 for Sculler B, and R = 0.45 for Sculler A, and for *PowerLine-Angle* and *PowerLine-Time* where R = 0.46 for Sculler B and R = 0.28 for Sculler A.

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[13] Single stroke analysis was deemed appropriate here as the stroke splitting problem is not a concern as the slip measures are taken at the same point of the stroke for all methodologies.
[14] SPSS Inc. Headquarters, 233 S. Wacker Drive, 11th floor, Chicago, Illinois 60606

Table 9: Mean ±SD for each stroke variable for Sculler A and Sculler B.

	Sculler A		Sculler B	
	n	Mean ±SD	n	mean ±SD
Boat velocity (m/s)*	120	4.71 ±1.09%	120	4.53 ±1.32%
Stroke rate(spm)	120	34.3 ±1.2%	120	32.3 ±2.5%
PowerLine-Angle (°)	120	5.5 ±0.3 (°)	120	7.2 ±0.3 (°)
PowerLine-Time (s)	120	0.09 ±13%	120	0.11 ±10%
Acceleration-Angle (°)	120	8.2 ±0.6 (°)	120	7.5 ±0.5 (°)
Acceleration-Time (s)	120	0.11 ±11%	120	0.10 ±9.9%
30% peak-Angle (°)	120	5.8 ±0.5 (°)	120	5.5 ±0.5 (°)
30% peak-Time (s)	120	0.08 ±15%	120	0.08 ±13%
Buried-Angle (°)	29	6.2 ±1.4 (°)	36	7.6 ±1.3 (°)
Buried-Time (s)	29	0.10 ±15%	36	0.10 ±19%

**Calibration has not been carried out on this value because Nielsen-Kellerman units are used as standard for velocity analysis on a daily basis in the Rowing New Zealand programme and the athlete time required for calibration of PowerLine™ for every crew is not deemed advantageous for use with this squad.*

As shown in Table 11, Sculler A showed significant relationships between *PowerLine-Angle* and *30% peak-Angle, 30% peak-Time* and *Buried-Angle*. Sculler A also showed significant relationships between *PowerLine-Time* and *Acceleration-Time* and *30% peak-Time*. Sculler B showed significant correlations between *PowerLine-Angle* and *Acceleration-Angle*, *Acceleration-Time*, *30% peak-Angle* and *30% peak-Time*. Sculler B also showed significant correlations between *PowerLine-Time* and *Acceleration-Time*, *30% peak-Angle* and *30% peak-Time*. Neither *PowerLine-Angle* nor *PowerLine-Time* showed significant correlations with neither *Buried-Angle* nor *Buried-Time* for Sculler B despite all versions of slip being negatively correlated with *boat velocity* in this sculler. The effect of *stroke rate* was not significant on any slip variable for Sculler A whilst Sculler B displayed significant correlations between *stroke rate* and all of the slip variables (R = -0.63 to -0.28) except *Acceleration-Angle* and *Acceleration-Time* (Table 11).

Table 10: Correlations for *boat velocity* versus slip values, and *stoke rate* using five-stroke averages. R values with 90% confidence intervals are presented.

Correlation with *boat velocity*	Sculler A		Sculler B	
	n	R (90% CI)	n	R (90% CI)
Stroke rate (spm)	116	0.02 (-0.13 to 0.17)	116	0.61 (0.50 to 0.70)*
PowerLine-Angle(°)	116	0.10 (-0.05 to 0.25)	116	-0.60 (-0.69 to -0.49)*
PowerLine-Time (s)	116	0.11 (-0.04 to 0.26)	116	-0.48 (-0.59 to -0.35)*
Acceleration-Angle (°)	116	0.18 (0.03 to 0.32)	116	0.14 (-0.01 to 0.29)
Acceleration-Time (s)	116	0.20 (0.05 to 0.34)*	116	-0.22 (-0.36 to -0.07)*
30% peak-Angle (°)	116	0.42 (0.28 to 0.54)*	116	-0.28 (-0.42 to -0.13)*
30% peak-Time (s)	116	0.29 (0.14 to 0.42)*	116	-0.35 (-0.48 to -0.21)*
Buried-Angle (°)	10	0.27 (-0.33 to 0.72)	28	-0.29 (-0.56 to 0.03)
Buried-Time (s)	10	0.29 (-0.31 to 0.73)	28	-0.31 (-0.57 to 0.01)

**correlation is significant at the 0.05 level*

Discussion

The lower variation in *stroke rate* shown by Sculler A than Sculler B may explain why Sculler A did not present strong correlations between slip values and *stroke rate* in contrast to Sculler B (see Table 11) – a 1.2% variation in *stroke rate* may not be enough to see changes in slip. Alternatively the ability of Sculler A to maintain low slip values at lower *stroke rates* may be representative of this sculler's performance level – Sculler A is arguably the better of the two scullers exhibited by results on the international stage. Both scullers fall between the "good" (0.12 s) and "very good" (0.08 s) *Buried-Time* values presented by Kleshnev (2007a).

Table 11: Linear regression analysis between pairs of slip values, and between each slip value and *stroke rate*. Sculler A in blue, Sculler B in yellow.

		PowerLine-Angle (°)	*PowerLine-Time (s)*	*Acceleration-Angle (°)*	*Acceleration-Time (s)*	*30% peak-Angle (°)*	*30% peak-Time (s)*	*Buried-Angle (°)*	*Buried-Time (s)*	*Stroke rate (spm)*
PowerLine-Angle (°)	R		0.28 (0.13 to 0.41)*	0.08 (-0.07 to 0.23)	-0.04 (-0.19 to 0.11)	0.62 (0.52 to 0.70)*	0.22 (0.07 to 0.35)*	0.47 (0.19 to 0.68)*	0.36 (0.05 to 0.60)	0.03 (-0.12 to 0.18)
	n		120	120	120	120	120	29	29	120
PowerLine-Time (s)	R	0.46 (0.33 to 0.57)*		-0.12 (-0.26 to 0.04)	0.63 (0.53 to 0.71)*	0.16 (0.01 to 0.30)	0.82 (0.76 to 0.86)*	0.21 (-0.11 to 0.49)	0.11 (-0.21 to 0.41)	0.03 (-0.12 to 0.18)
	n	120		120	120	120	120	29	29	120
Acceleration-Angle (°)	R	0.23 (0.09 to 0.37)*	-0.10 (-0.25 to 0.05)		0.51 (0.38 to 0.61)*	-0.03 (-0.18 to 0.13)	-0.12 (-0.27 to 0.03)	-0.15 (-0.44 to 0.17)	-0.13 (-0.43 to 0.19)	0.14 (-0.02 to 0.28)
	n	120	120		120	120	120	29	29	120
Acceleration-Time (s)	R	0.22 (0.07 to 0.36)*	0.68 (0.59 to 0.75)*	0.47 (0.35 to 0.58)*		-0.06 (-0.21 to 0.09)	0.64 (0.54 to 0.72)*	-0.12 (-0.41 to 0.20)	-0.12 (-0.41 to 0.20)	0.07 (-0.09 to 0.21)
	n	120	120	120		120	120	29	29	120
30% peak-Angle (°)	R	0.43 (0.30 to 0.55)*	0.62 (0.52 to 0.71)*	-0.01 (-0.16 to 0.15)	0.44 (0.31 to 0.56)*		0.45 (0.32 to 0.56)	0.50 (0.22 to 0.71)*	0.57 (0.31 to 0.75)*	0.05 (-0.10 to 0.20)
	n	120	120	120	120		120	29	29	120
30% peak-Time (s)	R	0.31 (0.17 to 0.44)*	0.84 (0.79 to 0.88)*	-0.09 (-0.24 to 0.06)	0.70 (0.62 to 0.77)*	0.81 (0.74 to 0.85)*		0.33 (0.02 to 0.58)	0.40 (0.10 to 0.63)*	0.02 (-0.13 to 0.17)
	n	120	120	120	120	120		29	29	120
Buried – Angle (°)	R	0.13 (-0.16 to 0.39)	0.02 (-0.26 to 0.29)	-0.01 (-0.29 to 0.27)	0.01 (-0.27 to 0.29)	0.21 (-0.08 to 0.46)	0.17 (-0.11 to 0.43)		0.85 (0.73 to 0.92)*	-0.11 (-0.41 to 0.21)
	n	36	36	36	36	36	36		29	120
Buried - Time (s)	R	0.05 (-0.23 to 0.32)	0.29 (0.01 to 0.53)	-0.07 (-0.34 to 0.21)	0.31 (0.04 to 0.54)	0.36 (0.09 to 0.58)*	0.49 (0.25 to 0.68)*	0.89 (0.82 to 0.94)*		-0.16 (-0.45 to 0.16)
	n	36	36	36	36	36	36	36		120
Stroke rate (spm)	R	-0.28 (-0.41 to -0.13)*	-0.36 (-0.48 to -0.22)*	0.15 (0.00 to 0.30)	-0.12 (-0.27 to 0.03)	-0.29 (-0.42 to -0.15)*	-0.31 (-0.44 to -0.17)*	-0.52 (-0.70 to -0.28)*	-0.63 (-0.77 to -0.42)*	
	n	120	120	120	120	120	120	36	36	

R is given with 90% confidence intervals. Correlation is significant at the 0.05 level.*

No significant correlations were found between *boat velocity* and *Buried-Angle* or *Buried-Time* due to insufficient video data being available to allow an adequate sample size for significant effects to be seen from statistical analyses. Although non-significant, the size of the resulting R values does warrant discussion. The fact that both scullers showed relatively strong correlations between B*uried-Angle* and *Buried-Time* and *boat velocity* (see Table 10 - R values of 0.64 and 0.44 for Sculler A and -0.35 and -0.41, Sculler B), despite being in opposite directions, indicates that buried slips may be important variables to measure. However, the difference in direction of the relationship with velocity between the two scullers shows that their effects on velocity are not consistent for elite scullers. Some scullers may get increased performance from faster blade entry and thus a longer effective stroke length. Other scullers, in burying the blade quicker may cause technical faults that decrease *boat velocity* - for example, reduced control of blade movement resulting in the blade being buried too deep, the loom being placed in the water, increasing drag and decreasing performance. Faster burying of the blade may also increase *boat velocity* fluctuations which decreased efficiency and performance (Baudouin & Hawkins, 2002, 2004; Hill & Fahrig, 2008; Hofmijster et al., 2007). The current method often used by coaches whereby frames are counted before the blade enters the water without synchronised *boat velocity* data is therefore not necessarily recommended - video "catch slip" analysis should only be performed in conjunction with performance data. Further investigation is needed with more extensive video footage to confirm the relationship between *Buried-Angle, Buried-Time* and *boat velocity*.

The discrepancy between Sculler A and Sculler B in the relationships between *PowerLine-Angle* and *Powerline-Time* slip values and *boat velocity* (Sculler A exhibited trivial or unclear relationships, Sculler B showed significant negative correlations, as shown in Table 10), highlights the need for an individualised approach to technique analysis in elite scullers. Sculler A does not need not to focus on reducing *PowerLine-Angle* and *PowerLine-Time* as these biomechanical stroke variables have only a trivial impact on *boat velocity*. In comparison Sculler B can increase performance to some extent by focusing on faster application of force at the catch, measurable as a decrease in *PowerLine-Angle* and *PowerLine-Time*. The reason for this between-subject difference is not clear from the data – it might be explained purely by an inter-individual difference in technique meaning that technical focus is required at different aspects of the stroke for the two scullers. Alternatively, a non-linear relationship may exist between *PowerLine-Angle* and *Powerline-Time* values and *boat velocity* meaning that once very small mean *PowerLine-Angle* and *Powerline-Time* values are achieved (as seen for Sculler A) a plateau in boat velocity is reached. Little to no change in *boat velocity* would then be seen by varying *PowerLine-Angle* and *Powerline-Time* by a magnitude that would significantly affect velocity at higher *PowerLine-Angle* and *Powerline-Time* values (as seen for Sculler A). More data are required to investigate such a theory with data from more subjects with a larger inter-individual range in PowerLine™ slip values.

Boat velocity was better explained in Sculler A by *30% peak-Angle* and *30% peak-Time* slips than *PowerLine-Angle and PowerLine-Time,* but the opposite was true in Sculler B. This highlights the precision and individualisation required in force threshold selection for these slip values in elite scullers and the need to collect both variables. Thirty percent of *peak force* was 18.2 ±0.4 kgF for Sculler A, meaning that reducing the threshold force by only 1.8 kgF (versus the 20 kgF threshold used for *PowerLine* slips) resulted in the R values for the correlations with *boat velocity* changing from 0.10 (90% CI: 0.05 to 025) for *PowerLine-Angle,* to 0.42 (90% CI: 0.28 to 0.54) for *30% peak-Angle*. Similarly, *Acceleration-Angle* and *Acceleration-Time* describe *boat velocity* better than *PowerLine-Angle and PowerLine-Time* slips for Sculler A but not Sculler B. No one version of catch slip can therefore be used universally across elite scullers and so all must be investigated. Particular technical characteristics that result in certain slip measures relating to *boat velocity* should be examined in the future.

Acceleration-Time showed significant positive relationships with *30% peak-Angle* and *30% peak-Time,* but *Acceleration-Angle* did not. Increasing the rate of force development to 30% of peak force therefore results in positive boat acceleration being reached more quickly, but it does not effect how much blade movement occurs before this point. This suggests that there may be a blade position at which positive acceleration occurs and only the time taken to reach this blade angle is affected by the rate of force development. Further investigation would be of interest as to whether boat set-up can reduce this blade displacement and allow boat acceleration to be reached sooner. The non-significant nature of the correlations between *Acceleration-Time* and both *Buried-Angle* and *Buried-Time* for Sculler A is interesting considering that all these variables are positively correlated with *boat velocity*. Burying the blade more quickly appears to decrease *boat velocity* in this sculler, as does reaching positive acceleration faster, but they are not related to each other.

Similarly, in Sculler B, *PowerLine-Angle and PowerLine-Time* were not significantly correlated with *Buried-Angle* and *Buried-Time,* despite both versions of slip showing negative correlations with *boat velocity*. Therefore in Sculler B, these two technical aspects (speed of blade burying and rate of force application to 20 kgF) affect *boat velocity* via unrelated mechanisms. Not only must the blade be buried quickly, but there must also be force applied to the pin as immediately as possible, and the two do not happen together automatically. Different pin forces are achieved at the same amount of blade cover during different strokes in this one sculler. This finding further justifies the avoidance of a purely visual analysis of the catch which assumes that blade cover equates to a certain level of boat propulsion occurring.

Correlations between pairs of slip values representing rate of force development (i.e., *PowerLine-Angle* versus *PowerLine-Time*, and *30% peak-Angle* versus *30% peak-Time*) were not as high as anticipated. The lowest correlations between pairs recorded for each sculler were between *PowerLine-Angle* and *PowerLine-Time* (R = 0.28 and 0.46 for Scullers A and B respectively). This indicates inconsistency in the rate of force development with respect to angular displacement, particularly in Sculler A, who showed lower R values for these relationships than Sculler A. However, *Buried-Angle* and *Buried-Time* showed high correlation in both scullers signifying that the time taken to bury the blade is directly related to the degrees through which the blade moves in this time (i.e., despite a differing rate of force development with respect to angular displacement on blade entry, the angular velocity of the blade is consistent between strokes in this area of the stroke. The relationship between *Buried-Angle* and *Buried-Time* seen in Scullers A and B (R = 0.85, 90% CI: 0.73 to 0.92; R = 0.89, 90% CI: 0.82 to 0.94) is supported by past research that presented an R value of 0.87 (Kleshnev, 2007a).

In both these scullers, *PowerLine-Angle* and *PowerLine-Time* showed the strongest correlations with *30% peak-Angle* and *30% peak-Time* (seven out of eight possible significant correlations with R ≥ 0.22). Strong positive relationships would be expected as both versions of quantifying catch technique ultimately measure rate of force development. Inconsistency in rate of force development means that these relationships were not as strong as expected. The fact that *PowerLine-Angle* and *PowerLine-Time* were positively correlated to *30% peak-Angle* and *30% peak-Time* means that the findings using PowerLine™ can be related to past research on rate of force development to 30% of peak force with performance, principally through increased blade efficiency (Kleshnev, 1999). Kleshnev (1999) found that by increasing the fraction of the stroke spent above 30% of peak force by 10% there was an increase in blade efficiency of approximately 6%, increasing boat velocity by between 1.5 and 2.0% (R = 0.30). In a later study, Kleshnev (2008b), found that horizontal angular oar displacement from the catch angle to the point where the force reaches 30% of maximum (termed *A30*) had an R value of -0.34 versus blade efficiency. Average *A30* for sculling was 3.8° ±1.5° at race rate (> 30 spm) (Kleshnev, 2008b). This is slightly lower than the values recorded in our study, but no precise details of rating, boat type or level were recorded by Kleshnev (2008b).

Summary

The velocity at which a sculler buries the blade appears to indicate the skill level of the athlete, but reducing the time taken to complete blade entry may either increase or decrease *boat velocity* dependant on individual scullers' techniques. It should not always be assumed that increasing the velocity of blade entry will increase performance as this change may bring about another technical characteristic detrimental to performance). During video analysis coaches need to not only focus upon reducing the frames taken to cover the blade, but also need to consider *boat velocity* and how blade cover will improve performance in that specific crew. The quick and easily produced *PowerLine-Angle* and *PowerLine-Time* generated by PowerLine™ can be useful for predicting performance, but this is not the case in all elite scullers. It is not clear from our data whether Sculler A presented another unmeasured performance predictor inversely related to *PowerLine-Angle* and *PowerLine-Time* that meant any positive effect of *PowerLine-Angle* or *PowerLine-Time* on *boat velocity* was cancelled out or, whether a threshold value exists in *PowerLine-Angle* and *PowerLine-Time* below which the augmenting effect on *boat velocity* is trivial. *PowerLine-Angle* and *PowerLine-Time* can be related to rate of force development to 30% of peak force for comparison with norms presented in previous studies, but they do not negatively relate to *boat velocity* in all elite scullers as previously presented (Kleshnev, 1999; Kleshnev, 2008b). The key finding is that there are large inter-individual differences between elite scullers in the effect of certain aspects of catch technique on performance. As such, all techniques for measuring catch technique should be utilised, elite sculler analysis should be individualised, and findings from past research and/or assumptions based on perceived optimal technique cannot always be applied.

Sculler recommendations

Sculler A

- Caution should be taken at the catch – at present, if the blade is buried more quickly boat speed appears to be lost. Technical focus should be on quick, but precise blade entry without decelerating the boat.
- Further analysis of other biomechanical stroke variables (for example, around the finish phase) is required as it does not appear that catch technique is the primary performance predictor in this sculler.

Sculler B

- This sculler should focus upon achieving a more effective catch BOTH by burying the blade faster AND applying force earlier. These two factors do not always happen simultaneously in this sculler.

Elite coaches should suggest specific technical drills to achieve these improvements.

