BIOMECHANICAL FACTORS AFFECTING INDIVIDUALS' PERFORMANCE IN SPRINT KAYAKING

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Abstract

Biomechanical Factors Affecting Individuals' Performance in Sprint Kayaking

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Sprint kayaking is a complex skill performed in a complex environment. This thesis aimed to identify and assess key parameters of performance and to understand the impact of the equipment used in order to better inform elite-level coaching.

Current elite sprint kayak coaching knowledge was documented through interviews and compared with biomechanics literature. Six mechanical factors were identified as important for performance: water interaction, boat connection, athlete kinematics, stroke rate (SR)/ distance per stroke (DPS), force/power and the influence of weather conditions. Athlete individuality in particular was considered highly important but was under-represented in academic literature. These conclusions informed the subsequent experimental studies, ensuring value to coaches and a positive impact on elite athlete performance.

Force-velocity and power-velocity profiles for an iso-inertial ergometer (n = 39), as well as performance profiles on-water (n = 25), were subsequently created for a group of elite, sub-elite and club sprint kayakers. Power and theoretical maximal force production (F0) were found to differentiate between groups, with elite athletes exhibiting the highest power (elite: 48.5 ± 8.8; sub-elite: 41.0 ± 7.9; club: 38.9 ± 7.2 $W \cdot kg^{-0.67}$) and force (elite: 17.6 ± 2.7; sub-elite: 14.5 ± 1.7; club: 14.2 ± 1.9 $N \cdot kg^{-0.67}$). Individual analysis of a subgroup of 18 athletes correlated F0 and V0 (theoretical maximal velocity) with stroke power across multiple trials per athlete. Eight athletes were found to exhibit trends of the group with a statistically significant positive correlation between F0 and stroke power, while for five athletes higher V0 correlated statistically significantly with higher stroke power.

On-water at group level, boat velocity was found to exhibit a stronger correlation with stroke rate (SR) than with distance per stroke (DPS; r = 0.85 vs 0.67). At individual level, DPS showed a higher correlation with boat velocity for eight of the 15 athletes in the subgroup tested, highlighting the importance of athlete individuality, in research and in elite training environments. Combining data from the two environments found strong

correlations between power, F0 and boat velocity, indicating the value of this ergometer profiling to understand force and power in a kayak-like movement.

The final study used individualised measures of variability to define whether changes in paddle length on the ergometer resulted in notable differences in performance measured by power, F0 and V0. Changes in paddle length of 1% relative to length normally used by the athlete, equivalent to around 2 cm, resulted in 'notable' improvements in stroke power for three athletes and caused changes in F0 or V0 in six of the ten athletes tested.

This thesis developed pertinent research questions based on key variables to performance, as identified from coaching interviews. Large differences were found in these simple mechanical parameters when analysed at individual, relative to group, level. Similar individual differences were found in response to paddle length changes on an ergometer. Based on the thesis findings, a set of recommendations for coaches have been presented, which it is hoped will facilitate the application of the research to improving on-water performance.

Publications

Conference Abstracts:

Shin, C., Willmott, A. P., Mullineaux, D. R. & Worsfold, P. (2017). The effect of bungee tension on power profiling in kayak ergometry. *Proceedings of the 35th International Conference of Biomechanics in Sport*, Cologne, Germany.

Shin, C., Willmott, A. P. & Mullineaux, D. R. (2018). Does isoinertial ergometry profiling represent on-water sprint capacity in kayakers? *Proceedings of the 36th International Conference of Biomechanics in Sport,* Auckland, New Zealand.

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Nomenclature and Abbreviations

Variable	Unit	Definition
SR	spm	Stroke rate
DPS	m	Distance per stroke
Stroke duration	s	Time from the start of one stroke to the start of the next stroke on the opposite side in seconds.
Pull duration	s	Time from the start of one stroke to the end of that same stroke.
Recovery duration	s	Time from the end of one stroke to the start of the opposite side stroke.
Peak power	$W \cdot kg^{-0.67}$	Highest calculated power within a stroke.
Pull power	$W \cdot kg^{-0.67}$	Average power across the duration of the pull.
Stroke power	$W \cdot kg^{-0.67}$	Average power across the duration of the stroke.
Peak force	$N \cdot kg^{-0.67}$	Highest calculated force within a stroke.
Pull force	$N \cdot kg^{-0.67}$	Average force across the duration of the pull.
Stroke force	$N \cdot kg^{-0.67}$	Average force across the duration of the stroke.
$Power_{str,max}$	$W \cdot kg^{-0.67}$	Maximum stroke power across the 12 strokes.
$Power_{str,ave}$	$W \cdot kg^{-0.67}$	Mean stroke power across the 12 strokes.
$Power_{pull,max}$	$W \cdot kg^{-0.67}$	Maximum pull power across the 12 strokes.
$Power_{pull,ave}$	$W \cdot kg^{-0.67}$	Mean pull power across the 12 strokes.
F-V		The force-velocity profile, created from averages across pull duration.
P-V		The power-velocity profile, created from averages across pull duration.
F-SR		The force-SR profile, created from averages across stroke duration.
$P\text{-}SR_{stroke}$		The power-SR profile, created from averages across stroke duration.
$P\text{-}SR_{pull}$		The power-SR profile, created from averages across pull duration.
F0	$N \cdot kg^{-0.67}$	Theoretical maximal force production calculated as the extrapolation of F-V
V0	$m \cdot s^{-1}$	Theoretical maximal velocity calculated as the extrapolation of F-V
P0	$W \cdot kg^{-0.67}$	Theoretical maximal power from the P-V curve generated.
$S_{F\text{-}V}$		Gradient of the resultant force-velocity profile
$SR_{opt,str}$	spm	SR at which P0 occurs from the $P\text{-}SR_{str}$ profile.
$SR_{opt,pull}$		SR at which P0 occurs from the $P\text{-}SR_{pull}$ profile.
SR0	spm	Theoretical maximal SR calculated as the extrapolation of F-SR
V_{max}	$m \cdot s^{-1}$	Maximum boat velocity
Vel_{SS}	$m \cdot s^{-1}$	Steady state boat velocity

Chapter 1: Introduction

This doctoral research was conducted in collaboration with the English Institute of Sport and British Canoeing. The introduction identifies key areas for potential research from the gaps in the literature, before stating the overall aim of the thesis and providing an overview of how research questions were developed.

1.1 Overview of Previous Research

Research into sprint kayaking is limited, in part due to the difficulties in measuring factors relating to performance where it is most relevant (on-water). Some of the key conclusions and limitations arising from the available literature in sprint canoeing are discussed below.

Rather than use complex technology or methods, researchers have often used ergometers and applied conclusions drawn from these directly to on-water performance (Bjerkefors, Tarassova, Rosén, Zakaria, & Arndt, 2018; Limonta et al., 2010; Lok, Smith, & Sinclair, 2016; Lopez Lopez & Ribas Serna, 2011; Michael, Smith, & Rooney, 2010; Saga, Saito, Chonan, & Murakami, 2007; Sprigings, McNair, Mawston, Sumner, & Boocock, 2006), despite differences found in kinematics and muscle activity when compared to on-water paddling (Begon, Lacouture, & Collad, 2008; Fleming, Donne, Fletcher, & Mahony, 2012). Ergometer studies which draw conclusions based on kinematics or muscle activity must therefore be treated with caution. However, ergometers have been found to accurately recreate the physiological (van Someren, Phillips, & Palmer, 2000) and mechanical demands of on-water performance, such as power and work (van Someren, & Palmer, 2003). Although the ability to measure force and power in a similar movement is of great value, caution should be used when looking at reported ergometer power, as it has been found to be consistently under-reported by commercially available systems (Borges, Bullock, Aitken, & Coutts, 2017).

Group-level research historically dominates biomechanics literature, and has done so in sprint kayaking research; Brown, Lauder and Dyson (2011) and Limonta et al. (2010) compared athletes of different performance levels and concluded that the factors that differentiate are the most important to performance, while others report only group averages (Bjerkefors et al., 2018). Inter-athlete variability has been quantified in sport biomechanics and shown to be high among elite athletes (Bartlett, Wheat, & Robins, 2007), including sprint kayakers (Wainwright, 2013).

Jackson (1995) divided performance factors into those affecting the athlete, the hull and the blade. While hull design developments can draw on research developed for shipping, developments in paddle technology in sprint kayaking have typically been athlete driven, with athletes' subjective opinions and anecdotal evidence used to guide decision making rather than the latter being informed by empirical research (Robinson, Holt, & Pelham, 2002). The only published study which has investigated the effect of changes to equipment set-up on-water used only three athletes and one trial in each condition (Ong, Elliott, Ackland, & Lyttle, 2006). Aside from this, paddle testing has been removed from the performance environment and methods or assumptions are limiting: use of an inflatable boat in a swimming pool (Lee, 2013a; Lee, 2013b); calculation of a recommended blade surface area based on hydrodynamic drag and one dimensional force production on an ergometer (Sprigings et al., 2006); correlation assumed to relate to causation in paddle length relative to anthropometrics (Diafas, Dimakopoulou, Diamanti, Zelioti, & Kaloupsis, 2011) or assumption of steady-state flow around the blade (Jackson, Locke, & Brown, 1992; Sumner, Sprigings, Bugg, & Heseltine, 2003).

The application of any sport science research is constrained by choice of research question and coach 'buy-in' (Fullagar, McCall, Impellizzeri, Favero, & Coutts, 2019); it is vital to address these issues to ensure research has impact in the elite sport environment. In a sport such as kayaking where empirical evidence is limited and decisions are made on anecdotal information, the potential impact of relevant research becomes even higher if these limitations are overcome.

A schematic overview of holistic factors affecting sprint kayak performance is presented in Figure 1.1; it is not intended to replicate the detail of the deterministic models, but to provide a signpost and overview of the key performance variables in order that they might be understood from an applied perspective and interlinking ideas explored. Not all of the factors shown will be explored in detail; those that are investigated or discussed are highlighted via coded box outlines which indicate where each is explored.

1.2 Statement of aims

The overall aim of this body of work was to collect and interpret biomechanical data to better inform coaching of elite sprint kayakers. As a first step, coaching interviews were conducted aiming to firstly **document coaching knowledge** and secondarily **compare it to the biomechanics literature**. Engaging coaches in this way would ensure further research questions were appropriate and that 'buy-in' was gained.

Using the findings from the interviews to guide the direction of the later studies, the aims for the subsequent studies were to **understand individual performance** and how it differs from group conclusions. This research was conducted in areas highlighted by both coaches and previous literature: **force and power generation;** and the relationship between **stroke rate and distance per stroke**. Finally, the thesis aimed to investigate the **influence of changing an element of paddle set-up** on performance as this area was highlighted by coaches and has received very little attention in published research.