CHAPTER 8 - THE EFFECT OF SCULLING BOAT CLASS ON BIOMECHANICAL STROKE VARIABLES IN ELITE SCULLERS

This chapter comprises the following technical report submitted to Rowing New Zealand.

Coker, J., Hume, P. A., & Nolte, V. (2010). *The effect of boat class on biomechanical stroke variables in elite scullers* (Technical report for Rowing New Zealand). (pp. 1 - 26). Auckland: Institute of Sport and Recreation Research New Zealand, Auckland University of Technology.

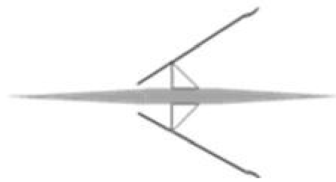
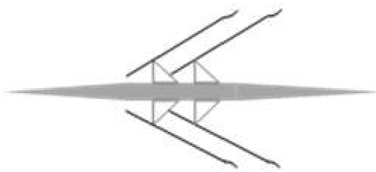
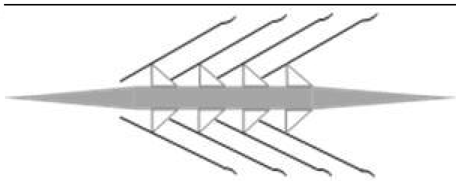
Overview

Elite scullers are highly consistent in the shape and size of the force profiles that they produce, but large variation exists between individuals. Different boat classes also produce disparities in the magnitude or timing of various biomechanical stroke variables. However, no data are available for elite scullers moving between sculling boat classes under controlled conditions, which would be useful in enhancing crew selection and training methods specific to different boat classes. This study investigated how the biomechanical stroke variables of four elite scullers altered when they were sculling in single, double and quad sculls. The scullers performed two 500-m trials at 32.4 ±0.9 spm in all three boat classes and eleven biomechanical stroke variables were collected for the middle 40 strokes of each trial. Changes in the means between boat classes were calculated for *stroke power, peak force, average force, total angle, catch angle, finish angle, catch slip, finish slip, peak force angle* and *degrees to peak force* for each sculler separately, controlling for *stroke rate.* All biomechanical variables measured were significantly different in all scullers between at least two boat classes. *Stroke power* generally decreased as boat class size increased, with individuals showing a change in mean *stroke power* between boat classes as high as 33.8% (90% CI: 32.7 to 34.9%; ES = -6.9). Stroke variables measured at the catch tended to alter more due to boat class than those measured at the finish. The largest effect sizes for change in *catch angle* (-8.3) and *catch slip* (10.4) were approximately double that seen for *finish angle* (4.1) and *finish slip* (5.1). Training in the targeted racing boat class and set-up appears to be important and the exaggerated change in *catch angle* from a relatively small span alteration should be utilised and accounted for when setting up foot-stretchers for increased performance. Biomechanical stroke variables do differ significantly between single, double and quad sculls in elite scullers, but some non-uniformity in this variation across the four scullers indicate potential training foci and boat class selection implications.

Introduction

Although small, differences in the shape and smoothness of rowing force profiles are evident between even experienced oarsmen (Ishiko, 1971; Mason, Shakespear, & Doherty, 1988; Schneider, Angst, & Brandt, 1978; Wing & Woodburn, 1995). Through training, rowers will develop a highly repeatable, "signature" force profile allowing individuals to be identified by subtle kinetic characteristics during the drive phase (Baudouin & Hawkins, 2004; Hill, 2002; Wing & Woodburn, 1995). It is not known to what extent this "signature" can be changed acutely (in particular, by moving between boat classes), or chronically, through technique training interventions. Although essentially the same movement pattern, the different boat speeds experienced in sculling boats of different classes (see Table 12) will result in slightly different physical demands (Lazauskas, 1997; Schwanitz, 1991). Quantifying the extent to which biomechanical requirements differ between boat classes may allow crew selection and training methods to be altered accordingly and potentially result in improved crew performances.

Table 12: Illustration of sculling boat classes with world best times (WRT) and the boat velocity required to achieve that time (WR boat velocity).

	Number of scullers	Boat Class	WRT (minutes)	WR Boat velocity (m/s)
	1	Heavyweight men's single sculls (M1x)	06:33.35	5.08
		Lightweight men's single sculls (LM1x)*	06:47.82	4.90
	2	Heavyweight men's double sculls (M2x)	06:03.25	5.51
		Lightweight men's double sculls (LM2x)	06:10.25	5.40
	4	Heavyweight men's quad sculls (M4x)	05:36.20	5.95
		Lightweight men's quad sculls (LM4x)*	05:45.18	5.79

*Non-Olympic events –the world best times may therefore be relatively slower than the other categories
The lightweight categories (denoted by the 'L' prefix) stipulate a racing weight of ≤ 70.0 kg

Schwantitz (1991) stated that as boat size increases, inboard (i.e. rower) power decreases during the drive despite higher inboard velocity. This would indicate a reduced average force, and potentially peak force, in the larger boat classes. Lazauskas (1997) used mathematical modelling to show that the power required to achieve World Championship winning times in larger boats was less than that in smaller boats. However, these findings may be explained by the suggestion that many countries place their top athletes in smaller boat classes and therefore, lower relative performance times would be achieved in the larger boats. Similarly, any boat class effect that has been noted tentatively in a wider range of biomechanical stroke variables in Rowing New Zealand athletes cannot be deemed attributable to boat class as no data were available from athletes moving between boat classes under controlled conditions

(Coker & Maher, 2008). To our knowledge, no study has been completed to investigate how the biomechanics of an elite sculler changes when moved between sculling boats of different sizes. It is therefore unknown whether boat specific trends are seen because the crew selection process (knowingly or not) has matched individuals with those characteristics to that boat class, or whether patterns are seen in those individuals purely because that boat class induces those features.

Aim

The aim of this study was to provide the Rowing New Zealand coaches with information concerning how the biomechanical stroke variables of four elite scullers, measured by PowerLine™, changed when moving between single, double and quad sculls. This information has the potential to enhance the ability of Rowing New Zealand to: (1) rank athletes across crews of different boat classes; (2) match athletes to boat classes more efficiently; and (3) adapt training programs or technical recommendations to better suit different boat classes.

Methods

Participants

Four elite-level male scullers (81.0 ±8.6 kg, 1.88 ±0.04 m 25.5 ±2.6 years) from the New Zealand Rowing programme volunteered for this study. All scullers went on to win gold or silver medals in sculling events at a World Cup series regatta within a month of data collection. All participants were informed of the procedures and gave written consent.

Procedures

Single, double and quad sculls were equipped with PowerLine™ to record pin force, oar angle and boat velocity at 50 Hz throughout each trial. On each of three consecutive days, the four scullers were instructed to perform three 500-m trials in either a single, double or quad scull according to the testing schedule shown in Table 13. The first 500-m trial each day was used as a familiarisation trial and the remaining two for data analyses. Participants were instructed to perform each 500-m trial from a flying start at a rate of 32 ±1 spm. Rest time of more than five minutes was given between 500-m trials to allow the scullers to perform at race pace without overly fatigued technique throughout the strokes that were analysed. All trials were carried out on the first 500 m of a pre-measured 2000-m rowing course with 500-m interval markers at the same time each morning after a 1-hour U2[15] warm-up row. Each sculler was set-up with the same oarlocks (identified by serial numbers) in each boat class.

Table 13: Testing schedule for data collection from four elite scullers in men's single (M1x), double (M2x) and quad (M4x) sculls. The 'L' prefix denotes a lightweight sculling boat class.

	Day1		**Day 2**		**Day 3**	
	Sculling boat class	**Seat**	**Sculling boat class**	**Seat**	**Sculling boat class**	**Seat**
Sculler 1	LM1x	-	M4x	Bow	LM2x	Bow
Sculler 2	LM1x	-		2		Stroke
Sculler 3	M2x	Bow		3	M1x	-
Sculler 4		Stroke		Stroke	M1x	-

The 'L' prefix is used here for scullers racing that season as lightweights. Their actual weights at time of testing were 72.9 kg for Sculler 1 and 74.3 kg for Sculler 2.

Following consultation with one of the elite Rowing New Zealand coaches, equipment set-up was standardised across sculling boat classes to match the individual set-up used by each sculler in their double sculls. The measures standardised within each sculler included oar inboard length, overall oar length, horizontal displacement of the foot-stretcher relative to the pin, foot-stretcher angle, foot-stretcher height relative to the seat, gate height relative to the seat, and blade type. Span was adjusted between sculling boat classes to be 1.60 m for the single sculls, 1.59 m for the double sculls, and 1.58 m for the quad sculls. It is standard sculling practice to increase the gearing ratio as boat size increases in an attempt to allow scullers to achieve the same level of

[15] "U2" is the term given to low intensity rows, standard for Rowing New Zealand athletes, where a low stroke rating is implemented (generally between 18 and 20 spm).

exertion despite the increase in boat velocity that would result in increased muscle contraction velocities and therefore, reduced force production (Hamilton & Luttgens, 2002). Based on the methods presented by Rowing Australia (1997) for calculating gearing ratio outlined in Equation 4, the standardised increase of 10 mm in span length from single to double, and double to quad sculls (as recommended by the Rowing New Zealand coach that requested this investigation) would match well with the pattern seen in the top 10 scullers from each sculling boat class at the 2006 World Championships (see Figure 19).

Equation 4: $$gearing\ ratio = \frac{oar\ length\ (m) - inboard\ length(m) - 0.15\ m}{0.5 * span\ (m)}$$

Variables recorded every stroke (n = 80 strokes for each sculler in each sculling boat class) included *boat velocity, stroke rate, stroke power, peak force, total angle, catch angle, finish angle, catch slip* and *finish slip* (Coker, Nolte et al., 2009). Three additional stroke variables were also computed:

- *average force* – total force produced during the drive phase averaged over the entire stroke time (drive and recovery phases)[16]
- *peak force angle* - oarlock angle at point of *peak force* occurrence
- *degrees to peak* - horizontal angular oar displacement between the *catch angle* and the angle at which *peak force* occurred

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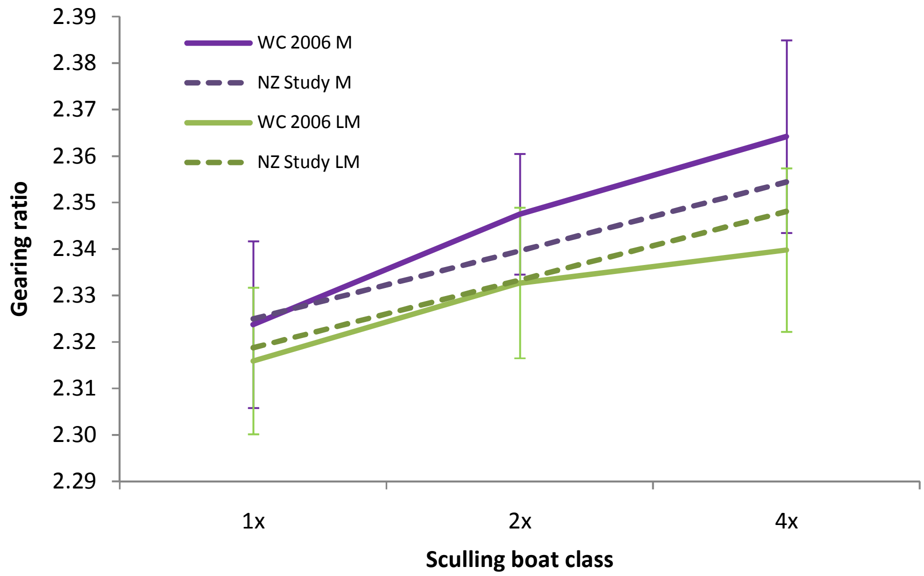
[16]Force values were included only during the drive phase but were averaged over the entire stroke rather than just the drive so that it better relates to the automatic *stroke power* variable produced by PowerLine™ and is more representative of how much work the scullers are achieving over a range of different ratings.



Gearing ratios calculated using the methods presented by Rowing Australia (1997)
WC 2006 = 2006 World Championships; M = Heavyweight men NZ study; LM = Lightweight men NZ study.

Figure 19: Mean ±SD gearing ratios for the top 10 scullers in each boat class at the 2006 World Championships, and for heavyweight and lightweight men in the New Zealand (NZ) study.

Statistical analyses

Previous testing highlighted the need for an intra-individual approach to biomechanical analyses in elite scullers (Coker, Hume, & Nolte, 2009a; Coker, Nolte et al., 2009; Schneider et al., 1978) so a case-study design was adopted for statistical analyses and repeated for four elite level scullers. Means and standard deviations (SD) were calculated for all variables, in each sculling boat class, for scullers separately and then grouped. Using a pre-formatted spreadsheet developed by Hopkins (2007b), change in mean statistics with 90% confidence intervals (90% CI), and effect sizes with qualitative outcomes were calculated for single versus double, single versus quad, and double versus quad sculls for *stroke power, average force, peak force, total angle,* *catch angle, finish angle, catch slip, finish slip, peak force angle* and *degrees to peak*, for each sculler individually. The impact of *stroke rate* on the change in mean was controlled by including *stroke rate* as a predictor variable in the spreadsheet (Hopkins, 2007b). Statistical significance level was set at $p \leq 0.05$. For the qualitative outcome statements, smallest worthwhile effect sizes were set at 0.44% for *stroke power* and 0.5° for all angular variables based on the findings of Coker *et al.* (2008a), and at the standardised mean difference of 0.2 for *peak force* and *average force* because smallest worthwhile effect sizes have not been obtained experimentally for these variables. All statistical analyses were performed via the log-transformed variables for all non-angular variables.

Results

Scullers performed all trials with a group mean *boat velocity* of 93.2 ±3.2% of that required for the world best time (WRT) for their respective sculling boat classes. The lowest and highest recorded mean *stroke rate* for any sculler in any boat class was 31.1 ±1.1 spm and 33.6 ±0.7 spm (Sculler 2 in the single, and Sculler 3 and Sculler 4 in their double respectively). Table 18 in Appendix 6 presents the mean ±SD for each variable from the three sculling boat classes for each sculler individually and then for all scullers as a group.

Change in variable means analyses

Changes in variable means between sculling boat classes with 90% confidence intervals (90% CI) are presented in Table 14 for each sculler. Changes in mean *stroke power* between all sculling boat classes were significant for all scullers. Scullers 1 and 4 displayed the highest mean *stroke power* in the single sculls whilst Scullers 2 and 3 displayed the highest *stroke power* in the double sculls. Sculler 1 showed a significant change in mean *peak force* between all three sculling boat classes, with the greatest mean *peak force* recorded in the single scull (54 ±3 kgF), and the smallest in the quad scull (34 ±2 kgF). The change in mean between these two sculling boat classes equates to a very large effect size of -7.8. Similarly, Sculler 4 recorded the highest mean *peak* *force* in the single scull, and the lowest in the quad scull but a significant change in mean *peak force* (-0.6 kgF, 90% CI: -2.0 kgF to 0.8 kgF) was not found between the double and quad sculls in this sculler. Scullers 2 and 3 both showed significant changes in mean *peak force* between all boat classes and the highest mean *peak force* in the double scull when *stroke rate* was co-varied. All scullers showed a decrease in mean *average force* from the single to quad and double to quad sculls. Three scullers showed a significant decrease in mean *average force* from the single to double sculls (effect sizes of between -0.9 and -4.0 – all greater than the smallest worthwhile effect size). Sculler 2 showed no significant change between these two sculling boat classes.

Mean *total angle* and *catch angle* increased progressively and significantly from single, to double, to quad sculls for all of the four scullers (see Table 19 in Appendix 6 and Table 14). The most predominant change in mean *catch angle* between boat classes was seen in Sculler 4 who showed a significant change in mean between the single and quad sculls of -12.9° (90% CI: -13.5° to -12.4°; ES = -8.9). Significant changes in mean *finish angle* were seen between boat classes but there was no uniformity in the change across the four scullers (see Figure 20). Mean *finish angle* showed a significant change in mean between almost all boat classes in all scullers (two exceptions being the double versus quad sculls for Sculler 3, and the single versus quad sculls for Sculler 4). However, the magnitudes of the changes in mean *finish angle* were much smaller than that seen in mean *catch angle* (see Figure 20). The greatest change in mean *finish angle* was for Sculler 2 between the single and double sculls (3.5°, 90% CI: 3.1° to 3.9°; ES = 4.1). Although this produced a very large effect size it was only approximately half the magnitude of the largest effect size seen for *catch angle* (ES = -8.3 for sculler 4 between the single and quad sculls).

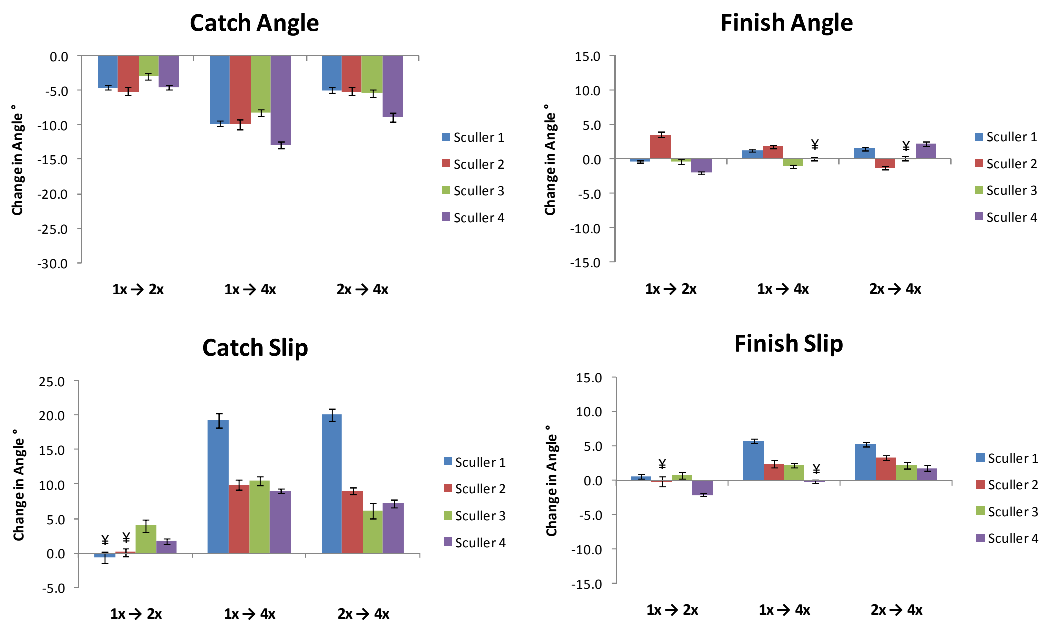
Table 14: Changes in means with 90% confidence intervals (90% CI) and effect sizes (ES) with qualitative outcome[a] (QO) for biomechanical stroke variables of four elite scullers moving between single, double, and quad sculls.

	Single → Double Scull		**Single → Quad Scull**		**Double → Quad Scull**	
SCULLER 1	**Change in Mean (90% CI)**	**ES & QO**	**Change in Mean (90% CI)**	**ES & QO**	**Change in Mean (90% CI)**	**ES & QO**
Stroke Power (%)	-2.8 (-4.1 to -1.5)	-0.6 S-M	-33.8 (-34.9 to -32.7)	-6.9 VL	-32.6 (-33.7 to -31.6)	-7.1 VL
Peak Force (%)	-4.5 (-5.7 to -3.4)	-1.1 L-M	-35.4 (-36.4 to -34.4)	-7.8 VL	-33.0 (-33.8 to -32.2)	-9.3 VL
Average Force (%)	-5.5 (-7.1 to -3.9)	-0.9 L-M	-53.6 (-54.8 to -52.3)	-8.1 VL	-51.4 (-52.5 to -50.3)	-8.8 VL
Total angle (°)	4.3 (3.9 to 4.7)	3.2 VL	11.0 (10.5 to 11.5)	6.3 VL	6.4 (6.0 to 6.9)	4.2 VL
Peak Force angle (°)	2.9 (1.4 to 4.4)	0.5 S-M	-5.3 (-6.9 to -3.8)	-1.0 M-L	-8.4 (-10.0 to -6.7)	-1.4 M-L
Degrees to Peak (°)	7.6 (6.0 to 9.1)	1.3 M-L	4.5 (2.9 to 6.0)	0.8 S-M	-3.4 (-5.1 to -1.7)	- 0.6 S-M
SCULLER 2	**Change in Mean (90% CI)**	**ES & QO**	**Change in Mean (90% CI)**	**ES & QO**	**Change in Mean (90% CI)**	**ES & QO**
Stroke Power (%)	7.9 (5.7 to 10.2)	1.3 M-L	-18.0 (-19.9 to -16.1)	-2.8 VL	-24.1 (-25.2 to -23.0)	-5.4 VL
Peak Force (%)	3.3 (1.5 to 5.0)	0.7 S-M	-24.4 (-26.0 to -22.8)	-4.5 VL	-26.4 (-27.4 to -25.4)	-6.4 VL
Average Force (%)	0.3 (-1.9 to 2.7) ¥	0.1 U	-32.9 (-35.2 to -30.5)	-3.9 VL	-32.0 (-33.5 to -30.4)	-4.5 VL
Total angle (°)	8.6 (7.9 to 9.3)	4.5 VL	11.7 (10.9 to 12.5)	4.8 VL	3.8 (3.3 to 4.3)	2.0 L-VL
Peak Force angle (°)	-0.2 (-1.9 to 1.4) ¥	-0.1 U	0.9 (-0.8 to 2.7) ¥	0.2 U	-1.3 (-2.5 to -0.1)	-0.3 U
Degrees to Peak (°)	4.9 (3.3 to 6.5)	1.2 M-L	10.8 (9.1 to 12.5)	2.2 L-VL	3.8 (2.6 to 5.0)	0.9 M-L
SCULLER 3	**Change in Mean (90% CI)**	**ES & QO**	**Change in Mean (90% CI)**	**ES & QO**	**Change in Mean (90% CI)**	**ES & QO**
Stroke Power (%)	6.6 (4.0 to 9.3)	1.1 M-L	-27.0 (-28.7 to -25.1)	-4.0 VL	-26.1 (-28.9 to -23.1)	-3.0 VL
Peak Force (%)	1.9 (-0.2 to 4.0) ¥	0.4 T-M	-32.1 (-33.6 to -30.6)	-5.5 VL	-26.3 (-34.8 to -16.8)	-0.9 S-L
Average Force (%)	-14.0 (-17.3 to -10.5)	-2.2 L-VL	-32.9 (-34.7 to -31.1)	-4.6 VL	-26.2 (-29.4 to -22.9)	-2.9 VL
Total angle (°)	1.5 (0.9 to 2.1)	1.1 M-L	7.2 (6.6 to 7.8)	4.1 VL	5.5 (4.8 to 6.2)	3.0 VL
Peak Force angle (°)	7.3 (5.5 to 9.2)	2.0 L-VL	-0.1 (-1.6 to 1.4) ¥	0 U	-8.6 (-10.8 to -6.4)	-1.5 M-L
Degrees to Peak (°)	9.5 (7.5 to 11.5)	2.4 L-VL	8.2 (6.7 to 9.7)	1.7 L-VL	-3.3 (-5.5 to -1.0)	-0.6 T-M
SCULLER 4	**Change in Mean (90% CI)**	**ES & QO**	**Change in Mean (90% CI)**	**ES & QO**	**Change in Mean (90% CI)**	**ES & QO**
Stroke Power (%)	-6.7 (-7.4 to -6.0)	-2.5 VL	-8.9 (-10.0 to -7.9)	-2.9 VL	-0.6 (-2.0 to 0.8) ¥	-0.2 U
Peak Force (%)	-16.8 (-23.6 to -9.3)	-0.6 S-M	-17.2 (-18.1 to -16.3)	-6.0 VL	0.5 (-10.6 to 13.1) ¥	0 U
Average Force (%)	-16.3 (-17.5 to -15.2)	-4.0 VL	-14.4 (-16.0 to -12.8)	-3.0 VL	4.4 (2.0 to 6.9)	0.8 S-M
Total angle (°)	2.5 (2.2 to 2.8)	2.0 L-VL	13.0 (12.4 to 13.5)	7.8 VL	11.0 (10.3 to 11.8)	5.9 VL
Peak Force angle (°)	-6.0 (-7.4 to -4.6)	-1.2 M-L	-1.7 (-3.8 to 0.4) ¥	-0.3 U	3.6 (0.8 to 6.4)	0.5 T-M
Degrees to Peak (°)	-1.6 (-2.9 to -0.2)	-0.3 U	11.3 (9.2 to 13.3)	-1.9 L-VL	12.5 (9.7 to 15.2)	1.8 L-VL

¥ change in mean is NOT significant at the 0.05 level.
[a]qualitative outcome states whether the effect size is S=small, M=moderate, L=large, VL=very large, T=trivial, or U=unclear/smaller than the smallest worthwhile effect size.[b]
[b]smallest worthwhile effect sizes were set as 0.44% for *stroke power* and 0.5° for all angular variables based on Coker *et al.* (2008a), and 0.2 for *peak force* and *average force* based on the standardised mean difference.

As Figure 20 shows, mean *catch slip* was significantly greater in the quad sculls than in both the single and double sculls in all four scullers (grouped mean *catch slip* was 7.6 ±1.3°, 8.7 ±1.0° and 19.6 ±5.7° for single, double and quad sculls respectively). Scullers 3 and 4 also showed a significant change in mean *catch slip* between the single and double sculls (4.0°, 90% CI: 3.1° to 4.9° for Sculler 3; 1.8°, 90% CI: 1.4° to 2.2° for Sculler 4). Once controlled for *stroke rate,* mean *finish slip* was significantly different between all boat classes for all scullers with the one exception of Sculler 4 between the single and quad sculls (change in mean was -0.2°, 90% CI: -0.4° to 0.1°). The greatest changes in mean *finish slip* (5.7°, 90% CI: 5.4° to 6.0°)) and mean *catch slip* (20.1°, 90% CI: 19.2° to 21.0°) were for Sculler 1 in the single versus quad sculls. Similar to the comparison between *catch angle* and *finish angle,* the largest effect size seen for change in *finish slip* and was approximately half the magnitude of that seen for *catch slip* (effect sizes of 5.1 and 10.4), and in general all scullers showed greater changes in mean *catch slip* than *finish slip* when moving between boats.

For Scullers 1 and 3, mean *peak force angle* was seen to occur with the handles significantly further towards the bow in the double sculls than in other boat classes. Mean *peak force* occurred in the double sculls at -12.1 ±6.2° and -12.5 ±4.7° for Scullers 1 and 3 respectively (see Table 18). In contrast, Sculler 4 peaked with the handles significantly further towards the stern in the double sculls than in either other boat class (mean *peak force* in the double of -25.9 ±6.5°), and Sculler 2 showed little change in mean *peak force angle* when moving between boat classes. Between the single and quad sculls only Sculler 1 had a significant difference in mean *peak force angle* (-5.3°, 90% CI: 6.9° to -3.8°). Regarding mean *degrees to peak,* Scullers 1 and 3 took the greatest horizontal oar-displacement from the catch position before *peak force* occurred in the double sculls and the least in the single sculls. Sculler 2 and Sculler 4 had the greatest mean *degrees to peak* in the quad scull (mean of 47.2° ±5.4° for Sculler 2, and 59.0° ±7.7° for Sculler 4).



N.B. Due to the negative nature of the *catch angle* values, a positive change in mean in *catch angle* signifies that size of this angle became smaller, whilst positive changes in means in *catch slip, finish angle* and *finish slip* signify increased angle sizes. Values for these changes in mean statistics are presented in Table 19.

Figure 20: Changes in means with 90% confidence interval bars for *catch angle, catch slip, finish angle* and *finish slip* for four elite scullers when moving between single sculls (1x), double sculls (2x) and quad sculls (4x). ¥ denotes that the change in mean was not significant ($p > 0.05$).

Discussion

The results indicate that there are trends in the effect of boat size on some biomechanical variables in elite scullers, but these trends exist in combination with intra-individual effects on other variables. Only three of the trials were performed outside the stipulated 32 ±1 spm but, since *stroke rate* was included as a predictor variable in the comparison of means, this additional variation should not impact upon the effect statistics presented.

Change in variable means analyses

Standardising gearing ratios across sculling boat classes would have allowed a more controlled comparison of the effect of sculling boat class, particularly on *stroke power, average force* and *peak force.* However, had we used standard double scull gearing across boat types the scullers would have been severely inhibited in both other sculling boat classes due to the different boat velocities and therefore muscular contraction velocities experienced. Since the increase in gearing ratios used in this study is standard practice and known to be beneficial for performance, it was deemed appropriate because we were looking to improve on current practice.

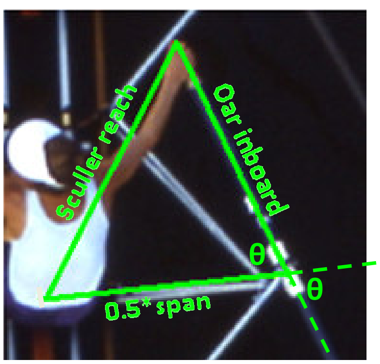
Stroke power is the product of the x-direction components of the pin force and handle velocity during the drive phase (Coker, Nolte et al., 2009). In order for scullers to produce a similar *stroke power* across all boat classes they would therefore need to be able to produce sufficient muscular forces with high inter-muscular coordination at a range of contractile velocities. Despite *boat velocity* and *total angle* (and therefore handle velocity) increasing with increased boat size, *stroke power* values were smallest for all scullers in the quad scull. This indicates that *average force* decreased by a greater degree than the handle velocity increased when moving into larger boat classes. The lowest *stroke power* values were recorded in quad sculls and were in accordance with the findings of Lasauskas (1997) and Schwanitz (1991) who stated that as boat size increased, rower power decreased. Since our scullers spend the least amount of time in the quad scull in comparison to the other two boat classes, and it has been shown that gains in force production are specific to the contraction velocity at which training occurs (Kanehisa & Miyashita, 1983), the lowest *stroke power* values recorded in quad sculls was not unexpected.

The force-velocity relationship of muscular contraction states that as the speed of contraction increases, the force that can be generated by the muscle decreases (Hamilton & Luttgens, 2002). Therefore, it was expected that the lowest *peak force* and *average force* values were recorded in the quad sculls where *boat velocity* and therefore, handle and contraction velocities were highest (see Table 18). Based on the force-velocity relationship, and the findings of Lasauskas (1997) and Schwanitz (1991), it was also anticipated that the highest *peak force* and *average force* would be seen in the single sculls where *boat velocity* and therefore handle and contraction velocities would be lowest. Scullers 1 and 4 did display the highest *peak force* in the single sculls, but Scullers 2 and 3 did not. However, in single sculls, scullers 2 and 3 recorded the slowest *boat velocities* relative to world best times (90.1 ±3.4% and 88.5 ±3.1% of WRT) compared to the mean of all trials (93.2 ±3.2% WRT), likely due to an inability to produce high pin force and *stroke power* in this boat class. The reason for this may be based in the muscular or technical characteristics of Scullers 2 and 3, and it may be concluded that these scullers are better suited to larger boat classes than scullers 1 and 4.

It was noted that in the quad sculls, Sculler 4 was able to maintain *stroke power* and *peak force* values not significantly different to those in the double sculls. The potential application for this is to put scullers who find it most difficult to apply force and power in a quad scull in the stroke seat where it appears to be easiest to achieve the same level of exertion as in smaller sculling boat classes. Data from more scullers is required to confirm this suggestion, but these findings support anecdotal verbal reports from Rowing New Zealand athletes and coaches who have commented that crew members seated further towards the bow of larger boat classes find it more difficult to achieve a high *stroke power.* Off-water profiling of athletes to analyse their force producing capacity in sculling-specific muscle groups at different contraction velocities may allow coaches to identify which athletes may be better suited to different boat classes and/or seats.

The change in mean *total angle* between boat classes is understandable because span length was reduced by 10 mm for each increase in boat size. However, the increase in mean *total angle* was of a much larger magnitude than would be expected from such a small change in span (see Table 14). Making the crude assumption that the sculler's reach is constant and using the methods presented in Figure 21, it would be expected that when moving from the 1.60 m span of the single sculls (with a *catch angle* of -

65.2° and a *finish angle* of 44.4°) to the 1.58 m span of the quad scull, a change in mean *catch angle* of -1.2° and a change in mean *finish angle* of +0.2° would occur resulting in a change in mean *total angle* of 1.4°. The actual changes in mean recorded in mean *total angle* between the single and quad sculls were -9.8°, -9.9°, -8.3°, and -12.9° for the four scullers (see Table 14). Potential explanations for this may include increased stability (reduced roll) of the quad scull compared to the single scull allowing the scullers to confidently reach out to a longer *catch angle* and greater momentum in the larger boats pushing the scullers forward due to the higher mass of the sculler-boat-blade system. Additionally, although gate height relative to seat height was controlled, gate height relative to water height was not fixed between boat classes and slight changes in the angle of the arm relative to the horizontal may result in order to maintain correct blade height during the recovery and drive. This would then lead to altered length at the catch and finish (see Figure 22).



Assuming oar inboard and sculler reach at the catch and finish are constant, if span is decreased by bringing the pin closer to the hull, then θ must increase based on the cosine rule; $a^2 = b^2 + c^2 - 2bc*\cos\theta$, where ‘a’, ‘b’ and ‘c’ are the sides of the triangle and ‘θ’, is the internal angle opposite ‘a’

$$\theta = \cos^{-1} \frac{[(\text{sculler reach})^2 - (\text{oar inboard})^2 - (0.5*\text{span})^2]}{-2*(\text{oar inboard})*(0.5*\text{span})}$$

Figure 21: Diagram to show how change in span may affect *catch angle* and *finish angle* and therefore stroke length where ‘θ’ could represent either the *catch angle* or *finish angle* (photograph courtesy of Dr Volker Nolte).

Figure 20 clearly displays that *catch angle* was affected by boat size by a much greater amount than *finish angle* in all of the scullers tested. The implications of this finding impact upon the boat set-up changes and coaching focal points that should be adopted when scullers are moved between boat classes. It appears that eilte scullers can better re-create a particular *finish angle* than *catch angle*, and tend to reach substantially further at the catch in larger boats. With the set-up used in this study, where span was reduced, but inboard was kept the same as boat size increased, the minimal change to the *finish angle* is understandable since there would be no further room for the scullers to reach to at the finish. Although it is agreed that a long *catch angle* is desirable, over-reaching at the catch requiring force application in unaccustomed body positions may cause injury, for example due to excessive lumbar flexion (Caldwell, McNair, & Williams, 2003), particularly since gearing, and therefore load, is high at long catch angles (Kleshnev, 2006b). Coaches must be aware of this and should focus upon achieving a safe and effective *catch angle* in scullers in new boat classes through coaching cues and boat set-up changes, specifically foot-stretcher position and angle. For example, the foot-stretcher may be raised and/or set at a steeper angle to allow more effective force application on the foot-stretcher because the accompanying reduction in catch length that usually occurs from such a change will be counteracted by the reduced span (Caplan & Gardner, 2005; Soper, 2004).

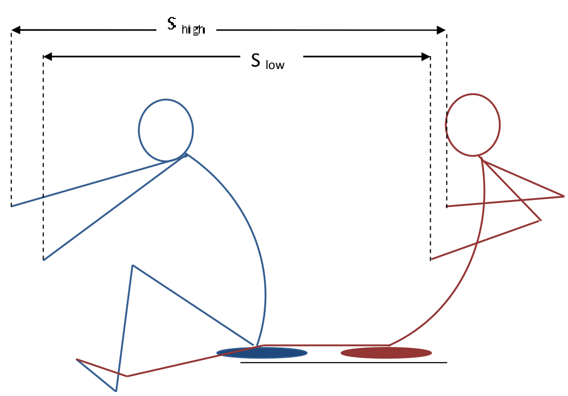


Figure 22: Diagram to show how stroke length (S) is affected by high and low handle height and altered arm angle relative to the horizontal (from Nolte (1991)).

As it is also known that increasing *catch angle* has the equivalent effect of increasing the oar gearing (Kleshnev, 2007b), adjustments to oar lengths may be required to counteract this effect and to allow the same level of exertion to occur over the race distance. Further investigation is needed into the precise three-dimensional joint angle and position changes responsible for this augmented alteration to *total angle,* specifically *catch angle,* through span adjustment. This would allow us to understand if, and how, reducing the span may allow rowers with specific inflexibility issues to achieve substantially longer stroke lengths, beyond that already applied by coaches.

Changes in mean *catch slip* were also much greater than in *finish slip*, further confirming that the catch is more affected than the finish by boat class (see Figure 20). Generally *catch slip* significantly increased ($p \leq 0.05$) with increased boat size (with one exception of Sculler 1 for single versus double sculls). This effect on *catch slip* could potentially be explained entirely by the fact that *catch angle* was influenced by a much greater magnitude than *finish angle.* Because the *finish angle* was relatively unaltered by boat size, the scullers would have finished the drive in a similar body orientation and could have been able to maintain force to a similar length across boat classes. In contrast, the substantially different *catch angle* and body position at the catch experienced in the different boat classes will mean that initial force development in the early drive would be produced at different joint angles and therefore by muscles at altered lengths. The length-tension relationship states that the maximal tension (i.e. force) that a muscle can exert is dependent upon the length of the muscle, and at muscle lengths greater than the resting length less tension will be produced under the same stimulus (Hamilton & Luttgens, 2002). Reaching further at the catch in the larger boats will most likely result in longer muscle lengths and therefore lower force production during the initial drive phase and longer *catch slips.* Additionally, in the faster boat classes, horizontal oar displacement to the fixed threshold force will be greater (i.e. longer *catch slip*) because *boat velocity* and therefore handle velocity will be higher resulting in a lower rate of force development in accordance with the force-velocity relationship of muscular contraction (Hamilton & Luttgens, 2002).