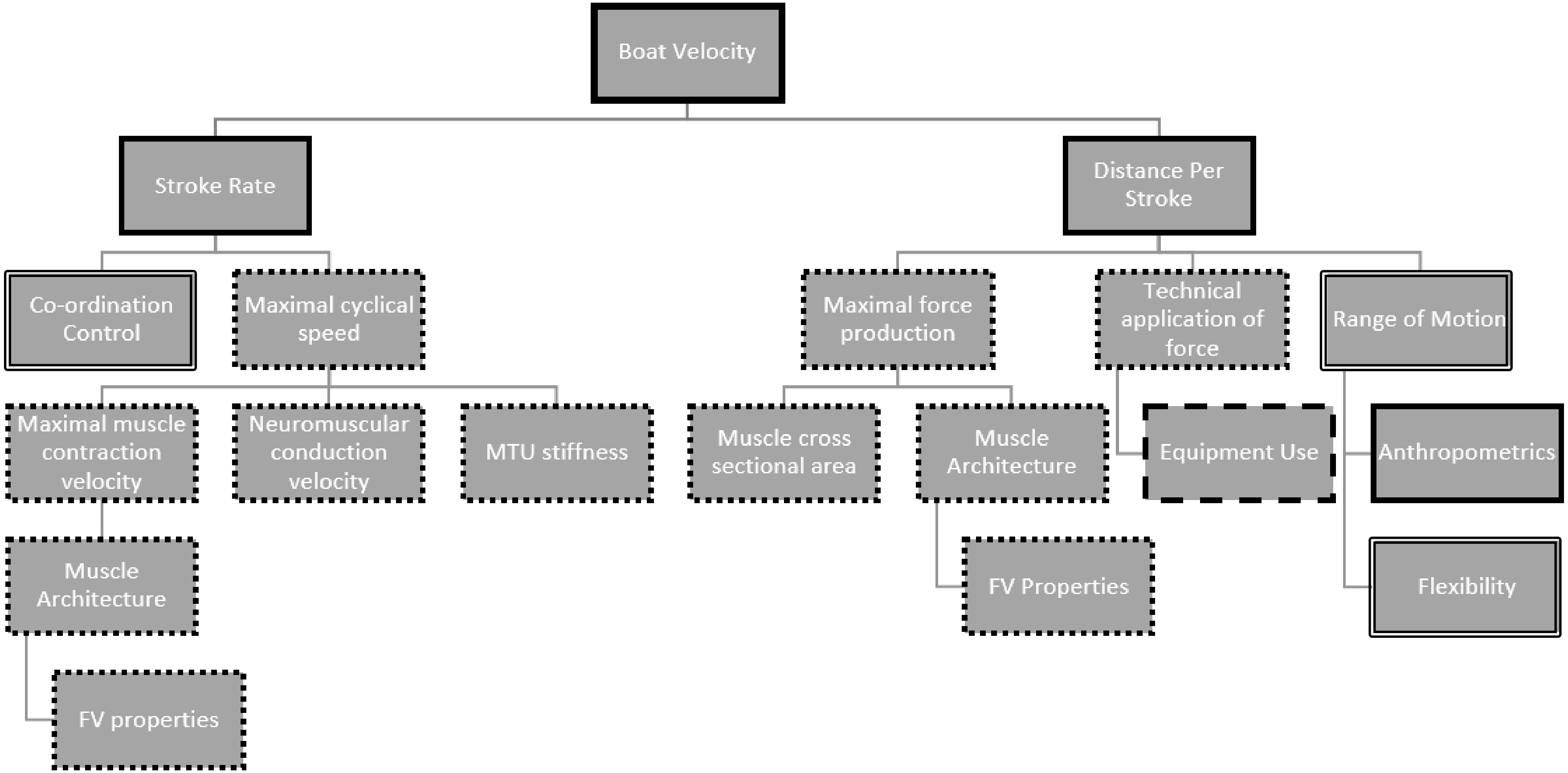


Figure 1.1: A schematic of some of the key mechanical and physiological factors contributing to sprint kayak performance. Each box outline is coded to show where an area is covered in most depth; the double line indicates Chapter 2, a solid line indicated Chapter 3, a dotted line indicated Chapter 4 and a dashed line Chapter 5.

1.3 Development of research questions

The development of relevant research questions for application in elite sprint kayaking was paramount for this thesis, therefore an initial exploration of coaches' ideas and current research was undertaken to ensure relevance of later studies. The research questions can be considered chronologically in three sections (Figure 1.2).

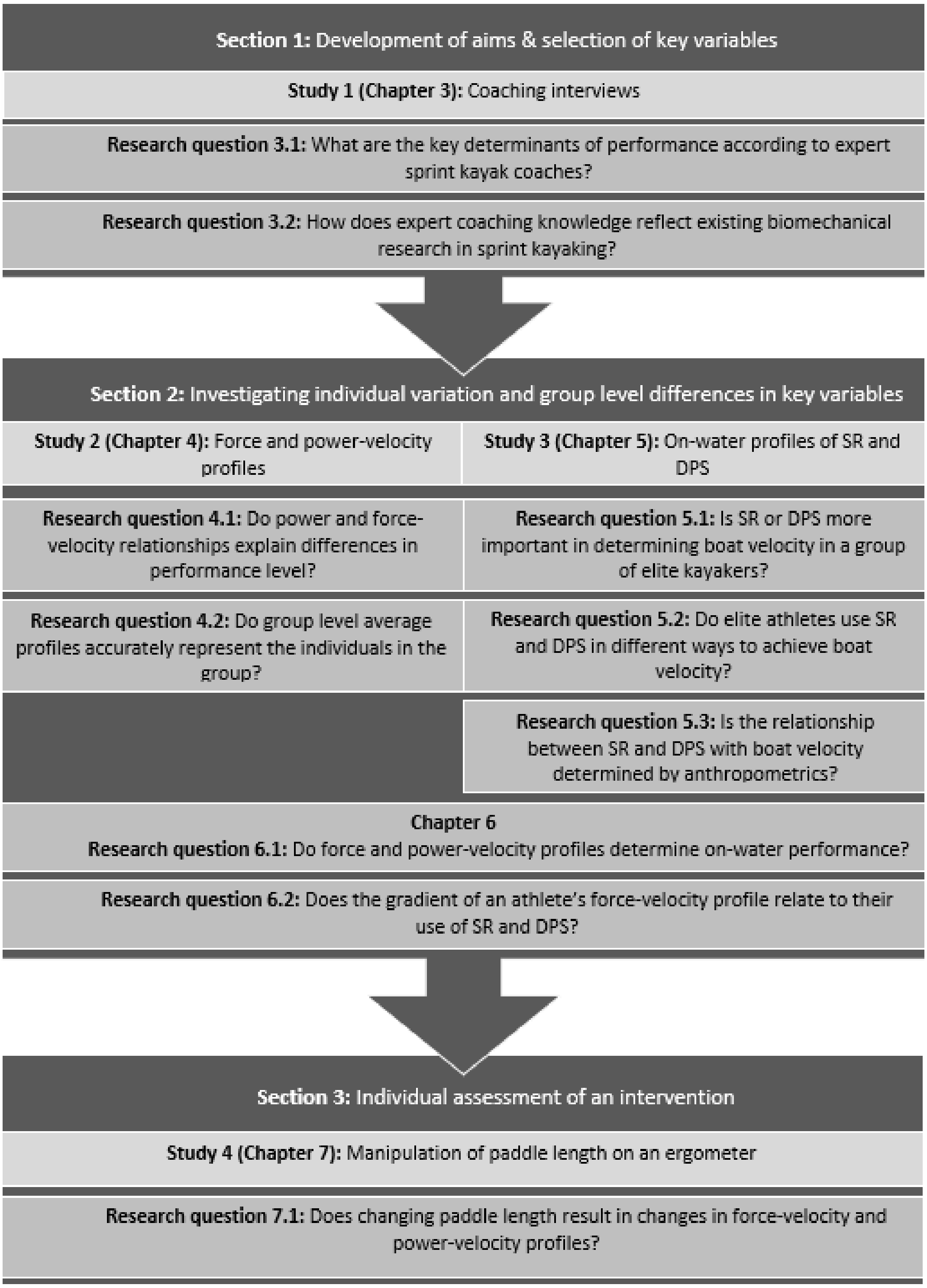


Figure 1.2: Schematic of the three section definitions and the research questions within each which are encompassed in this thesis

1.3.1 Section 1: development of aims and selection of key variables

Models of sprint kayak performance have been generated based on theory (Gomes, 2015; Wainwright, Cooke, & Low, 2016) or previous literature (McDonnell, Hume, & Nolte, 2013a) but it is not clear if these were in any way influenced by, or useful to, coaches in the field. In order to understand what is most important to the coaches who, it is hoped, will ultimately be using the research, it is important first to identify which factors they feel are most important to performance as has been done in other sports (Smith et al., 2015). Therefore, the first research question defined was:

Research Question 3.1: *What are the key determinants of performance according to expert sprint kayak coaches?*

By combining and contrasting coaching ideas with mechanical theories and published literature, variables which are key across all areas are highly likely to be important to performance. Additionally, any discrepancies or under-represented areas in any of these fields provide justification for areas to focus research. To this end, the second research question for the coaching interview was developed:

Research Question 3.2: *How does expert coaching knowledge compare to existing biomechanics research in sprint kayaking?*

1.3.2 Section 2: investigating individual and group level differences in key variables

Force and power development and the relationship between stroke rate (SR) and distance per stroke (DPS) were two key factors for performance according to coaches. No robust research could be found that investigated the differences and underlying causes between individuals.

Power produced on an ergometer is related to on-water sprint performance (van Someren & Palmer, 2003), although the component parts of power - force and velocity - have not been investigated in sprint kayakers. Force-velocity and power-velocity profiles have been linked to sprint performance in other sports, with higher maximal velocity linked to athletics track sprinting (Morin et al., 2012) and higher maximal force linked to cycling track sprinting (Dorel et al., 2005). Commercially available kayak ergometers have been found to underestimate power by 20% by not accounting for the tension in the bungee cord (Borges et al., 2017). To understand the importance of power, force and velocity to sprint kayak performance, an ergometer based on iso-inertial methods (Martin, Wagner, & Coyle, 1997) was used and developed to account for force applied to the bungee cord. This allowed quantification of power, force and velocity from stationary up to maximum velocity in a kayak-specific movement in seconds, allowing the following question to be addressed:

Research Question 4.1: *Do power and force-velocity relationships explain differences in performance level?*

Force-velocity profiles have been found to exhibit differences between individuals even when performances or power output are similar, when measured in vertical jumping (Samozino, Rejc, Di Prampero, Belli, & Morin, 2012). Using these differences to tailor training has been found to result in significant improvements in performance relative to non-specified training (Jiménez-Reyes, Pedro, Samozino, & Morin, 2019). Many of the kayak coaches emphasised during their interviews how individual athletes are very different to each other, although this did not result in individualised training. To understand the extent of individual variation in F-V and P-V profiles within a group of experienced sprint kayakers, the following question was developed:

Research Question 4.2: *How well do group level average profiles represent individual athlete profiles in the group?*

In sprint kayaking, boat velocity is the primary measure of performance and it is the product of SR and DPS. Stroke rate has been shown to differentiate between performance levels (Brown et al. 2011) but a range of SR and DPS have been shown to be used during international competition (McDonnell, Hume, & Nolte, 2013b). In athletics sprinting, step length (Debaere, Jonkers, & Delecluse, 2013) and step frequency (Nagahara, Takai, Kanehisa, & Fukunaga, 2018) have been shown to determine performance independently, with different studies reaching different conclusions. To try and identify if one of these variables is most important the following questions was posed:

Research Question 5.1: *Is SR or DPS more important in determining boat velocity in a group of elite sprint kayakers?*

As observed by coaches during interviews and by McDonnell and colleagues (2013b), different SR are used by different athletes. Again, drawing from athletics, athletes have been found to be individually 'reliant' on either step length or step frequency to maximise velocity (Salo, Bezodis, Batterham, & Kerwin, 2011). It is not known if this individuality is present in sprint kayak athletes. In crew boats, athletes must use the same SR as their teammates, which could limit performance if optimum SR are different between athletes. In order to understand the difference between athletes, the next research question was developed:

Research Question 5.2: *do elite athletes use SR and DPS in different ways to achieve boat velocity?*

One of the potential explanations provided by coaches as to why athletes use different SRs was that of arm length, with a number of coaches postulating that those with longer arms were likely to use longer strokes. This was investigated using the research question of:

Research Question 5.3: *is the relationship between SR and DPS with velocity determined by anthropometrics?*

The information available from two profiling studies- one on water and one on an ergometer- in isolation would answer the aim of this thesis which looked at group level and individual differences. However, understanding the relationship between the ergometer and the on-water data would allow coaches to better interpret the ergometer data which can be readily collected in a reliable way, regardless of environmental conditions. Therefore, the following question was asked:

Research Question 6.1: *do force- and power- velocity profiles determine on water performance in a group of elite kayakers?*

As both SR and F-V profiles have been found to show differences between athletes (McDonnell et al., 2013b; Samozino et al., 2012), it could be postulated that the relationship of one underpins the use of the other. Someone who had a higher maximal velocity might be expected to reach higher SR, while someone who can achieve higher maximum force might use longer DPS. To investigate this, the question below was investigated:

Research Question 6.2: *does the gradient of an athlete's force-velocity profile relate to their use of SR and DPS?*

1.3.3 Section 3: individual level assessment of an intervention

The results for section two showed that individuals do vary considerably, and that group level data can disguise individual differences in factors relating to sprint kayaking performance. It is therefore important to analyse any intervention change at individual level. The topic of paddle set-up is distinctly under-researched and was an area in which coaches were not confident. As research question 6.2 had shown strong correlations between ergometer profiling and on-water performance, and the ergometer allows for changes to one aspect to be changed while retaining (relative) control over others, this environment was used to examine the question:

Research question 7.1: *does changing effective paddle length result in changes in force-velocity and power-velocity profiles?*

Chapter 2: Literature Review

This literature review first outlines the aims of kayak performance and discusses the models that have been created to describe the key elements of performance. While not every factor mentioned in the models will be covered in detail, a more in-depth review of the underlying factors considered to most affect athlete, paddle and boat movement is conducted. Following this, an overview of the differences found between individuals in kayaking is given and discussion of the underpinning physiological and mechanical characteristics affecting kayak performance undertaken.

2.1 Olympic kayaking

Sprint canoeing and kayaking are raced over 200 m, 500 m and 1000 m with one, two or four athletes in a boat. Each event is given a code, for example a K4 is a kayak with a crew made up of four athletes, and elite races last from around 30 seconds to three and a half minutes (Table 2.1). While Olympic events are the focus for most athletes in the UK, as these dictate a National Governing Body's (NGB) funding, there are 22 additional canoe and kayak events competed in at a World Championship.

Table 2.1: Sprint kayak gold medal winning times (m:ss.ms) from the Rio 2016 Olympic Games (Olympic, 2016).

	Time	
Event	**Men**	**Women**
K1 200 m	35.197	39.864
K2 200 m	32.075	NA
K1 500 m	NA	1:52.494
K2 500 m	NA	1:43.687
K4 500 m	NA	1:31.482
K1 1000 m	3:31.447	NA
K2 1000 m	3:10.781	NA
K4 1000 m	3:02.143	NA

2.2 Performance evaluation

To understand the key factors affecting performance, researchers have broken sprint kayak performance down into shorter phases (McDonnell, Hume, & Nolte, 2012) or created deterministic models (Wainwright et al., 2016). These reductionist approaches are often used by biomechanists to understand how mechanical principles underpin sporting success (Hay, 1993).

2.2.1 Phases of the stroke

There is little consistency between researchers in how a kayaking stroke is broken down into separate phases (McDonnell et al., 2012) and discrepancies in terminology can lead to misunderstandings between athletes, coaches and researchers, making improvements in performance more difficult to facilitate. McDonnell et al. (2012) discussed three main ways in which phases have been determined: water-phase defined, paddle shaft position defined, and body position defined. As descriptions for some of these phase definitions were not clear in previous research, use of a water-phase defined model with sub-phases based on paddle position outlined was recommended based on ease of use and understanding to allow consistency between researchers and coaches. McDonnell et al. (2012) focused their research on phases that could easily be defined through video, but instrumented paddles have also been used to identify contact (Gomes et al., 2015) and it is not clear how well video and force definitions of the stroke start or end relate. In future, technology such as inertial measurement units (IMU) on the paddle may also be used to detect paddle position but no research could currently be found which has used IMU on a kayak paddle. For clarity, the terminology that will be used throughout this thesis is provided and defined in Table 2.2, based on the conclusions of McDonnell et al. (2012) and common coaching language.

Table 2.2: phase specific terminology and associated definitions that are used throughout this thesis

Term	Also known as	Definition
Catch	Entry	The beginning of the stroke, the first point at which the tip of the blade has entered the water.
Blade exit	Exit	The end of the stroke, the first point at which the whole blade has left the water at the back of the stroke.
Pull time	Water phase time	Duration from catch to exit.
Glide time	Air phase time	Duration from exit to the subsequent catch.
Stroke time		The time taken from the catch on one side to the catch on the other.
Displacement per stroke	DPS	The displacement of the kayak during stroke time.
Pull distance	Water phase displacement	The displacement of the kayak during pull time.

Table 2.2 continued

Term	Also known as	Definition
Glide distance	Air phase displacement	The displacement of the kayak during stroke time.
Stroke rate	SR	The number of strokes taken within a certain time; reported in strokes per minute.

2.2.2 Deterministic modelling

Biomechanical deterministic models describe the mechanical factors that directly influence performance, with all factors of a level completely determining the factors of the level above (Hay, 1993). Two deterministic models of sprint kayaking have been created: (McDonnell et al., 2013a, Figure 2.1; Wainwright et al., 2016, Figure 2.2). These models have differing levels of complexity and may be considered to have different intended audiences; McDonnell's model may be intended for coaches as the language is focused on time and displacement terms, while the Wainwright model is more complex, with use of mechanical terms. Although not described as a deterministic model, Gomes (2015) included an overview model of the factors affecting sprint kayaking (Figure 2.3).

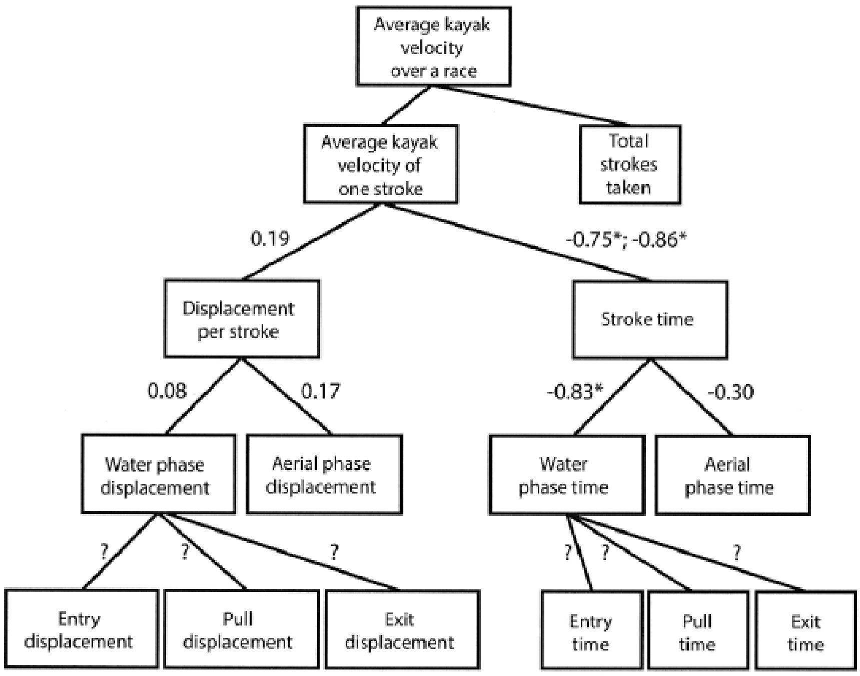


Figure 2.1: Deterministic model for sprint kayaking from McDonell et al (2013a). Values are correlational r values between the variable in the lower box and average kayak velocity of one stroke from Hay & Yanai, 1986.

McDonnell and colleagues’ (2013a) narrative review was based on 35 literature sources, but the paucity of quantitative data meant that the values reported in the deterministic model (Figure 2.1) are all from Hay and Yanai (1996), with the addition of a single value correlating DPS with boat velocity (-0.86) from Mononen and Viitasalo (1995). Hay and Yanai (1996) are reported as having conducted correlations on a group of 10 elite athletes but the report cited is not publicly available and therefore methods cannot be checked. The use of 10 athletes for a correlation, without evidence of assumption checks, reduces the power of these conclusions and therefore of the McDonnell et al. model.