Catch angle changed by a similar amount between the single and double sculls compared to between the double and quad sculls, whilst *boat velocity* changed by a smaller amount between the double and quad sculls compared to the single and double sculls (grouped mean *boat velocity* increased by 12.4% from the single to double sculls and by 4.6% from the double to quad sculls). Despite this, differences in *catch slip* were smaller for the single versus double than double versus quad sculls. This could be explained by the fact that increases in strength are greatest at the muscle length and contraction velocity adopted during training (Jones, Rutherford, & Parker, 1989; Kanehisa & Miyashita, 1983). These scullers spend the majority of their training time in double sculls, therefore their rate of force development will be disproportionately high in the double sculls causing a lower than anticipated *catch slip* in comparison to the other boat classes. Differences between boat classes in *catch slip* may be reduced by setting the force threshold as 30 percent of *peak force* because *peak force* significantly altered between boat types and therefore the 20 kgF threshold equated to varying percentages of *peak force* in the different boat types.

One limitation of this study was that the scullers were only tested in one seat in each boat class and therefore, individual sculler responses may only be symptomatic of the seat in which they were placed. However, other than trends universal to all four scullers, neither scullers 1 and 3 (both bow seats in their respective double sculls), nor scullers 2 and 4 (both stroke seats), shared trends in any variables except *peak force angle* and *degrees to peak*. Scullers 1 and 3 both took the greatest horizontal oar displacement to *peak force* in the double scull and peaked with their handles further towards the bow (relative to other boat classes and relative to their respective stroke seat scullers (see Table 18)). It is well known that the stroke and bow seats have differing force profiles during the drive phase in a skilled pair-oared sweep boat, where the stroke seat should peak earlier than the bow seat to counteract the non-matching lever arm lengths of the two rowers relative to the centre of rotation of the boat (Hill, 2002; Roth et al., 1993; Smith & Loschner, 2002). It would not be anticipated that this would translate to a symmetrically rigged double scull, however this is the pattern noted in the double sculls in our study. Whether this is a random effect or whether this is due to other effects of “seat” in two-man rowing boats cannot be determined from these data. In order to further investigate this phenomenon additional data must be collected where a larger number of elite scullers switch seats in double sculls.

Another limitation to be considered is that the scullers were only tested in each crew boat with the same additional crew members. The resulting changes noted in biomechanical variables may have merely been indicative of the influence of the other scullers on each individual’s technique. The justification for the methods used was the study of Wing and Woodburn (1995) where rowers were switched within an eight and no significant changes were seen in the force profiles of the remaining rowers. However, the athletes in our study were more elite and the boat classes were smaller perhaps meaning that they may have enhanced awareness of the other crew members’ kinetics and were better able to synchronise to increase performance. In support of this, rowers in pairs were seen to alter their force profiles in order to increase synchrony when partners were switched (Baudouin & Hawkins, 2004). Additionally, the stroke remained the same throughout the Wing and Woodburn (1995) study whilst Scullers 1 and 2 in our study experienced a different stroke seat sculler in the quad scull compared to the double scull. In general, scullers 1 and 2 were least affected by the change from the double to the quad sculls than scullers 3 and 4 and Sculler 4 showed the greatest change in *total angle* and *angle to* peak of all the scullers despite being the only sculler seated in the stroke seat of all the boat classes tested (11.0°, 90% CI: 10.3° to 11.8° change in *total angle,* and 12.5°, 90% CI: 9.7° to 15.2° change in *angle to peak*).

Summary

The elite scullers in this study generally exhibited the lowest *stroke power, peak force* and *average force* in the quad sculls. This is likely to be due to the higher muscular contraction velocities required in this faster boat class reducing the force-producing capacity of the muscles during the drive. Some discrepancies were seen as to whether the scullers achieved their highest *stroke power* and *average force* values in the single or double sculls. This may indicate that different scullers are better suited to different sculling boat classes due to their different muscular characteristics and/or training experiences allowing them to better exert themselves in single or double sculls.

The sculler placed in the stroke seat of the quad scull was the only sculler not to significantly reduce his *stroke power, average force* and *peak force* when moving from the double to quad sculls. This may indicate that this individual is well suited to rowing in quad sculls or, more likely, is indicative of the characteristics of the stroke seat in larger boat classes. This could potentially be applied in seating strategies, allocating the stroke seat either to the weakest crew member in order to bring their performance closer to the crew average, or to the strongest person, in order to allow them to reach their full potential.

The relatively small (10 mm) change in span employed between boat classes brought about a surprisingly large change in mean *total angle*, particularly through an increase in mean *catch angle*. This had a knock-on effect on *catch slip* which was significantly higher in the quad scull than the single scull in all scullers. This large alteration to the catch when scullers moved between boat classes should be considered in technical focus points and boat set-up. Higher, steeper and/or less stern-ward foot-stretcher settings should be used if coaches wish to achieve the same *catch angle* when span lengths are reduced, as is generally the case in larger boat classes.

Interestingly, in both double sculls (both medal-winning crews at senior international level), the stroke seat sculler peaked their force earlier than the bow seat. This pattern is known to be preferable in pair-oared rowing but the importance of this synchronisation is not known for performance in symmetrically rigged double sculls. Further investigation is needed on this topic.

CHAPTER 9 - THE EFFECT OF SEATING ORDER AND FORCE SYNCHRONISATION ON PERFORMANCE IN ELITE DOUBLE SCULLS

This chapter comprises the following technical report submitted to Rowing New Zealand.

Coker, J., Hume, P. A., & Nolte, V. (2010). *The effect of seating order and force synchronisation on performance in elite double sculls* (Technical report for Rowing New Zealand). (pp. 1-12). Auckland: Institute of Sport and Recreation Research New Zealand, Auckland University of Technology.

Overview

The stroke seat rower's force in a pair-oared rowing boat must peak higher and earlier than the bow seat rower's in order to counteract their non-matching lever arms relative to the centre of rotation of the boat. It has not previously been thought that the same staggered peaking would be required in symmetrically rigged sculling boats, but recent findings have shown this pattern exists in successful senior international double sculls. The aims of this study were to investigate the effect of synchronization of force profiles in doubles sculls and to determine whether the previously noted pattern does have a positive effect on performance. Four elite-level scullers completed twelve 500-m trials at race pace over three days in different crew combinations. Pearson correlation coefficients were computed to quantify the relationship between change in performance and change in synchronization, measured as the difference between the bow and stroke seat rowers in the following variables; catch slip (*CS angle-diff*), time to peak force (*PF time-diff*) and oar angular displacement to peak force (*PF angle-diff*). Mean *boat velocity* changed by as much as 5.8% of world record time when seating order was switched. Percentage change in *boat velocity* versus change in the relative *PF time-diff, PF angle-diff* and *CS angle-diff* resulted in R values of 0.55 (90% CI; -0.32 to 0.92), 0.59 (90% CI; -0.27 to 0.93) and 0.16 (90% CI; -0.66 to 0.80) respectively. Seating order is crucial for performance in elite double sculls and crew trials should therefore be seat-specific and carried out in both seating orders. It appears that the stroke and bow seats in an elite double scull should not match their force profiles, but instead, the stroke should peak earlier in the drive phase and with the handles further to the stern. A full explanation is not known for why this seat-specific staggered peaking pattern is beneficial for performance, but it may be that it causes the crew average peak force to occur earlier in the drive phase, perhaps increasing efficiency.

Introduction

It is generally assumed that optimal boat propulsion will result from crew members applying force in an identical fashion in order to minimize yaw and additional drag about the shell (Baca & Kornfeind, 2008; Baudouin & Hawkins, 2002). Although it is true that yaw should be avoided, the situation is actually more complicated. Not only will almost all rowers have force profiles that are distinctly different from one another, even in successful elite crews, but rowers in different seats within a crew will also apply their forces with different lever arm lengths and will therefore put different turning forces, or moments on the boat (moment = force*lever arm length, where lever arm length is the perpendicular distance from the centre of rotation of the boat to the line of force application – see Figure 23). This means that it is not forces that need to be matched on both sides of the boat, but instead moments, as they are responsible for any rotation (yaw).

This issue is most noticeable in pair-oared boats where it is well documented that the stroke seat must peak earlier and higher than the bow seat in order to counteract the non-matching lever arm lengths of the two rowers and make the boat travel straight (Hill, 2002; McBride et al., 2001; Roth et al., 1993; Schneider et al., 1978; Smith & Loschner, 2002; Zatsiorsky & Yakunin, 1991) (see Figure 23). Specific rigging has also been recommended for four and eight-oared sweep boats that help to match the average moments on each side of the boat (Barrow, 2010). However, there is little information on the real effect of having unmatched force patterns within symetrically-rigged sculling boats. As long as each sculler produces force evenly on their own left and right blades, synchronous peaking between crew members is not necessary to keep the boat straight (Wing & Woodburn, 1995). If blade entry and release timings are matched to avoid additional boat velocity fluctuations, it might even be beneficial to use staggered peak forces that result in a more rectangular average crew profile - known to be more efficient than a triangular shape profile (Kleshnev, 2001b).

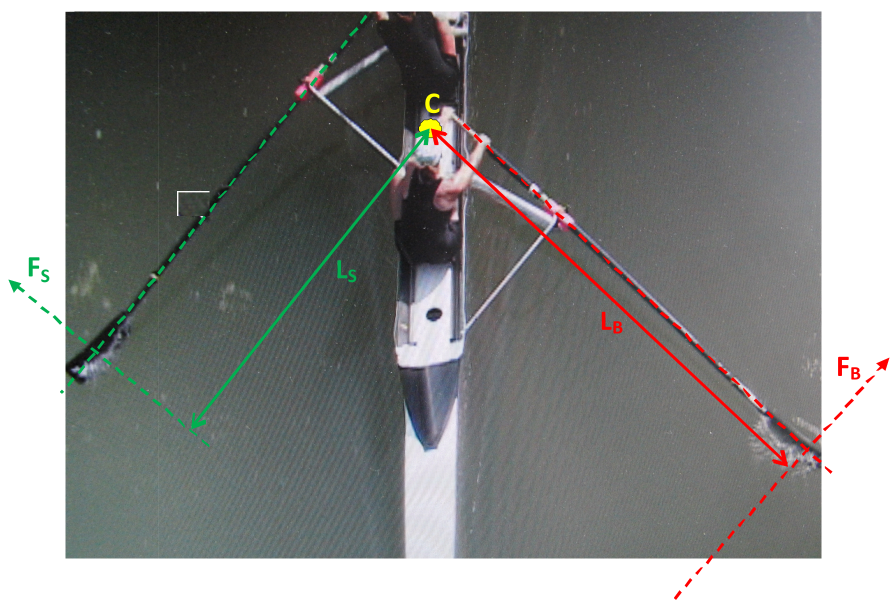


Figure 23: Non-uniform lever arm lengths, L_S and L_B for stroke and bow rowers in a pair respectively. L_B and L_S are the perpendicular length between the centre of rotation of the boat, C (estimated here based on a similar figure in Kleshnev (2009)) and the line of force application at the blade (F_S and F_B) (photo courtesy of Brett Smith).

In a previous study, the bow seat scullers in two double sculls took greater horizontal oar displacements to reach peak force than their stroke seat scullers and peaked with their handles further towards the bow (Coker, Hume, & Nolte, 2010a). Although both were successful crews – winning gold or silver medals at world cup regattas that season - it cannot be confirmed whether this noted pattern is the most beneficial or whether this is merely a result of the Rowing New Zealand coaches and selectors placing “quicker” athletes in the stroke seat.

Aim

The aims of this study were to investigate the effect of synchronisation on performance in elite double sculls and to determine whether the previously recorded pattern was preferable with the stroke seat sculler peaking with their force before the bow seat sculler. This information may enhance seating order selection and understanding of the technique and/or boat set-up required for maximal performance in double sculls.

Methods

Participants

Four elite heavy-weight male scullers (90.9 ±3.2 kg, 1.86 ±0.05 m, 26.4 ±6.1 years) volunteered for the study. All were members of the Rowing New Zealand elite summer squad for 2009/2010 and had won at least silver medals at Senior World Cups or gold medals at U23 World Championships. All participants were informed of the procedures and gave written consent.

Procedures

Two double sculls were equipped with PowerLine™ to record pin force and oar angle at 50 Hz throughout each trial. On each of three consecutive days the scullers were paired with a different sculler and asked to warm-up for approximately 4 km including at least 20 familiarization strokes at race rate. During the warm-up horizontal foot-stretcher position was adjusted to set bow and stroke seat catch angles at 70 ±1° using data telemetered to a laptop in the coach boat. The scullers were then instructed to perform two 500-m trials in different directions on the lake (i.e. a head and tail wind trial) from flying starts at a rate of 32 ±1 spm. A rest time of 10 minutes was specified between trials to allow the scullers to perform at race pace without fatigue. Scullers then switched bow and stroke seats within the same double scull and set-up their foot-stretchers to the exact settings that had been used in the previous seat. Scullers then repeated the warm up, familiarization and two, 500-m trials. All trials were carried out on a pre-measured 500-m section of the national training lake. Times for each trial were taken using synchronized stop watches and the harmonic mean[17] of the head and tail wind trials was taken for each seating order. This is in accordance with Adam *et al.* (1977) and their recommendations for conditions where the difference between the head and tail wind boat velocities would result in 12 seconds difference, or more, over 560 m (as was the case in this study for two of the 12 comparisons). *Stroke rate* and *boat power*[18] were extracted for the middle 45 strokes of each 500-m trials for each boat. *Catch slip*[19], *peak force (PF) angle*[20] and *PF time*[21] were also extracted for each oar and averaged for the whole crew. The following variables were then computed to quantify synchronization of the stroke and bow seat force profiles:

- ***CS angle-diff* (°)**; bow seat *catch slip* angle - stroke seat *catch slip* angle
- ***PF angle-diff* (°)**; bow seat *PF angle* – stroke seat *PF angle*
- ***PF time-diff* (s)**; bow seat *PF time* – stroke seat *PF time*

Both the absolute difference (ABS) and the relative difference (REL) (i.e. with the positive or negative sign) were recorded. The methods by which these synchronization

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[17] Harmonic mean = $(2*v_t*v_h)/(v_t + v_h)$, where v_t and v_h are boat velocities from tail and head wind trials respectively.
[18] Bow seat stroke power + stroke seat stroke power.
[19] Angular displacement from the minimum gate angle to the point at which the force value exceeded 196 N (20 kgF as displayed by the system) in the direction of the longitudinal axis of the boat.
[20] The oar angle at which peak force was reached.
[21] The time taken between the stroke seat's catch angle occurring and peak force being reached on the pin.

variables are computed means that if the stroke seat is quicker at the catch and applies their peak force earlier, the relative values will be positive. The bilateral average was taken for all values.

Statistical analyses

Percentage change scores were calculated for each crew (i.e. two crews per day over three days, total n = 6) between the two seating orders for *boat velocity* (harmonic mean of tail and head wind trials), *stroke rate* and *boat power* (arithmetic means of tail and head wind trials) along with actual change in absolute and relative *CS angle-diff*, *PF angle-diff* and *PF time-diff*. Pearson correlation coefficients were computed in SPSS for the relationships between percentage change in *boat velocity* from each seating order switch and percentage changes in *stroke rate* and *boat power,* and changes in absolute and relative *CS angle-diff*, *PF time-diff, PF angle-diff.* Correlations between percentage change in *boat velocity* and changes in crew average *PF angle* and *PF time* were also computed. R and p values were presented, and a pre-formatted spreadsheet was used to obtain the 90% confidence intervals (Hopkins, 2007a). Correlations were taken to be significant when $p \leq 0.05$.

Results

Mean *boat velocity* across trials was 5.12 ±0.24 m/s, which was an equivalent of 92.9% WRT[22]. Mean *stroke rate* and *boat power* across trials were 32.2 ±0.4 spm and 780 ±37 W. Means and standard deviations across all crews in all trials are presented in Table 15 for the synchronization variables and for *catch slip, PF time* and *PF angle.* These variables are also presented separately for each double scull pairing in both seating orders in Table 20 in Appendix 6. The mean absolute change in *boat velocity* following seating order switch was 1.5 ±2.1% WRT with a range of 0.4 to 5.8% WRT. Mean

[22] % WRT expresses the boat velocity as a percentage of that required to achieve the World Record Time for that boat class – achieved for the double scull in Poznan in 2006.

change after switching seats was 0.92 ±0.01% in *stroke rate* and 2.59 ±0.01% in *boat power*.

Table 15: Mean ±SD for all crews across all trials for synchronization variables and for *catch slip*, *PF-time* and *PF-angle*.

Variable	**Mean ±SD**
CS angle-diff (ABS)(°)	1.6 ±0.9
CS angle-diff (REL) (°)	-0.3 ±1.9
PF time-diff (ABS) (ms)	30 ±19
PF time-diff (REL) (ms)	-5 ±36
PF angle-diff (ABS) (°)	3.3 ±2.3
PF angle-diff (REL) (°)	-0.3 ±4.1
PF time (ms)	433 ±24
PF angle (°)	-24.4 ±3.2
Catch slip (°)	7.2 ±0.8

As shown in Table 16, no significant correlations were found between change in *boat velocity* and change in any other variable at the $p \leq 0.05$ level. Regarding the synchronization variables, the highest R-values were seen for correlations between change in *boat velocity* and change in relative *PF-angle diff* (0.59, 90% CI; -0.27 to 0.93), and relative *PF time-diff* (0.55, 90% CI; -0.32 to 0.92), but neither were significant. Correlations between change in crew average *PF time* and *PF angle*, and percentage change in boat velocity resulted in negative R values of -0.45 (90% CI; -0.89 to 0.43) and -0.61 (90% CI; -0.93 to 0.24) respectively. Weather conditions during testing were not ideal with wind speeds between 2.8 and 5.3 m/s.

Table 16: R-values for Pearson correlations between percentage change in *boat velocity* and change in the predictor variables, *stroke rate, total power, PF time, PF angle, CS angle-diff, PF time-diff* and *PF angle-diff* [both absolute (ABS) and relative (REL) versions of the three synchronization variables were used]. Δ denotes "change in".

		Δ *boat velocity* (%)	
		R	**90% CI**
	Δ stroke rate (%)	0.59	-0.27 to 0.93
	Δ boat power (%)	0.17	-0.65 to 0.81
Synchronization variables	*Δ CS angle-diff (ABS)*	0.13	-0.67 to 0.79
	Δ CS angle-diff (REL)	0.16	-0.66 to 0.80
	Δ PF time-diff (ABS)	0.3	-0.56 to 0.85
	Δ PF time-diff (REL)	0.55	-0.32 to 0.92
	Δ PF angle-diff (ABS)	-0.26	-0.84 to 0.59
	Δ PF angle-diff (REL)	0.59	-0.27 to 0.93
	Δ PF time	-0.45	-0.89 to 0.43
	Δ PF angle	-0.61	-0.93 to 0.24

No correlations were significant at the $p \leq 0.05$ level.