Wainwright’s (2013) deterministic model was first based in theory and then tested during a data collection with 12 elite athletes. Paddle force, within-stroke acceleration, paddle angle, paddle position, kayak displacement, paddle entry and exit times were measured for every stroke during three 250 m efforts with 18-54 strokes input into linear regression per athlete. Further break down of the ‘change in velocity during pull phase’ was found to be necessary to accurately describe the factors determining performance (levels 5-6, Figure 2.2). Correlation coefficients and beta coefficients are given for all athletes for all levels, with variation between athletes. The author notes that as a mechanical model, statistically significant correlations are not required between all variables to validate the model. Gomes’ (2015) model was developed in a similar way to McDonnell’s, as an overview following a review of the kayaking biomechanics literature available, although correlational values were not reported, and the model provided a broader overview of the factors affecting performance results.

The variation in the literature with regards to definitions and identified performance variables make it difficult to draw concise conclusions. Understanding the factors which are directly important to elite coaches, and therefore regularly used in the applied setting, would allow a better appreciation of where impact may be gained. Contrasting these areas to specific research will further identify areas of valuable research.

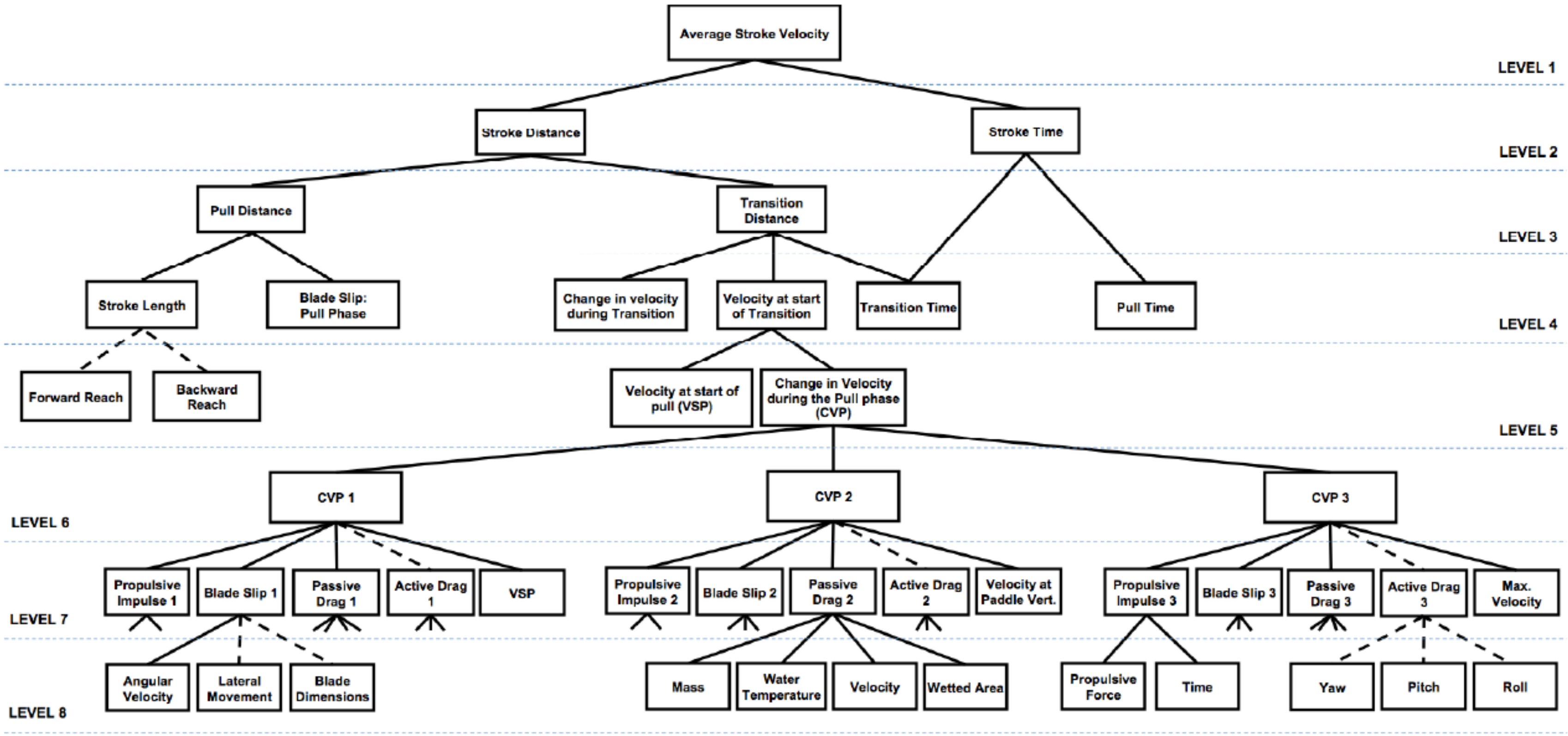


Figure 2.2: Deterministic model for sprint kayaking from Wainwright (2013). Level 8 is reduced for diagram clarity. Dashed lines represent untested relationships.

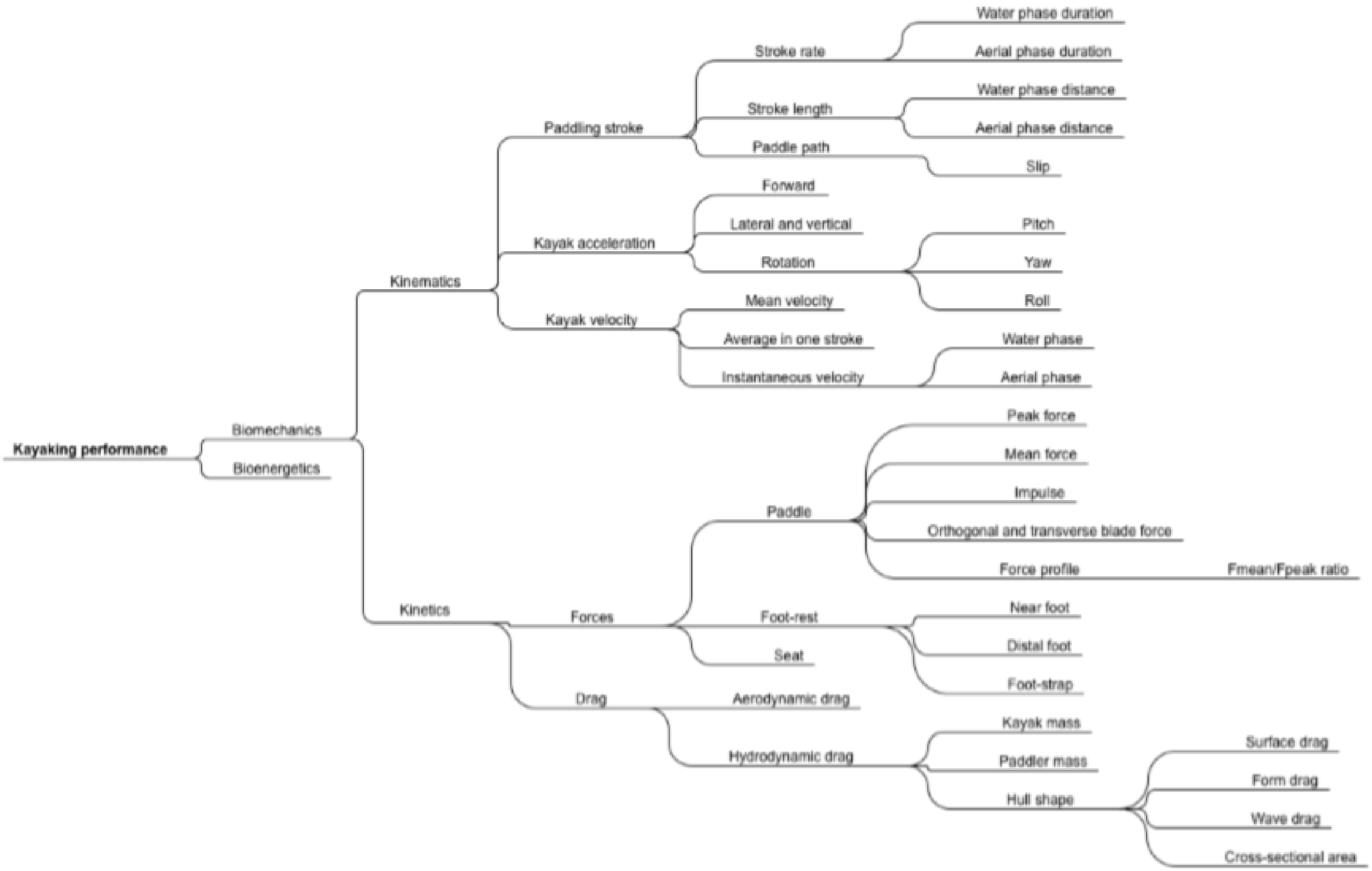


Figure 2.3: Gomes' (2015) outline of variables contributing to kayak performance

2.3 Athlete Movement

The deterministic models above focus on the boat and paddle movement, without direct reference to athlete kinematics. This does not reflect the overall literature, which has a proportionally larger number of papers focused on athlete movement.

2.3.1 On water paddling

Some of the difficulties associated with data collection in the environment of sprint kayaking are outlined in Table 2.3, focusing on three motion analysis technologies: traditional optical camera based systems; opto-electronic systems (often considered the gold standard); and more recently developed IMU based wearable systems.

Table 2.3: An overview of some of the strengths and weaknesses of kinematic measurement systems as would relate to use in sprint kayaking

Measurement System	Strengths	Weaknesses
Optical Camera	• Inexpensive • High ecological validity • Can be waterproof	• Time consuming processing • Complex calibration for 3D • Parallax error for 2D • Perspective error for 2D • Calibration risk
Opto-electronic	• High accuracy • Faster post-processing • High frame rates	• Expensive • Long set-up time • Markers on athlete • Range too small for regatta course use • Electrical power needed • Reflections from water cause errors • Not waterproof
IMU-based	• Large capture volume • Fast post-processing	• Expensive • Lack of validation for rotational movement • Markers on athlete • Not waterproof

Table 2.4 provides an overview of camera based kayak studies, some of which have mitigated the weaknesses listed in Table 2.3 via methodological considerations such as careful camera placement, floating calibration frames (Ong et al., 2006) and digitiser

reliability checks (Brown et al. 2011; Ong et al., 2006). The environment will always be a confounding factor in on-water measurement; while some researchers limit collections to below certain wind speeds (2 $m \cdot s^{-1}$ van Someren et al., 2000; Wainwright, 2013; 3 $m \cdot s^{-1}$ Fisher, 2015) or use an indoor towing tank (Begon et al., 2008) to reduce the influence of these factors, many disregard this factor completely, or cite that data were recorded on, for example a "calm bay" (Ong et al., 2006).

Due to the paucity of data available, conference abstracts have been included in Table 2.4; these often do not describe the methodologies used in detail but contain potentially important conclusions. For example, Mann (1978) reported smooth velocity and acceleration curves led to "the most economical utilisation of forces produced by performers" (p. 63) although no further documentation was provided. Inter-participant variation and a link between increasing velocity and balance problems were also reported by Mann (1978) but without detailed methodology, it is not possible to assess the validity of the conclusions.