Discussion

Mean *boat velocity* was lower than previously seen in elite double sculls performing similar trials (Coker et al., 2010a). This will be because, unlike in the previous study, these crews were not selected crews racing internationally, and higher wind speeds were experienced during data collection. Compared to the heavyweight men's double scull in a previous study (Coker et al., 2010a), *boat power* was slightly lower (on average 12 W), but the athlete with the highest *stroke power* from the previous study was not included in the present analyses due to commitments overseas. Small subject numbers prevented analyses to be computed including *stroke rate* and *boat power* as covariates, but this should not prevent effects of synchronization on *boat velocity* being identified because the mean *stroke rate* across all trials fell within the stipulated narrow range of 32 ±1 spm and change in *boat power* was not significantly correlated with change in *boat velocity* between seating orders (see Table 16).

Seating order was shown to be crucial in these elite doubles sculls where switching the bow and stroke seats scullers resulted in a change in *boat velocity* of as much as 5.8% WRT. Although surprising, this extreme change in boat velocity cannot be attributed to altered effort because these elite scullers were in the build up to selection trials for the New Zealand elite double scull and all training sessions were monitored and were thought by the scullers to contribute, to some extent, to the selection decision. The mean change was 1.5 ±2.1% WRT, which is relevant for performance based on the difference between the fourth placed (New Zealand) men's double sculls and the gold medal winners being 0.50% WRT and 0.72% WRT at the 2009 World Championships and 2008 Olympic Games respectively. The implications of this finding are that crew combinations for double sculls should be trialed in both seating orders as the slower of two doubles sculls may be in fact be the fastest boat if switched.

The non-significant nature of the correlations between change in *boat velocity* and change in absolute *CS angle-diff* were not anticipated. Past findings have shown that between-individual catch synchronization is indicative of a high level of performance (Hill, 2002; Schneider et al., 1978) and therefore it was anticipated that if the bow and stroke seat scullers had a greater difference in *catch slip,* performance would have been lower. As previously noted however, there have been a number of approaches for specifying when the catch occurs (Coker, Hume, & Nolte, 2010b) and when different methodologies are used correlations with *boat velocity* vary (Coker, Hume, & Nolte, 2010c). Previous studies used moment of blade contact with the water (Schneider et al., 1978) and onset of a corrected force profile (with inertial force removed) (Hill, 2002) to quantify when the "catch" occurred – both of which differ from the *catch slip* variable used in the present study which is based on the angular displacement to a threshold force using the raw force data. This may explain the discrepancies in our findings. No one method for quantifying *catch slip* has been proven to be most appropriate as all methods, to some extent, measure a different aspects of catch technique (Coker et al., 2010c). No study can therefore be deemed to have taken the best approach. The particular method used in this study was chosen because it could be obtained automatically from PowerLine™. If synchronization of PowerLine™ *catch slip* was beneficial for performance, the Rowing New Zealand coaches could then apply this knowledge without needing expert post-analysis of the raw force and angle data.

Opposing traditional beliefs that advise matching the force profiles of crew scullers', neither change in absolute *PF-time* nor change in absolute *PF-angle* were significantly correlated with percentage change in *boat velocity.* It is therefore not crucial for the two scullers in a double scull to peak in force either at exactly the same time within the drive phase or at the same oar position. In fact, it was the relative versions of *PF-time* and *PF-angle* that were better correlated with *boat velocity* (R values of 0.55, 90% CI; -0.32 to 0.92 and 0.59, 90% CI; -0.27 to 0.93). Although these correlations were not significant at the $p \leq 0.05$ level, they were notably larger than the correlations resulting from the absolute versions of these variables. This suggests that it is likely to be beneficial for performance if the stroke seat sculler produces their peak force earlier and with the handles more sternward than the bow seat rower. A possible explanation is that this staggered peaking will create a more rectangular crew average force profile with a more prolonged maximal force which would reduce boat velocity fluctuations and be more efficient (Kleshnev, 2001b). However, this does not account for the fact that the stroke must peak in their force before the bow rather than vice versa. Although this pattern is agreed to be necessary in order to keep a pair-oared boat straight (Hill, 2002; McBride et al., 2001; Roth et al., 1993; Schneider et al., 1978; Smith & Loschner, 2002; Zatsiorsky & Yakunin, 1991) there is no known mechanical argument as to why this may be beneficial in a symmetrically-rigged double scull. Part of the cause may be that if the stroke seat sculler tends to peak earlier in the stroke, the bow seat will tend to follow, meaning that the crew average peak force will occur further towards the front end of the drive phase. Since front-loaded force-profiles are known to be more efficient this argument would be reasonable (Affeld & Schichl, 1985; Kleshnev, 2006b, 2007c; Nolte, 1984; Nolte & Morrow, 2002; Schwanitz, 1991) and the negative correlations between change in *boat velocity* and changes in *PF time* and *PF angle* (see Table 16) do indicate that this may be the case – *boat velocity* increased as the peak force occurred earlier and further to the stern.

A limitation of this study was that there was wind of at least 2.8 m/s on each day of the testing. Although relatively consistent throughout each day, the existance of wind meant that in order to confidently make comparisons between the two seating orders, the head and tail wind trials for each seating order were averaged. This meant that two comparisons (head versus head, and tail versus tail wind trials) could not be made for each crew combination and effectively the number of samples were halved, increasing 90% confidence intervals and meaning that covariates could not be included in the regression analysis. This highlights a need for a valid and reliable weather station at the Rowing New Zealand training lake and a fully validated conversion method that allows *boat velocity* in any weather condition to be converted into the equivalent *boat velocity* for windless and currentless conditions. The methods presented by Adam *et al.* (1977) and used in this study have been used successfully in the past but still require both a head and a tail wind trial, doubling the exertion and fatigue level of the athletes. This is not always achievable, particularly when collecting longer distance trials. A comprehensive spreadsheet has been provided by Kleshnev (2006a) and has been used successfully in the conversion of velocities in kayaking (Maher, 2010) but the data collected for this study were clearly erroneous when converted using this spreadsheet. Regardless, full validation studies have not, to our knowledge, been published for the techniques suggested by Adam *et al.* (1977) or Kleshnev (2006a), and definitely not from studies on the New Zealand training lake. It is therefore of key importance that such analyses are completed in future rowing biomechanics research.

Summary

Seating order in elite double sculls was crucial for performance - switching the bow and stroke seat scullers changed performance by as much as 5.8% WRT. Seat trials must therefore be seat-specific and include racing in both seating orders. It does not appear that the *catch slip* variable produced by PowerLine™ must be matched between bow and stroke seat rowers in elite double sculls for optimal performance. It appears that it is more beneficial for performance if the stroke seat peaks earlier in the drive and with the handles further to the stern than the bow seat. The full mechanical explanation for this is not yet known. In order for future studies to reach sound conclusions that result in correct recommendations for improved international performances, there is a clear need for a weather station and a fully validated *boat velocity* conversion method for weather conditions specific to the New Zealand national training lake at Karapiro.

CHAPTER 10 - DISCUSSION/CONCLUSIONS

The objective of this thesis was to expand knowledge regarding biomechanical measurement of sculling force profiles and to understand how the PowerLine™ boat instrumentation system could be used effectively to measure and improve elite on-water sculling performance. This was achieved by way of two literature reviews, a laboratory based validity study, an on-water reliability study, two linear modelling investigations, and two intervention studies. This chapter summarises the key findings from each of these studies, discusses the limitations and delimitations placed upon the research, and suggests a number of directions for future investigations.

Past literature has shown that effective rowing force profiles have a large area under the force-time, or force-angle, curve, generally assisted by having a smooth shape with no dips in force (Rekers, 1999; Smith & Spinks, 1998). Similarly, achieving a more rectangular rather than triangular shaped force profile with a high rate of force development will maximise drive-phase work and impulse for a fixed peak force magnitude (Kleshnev, 1999; Kleshnev & Kleshnev, 1998; Millward, 1987). It is now also agreed that it is preferable for the peak force to occur in front of the position where the oar shaft is perpendicular to the longitudinal axis of the boat (Affeld & Schichl, 1985; Kleshnev, 2006b, 2007c; Nolte, 1984; Nolte & Morrow, 2002; Schwanitz, 1991).

A number of techniques have been identified for defining when the catch occurs and as such, a range of methods have been utilised for quantifying catch technique or "catch slip" (Kleshnev, 1999; Kleshnev & Baker, 2007a; Peach Innovations). The different methods all have their limitations and to some extent, measure different aspects of catch technique. Chapter 3 identified the need for a study determining which method(s) best relate to sculling performance and which should therefore be used in regular athlete testing. The literature reviewed highlighted another key gap in this area of knowledge; although specific within-crew coordination of force profiles is known to be vital in non-symmetrically-rigged boats, especially pairs (Hill, 2002; McBride et al., 2001; Roth et al., 1993; Schneider et al., 1978; Smith & Loschner, 2002;

Zatsiorsky & Yakunin, 1991), there was very little information regarding the effect of synchronisation in sculling boats.

Having acknowledged the relevance of measuring sculler force profiles and identified areas of uncertainty for research, it was necessary to assess the accuracy and reliability of the instrumentation intended for use in the proposed investigations. When compared with known measures from a load cell and an inclinometer, the PowerLine™ system was proven to have a high enough accuracy level for use with elite scullers, displaying a standard error of the estimate of less than 0.90 kg for force measures and less than 0.5° for angle measures (see Chapter 4). On-water reliability testing confirmed the system's suitability and smallest worthwhile effect sizes were established for six elite scullers when completing repeated 500-m trials at race pace. These values were 0.13% for *boat velocity*, 0.16% for *stroke rate*, 0.44% for *stroke power* and 0.5° for all angular variables (see Chapter 5). Scullers in double sculls displayed higher stroke-to-stroke and trial-to-trial variability than scullers in single sculls and so it was suggested that consistency training may improve efficiency in double sculls. The issue of there being multiples of each PowerLine™ variable per stroke in crew sculling boats (one per oar) but only one *boat velocity* measure is introduced in this chapter. Future investigations into the requirements of different seats in crew sculling boats may resolve whether it is appropriate to use a crew average for these variables when predicting performance in elite crews.

PowerLine™ differed to other rowing boat instrumentation described in literature in that it computed *stroke power* based on force measured at the pin. It was therefore necessary to confirm the relationship between sculling performance and this version of *stroke power* alone, and in combination with the other stroke variables that PowerLine™ could produce. *Stroke power* was shown to be a predictor of sculling performance for the two elite scullers tested, but its relationship with *boat velocity* was not direct and could not be generalised to all scullers at a fixed race rate. Due to the way in which PowerLine™ separated strokes, sculler analyses using this system were better performed using the average of five strokes rather than single strokes.

Using this approach, models were presented from step-wise linear regression analyses (with the PowerLine stroke variables as independent variables) that explained 84% and 85% of variation in *boat velocity* for the two scullers (see Chapter 6). However, numerous differences between the two scullers highlighted the importance of an individualised approach for elite sculler analyses.

Similarly, large inter-individual differences were seen between the two elite scullers in the effect of certain aspects of catch technique on performance (Chapter 7). It was therefore recommended that all of the methods outlined in Chapter 3 for measuring catch technique should be utilised in elite sculler analyses. The negative effect on performance of some supposed improvements in catch technique showed that assumptions based on a perceived optimal technique could not always be applied for short term improvements in performance and relationships between *boat velocity* and biomechanical variables must be analysed for each sculler separately.

The four elite scullers in single, double and quad sculls in Chapter 8 generally exhibited the lowest *stroke power, peak force* and *average force* in the quad sculls. However, the sculler stroking the quad scull was the only one that did not show a significant reduction in these three variables when moving from the double to quad sculls. Analyses of additional elite scullers performing trials in different seats in a quad scull are necessary before it can be generalised confidently, but there are possible applications to this finding. Coaches may choose to allocate the stroke seat in a quad scull either to the weakest crew member, in order to bring their performance closer to the crew average, or to the strongest person, in order to allow them to reach their full potential. Across the four scullers, *catch angle* and *catch slip* were altered by a much greater degree than *finish angle* and *finish slip* when moving between sculling boat classes. With increasing boat size, *catch angle* values were lengthened by a surprising amount despite only minimal reduction in span length. This effect must be considered in technical focus points and boat set-up. Higher, steeper and/or less stern-ward foot-stretcher settings should be used to prevent excessive over-reaching at the catch when span lengths are reduced in larger boat classes. This study showed that biomechanical stroke variables do differ in general between sculling boat classes. Training should therefore be specific to boat class and ranking and/or comparisons cannot always be made for scullers in different crews.

It was noted in Chapter 8 that the stroke seat sculler in both double sculls peaked with their force earlier, and with their handles further towards the stern, than the bow seat. By switching seating orders in elite double sculls, the study described in Chapter 9 showed that this pattern was indeed likely to be more beneficial for performance than if the scullers' peak forces occurred at the same time and position. This is potentially in part due to the resulting shape of the average crew force profile being more rectangular, but the necessity for the specific order (stroke before bow) is not yet understood. Another key point from this final study was that seating order in elite double sculls was crucial for performance. Although this was not a novel idea and a fact well known by all coaches, the large magnitude of the effect in some cases was surprising - switching the bow and stroke seat scullers was seen to change performance by as much as 5.8% WRT (more than eight times the difference between fourth placed New Zealand and the gold medal position at the most recent Olympic Games). It is therefore of paramount importance that seat trials are seat-specific and include racing in both seating orders.

Limitations

As acknowledged before this thesis commenced, the main limitation to the research presented was the unavoidably low subject numbers given the desired focus on elite scullers. It was deemed more important to maintain the homogeneity of the group by limiting the participants to only elite scullers (rather than including sub-elites) so as to enable specific and applicable findings to be established for Rowing New Zealand. The high number of strokes obtained, and the use of a case study approach where appropriate, overcame this issue as much as possible without having to include scullers from other nationalities. Inclusion of non-New Zealand scullers was not an option as it would have caused a conflict of interest with Rowing New Zealand's wishes to keep this thesis confidential and to protect any potential competitive advantage that its findings may give.

A second limitation inherent in all on-water rowing biomechanics research is the uncontrollable nature of the weather conditions. Notable discrepancies between ergometer and on-water sculler biomechanics (Dawson et al., 1998; Elliott et al., 2002; Kleshnev, 2008b; Lamb, 1989; Li et al., 2007) meant that testing in a controlled laboratory setting was not an appropriate substitute for on-water analysis in the competitive environment. Inconsistent weather conditions were avoided and when comparisons of performance were necessary across trials in non-negligible wind *boat velocity* was corrected using the harmonic mean of head and tail wind trials in accordance with (Adam et al., 1977).

It could be claimed that the uni-directional nature of the force measure provided by PowerLine™, and the fact that it measures pin force rather than actual propulsive force at the blade, were limitations of this thesis (see Appendix 3). Additionally, within-stroke fluctuations in *boat velocity* and pitch, yaw and roll are not analysed by the system, all of which will be influenced by changes in pin force and will alter drag forces acting on the boat. Although a more comprehensive model of sculling performance could possibly be determined from instrumentation capable of recording additional measures, the rationalisation of using the PowerLine™ system is actually an integral part of this thesis. This system had been chosen above all others by Rowing New Zealand, due to the coach-friendly nature of its fast and simple set-up – crucial if it was going to be used on a regular basis within the tight time frames of the elite training schedule. It was therefore necessary to assess the system and its ability to measure and improve performance despite these limitations.

Delimitations

- Only elite scullers were invited to participate (defined as scullers winning medals at senior level, or gold medals at U23 level, international regattas).

- No scullers with any current injuries that could have inhibited their performance were invited to participate.
- Only male elite scullers were asked to participate in the final two intervention studies due to availability of scullers at the time of testing.

Future directions

The discovery that it is likely to be beneficial for performance if the stroke seat sculler in a double scull peaks before the bow seat is an original finding that generates a number of new questions. Initially, it is important that future research aims to substantiate the reasoning behind this effect, and then investigations can proceed into the effect of similar synchronization patterns on performance in quad sculls. If such patterns are also beneficial in quad sculls the requirements of different seats in these crews could be better understood and seats could be assigned more scientifically, minimising the time required to find the most effective seating order. It is proposed that foot-stretcher force sensors will be available within the next year that can be integrated into the PowerLine™ system. The addition of this force measure should greatly increase the percentage of variation in *boat velocity* that can be explained by the system and should also allow improved measures of catch technique to be developed that incorporate timing between handle and foot-stretcher force application. Future research will be required to validate such measures and to investigate the ability of this integrated system to predict sculling performance.

Finally, there is a vital need for an extensive analysis of weather conditions and sculling performances on the New Zealand training lake at Karapiro from which to develop a valid and reliable conversion method. This would allow performances in different weather conditions to be compared enabling future on-water athlete monitoring and analyses to reach sound conclusions that result in correct recommendations for improved international performances.

Conclusion

The importance of seating order in double sculls and the benefit of staggered peak forces, specifically the stroke seat peaking before the bow, have implications upon crew selection, seat allocation, and technical recommendations. Different characteristics of certain seats in a quad are also implied, further signifying that seat trials for crew sculling boats must be seat-specific and include racing in all seating orders. Further research is necessary into the synchronisation requirements of crew sculling boats before more scientific and economical seat allocation can be achieved in these boat classes. The PowerLine™ system is a sufficiently valid and reliable tool for use with elite scullers and its force profiles can be used effectively to measure and improve elite on-water sculling performance. However, extensive inter-individual differences existed between elite scullers in the strength and direction of the relationship between *boat velocity* and these characteristics. No pre-conceived relationships between technique changes and performance can therefore be assumed and an abridged list of stroke variables cannot be used in technical evaluations. Full analyses of all variables must be carried out for each elite sculler individually.

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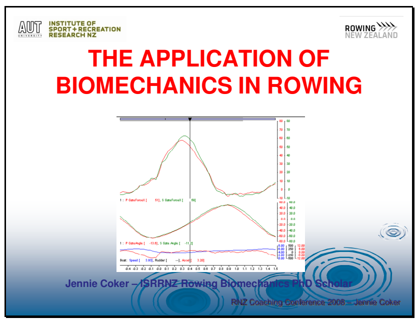
APPENDIX 1 - THE APPLICATION OF BIOMECHANICS IN ROWING

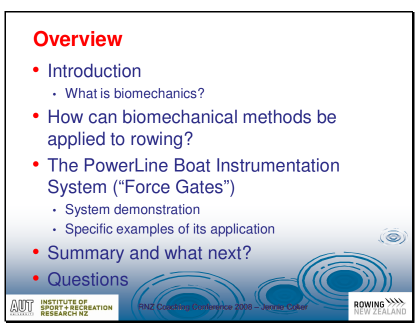
This appendix comprises the following oral presentation given at the AON Rowing New Zealand Coaches Conference.

Coker, J. (2008). The application of biomechanics in rowing, *The AON Rowing New Zealand Coaches Conference*. Wellington.

Slide 1



Slide 2



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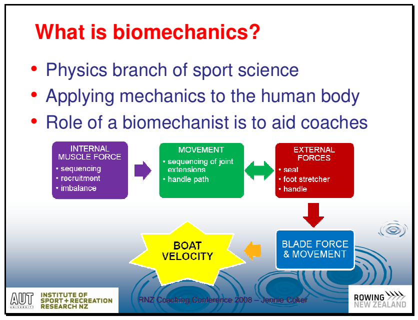


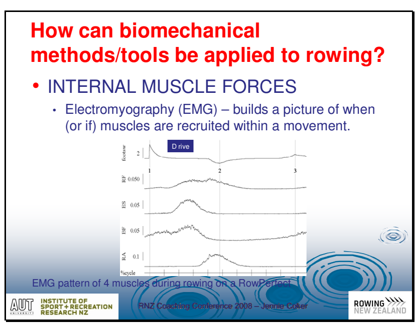
Lesser used discipline of sport science, particularly in NZ sports.

Information (Data/images/graphs) that coaches either cannot normally see with the naked eye OR information that they cannot easily relay to athletes.

2 sections of biomechanics – injury prevention and performance enhancement – 2 obviously linked and you cannot, with elites especially, consider one without the other.

Things that we can analyse/measure can be broken down as follows…..schematic

Slide 4



RF = rec fem (quad)

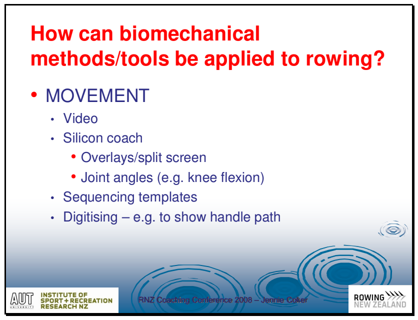
ES = erector spinae (back extensors)

BF = biceps femoris (hamstring)

RA = rec ab (abs)

Problems – tricky on water, no real idea of AMOUNT of force production

Slide 5



Video – used extensively on its own

"Proof" to athlete

Slow motion capability

BUT gives no real understanding of what forces are being applied.

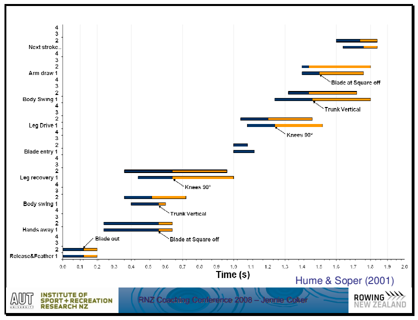
Slide 6

Trial

Many more options

Slide 7

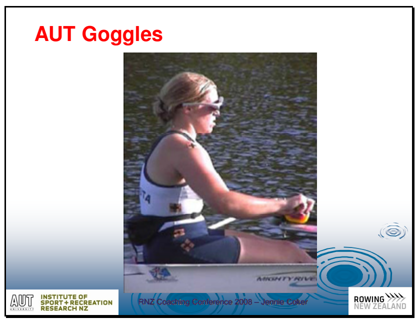
Slide 8



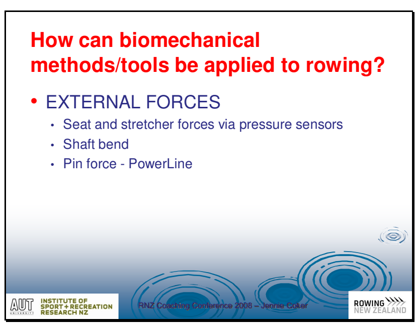
Segmental sequencing AND crew synchrony

Hume, P. A., & Soper, C. (2001). Segmental sequencing reports (Athlete report). (pp. 2). Auckland: Auckland University of Technology.

Slide 9



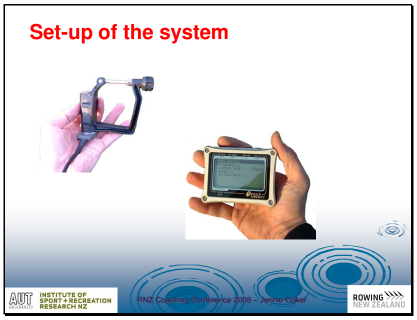
Slide 10



"PowerLine Boat Instrumentation System" is used together with video to show exact force patterns at the pin and what the rower is doing to create this.

Ultimately what creates boat movement…what is important

Slide 11

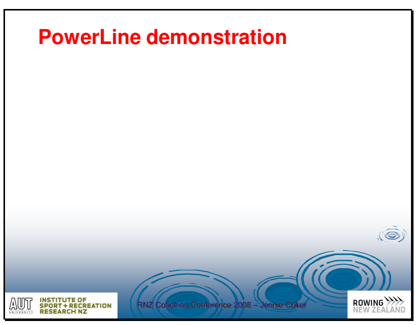


No real change – only one pitch – can order other swivels with specific pitch

System we have been using is a system from the UK called Powerline – there are others out there that are used by the UK and OZ teams – all provide basically the same types of values but there will be both force-time and force-angle profiles. Important to use the right one for the right use. Basically gives an idea of how the rowers are moving and creating force as they drive – the system will give you both angle and force values over time.

50 points per second –drive with time of 1 seconds – 50 points

Slide 12



Explain each trace

Explain that as a crew what it would look like

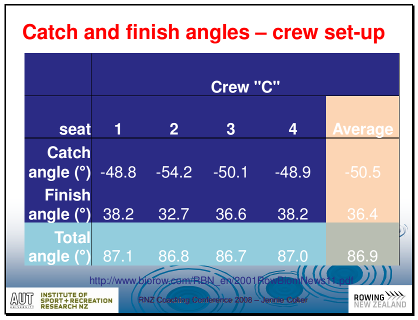
Show timing at catch and how it could be out

Tightness of angle curves

Blade entry

Pick a slight dip and show that you can locate where it happens

Slide 13



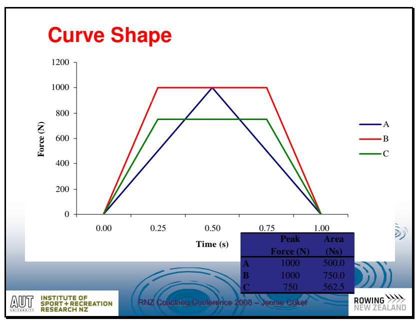
Check 1 – all rowers have similar stroke length

Check 2 - 2 seat is further to the stern than the other 3

Decision – move 1,3 and 4 seat to the stern or move 2 seat to the bow

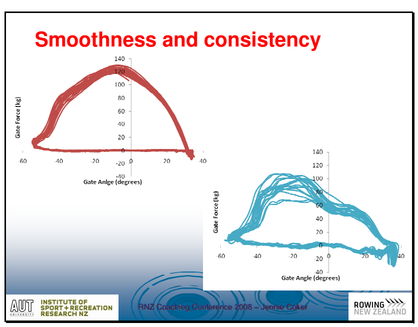
Recommendation – in first instance move 1, 3 and 4 – longer catch angle more efficient - REASSES

Slide 14



Rectangular more effective/efficient than triangular

Slide 15



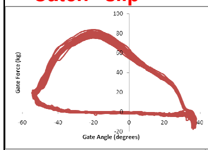
Give good description of what the curve/axis are – describe the stroke.

Potential reasons for lack of smoothness/consistency?

We want smoothness and consistency to minimize boat velocity fluctuations – which decrease efficiency

Slide 16

Catch "slip"



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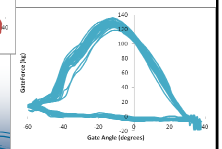

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RNZ Coaching Conference 2008 – Jennie Coker

ROWING NEW ZEALAND

Slide 17

Summary

- Various biomechanical tools exist to aid rowing coaches.
- How can the "force gates" be used?
  - Set-up
  - Smoothness and consistency
  - Catch/finish technique/timing
- What next?
  - Can we actually change a curve significantly??
  - Crew synchronisation
  - Matching rowers to boats/seats
- Questions?

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ROWING NEW ZEALAND

Slide 18

Websites to explore

- www.siliconcoach.com to download a free trial of the video analysis software
- www.biorow.com to see Dr. Valery Kleshnev's Rowing Biomechanics Newsletter
- www.precisionsport.co.uk in the "information" section for more biomechanics articles, particularly related to "slips"

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RNZ Coaching Conference 2008 – Jennie Coker

ROWING NEW ZEALAND

APPENDIX 2 - EVALUATING ROWING FORCE PROFILES: IMPLICATIONS FROM LITERATURE

This appendix comprises the following oral presentation given at the New Zealand Sports Medicine and Science Conference.

Coker, J. (2008, 10-11 October 2008). *The application of biomechanics in rowing.* Paper presented at the AON Rowing New Zealand Coaches Conference, Wellington.

EVALUATING ROWING FORCE PROFILES: IMPLICATIONS FROM LITERATURE

Coker, J.[1], Hume, P.A.[1], Nolte, V.[2]

[1]ISRRNZ, AUT University, New Zealand, [2]University of Western Ontario, Canada

BACKGROUND: Coaches and rowers must understand the forces that act on the blade in order to improve boat propulsion [1]. Modern equipment such as the PowerLine Boat Instrumentation System allows on-water propulsive pin force and gate angle to be measured with minimal alteration to boat set-up and rowers' feel during strokes. Pin force and gate angle allows force-time and force-angle profiles to be plotted and biomechanical feedback presented to coaches and rowers. **AIM:** This review presents the key characteristics of effective force profiles as outlined in past rowing literature and suggests guidelines and recommendations for rower force profile evaluation. **METHODS:** The SportDiscus data base was searched using the key words rowing and force. Relevant journal articles and their referenced material were reviewed.

EFFECTIVE ROWING FORCE PROFILES HAVE...

1. Large area under the curve which maximises impulse and work during the drive phase resulting in a more rectangular than triangular shaped curve (see Figure 2). A triangular shaped force-time curve has a high rate of force development, increasing efficiency and drive impulse for the same maximum force output [2-5].
2. Smooth shape which is potentially more effective due to reduced boat velocity fluctuations and an increased area under the curve [6, 7].
3. High stroke-stroke consistency which reduces boat velocity fluctuations and increases efficiency [8].
4. "Front loaded" shape (see Figure 1) with the peak force before the perpendicular oar shaft position resulting in:
   - a more evenly distributed power curve reducing boat velocity fluctuations and increasing efficiency [1, 9]
   - increased use of lift for propulsion (a more efficient means of propelling the boat versus levering past a stalled blade) [1, 10]
   - enhanced use of the recoil of elastic energy stored with the bend of the oar shaft [11]
   - reduced overload on arms
   - the body better positioned to allow force production proportional to body segment strength [12]

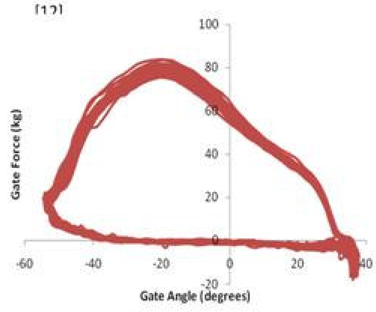

Figure 1. A "front-loaded" rower force-angle profile.

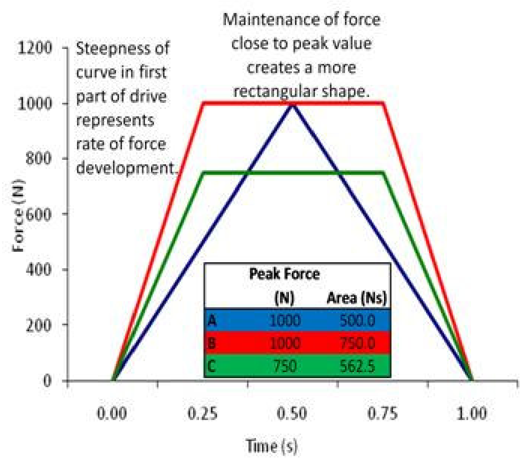

Figure 2. Theoretical illustration of the effect of force-time profile shape on the impulse vs. peak force.

FUTURE INVESTIGATIONS: The need for crew coordination of force profiles is evident but the exact pattern of this synchronisation is not known for different boat types [13]. Differences in body size, physical abilities, power application and technique exist between rowers in any crew resulting in variations in blade movement patterns and therefore force profiles [14]. Whether the differences between crew members in oar excursion and force patterns can be reduced via rigging alterations, and whether this would be beneficial to boat velocity, is unknown. Information is required to better match rower characteristics to specific boat types for effective performance.

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APPENDIX 3 - LIMITATIONS OF THE UNI-DIRECTIONAL FORCE MEASURE PROVIDED BY POWERLINE™

This appendix comprises the following technical report submitted to Rowing New Zealand.

Coker, J., Hume, P. A. & Nolte, V., (2010). *Limitations of the uni-directional force measure provided by PowerLine™* (Technical report for Rowing New Zealand). (pp. 1-7). Auckland: Institute of Sport and Recreation Research New Zealand, Auckland University of Technology.

Overview

A sculler's force will have components both perpendicular and parallel to the oar shaft. The only "useful" component is that acting perpendicular because it creates oar rotation about the pin and therefore blade movement and through this, force that results in boat propulsion. The aim of this study was to investigate whether force acting parallel to the oar shaft is included in the PowerLine™ force measurement and the extent to which PowerLine™ may therefore misrepresent useful force production in scullers. Using a photograph of a quad scull, arm angle relative to the oar shaft and oar angle were measured. Ratios between various force components resulting from a sculler force of 10 kgF were then calculated based on these angles in order to estimate the degree to which PowerLine™ may under or over estimate useful sculler force. A PowerLine™ sculling oarlock was then fixed to a pin at known oar angles (-72° and -36°), and a dynamic force equivalent to that acting parallel to the oar shaft was applied with a 1kN load cell in series. Data were collected from the oarlock and load cell at 50 Hz. The percentage of mean x-direction load cell force to mean force recorded by the oarlock was calculated. Force was registered on the oarlock despite the force being applied only in the direction parallel to the oar shaft. The ratio of x-direction oarlock forces to load cell forces was lower for the -36° setting compared to the -72° (11.6% versus 40.5%). A large range in arm angles relative to the oar shaft (48° to 67°) was seen in the quad scull which would result in different over and under estimations of useful force by PowerLine™ (by factors of 0.83 to 1.13) within this one crew. PowerLine™ overestimates useful *x-direction* force in all cases other than where the oar angle is zero and arm angle relative to the oar shaft is 90°. Depending on oar angle and arm angle relative to the oar shaft, PowerLine™ will either over or underestimate *total* useful force. Individualized testing is required before this can be fully quantified and incorporated into athlete feedback sessions.

Introduction

A sculler's force will be applied in the direction of the line between the hand and shoulder (the longitudinal axis of the arm whilst the arm is straight) and will have components both perpendicular and parallel to the oar shaft. The only "useful" component is that perpendicular to the oar shaft (F_{Sh}) because it creates oar rotation about the pin and therefore blade movement and force on the blade that results in boat propulsion. The parallel component (F_{Sp}) will not contribute directly to propulsion and only acts to press the collar of the oar against the oarlock ensuring that the ratio of the inboard to outboard is as intended by overcoming the force acting on the blade that pushes the collar inwards and away from the oarlock. For a given oar angle θ, the proportion of the sculler's force F_S, that acts parallel to the oar shaft will depend upon the angle α, that the direction of the handle force forms with the oar shaft (see Figure 24). PowerLine™ measures force in the direction of proposed boat travel (direction 'x' in Figure 24) meaning that the entirety of F_{Sh} in the x-direction will be measured but some part of F_{Sp} in the x-direction may also be recorded. The force measure from PowerLine™ will, of course, underestimate the sculler's force F_S at times other than when θ is zero and α is 90°, but because the extent to which F_{Sp} is recorded has not previously been documented, it is not known whether PowerLine™ will over- or under-estimate the "useful" force, F_{Sh}.

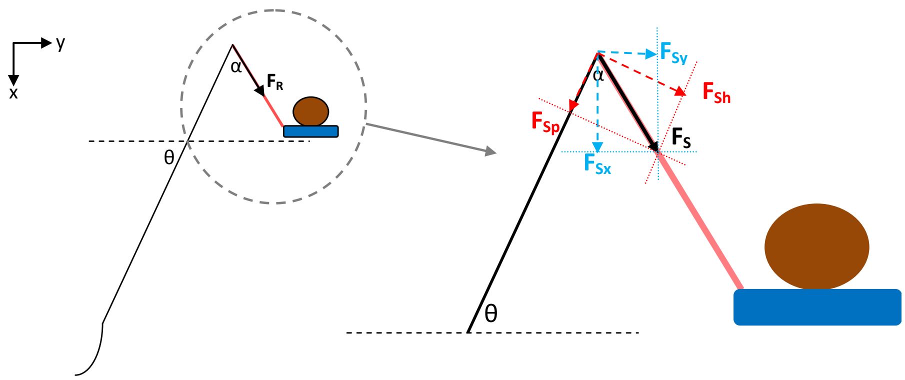


Figure 24: Schematic bird's-eye view of a sculler at the catch with sculler force, F_S, resolved into components in the x and y directions (F_{Sx} and F_{Sy} respectively) and into components parallel and perpendicular to the oar shaft (F_{Sp} and F_{Sh} respectively) based upon the catch angle, θ, and the angle, α, that the arm makes with the oar shaft.

For a fixed θ and F_S, the smaller α becomes, the greater F_{Sp} and the smaller F_{Sh} becomes. The extent to which the PowerLine™ reading represents useful forces will therefore depend upon the angle that the line between the sculler's hand and shoulder forms with the oar shaft. The aim of this paper is to investigate whether force acting parallel to the oar shaft is included in the PowerLine™ force reading and the extent to which PowerLine™ may therefore misrepresent useful force production in scullers.

Methods

Part 1. Investigating theoretical inter-individual differences in the components of sculler force, F_S.

Using a photograph of a quad scull at the catch position, arm angle relative to the oar shaft α, and oar angle θ, were measured using a protractor for each sculler on both sides (i.e. eight blades from four scullers) (see Figure 25). The reference y axis was taken as the line between the left and right pins for each sculler (for stroke seat, the blue line in Figure 25). Based on typical force readings in Rowing New Zealand female scullers, F_S was taken to be 10 kgF. F_{Sp}, F_{Sh}, F_{Sx} and F_{Sy} and F_{Shx} (x-component of F_{Sh}) were presented by resolving F_S, and the ratios; F_{Sx}:F_{Sh}, and F_{Shx}:F_{Sh} were calculated. The ratio F_{Shx}:F_{Sh} represents the proportion of F_{Sh} which would be included in the PowerLine™ reading if no force parallel to the oar shaft was included. This ratio will be 1.00 only when $\alpha = 90°$ and $\theta = 0°$. At all other angles this ratio will be less than 1.00 because F_{sh} will be underestimated if PowerLine™ does not measure any force parallel to the oar shaft. The extent of this underestimation at different oar and arm angles will be presented by this ratio. The ratio F_{Sx}:F_{Sh} represents the extent to which "useful" force F_{Sh} (that acts to rotate the oar) would be estimated by the PowerLine™ reading if all of the x-component force parallel to the oar shaft was included (i.e. PowerLine™ measures the entirety of F_{Sx}). If this is the case, useful sculler force F_{Sh}, may be underestimated (ratio < 1.00) or overestimated (ratio > 1.00) at different arm and oar angles.