Table 2.4: Summary of studies investigating on-water kinematics of sprint kayaking using optical cameras

Paper	Number; gender; level of participants	Movement speed	Camera Frequency	Camera set-up	Calibrated area	Number of digitised points	Digitised locations	Study conclusions
Baker et al. (1999)	10; 6 male, 4 female; international	Race pace	50 Hz	2 cameras; 40° to left & 15° to right of travel	6 m x 2 m x 2 m	8 markers	Arms and paddle	Significant differences between male and females in boat velocity, glide distance and total stroke length
Begon et al. (2008) *Abstract*	2; male; international	84 strokes per minute (speed not dictated)	50 Hz	Five cameras around an indoor towing tank	One full stroke	8 segments	Upper body, paddle and kayak	On-water and ergometer kayaking are similar
Brown et al. (2011)	135; Gender unknown; national & international	Racing	50 Hz	Panning camera 100 m from finish line	None	None	None	Elite athletes have higher SR, shorter glide time, higher stroke width, forward reach, trunk rotation and leg motion

Table 2.4 continued

Paper	Number; gender; level of participants	Movement speed	Camera Frequency	Camera set-up	Calibrated area	Number of digitised points	Digitised locations	Study conclusions
Fleming et al. (2012)	10; male; international	85% $\dot{V}O_2$	50 Hz	Single camera, sagittal plane	Unknown	Unknown	Unknown	Ergometer comparable to on-water, differences in shoulder muscle activity
Kendal & Sanders (1992)	5; male; international	Maximum velocity	100 Hz	Lateral and frontal cameras	One full stroke	15 (frontal camera)	Paddle, kayak and upper body	Technique description- paddle path & kinematics differ, better paddlers more lateral and forward blade
Mann & Kearney (1980)	11; 9 male; 2 female; international	Maximum velocity	70 Hz	One lateral camera	12 m	13	Upper body, hips & knees	Technique description

Table 2.4 continued

Paper	Number; gender; level of participants	Movement speed	Camera Frequency	Camera set-up	Calibrated area	Number of digitised points	Digitised locations	Study conclusions
Mann et al. (1978) *Abstract*	5; unknown; international	80-100% race pace	100 Hz (frontal) 64 Hz (lateral)	Lateral and frontal cameras	Unknown	Unknown	Unknown	Technique description- smooth acceleration curves in elite. Balance problems at higher speeds. Between athlete differences.
Ong et al. (2006)	3; 1 male, 2 female; International	Maximum velocity	50 Hz	Lateral and frontal cameras	6 m x 1.2 m x 2 m	10	Upper body and paddle	Paddle set-up intervention; boat set-up changes were detrimental to performance
Sanders & Kendal (1992) *Abstract*	5; unknown; novice to international	Maximum velocity	100 Hz	Lateral and frontal cameras	Unknown	Unknown	Unknown	Better performers indicated by higher SR. Paddle path differences also exist between levels.

Kendal and Sanders (1992) conducted the most detailed analysis of kayaker kinematics to date, using a floating calibration frame and two cameras to recreate 3D joint centre positions for a single 'maximal' velocity stroke of five international standard paddlers. Comparing the two paddlers with best performance time against the other three, the movement patterns of the two better paddlers were found to be consistent with each other and to involve more lateral movement of the paddle. In a notational analysis, Brown et al. (2011) subjectively graded and compared the movements of international (n = 78), national (n = 38) and club (n = 19) level paddlers during racing and found rotation, leg contribution, lateral paddle movement and forward reach to differentiate between performance levels. While this gives direction for the important features of technique to performance, these factors were recorded from one fixed, panning video camera and each factor was subjectively rated from one to five. Brown et al. originally investigated 22 variables in this way but five were removed from analysis after test-retest reliability of the scores from a Spearman's correlation was found to be low ($r < 0.55$). This reliability check highlights the difficulty in quantifying differences, while also providing more confidence in the values which were reported.

No research could be found that has used optoelectronic systems in a competition environment, likely due to the factors mentioned in Table 2.3. Begon et al. (2008) used a 'semi-automatic tracking' system around an indoor tow tank to compare to ergometer paddling, although detailed kinematics were not described in the conference abstract. Funato, Shibuya, Hond and Techi (2006) reported physiological data from athletes paddling in a circulating water channel but despite the complexity of the set-up, including an optoelectronic system and force and boat movement measurement via a tether, no further published research could be found which uses this system.

Wearable systems are a developing technology that use IMUs and data fusion algorithms to reproduce 3D kinematics of movements. Despite marketing suggesting data collection has occurred on both ergometers and on-water (Xsens, 2016), no published research could be found which has used a wearable system to quantify sprint kayaking kinematics. Local dynamic stability during ergometer paddling has been measured using IMUs (Hamacher, Krebs, Meyer, & Zech, 2018) but no validity checks are reported and therefore the accuracy of these systems for such a 3D movement remains a question, as published validation work has focused on sagittal plane movement or non-sporting movements (Blair, Duthie, Robertson, Hopkins, & Ball, 2018; Robert-Lachaine, Mecheri, Larue, Plamondon, & Plamondon, 2017; Zhang, Novak, Brouwer, & Li, 2013).

2.3.2 Ergometer paddling

Researchers have compared on-water and ergometer paddling for both the physiological (van Someren et al., 2000) and mechanical components of performance (Begon et al., 2008; Fleming et al., 2012). Fleming et al. (2012) compared muscle activation, stroke force and 2D kinematics of three-minute efforts at pre-defined stroke and heart rates on an ergometer and during on-water paddling in 10 elite level sprint kayakers. The three-minute duration and relatively low SR (82 strokes per minute; spm) used mean the data are not applicable to maximal effort but may correspond with the 1000 m racing distance. There were limitations to some of the measurements employed, as listed below.

- Video in 2D
    - The 2D video was used to measure position relative to the waterline and create a virtual water line during ergometer paddling. This assumes there is no roll present during on-water kayaking which is unlikely to be accurate.
    - Video was used to define blade entry and exit and would therefore have an accuracy limited to 0.02 s; this level of accuracy is acceptable for the SR investigated but would be low for the rates found at elite sprint level (McDonnell et al., 2013b).
- Limited calibration of strain gauges
    - Only 10 and 20 kg calibrations were used for force measurement. Two data points would not be enough to definitively confirm a linear relationship between voltage and force. Peak forces were reported to reach 238 N, roughly equivalent to 24.2 kg, beyond the calibrated measurement.
- Ergometer paddle length matched
    - Hand position was adjusted on the ergometer, but it is not clear how this was maintained or controlled.
    - Paddle length on the ergometer was matched by “adding an extension element to the end of the ergometer shaft” (p. 18). Although this means total length would be matched, the distance between the hand and the force application would be variable and not representative of that on-water.

- Paddles were matched for length and angle on-water but Alpha M+ blades (Jantex, Sokolovce, Slovakia) were used for all participants, with no mention of what the athletes would usually use.
- EMG compared across days
    - Although normalised to a maximum voluntary contraction each day, the placement of an EMG electrode is extremely difficult to replicate exactly and changes in position will change readings (Ahamed et al., 2014).

A shorter time from the start of the stroke until the paddle reaches a vertical position on the ergometer was the only reported kinematic difference between ergometer and on-water paddling, while recoil of the bungee cord was thought to be the cause of measured muscle activity differences and of the additional force during the recovery phase found during ergometer trials.

Begon et al. (2008) measured two paddlers during 40 seconds of paddling on a sliding-complex ergometer and one full stroke on an indoor dock using a motion analysis system operating at 50 Hz. Using time-series data and a coefficient of multiple correlation (CMC), the two conditions were compared. Unlike Fleming et al. (2012), the authors found the stroke timing to be comparable between ergometer and on-water trials, with upper limb kinematics similar (CMC > 0.76) except for the shoulder movement in the frontal plane (CMC = 0.66), which the authors attributed to balance differences. The sliding-complex design of this ergometer compared to the standard one used by Fleming et al. (2012) may be the cause of the different results found (Table 2.5).

Comparing three-dimensional (3D) kinematics of elite, intermediate and novice paddlers while using an ergometer, Limonta et al. (2010) found that elite performers were characterised by higher 'paddling amplitude', larger elbow and knee range of motion, lower asymmetry in a number of joint angles (e.g. maximum elbow flexion and extension, knee flexion and range of motion) and lower seat and pelvic movements in the frontal plane. Unlike standard ergometers, the seat Limonta et al. (2010) used oscillates with the ergometer design, although it is not clear what the range or damping of this oscillation is. Increasing seat movement in the frontal plane in a kayak would create additional boat roll and therefore higher hydrodynamic drag, so the reduction of this parameter in elite athletes matches expectation. The metrics reported by Limonta et al. are comparable to those found to differentiate performance of elite and novice paddlers on-water (Brown et al., 2010) and are comparable to the differences found during ergometer paddling at different intensities (Bjerkefors et al., 2018). Bjerkfors et al. (2018) additionally found higher ranges of motion at all lower limb joints at high intensities compared with low intensity (e.g. 45.5 vs 31.4° at the knee and 31.4 vs 20.0° at the hip). Studies involving 3D analysis have reported only group level results and so individual differences which may occur have been disguised.

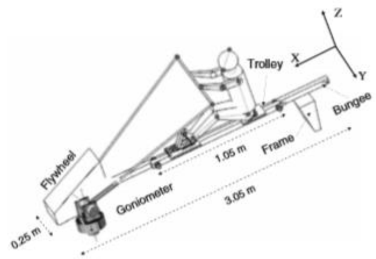
It is important to note the differences in ergometer design when considering research involving ergometers. While some studies have used commercially available machines, replicating what athletes typically use in training, others have designed ergometers to make the mechanics better replicate paddling on water (e.g. Begon et al., 2008). Table 2.5 demonstrates some of the available designs. There are three ergometer designs that have predominantly been used in kayaking research: the University of Poitier research team design (Begon & Colloud, 2007); the K1 ERGO preferred by van Someren and developed by the Australian Institute of Sport (e.g. van Someren et al. 2000) and the Dansprint, a commercial design (Dansprint, Hvidovre, Denmark). All the ergometers in Table 2.5 are 'air-braked' meaning they use a fan on the front to create resistance. The main difference between designs is that most use a fixed seat and footrest whereas the Poitier ergometer uses a 'sliding complex' where the footrest and seat are connected on a trolley which moves up and down the main body of the ergometer. This allows the athlete to move relative to the paddle which may better replicate the mechanics of paddling on water. No comparison between the kinematics on a sliding ergometer and a fixed ergometer could be found.