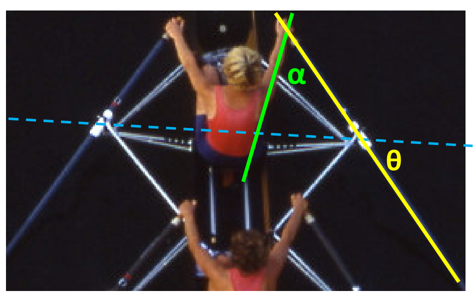


Figure 25: Part of the photograph (courtesy of Volker Nolte) used to assess an example of the range of oar angles θ, and arm angles α, and the resulting force components in a quad scull. Stroke seat is shown in this section.

Part 2. Laboratory based testing.

Testing was carried out in a laboratory setting with a PowerLine™ sculling oarlock fixed to a pin with a plate aligned across the oarlock in the same position as an oar collar during sculling. With the oarlock fixed at known oar angles (-72° and -36°), ten repetitions of dynamic force were applied at a rate of approximately 30 rpm with a 1kN load cell in series (see Figure 26) and collected at 50 Hz. The oar angle, -72° was chosen as it is the catch angle commonly seen in New Zealand scullers. A second angle, half way between this and the zero oar angle point was also chosen to investigate whether different proportions of the applied force are transferred onto the pin at different oarlock angles. The force applied represents F_{Sp}. Data from the load cell and the oarlock were cropped taking 0.2 kgF on the load cell as the threshold for the start of force application. The load cell force was then resolved to its component in the x-direction using the oarlock angle. The percentage of mean load cell force resolved in the x-direction to mean force recorded by the oarlock was calculated and line graphs were used to assess the difference between the two forces throughout the testing period.

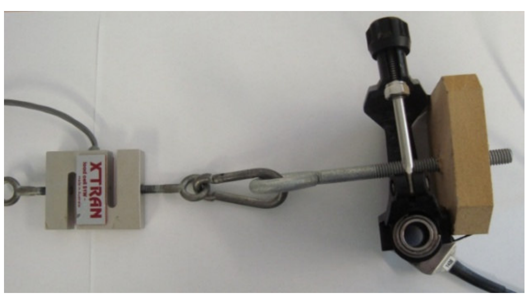


Figure 26: Oarlock set-up for laboratory testing.

Results and Discussion

Part 1. Investigating theoretical inter-individual differences in the components of sculler force, F_S.

As shown in Table 17, mean oar angle θ across the eight blades was -56 ±6° (range; -49° to -66°), and mean arm angle α was 58° ±7° (range; 48° to 67°). These ranges were larger than expected based on previously recorded within-crew ranges in New Zealand quad sculls but allow for a better insight into the possible variation in force components due to different oar and arm angles. For all blades, F_{Shx}:F_{Sh} was less than 1.00, as anticipated for all non-zero oar angles (θ ≠0°). Therefore, if PowerLine™, does not measure any force parallel to the oar shaft, useful force, F_{Sh} is underestimated. There was a larger variation between blades in F_{Sx}:F_{Sh} meaning that, if all x-direction force components are included in the PowerLine™ measure (including that acting along the oar shaft), useful force may be either under OR over estimated at times throughout the stroke depending on the scullers arm position, specifically the ratio of their arm angle to oar angle (if arm angle is smaller than oar angle, overestimation would occur).

Part 2. Laboratory based testing.

Force was applied to the load cell in the range -0.1 to 4.9 kgF which is similar to the F_{Sp} values shown in Table 17 justifying this range used. As can be seen in Figure 27, force was registered on the oarlock despite the force being applied only in the direction parallel to the oar shaft. The ratio of x-direction oarlock to load cell forces was lower for the -36° setting compared to the -72° setting which may be because of the slightly flexible nature of the plastic swivel part of the oarlock transferring different proportions of the applied force onto the pin at different oarlock angles. At -72°, on average, the oarlock reading was 40.5% of the total force recorded by the load cell, at -36°, this value was 11.6% (see Figure 27).

Table 17: Oar angles (θ), arm angles (α), and sculler force (F_S) components parallel to the oar shaft (F_{Sp}) and in the direction of the longitudinal axis (x-axis) of the shell (F_{Sx}). The component of F_S acting perpendicular to the oar shaft resolved in the x-axis (F_{Shx}) is also given along with ratios of F_{Sx} to F_{Sh}, and F_{Shx} to F_{Sh}. F_S was taken to be 10 kgF.

		Angles (°)		**Force components (kgF)**			
Seat	**Side**	**θ**	**A**	F_{Sp}	F_{Shx}	F_{Shx}: F_{Sh}	F_{Sx}: F_{Sh}
4	Left	-53	63	4.5	5.4	0.60	0.90
	Right	-56	48	6.7	4.2	0.56	1.12
3	Left	-49	64	4.4	5.9	0.66	0.84
	Right	-59	55	5.7	4.2	0.52	1.05
2	Left	-50	67	3.9	5.9	0.64	0.83
	Right	-61	51	6.3	3.8	0.48	1.13
1	Left	-55	61	4.8	5.0	0.57	0.94
	Right	-66	58	5.3	3.4	0.41	1.08
	Mean	**-56**	**58**	**5.2**	**4.7**	**0.56**	**0.98**
	SD	**6**	**7**	**1.0**	**1.0**	**0.08**	**0.12**

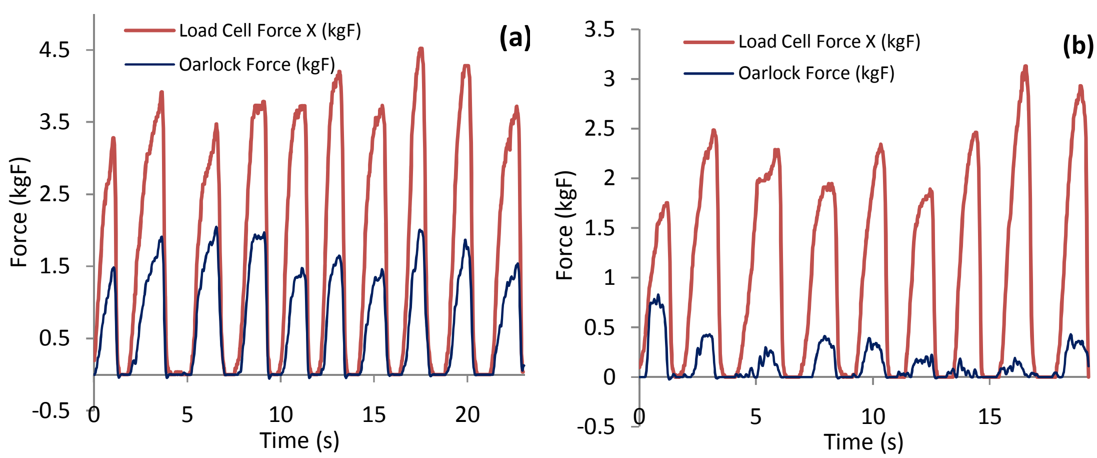


Figure 27: X-direction oarlock and load cell readings for dynamic force application at oar angles (a) -72° and (b) -36°.

Although more extensive data collection is required, there are practical implications of this study. Firstly, force from scullers pressing their oar collar against the gate at the catch will be recorded by PowerLine™ and should be discussed with scullers and coaches when presenting feedback, particularly when focusing on catch technique where large proportions of this force parallel to the oar shaft are recorded. Additionally, reducing the span in order to increase sculler *total angle* will reduce the arm angle relative to the oar shaft and result in a smaller proportion of sculler force acting in the desired direction, perpendicular to the oar. The advantages of this boat set-up technique should therefore be considered carefully before it is applied, particularly in weak scullers.

Limitations

This study was not designed to fully quantify the proportion of sculler force acting parallel to the oar shaft that is included in the PowerLine™ measurement. As such it forms only an initial insight into this issue. Further testing is required on-water with additional instrumentation (possibly pressure sensors fixed to the collar of the oar where it presses against the oarlock) to separate the force components and quantify the proportions of the PowerLine™ reading attributable to the different force components. This testing would be required for each individual sculler due to differences in anthropometrics and therefore arm angles at different oar angles and is therefore not within the time and/or financial constraints of this PhD. In later testing automatic synchronization of the different data sets would enable better statistical analyses comparing the two force readings and a greater range of oar angles would be required.

Summary

Although only basic comparisons can be made it is clear that some proportion of the sculler's force acting to press the collar of the oar against the oarlock is recorded by the PowerLine™. This component of force is not aiding propulsion and therefore PowerLine™ overestimates useful *x-direction* force in all cases other than where the oar angle θ, is zero and the arm angle, α is 90° (i.e. square off). Depending on oar angle and arm angle relative to the oar shaft, PowerLine™ will either over or underestimate *total* useful force (including the y-direction force that assists oar rotation and blade forces) but this cannot be quantified universally at present. Individualized testing is required before this can achieved and incorporated into athlete feedback sessions.

APPENDIX 4 - ETHICS INFORMATION FOR CHAPTERS 5, 6 AND 7.

The ethics application "08/10 The combined reliability of the PowerLine boat instrumentation system and elite rowers and scullers" and the amendment covered the study on PowerLine™ boat instrumentation system and elite scullers (Chapter 5), PowerLine™ biomechanical variables as predictors of sculling performance (Chaper 6), and quantifying catch technique using an experimental evaluation of different methodologies (Chapter 7). The approval letter and the subject information sheet and consent form are shown.

MEMORANDUM

Auckland University of Technology Ethics Committee (AUTEC)

To: Patria Hume

From: **Madeline Banda** Executive Secretary, AUTEC

Date: 29 February 2008

Subject: Ethics Application Number 08/10 **The combined reliability of the powerline boat instrumentation system and elite rowers and scullers.**

Dear Patria

Thank you for providing written evidence as requested. I am pleased to advise that it satisfies the points raised by the Auckland University of Technology Ethics Committee (AUTEC) at their meeting on 11 February 2008 and I have approved your ethics application. This delegated approval is made in accordance with section 5.3.2.3 of AUTEC's *Applying for Ethics Approval: Guidelines and Procedures* and is subject to endorsement at AUTEC's meeting on 10 March 2008. Your ethics application is approved for a period of three years until 1 March 2011. I advise that as part of the ethics approval process, you are required to submit the following to AUTEC:

- A brief annual progress report using form EA2, which is available online through *http://www.aut.ac.nz/about/ethics*. When necessary this form may also be used to request an extension of the approval at least one month prior to its expiry on 1 March 2011;
- A brief report on the status of the project using form EA3, which is available online through *http://www.aut.ac.nz/about/ethics*. This report is to be submitted either when the approval expires on 1 March 2011 or on completion of the project, whichever comes sooner;

It is a condition of approval that AUTEC is notified of any adverse events or if the research does not commence. AUTEC approval needs to be sought for any alteration to the research, including any alteration of or addition to any documents that are provided to participants. You are reminded that, as applicant, you are responsible for ensuring that research undertaken under this approval occurs within the parameters outlined in the approved application.

Please note that AUTEC grants ethical approval only. If you require management approval from an institution or organisation for your research, then you will need to make the arrangements necessary to obtain this.

When communicating with us about this application, we ask that you use the application number and study title to enable us to provide you with prompt service. Should you have any further enquiries regarding this matter, you are welcome to contact Charles Grinter, Ethics Coordinator, by email at charles.grinter@aut.ac.nz or by telephone on 921 9999 at extension 8860.

On behalf of the AUTEC and myself, I wish you success with your research and look forward to reading about it in your reports.

Yours sincerely

Madeline Banda

Executive Secretary

Auckland University of Technology Ethics Committee

Cc:Jennifer Coker jennifer.coker@aut.ac.nz

MEMORANDUM

Auckland University of Technology Ethics Committee (AUTEC)

To: Patria Hume

From: **Madeline Banda** Executive Secretary, AUTEC

Date: 4 September 2008

Subject: Ethics Application Number 08/10 **The combined reliability of the powerline boat instrumentation system and elite rowers and scullers.**

Dear Patria

I am pleased to advise that, as Executive Secretary of AUTEC, I have approved minor amendments to your ethics application altering the way in which data is analysed. This delegated approval is made in accordance with section 5.3.2 of AUTEC's *Applying for Ethics Approval: Guidelines and Procedures* and is subject to endorsement at AUTEC's meeting on 13 October 2008. I remind you that as part of the ethics approval process, you are required to submit the following to AUTEC:

- A brief annual progress report using form EA2, which is available online through *http://www.aut.ac.nz/about/ethics*. When necessary this form may also be used to request an extension of the approval at least one month prior to its expiry on 1 March 2011;
- A brief report on the status of the project using form EA3, which is available online through *http://www.aut.ac.nz/about/ethics*. This report is to be submitted either when the approval expires on 1 March 2011 or on completion of the project, whichever comes sooner;

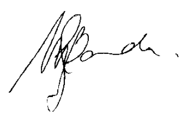
It is a condition of approval that AUTEC is notified of any adverse events or if the research does not commence. AUTEC approval needs to be sought for any alteration to the research, including any alteration of or addition to any documents that are provided to participants. You are reminded that, as applicant, you are responsible for ensuring that research undertaken under this approval occurs within the parameters outlined in the approved application.

Please note that AUTEC grants ethical approval only. If you require management approval from an institution or organisation for your research, then you will need to make the arrangements necessary to obtain this.

When communicating with us about this application, we ask that you use the application number and study title to enable us to provide you with prompt service. Should you have any further enquiries regarding this matter, you are welcome to contact Charles Grinter, Ethics Coordinator, by email at charles.grinter@aut.ac.nz or by telephone on 921 9999 at extension 8860.

On behalf of the AUTEC and myself, I wish you success with your research and look forward to reading about it in your reports.

Yours sincerely



Madeline Banda

Executive Secretary

Auckland University of Technology Ethics Committee

Cc:Jennifer Coker jennifer.coker@aut.ac.nz

Participant Information Sheet

Date Information Sheet Produced:

16 January 2008

Project Title

The reliability of the Powerline boat instrumentation system for elite rowers and scullers.

An Invitation

You are invited to participate in the above project being carried out by Jennifer Coker as part of her PhD thesis. Participation is strictly voluntary and you may withdraw at any time without adverse consequences.

What is the purpose of this research?

The aim of the study is to determine the reliability of the Powerline boat instrumentation system (force gates) when used by elite rowers and scullers. This will enable us to decide how large a change is required in the data to conclude that a significant change has been made to your force profile – this may be due either to technical or equipment alterations that will be made in the future.

How was I chosen for this invitation?

Members of the Rowing New Zealand summer squad were chosen for this invitation.

What will happen in this research?

Following completion of a consent form (attached) and weighing, you will be asked to perform three 500m pieces from a flying start at "middle race pace" (a rate and pace, maintained as constant as possible, with which you would perform the middle 1000m during a 2000m race). Between pieces you will be given approximately 5 minutes rest. Video footage will be taken of the pieces and synchronised with data from the force gates.

What are the discomforts and risks?

You will not experience any risk or discomfort above that normally occurring in a training session of similar intensity.

What are the benefits?

You may benefit from this study in the future by the enhanced understanding of the equipment and the reliability of performance measures. Future feedback sessions may be able to give you a better understanding of the level to which you have actually changed your force profile.

How will my privacy be protected?

None of the information collected will be shared with anyone external to the Rowing New Zealand High Performance Programme staff members, except the supervisors of the project, namely Professor Patria Hume and Dr. Volker Nolte. When shared with the supervisors all efforts will be made to maintain your anonymity. Due to the small, distinct population used, if gender and boat type are discussed there is the possibility that external parties may be able to form an educated guess as to who the participants may be, but no names will be attached to the data.

What are the costs of participating in this research?

The only cost to you is that of time. The consent form and body mass weighing process should not take more than 15 minutes and the on-water data collection will be incorporated into the beginning of your normal training time period.

What opportunity do I have to consider this invitation?

You will have at least 3 days between receiving this information sheet and the testing date (available from your coach or me, Jennifer Coker).

How do I agree to participate in this research?

If you agree to participate please fill in the attached consent form and return to myself or your coach.

Will I receive feedback on the results of this research?

The level of group results feedback you receive will be at your coach's discretion. You can request an individual report of your own individual data if you want it at any time.

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,

Professor Patria Hume, Institute of Sport & Recreation Research New Zealand, School of Sport and Recreation, AUT University, Private Bag 92006, Auckland 1020, Ph 921 9999 ext. 7306, patria.hume@aut.ac.nz

Concerns regarding the conduct of the research should be notified to the Executive Secretary, AUTEC, Madeline Banda, *madeline.banda@aut.ac.nz*, 921 9999 ext 8044.

Whom do I contact for further information about this research?

Researcher Contact Details:

Jennifer Coker, Rowing New Zealand, Cambridge PO BOX 765,
Jennifer.coker@aut.ac.nz

Project Supervisor Contact Details:

Professor Patria Hume, Institute of Sport & Recreation Research New Zealand, School of Sport and Recreation, AUT University, Private Bag 92006, Auckland 1020, Ph 921 9999 ext. 7306, patria.hume@aut.ac.nz

Approved by the Auckland University of Technology Ethics Committee on 26th February 2008

Consent to Participation in Research

Title of Project: **The combined reliability of the Powerline boat instrumentation system and elite rowers and scullers.**

Project Supervisor: **Professor Patria Hume**

Researcher: **Jennifer Coker**

- I have read and understood the information provided about this research project (Information Sheet dated 16th January 2008).Yes/No
- I have had an opportunity to ask questions and to have them answered. Yes/No
- I am not suffering from any injury or illness which may impair my physical performanceYes/No
- I understand that I may withdraw myself or any information that I have provided for this project at any time prior to completion of data collection, without being disadvantaged in any way. Yes/No
- If I withdraw, I understand that all relevant information will be destroyed. Yes/No
- I understand that the video collected will be used for academic/feedback purposes only and will not be published in any form outside of this project without my written permission.
- I agree to take part in this research. Yes/No
- I wish to receive a copy of the report from the research: tick one: Yes O No O

Participant signature: ....

Participant name: ……………………………………………………………

Date: ……………………………………………………………

Participant's Contact Details:

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Project Supervisor Contact Details:

Professor Patria Hume

Institute of Sport & Recreation Research New Zealand

School of Sport and Recreation

Auckland University of Technology

Private Bag 92006

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Ph 921 9999 ext. 7306

patria.hume@aut.ac.nz

***Approved by the Auckland University of Technology Ethics Committee on 26th February 2008 AUTEC Reference number* 08/10**

APPENDIX 5 - ETHICS INFORMATION FOR CHAPTERS 8 AND 9.