Measuring athlete movement is difficult on-water and as such, much of the research which has attempted to is methodologically limited. There are some simple factors which are common across water and ergometer research in differentiating between elite and lower lever paddlers such as stroke length ('forward reach' or 'paddling amplitude'), but there does not appear to be a clearly defined optimal movement pattern for elite kayaking. Along with elite level individual differences (Kendal and Sanders, 1992), this suggests that simple metrics may have more value for impactful research in an applied setting. Understanding which of these factors is valuable to coaches will further help direct research to increase impact.

Table 2.5: Some kayak ergometer designs used in research and/or training. *indicates which reference image has been taken from.

Manufacturer	Device	Description	Image	Research Using this design
KayakPro	SpeedStroke Gym	Fixed seat and foot rest. Air braked flywheel. There is also a high resistance version available.		None found Reportedly used by elite athletes (KayakPro, www.kayakpro.com)*
WebaSport	Kayak Ergometer	Fixed seat and footrest. Air braked flywheel.		None found Reportedly used by elite athletes (WebaSport, weba-sport.com)*
DanSprint	Kayak Ergometer	Air braked flywheel with variable resistance. Fixed seat and footrest. Commercially available ergometer with on-board computer.		Used by elite athletes (Dansprint, www.dansprint.com)* Fleming et al. (2012) Lopez & Serna (2011) Saga et al. (2007) Bjerkfors et al. (2018) Bjerkfors et al. (2019) Gomes et al. (2012) Tornberg et al. (2019)

Table 2.5 continued

Manufacturer	Device	Description	Image	Research Using this design
Australian Sport Commission	K1 ERGO	This ergometer was developed by the Australian Institute of Sport (AIS) and later sold commercially.		Reportedly used by elite athletes (K1 Trainer, www.k1trainer.com)* Sprigings et al. (2006) Van Someren & Howatson (2008) Van Someren & Oliver (2002) Van Someren & Palmer (2003) Van Someren et al. (2000)
Concept	Adapted Rowing ergometer	Adaptation of a Concept II rowing ergometer design to replicate the K1 ERGO outlined above.	No image available	Michael et al. (2010) Micheal et al. (2012)
University of Poitiers	NA	Sliding complex ergometer designed to more closely mimic the movements used on-water sprint kayaking. Seat and footrest slide forward and back, attached to the main frame by a bungee.		Reportedly used by elite athletes Begon et al. (2008) Begon et al. (2009)* Begon et al. (2010) Fohanno et al. (2014) Therrien et al. (2012) Limonta et al. (2010)

2.4 Paddle Movement

The 'fixed' blade position recommended by sprint kayak coaches (e.g. Nikonorov, 2017) is not replicated by most commercially available ergometers, which generally have a fixed seat which the paddle moves past (Table 2.5). This mechanical difference is likely to result in different paddle path on an ergometer compared to on-water, reducing the ability to learn more about the importance of paddle path in generating boat velocity from ergometer research.

2.4.1 Hydrodynamics

Understanding the influence of the paddle path on performance requires an understanding of the hydrodynamics of the paddle and kayak. The optimal movement of a kayak has been described as resulting from maximising thrust (i.e. positive) while minimising drag (i.e. negative) forces acting on the hull (Jackson et al., 1992). Papers primarily looking at paddle forces have considered higher drag as positive for performance: "the propulsive efficiency of the paddle blade can be optimised by maximising the amount of drag force produced by the blade" (Sumner et al. 2003, p. 12). The equation for drag is shown below:

$$\text{Drag} = \frac{1}{2} C_D \rho A v^2 \qquad \text{(Equation 1)}$$

where C_D is the coefficient of drag, ρ is the water density, A is the frontal surface area of the blade and v is the speed of the blade relative to the water. The view of Sumner et al. (2003) that efficiency is determined by drag force alone is an oversimplification of the 3D movement of the paddle, which has been shown to move laterally (Kendal & Sanders, 1992) and is thought to make use of lift forces in addition to drag (Jackson et al., 1992).

2.4.2 Force measurement

While measurement both force and direction of application is currently extremely difficult, a number of studies have measured forces either on-water or on an ergometer.

2.4.2.1 On-water

Many authors have outlined their attempts to instrument the kayak-paddle system, with varying degrees of success (Aitken & Neal, 1992; Gomes et al., 2011; Helmer, Farouil, Baker, & Blanchonette, 2011; Mononen & Viitasalo, 1995; Nilsson & Rosdahl, 2014;

Stothart, Reardon, & Thoden, 1987). Research has focused on measuring force via the bending moment in the paddle shaft using strain gauges, often making assumptions about the centre of pressure or the direction of force application. Using these assumptions, higher paddle force has been found to correlate with faster performances in sprint kayaking (r = 0.72, Brown, 2009; r = 0.79, Mononen & Vitasalo, 1995).

In 1986 a new 'wing' paddle design was used in an international race, substantially beating the previous World Best time and this new design was subsequently taken up by all elite kayakers. Jackson et al. (1992) considered the hydrodynamics of paddle propulsion from first principles and the wing paddle was found to increase efficiency significantly by utilising lift as well as drag forces. Measured experimentally using a towing tank, an angle of attack (the angle between the blade chord and the relative velocity of the water; α; Figure 2.4) of 20-30° was found to be most efficient for generating thrust, corresponding to a stroke angle (angle defining paddle position relative to hull movement direction; θ; Figure 2.4) of 65° to the hull. Both angles will change through a kayak stroke (Sanders & Baker, 1998) and the values found in Jackson's study are seemingly within the range used by elite athletes (Baker et al., 1999), although it is not clear if they would occur simultaneously. The simplifications and assumptions made lessen the impact of this study on competition kayaking; Jackson et al. (1992) calculated the impulse required from a fluid motion simplified so that paddle movement was assumed to create a single vortex ring and measured single positions per trial, disassociating the test procedure from the three dimensional, fast-paced movement of a kayak paddle in real-time competition sprinting.

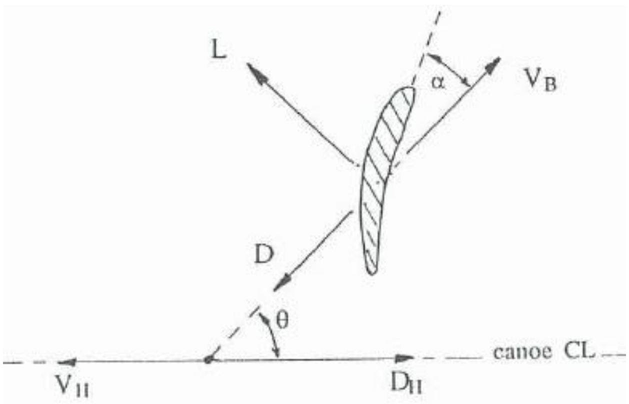


Figure 2.4: Schematics of paddle propulsion forces (drag: D; lift: L; D_H: drag of the hull) velocities (V_H: velocity of the kayak hull; V_B: velocity of the blade relative to the water) and angles (α: angle of attack; θ: stroke angle) during kayak paddling with a wing blade from Jackson (1995).

A comparison of the force generated at different stroke rates (SR) was conducted by Gomes et al. (2015) using strain gauges bonded to the athlete's own paddle shaft to record bending moment perpendicular to the surface of the blade. The system was calibrated with masses hung from the grip position while the paddle was supported at the theoretical centre of pressure of the blade nearest the mass and at the contralateral grip position, using increments of 5 kg from 5 to 30 kg. Ten international level athletes (five male, five female) completed four trials of 200 m one at each of 60, 80, 100 spm and self-selected (race pace) SR- with five minutes recovery between trials. Calculations from the force measured in the shaft, near to the lower hand grip, were used to infer force at the blade and assume a fixed rotational point at the top hand. The validity of this assumption is difficult to ascertain but the kayak stroke is more complex than a simple pivot, as will be discussed in the paddle path section below (Section 2.4.3).

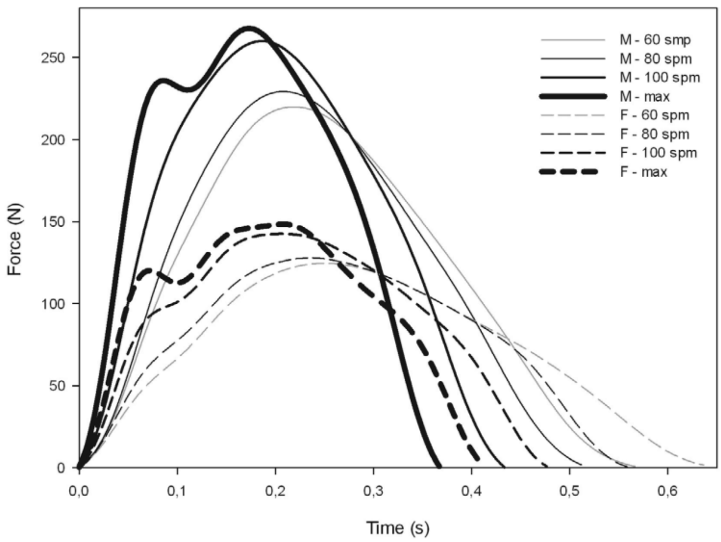


Figure 2.5: on-water paddle force traces for men and women at each of four different SRs from Gomes et al. (2015)

In Gomes et al.'s paper, once the athlete reached the desired SR, all strokes within a SR condition were time normalised to the median duration of the water phase and analysed, meaning any differences due to acceleration phase, fatigue or timing differences are unclear. Mean force curves (Figure 2.5), showed an increase in the initial gradient of the force-time curve with increases in SR. Gomes and colleagues attributed the double peak seen in the race pace SR to the paddle shaft elasticity, but it could correspond with Jackson's findings on paddle propulsion, with a peak in force generated by lift, followed by a peak generated from drag forces when they are thought to be highest, at paddle vertical (Plagenhoef, 1979), although without kinematic data this cannot be assessed. Peak force ($r = 0.66$) and mean force ($r = 0.80$) were found to correlate significantly with trial velocity. Although individual analysis was not conducted, the high coefficient of variation in force measurement (% CV = 42.78 and 44.90 at race pace SR for female and male respectively) alludes to large inter-athlete variability.

Wainwright and colleagues (2013) correlated change in velocity during the pull against the factors considered to influence it from the mechanical-theory based model (propulsive impulse, blade slip, passive drag and active drag) and originally showed few significant relationships. Taking into account paddle orientation and in-cycle velocity changes by breaking down into sub-phases (Figure 2.6) subsequently resulted in many more significant correlations. Differences between individuals were apparent as the coefficient of determination differed between athletes for all variables reported. For example, the explained variance between propulsive impulse and change in velocity of the paddle during the start to paddle vertical phase for a given athlete ranged from an r^2 value of 17% to 89%.

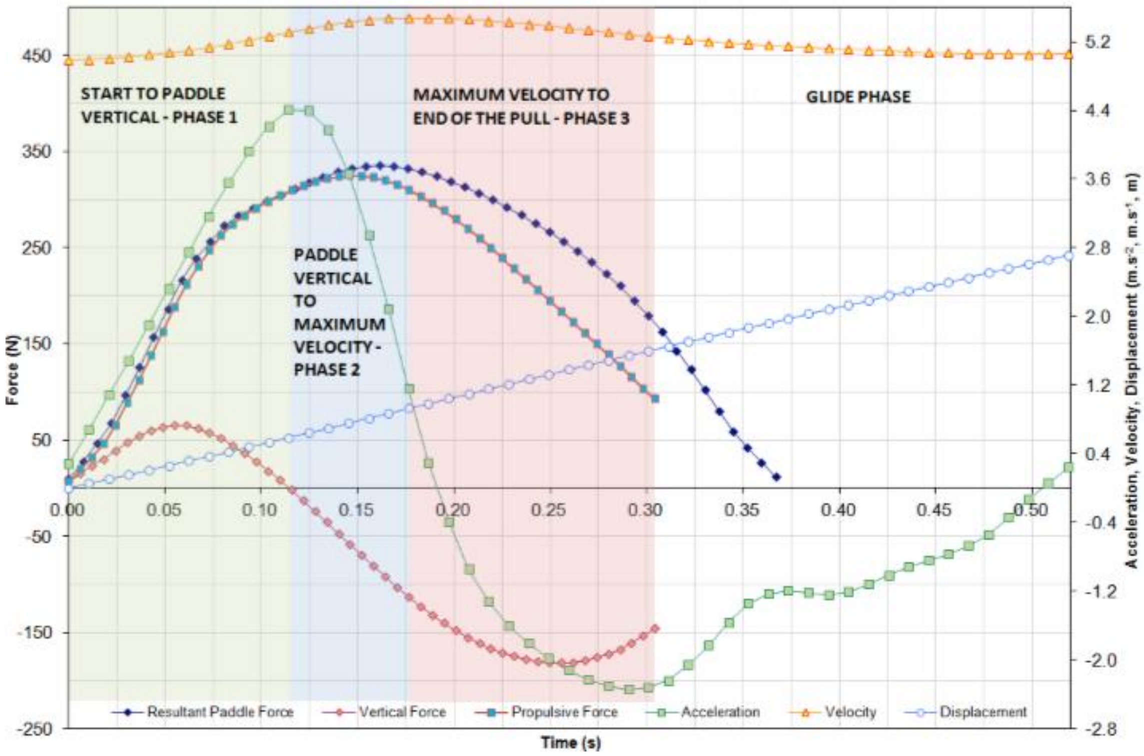


Figure 2.6: Paddle forces and boat movement for a sprint kayak paddle stroke, with phase breakdown marked by coloured shading from Wainwright et al. (2013)

2.4.2.2 Ergometer Forces

Multiple researchers have measured paddle force on ergometers (Bjerkefors et al., 2018; Fleming et al., 2012; Gomes et al., 2015; Michael et al., 2012; Therrien, Collad, & Begon, 2012). Michael et al. (2012) used strain gauges attached to the paddle and found mean peak forces (303.6 N) similar to those reported for on-water in elite athletes (274 N; Gomes et al. 2015). In a direct comparison between ergometer and on-water performance, Fleming et al. (2012) used strain gauges on an ergometer and on-water paddling of the same athletes and also found slightly higher forces on the ergometer (238 N on ergometer vs 223 N on-water), although this difference was not statistically significant. Higher forces during ergometer paddling might be expected to be due to the ability of athletes to apply more force when they are not required to balance the kayak and/or the reduced importance of direction of force application allowing higher forces to be produced. By combining force data with kinematics, Michael et al. (2012) also investigated 'efficiency' by quantifying the component of anterior-posterior force relative to the total force, although the assumption of drag force being the only positive contribution to performance is incorrect, as will be discussed below in the paddle path section.

Power measured on an ergometer has been found to increase with higher intensities (Bjerkefors et al., 2018) and to correlate with on-water 200 m time (n = 26; r = -0.69; van Someren & Palmer, 2003). Bjerkfors et al. (2018) conducted an ergometer study involving both force and 3D kinematics measurement at different intensities. Increasing intensity from a controlled 'low' to the highest power output that could be stably maintained for 20 stroke cycles ('high') resulted in large difference in power output and range of motion; increasing from 'high' to 'maximal' (20 maximal effort strokes without need for stable maintenance) resulted in large increases in power output but small differences in range of motion, leading the authors to attribute increased power output to higher SR and muscle activations, although the latter was not measured. Large differences were found between males and females, increasing at higher intensities (male: high intensity 433 W, maximal intensity 610 W; female: high intensity 277 W, maximal intensity 359 W). The ten elite kayakers tested by Bjerkefors et al. (2018) were all reported to produce higher power on the right, regardless of which hand was dominant, although no explanation was suggested.

By comparing calculated power with the output from a commercially-available ergometer (DanSprint, Denmark), Bjerkefors et al. (2018) were able to validate the latter, with correlational r values of 0.99, using an equation of measured power = 1.18 x ergo power + 27.6. An 18% difference in power output was lower than the 22.5% previously found for DanSprint ergometers (Borges et al., 2017). Borges et al. (2017) compared KayakPro, Weba and DanSprint ergometers (Table 2.5) to a 'first principles torque meter' designed by the South Australian Institute of Sport and described in Gore, Tanner and Fuller (2013; Figure 2.7), taking into account both the flywheel and bungee cord resistance. By measuring the angular velocity of the 'arms' of the calibration rig, and the 'reaction torque' created, mechanical power was calculated and compared to the direct ergometer output. The range of 50-350 W and SR of 54 to 118 spm are relatively low for elite athletes and the controlled bungee load of 1.5 kg would not allow the bungee to retract fully between strokes at high stroke rates. Underestimation of power output was found by all commercial systems: 22.5% for DanSprint, 27.6% for Weba and 4.5% for KayakPro. DanSprint ergometers have also been found to underestimate power by 21-23%, much which was removed when bungee cord tension was corrected for (Gore et al., 2013).

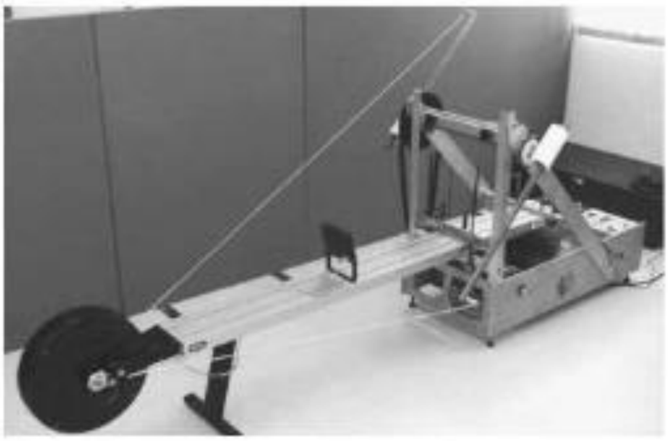


Figure 2.7: The South Australian Institute of Sport designed calibration rig, used here with a DanSprint ergometer (from Gore et al., 2013)

2.4.3 Paddle path

Adding to the complexity of force measurement on water is the importance of understanding the direction of force application relative to forward boat direction. Gomes et al. (Figure 2.8; 2011) found that 2D forces provided more information than the 1D strain gauge systems which have typically been used, which only investigate the force perpendicular to the blade surface. However, even with this additional information, forces are only known with respect to the blade surface, not with respect to the direction of boat movement and it cannot be known for certain that increases in force in a given direction are necessarily advantageous to forward boat speed. If the resultant force is directed outward from the boat, it is likely to result in a yaw motion of the boat hull, increasing frontal surface area and decreasing performance.

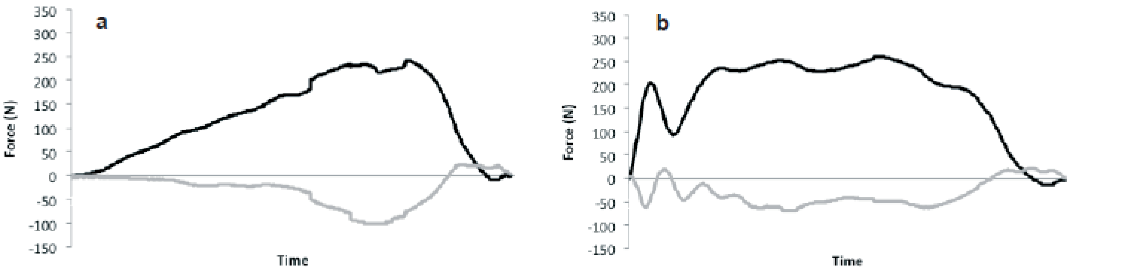


Figure 2.8: On-water kayak paddle force profile with two dimensions from Gomes et al. (2011). The grey line represents the force in the plane of the blade surface and the black line represents the plane at 90° to this. Starting stroke (a) and later stroke (b).

To accurately measure the direction of force application, a blade would need to be instrumented in 3D and its orientation in a global reference frame be clarified. Morgoch, Galipeau and Tullis (2016) instrumented a canoe blade using strain gauges and an IMU, allowing measurement of blade position in 3D. Unfortunately, only two blade angles were reported, with a range of blade rotation angle (around the shaft axis) of around 50° and range of pitch angle of around 120°. The canoe blade has a different design to a kayak blade, meaning the stroke path is not transferable but this research shows that the necessary technology has been used to determine blade orientation and calculate force direction relative to the boat.

The frame of reference is important to consider in kayak research. The movement of the paddle can be reported in 2D or 3D and either within a global co-ordinate system (GCS), an external reference frame (ERF; measured relative to a specific point) or an internal reference frame (IFR; relative to the paddler/kayak). Kendal and Sanders (1992) re-created the paddle path of an elite kayaker in the GCS (Figure 2.9), showing a much reduced forward-backward movement when compared to the IRF (x axis, Figure 2.9a), which additionally masks the large proportion of movement to occur laterally to the boat.