The ethics application “08/209 Summary of PowerLine data from 2007/2008 Rowing New Zealand squad members. 08209_15102008” covered the study on the effect of sculling boat class on biomechanical stroke variables in elite scullers (Chapter 8) and the effect of seating order and force synchronisation on performance in elite double sculls (Chapter 9). The approval letter and the subject information sheet and consent form are shown.

MEMORANDUM

Auckland University of Technology Ethics Committee (AUTEC)

To: Patria Hume

From: **Madeline Banda** Executive Secretary, AUTEC

Date: 15 October 2008

Subject: Ethics Application Number 08/209 **Summary of PowerLine data from 2007/2008 Rowing New Zealand squad members.**

Dear Patria

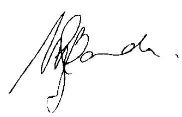
Thank you for providing written evidence as requested. I am pleased to advise that it satisfies the points raised by the Auckland University of Technology Ethics Committee (AUTEC) at their meeting on 8 September 2008 and that on 10 October 2008, I approved your ethics application. This delegated approval is made in accordance with section 5.3.2.3 of AUTEC's *Applying for Ethics Approval: Guidelines and Procedures* and is subject to endorsement at AUTEC's meeting on 10 November 2008. Your ethics application is approved for a period of three years until 10 October 2011. I advise that as part of the ethics approval process, you are required to submit the following to AUTEC:

- A brief annual progress report using form EA2, which is available online through *http://www.aut.ac.nz/about/ethics*. When necessary this form may also be used to request an extension of the approval at least one month prior to its expiry on 10 October 2011;
- A brief report on the status of the project using form EA3, which is available online through *http://www.aut.ac.nz/about/ethics*. This report is to be submitted either when the approval expires on 10 October 2011 or on completion of the project, whichever comes sooner;

It is a condition of approval that AUTEC is notified of any adverse events or if the research does not commence. AUTEC approval needs to be sought for any alteration to the research, including any alteration of or addition to any documents that are provided to participants. You are reminded that, as applicant, you are responsible for ensuring that research undertaken under this approval occurs within the parameters outlined in the approved application.

Please note that AUTEC grants ethical approval only. If you require management approval from an institution or organisation for your research, then you will need to make the arrangements necessary to obtain this. When communicating with us about this application, we ask that you use the application number and study title to enable us to provide you with prompt service. Should you have any further enquiries regarding this matter, you are welcome to contact Charles Grinter, Ethics Coordinator, by email at charles.grinter@aut.ac.nz or by telephone on 921 9999 at extension 8860. On behalf of the AUTEC and myself, I wish you success with your research and look forward to reading about it in your reports.

Yours sincerely



Madeline Banda

Executive Secretary

Auckland University of Technology Ethics Committee

Cc:Jennifer Coker jennifer.coker@aut.ac.nz

Participant Information Sheet

Date Information Sheet Produced:

09 October 2008

Project Title

Summary of PowerLine data from 2007/2008 Rowing New Zealand squad members.

An Invitation

You are invited to participate in the above project being carried out by Jennifer Coker as part of her PhD thesis. Participation is strictly voluntary and you may withdraw at any time without adverse consequences.

What is the purpose of this research?

This study will analyse and summarise Rowing New Zealand PowerLine ("force gate") feedback data in order to provide coaches with data that will better the understanding of trends within the squad and help with comparisons and technique alterations.

How was I chosen for this invitation?

Rowing New Zealand squad members were chosen for this invitation.

What will happen in this research?

Data collected during your normal training sessions will be analysed further following your standard feedback session. No additional time is required from you, just your permission for me to use the data at a later date.

What are the discomforts and risks?

You will not experience any risk or discomfort above that normally occurring in a training session of similar intensity.

What are the benefits?

You will benefit from this study in the future by the enhanced understanding of the equipment and the measures that is gives. This will enable better feedback sessions with a more detailed understanding and knowledge of expected and desirable values.

How will my privacy be protected?

None of the information collected will be shared with anyone external to the Rowing New Zealand High Performance Programme staff members, except the supervisors of the project, namely Professor Patria Hume and Dr. Volker Nolte. When shared with the supervisors all efforts will be made to maintain your anonymity. Due to the small, distinct population used, if gender and boat type are discussed there is the possibility that external parties may be able to form an educated guess as to who the participants may be, but no names will be attached to the data.

What are the costs of participating in this research?

The only cost to you is that of time. The consent form should not take more than 5 minutes and the on-water data collection is incorporated into your normal training time period.

What opportunity do I have to consider this invitation?

After consideration you may withdraw your participation at any time before the end of the competition year (August of the year in which your data was collected) but, wherever possible, please try and inform me of any such decisions within a month after data collection.

How do I agree to participate in this research?

If you agree to participate please fill in the attached consent form and return to myself.

Will I receive feedback on the results of this research?

The level of group results feedback you receive will be at your coach's discretion. You can request an individual report of your own individual data if you want it at any time.

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, Professor Patria Hume, Institute of Sport & Recreation Research New Zealand, School of Sport and Recreation, AUT University, Private Bag 92006, Auckland 1020, Ph 921 9999 ext. 7306, patria.hume@aut.ac.nz

Concerns regarding the conduct of the research should be notified to the Executive Secretary, AUTEC, Madeline Banda, *madeline.banda@aut.ac.nz* , 921 9999 ext 8044.

Whom do I contact for further information about this research?

Researcher Contact Details:

Jennifer Coker, Rowing New Zealand, Cambridge PO BOX 765, 021842006, Jennifer.coker@aut.ac.nz

Project Supervisor Contact Details:

Professor Patria Hume, Institute of Sport & Recreation Research New Zealand, School of Sport and Recreation, AUT University, Private Bag 92006, Auckland 1020, Ph 921 9999 ext. 7306, patria.hume@aut.ac.nz

Approved by the Auckland University of Technology Ethics Committee on 15th October 2008 # 08/209

Consent to Participation in Research

Title of Project:	**Summary of PowerLine data from 2007/2008 Rowing New Zealand squad members**
Project Supervisor:	**Professor Patria Hume**
Researcher:	**Jennifer Coker**

- I have read and understood the information provided about this research project (Information Sheet dated 9th October 2008).Yes/No
- I have had an opportunity to ask questions and to have them answered. Yes/No
- I am not suffering from any injury or illness which may impair my physical performanceYes/No
- I understand that I may withdraw myself or any information that I have provided for this project at any time prior to completion of data collection, without being disadvantaged in any way. Yes/No
- If I withdraw, I understand that all relevant information will be destroyed. Yes/No
- I understand that the video collected will be used for academic/feedback purposes only and will not be published in any form outside of this project without my written permission.
- I agree to take part in this research. Yes/No
- I wish to receive a copy of the report from the research: tick one: Yes O No O

Participant signature: ....

Participant name: …………………………………………………………….

Date: …………………………………………………………….

Participant's Contact Details:

…………………………………………………………………………………….

…………………………………………………………………………………….

Project Supervisor Contact Details:

Professor Patria Hume

Institute of Sport & Recreation Research New Zealand

School of Sport and Recreation

Auckland University of Technology

Private Bag 92006

Auckland 1020

Ph 921 9999 ext. 7306

patria.hume@aut.ac.nz

Approved by the Auckland University of Technology Ethics Committee on 15th October 2008 # 08/209

APPENDIX 6 - ADDITIONAL DATA FROM CHAPTERS 7 AND 8

This appendix comprises two tables providing supplementary data for Chapter 8 as contained in the following technical report.

Coker, J., Hume, P. A., & Nolte, V. (2010). *The effect of boat class on biomechanical stroke variables in elite scullers* (Technical report for Rowing New Zealand). (pp. 1 - 26). Auckland: Institute of Sport and Recreation Research New Zealand, Auckland University of Technology.

Table 18: Mean ±SD of biomechanical stroke variables for four elite male scullers in single, double and quad sculls (n = 80 for all statistics except *average force* where, due to missing values, n is in the range 60 to 80). Only one quad scull was tested so no grouped SD presented.

	Boat class	*stroke rate (spm)*	*boat velocity (m/s)*	*stroke power (W)*	*peak force (kgF)*	*Average force (kgF)*	*Total angle (°)*	*catch angle (°)*	*finish angle (°)*	*catch slip (°)*	*finish slip (°)*	*peak force angle (°)*	*degrees to peak (°)*
SCULLER 1	**Single**	32.7 ±0.9	4.75 ±0.18	374 ±26	54 ±3	13.6 ±8.0	109.4 ±1.6	-65.2 ±1.3	44.2 ±0.9	8.4 ±3.4	12.3 ±1.0	-15.3 ±5.3	50.0 ±5.5
	Double	32.5 ±0.4	5.08 ±0.16	362 ±18	51 ±2	12.8 ±3.9	113.8 ±1.2	-70.0 ±1.0	43.8 ±0.5	7.9 ±2.0	12.8 ±0.8	-12.1 ±6.2	57.9 ±6.3
	Quad	32.2 ±0.6	5.41 ±0.07	243 ±17	34 ±2	6.2 ±11	120.3 ±1.9	-75.1 ±1.8	45.3 ±0.6	27.9 ±4.1	17.9 ±1.2	-20.2 ±5.8	54.9 ±5.7
SCULLER 2	**Single**	31.1 ±1.1	4.41 ±0.15	303 ±24	49 ±3	12.7 ±8.7	108.9 ±2.7	-64.0 ±2.3	44.8 ±1.0	8.9 ±2.3	15.1 ±2.4	-25.1 ±5.2	38.9 ±4.9
	Double	32.5 ±0.4	5.08 ±0.16	333 ±10	50 ±1	12.9 ±3.1	115.9 ±1.1	-68.2 ±0.7	47.7 ±0.8	9.5 ±0.9	14.9 ±0.9	-25.1 ±2.8	43.1 ±2.9
	Quad	32.2 ±0.6	5.41 ±0.76	252 ±18	37 ±2	8.7 ±11.5	119.7 ±2.4	-73.2 ±2.2	46.4 ±0.7	18.5 ±2.0	18.0 ±1.3	-26.0 ±5.3	47.2 ±5.4
SCULLER 3	**Single**	31.3 ±0.9	4.48 ±0.14	362 ±14	55 ±2	15.0 ±3.5	109.3 ±1.5	-65.8 ±1.1	43.5 ±0.6	7.1 ±0.8	12.2 ±0.5	-21.3 ±2.2	44.5 ±2.4
	Double	33.6 ±0.7	5.27 ±0.15	375 ±41	53 ±5	13.4 ±9.2	110.2 ±1.4	-67.6 ±1.2	42.6 ±0.8	9.6 ±3.0	12.4 ±1.5	-12.5 ±4.7	55.1 ±5.1
	Quad	32.2 ±0.6	5.41 ±0.08	265 ±29	37 ±4	9.9 ±11.9	115.4 ±2.2	-73.2 ±1.9	42.3 ±0.8	17.2 ±2.7	14.5 ±1.2	-21.2 ±6.3	52.0 ±6.3
SCULLER 4	**Single**	33.3 ±0.7	4.77 ±0.06	442 ±9	62 ±2	16.6 ±3.6	111.1 ±1.0	-65.8 ±0.8	45.3 ±0.6	5.9 ±0.7	14.2 ±0.9	-19.6 ±3.4	46.2 ±3.4
	Double	33.6 ±0.7	5.27 ±0.15	417 ±21	54 ±2	14.0 ±6.3	113.6 ±1.5	-70.3 ±1.1	43.3 ±0.8	7.7 ±2.0	12.1 ±1.0	-25.9 ±6.5	44.4 ±6.4
	Quad	32.2 ±0.6	5.41 ±0.76	399 ±16	52 ±2	14.2 ±6.2	124.5 ±2.2	-79.0 ±2.0	45.5 ±0.6	14.9 ±1.0	13.6 ±0.8	-20.0 ±7.7	59.0 ±7.7
GROUP	**Single**	32.1 ±1.1	4.60 ±0.18	367 ±59	55 ±5	14.4 11.9	109.7 ±1.0	-65.2 ±0.8	44.4 ±0.8	7.6 ±1.3	13.4 ±1.4	-20.3 ±4.1	44.9 ±4.6
	Double	33.0 ±0.8	5.17 ±0.13	370 ±33	52 ±2	13.3 ±4.1	113.4 ±2.4	-69.0 ±1.3	44.4 ±2.3	8.7 ±1.0	13.0 ±1.3	-18.9 ±7.6	50.1 ±7.5
	Quad[1]	32.2	5.41	283 ±65	40 ±7	9.4 ±34	120.0 ±3.7	-75.1 ±2.7	44.9 ±1.8	19.6 ±5.7	16.0 ±2.3	-21.8 ±2.8	53.3 ±4.9

Table 19: Change in mean with 90% confidence interval (90% CI) and effect size (ES) with qualitative outcome[a] (QO) for *catch angle, finish angle, catch slip* and *finish slip* for four elite scullers moving between single, double, and quad sculls.

	Single → Double Scull		Single → Quad Scull		Double → Quad Scull	
SCULLER 1	**Change in Mean (90% CI)**	**ES & QO**	**Change in Mean (90% CI)**	**ES & QO**	**Change in Mean (90% CI)**	**ES & QO**
Catch Angle (°)	-4.7 (-5.0 to -4.4)	-4.3 VL	-9.8 (-10.2 to -9.4)	-6.4 VL	-5.0 (-5.4 to -4.6)	4.2 VL
Finish Angle (°)	-0.4 (-0.6 to -0.2)	-0.5 S-M	1.2 (0.9 to 1.4)	1.5 L	1.5 (1.3 to 1.6)	2.6 VL
Catch Slip (°)	-0.7 (-1.4 to 0.1) ¥	-0.2 U	19.3 (18.3 to 20.3)	5.2 VL	20.1 (19.2 to 21.0)	6.2 VL
Finish Slip (°)	0.5 (0.3 to 0.8)	0.6 S-M	5.7 (5.4 to 6.0)	5.1 VL	5.2 (4.9 to 5.5)	5.0 VL
SCULLER 2	**Change in Mean (90% CI)**	**ES & QO**	**Change in Mean (90% CI)**	**ES & QO**	**Change in Mean (90% CI)**	**ES & QO**
Catch Angle (°)	-5.1 (-5.7 to -4.5)	-3.2 VL	-9.9 (-10.6 to -9.1)	-4.5 VL	-5.1 (-5.5 to -4.6)	-3.0 VL
Finish Angle (°)	3.5 (3.1 to 3.9)	4.1 VL	1.8 (1.6 to 2.1)	2.3 L-VL	-1.3 (-1.5 to -1.0)	-1.6 L
Catch Slip (°)	0.1 (-0.6 to 0.7) ¥	0 U	9.9 (9.2 to 10.6)	4.7 VL	9.0 (8.6 to 9.5)	5.7 VL
Finish Slip (°)	-0.2 (-0.9 to 0.4) ¥	-0.1 U	2.4 (1.8 to 3.0)	1.2 M-L	3.3 (2.9 to 3.6)	2.9 VL
SCULLER 3	**Change in Mean (90% CI)**	**ES & QO**	**Change in Mean (90% CI)**	**ES & QO**	**Change in Mean (90% CI)**	**ES & QO**
Catch Angle (°)	-2.9 (-3.4 to -2.4)	-2.8 VL	-8.3 (-8.8 to -7.8)	-5.7 VL	-5.4 (-6.0 to -4.7)	-3.4 VL
Finish Angle (°)	-0.4 (-0.7 to -0.1)	-0.7 T-M	-1.1 (-1.3 to -0.9)	-1.7 L-VL	0.1 (-0.2 to 0.4) ¥	0.2 U
Catch Slip (°)	4.0 (3.1 to 4.9)	1.9 L-VL	10.5 (9.8 to 11.1)	5.3 VL	6.2 (5.1 to 7.2)	2.2 L-VL
Finish Slip (°)	0.7 (0.2 to 1.2)	0.7 S-M	2.2 (1.9 to 2.5)	2.5 VL	2.1 (1.6 to 2.6)	1.6 L-VL
SCULLER 4	**Change in Mean (90% CI)**	**ES & QO**	**Change in Mean (90% CI)**	**ES & QO**	**Change in Mean (90% CI)**	**ES & QO**
Catch Angle (°)	-4.5 (-4.7 to -4.2)	-4.7 VL	-12.9 (-13.5 to -12.4)	-8.3 VL	-8.9 (-9.5 to -8.2)	-5.4 VL
Finish Angle (°)	-2.0 (-2.2 to -1.8)	1.2 M-L	0.0 (-0.2 to 0.2) ¥	0 U	2.2 (1.9 to 2.4)	3.2 VL
Catch Slip (°)	1.8 (1.4 to 2.2)	1.2 M-L	9.0 (8.7 to 9.3)	10.4 VL	7.2 (6.6 to 7.8)	4.6 VL
Finish Slip (°)	-2.1 (-2.4 to -1.9)	-2.3 L-VL	-0.2 (-0.4 to 0.1) ¥	-0.2 U	1.7 (1.3 to 2.0)	1.8 L-VL

¥ change in mean is NOT significant at the p ≤ 0.05 level
[a]qualitative outcome states whether the effect size is S=small, M=moderate, L=large, VL=very large, T=trivial, or U=unclear/smaller than the smallest worthwhile effect size[b]
[b]smallest worthwhile effect sizes were set as 0.44% for *stroke power* and 0.5° for all angular variables based on Coker *et al.* (2008a), and 0.2 for *peak force* and *average force* based on the standardised mean difference

Table 20: Crew average stroke variables from each double scull pairing (average of tail and head wind trials) in both seating orders for four elite scullers (A, B, C and D).

BOW SCULLER	STROKE SCULLER	*Boat velocity (m/s)*	*stroke rate (spm)*	*boat power (W)*	*CS angle-diff REL (°)*	*PF time-diff REL (ms)*	*PF angle-diff REL (°)*	*PF time (ms)*	*PF angle (°)*	*Catch slip (°)*
A	B	4.99	32.0	763	1.0	12	1.1	443	-23.6	7.7
B	A	5.04	32.4	780	-1.9	-6	-1.5	464	-24.2	8.0
C	D	5.17	31.6	765	3.0	-30	-0.7	422	-25.9	7.5
D	C	5.13	31.8	801	-2.3	26	2.1	435	-22.4	7.4
B	D	5.07	31.7	784	0.8	-9	-1.6	447	-25.7	6.2
D	B	5.09	32.6	807	-1.7	-12	-1.1	397	-26.8	5.7
C	A	4.95	32.2	766	0.0	-63	-6.1	416	-28.0	8.3
A	C	5.27	32.4	789	-0.6	53	6.7	462	-18.3	8.0
D	A	5.19	32.8	721	-3.1	-47	-6.8	414	-26.3	6.7
A	D	5.23	32.4	740	1.7	27	4.1	462	-18.7	6.5
B	C	5.07	31.9	823	-1.2	36	3.1	436	-24.9	7.2
C	B	5.09	32.4	824	0.7	-41	-3.6	394	-28.1	7.7