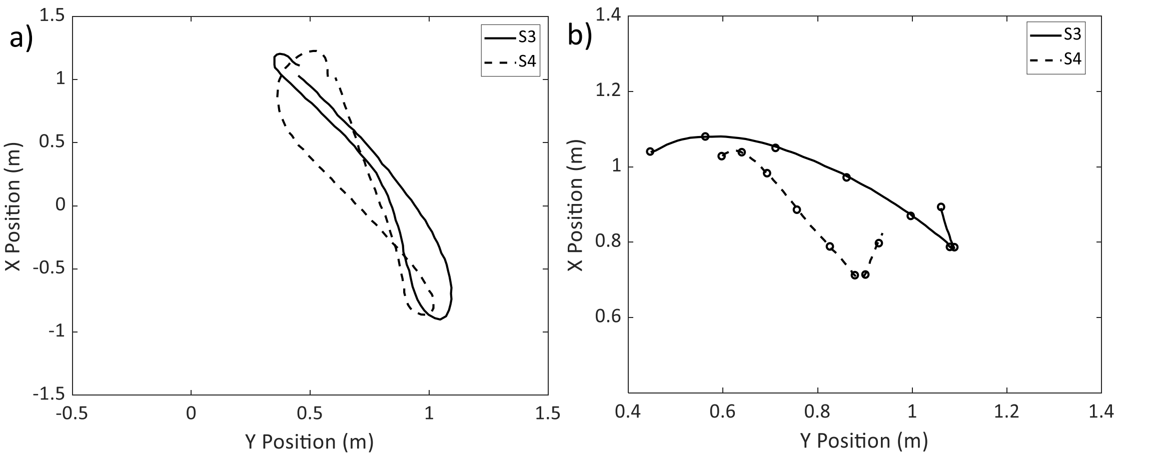


Figure 2.9: Kendal & Sanders (1992) measured paddle path of the best (S4) and worst (S3) of the elite paddlers in their cohort in the a) internal reference frame and b) global coordinate system. 'X Position' on y axis represents the direction of kayak movement; 'Y Position' on the x axis is lateral movement relative to the kayak.

The lateral component of motion supports the idea of those who have attributed the value of the wing paddle to utilising lift forces along with drag to optimise force (Jackson et al., 1992), although without the orientation of the blade surface or force vectors, the contribution of lift cannot be quantified. Kendal and Sanders (1992) used co-ordinates from two cameras filming the sagittal and frontal planes but as footage was only of one stroke, the generalisability of these results to kayaking performance is limited. Therrien et al. (2012) used an ergometer with a sliding complex so that the athlete moved relative to the blade in a more similar way to on-water. Paddle path was reported relative to the IRF and to a GCS and the authors found similar results to Kendal and Sanders, with a large quantity of lateral movement of the blade which is not obvious until viewed in the GCS. This design of ergometer is different to most commercially available machines (Table 2.5) and lateral movement quantification could not be found within the research using standard ergometers. No other papers could be found that have documented the paddle blade path during sprint kayaking.

The direction of the lift force in kayaking is slightly ambiguous within the literature; described as perpendicular to the drag forces that act parallel to blade movement (Lopez Lopez & Ribas Serna, 2011), it is not clear in which of the other two planes it is considered to act. In horizontal aeroplane flight lift forces act vertically, while in rowing, lift forces have been described to act laterally (Baudouin & Hawkins, 2002; Pulman, 2004), with similar descriptions used in kayaking (Jackson et al., 1992; Figure 2.4). A typical rowing blade curves from the connection with the shaft to the tip, but not from top to bottom when viewed end on and moves through an arc. Through the angles of the arc taken, absolute and relative contribution from lift and drag vary (Caplan & Gardner, 2007; Sliasas & Tullis, 2010, Figure 2.10).

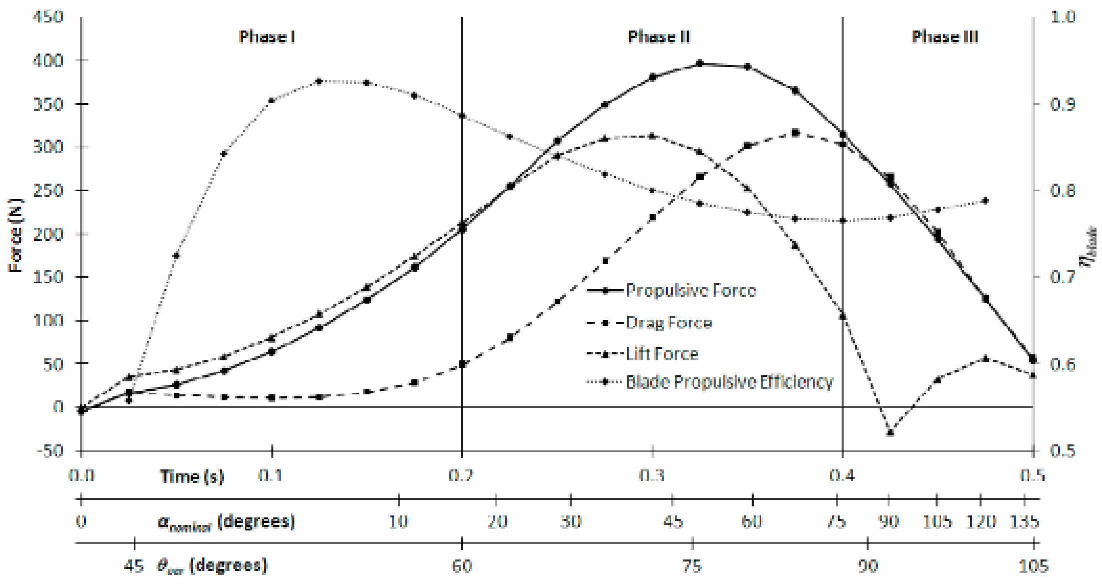


Figure 2.10: blade forces and efficiency across a rowing stroke, with multiple x axis showing changing angle of attack and oar angle through time (Sliasas & Tullis, 2010)

The concave shape of a kayak blade (e.g. Figure 2.11) could be considered to make use of these 'lift' forces in multiple directions by having an aerofoil shape in both the vertical and horizontal cross sections, but no published research could be found in which three dimensional forces on the paddle have been investigated.

Figure 2.11: Jantex Gamma Rio blade is concave in shape (Jantex, www.jantex.sk)

Both the land and water studies above highlight the importance of force and power to sprint kayaking with strong correlations across measurement systems used. However, the complexity of accurate power calculations on water involving 3D motion capture and instrumented paddle shaft makes it unrealistic for practitioners to measure these metrics within normal training, while the consistent offset from commercial ergometer systems makes the underestimation of power misleading. An easy to use, accurate, sport-specific force and power measurement system would add value to an elite programme and additional insight for researchers.

2.5 Paddle set-up

There are no set rules for the paddle size or weight, with the International Canoe Federation (ICF) rule book (ICF, 2019; page 43) stating: *"*kayaks shall be propelled solely by means of double-bladed paddles… paddles may not be fixed on the boats in any way." Despite this flexibility, there is relatively little variability in paddle set-up at elite level (Ong et al., 2005). The ICF level 1 coaching manual states a general recommendation that "total paddle length should be determined by the athlete standing and reaching an arm up and curling their fingertips over the upper blade" (ICF, 2011; page 14), indicating that anthropometrics of standing height and arm reach could describe paddle length in totality, but Ong et al. (2005) found anthropometric measures of height, biacromial breadth, chest girth, arm length and arm span to account for only 20-25% of the variability in paddle length of international level kayakers (31 male, 11 female).

High importance has been attributed to oar length in rowing (Nolte, 2009) and crank length in cycling (Barratt, Korff, Elmer, & Martin, 2011), but no studies could be found that have directly investigated the effect of changing paddle length on kayak performance. Diafas et al. (2011) used a principal component analysis (PCA) to group anthropometrics based on 71 national and international level sprint kayak athletes and input the subsequent components into a regression equation. Two factors from the PCA were included in the resultant regression equation: one made up of height, arm span, arm and leg length and the other of body mass index (BMI), body mass and lean body mass. Despite reporting the variance inflation factor showed no multicollinearity, the equation for BMI ($\frac{mass}{height^2}$) in one factor is innately reliant on height, which features in the other factor, so there is an innate reliance between factors. The authors did not group athletes according to performance level to compare regression equations and therefore using the resultant equation would produce a paddle set-up in line with that of the whole group athletes tested, rather than with better performance.

Regarding blade size, Sprigings et al. (2006) used ergometry to measure power output of elite sprint kayakers and used the force and velocity at which peak power occurred to recommend a blade size based on an equation rearranged from the equation for drag (Equation 1, page 27). As this paper used an ergometer and considered only drag force and movement of the paddle in the sagittal plane, its application is limited. Of the 12 elite athletes tested, five were considered to be using the correct size of blade, while seven were advised to increase blade size by 5-10%. No subsequent performance tests were conducted so it is not clear if these recommended changes resulted in performance improvements.

Only one research paper could be found that has investigated blade shape: Sumner et al. (2003) measured drag and 'side' (lift) forces in a wind tunnel of a flat plate, conventional, Norwegian and Turbo blades, the latter two described as 'asymmetrical and spoon-shaped' with surface areas of 0.074 and 0.078 m^2 respectively. Rotating the paddle around the shaft up to 20° in either direction, the Norwegian paddle was found to have consistently higher drag coefficient, thought to be due to the 'greater depth of curvature', although no differences were found in lift force. The curvature was also considered to be the cause for considerably higher drag forces when the paddle was moved through pitch angles. These interesting conclusions must be taken with some caution as the wind tunnel testing used steady flow conditions, which do not well reflect the flow around a paddle during a kayak stroke and may be why the study found less difference than might be expected between blade designs. Sanders and Baker (1998) postulated the theoretical advantages of the wing blade from their applied work with elite athletes and National Governing Bodies (NGBs) and discussed a number of possibilities, none of which seem to link directly to the increase in drag force found by Sumner et al. (2003). Sanders and Baker's (1998) ideas included increased efficiency (through less water movement, better use of the human system and curved motion at entry and exit), an increase in time during pull and at paddle vertical, and creation of a larger vortex area. While some of these theories were backed up by research, much of the references were to their own work in unpublished reports to canoeing NGBs so cannot be corroborated.

The paucity of research in the area of paddle set-up highlights a large potential for improvements in both athlete performance and academic understanding. The research which has been conducted is limited or makes recommendations based on assumptions which are unlikely to hold true. The complexity of on-water data collection, as already discussed, makes accurate measurement difficult and therefore an understanding of how paddle set-up affects force and power generation off-water would be valuable. In addition, as highlighted by Sanders and Baker (1998), there may be insight from NGBs which is not present in the literature.

2.6 Boat movement

2.6.1 Athlete-boat connection

A sprint kayak athlete is connected to the boat via only the seat and footrest. Through these connections, external forces such as those generated at the blade, are transferred to boat movement. Pushing and pulling forces occur at the feet during a stroke, via the footplate and the pull bar respectively (Figure 2.12a). To improve force transfer, some athletes also choose to use heel bars (Figure 2.12 c and d).

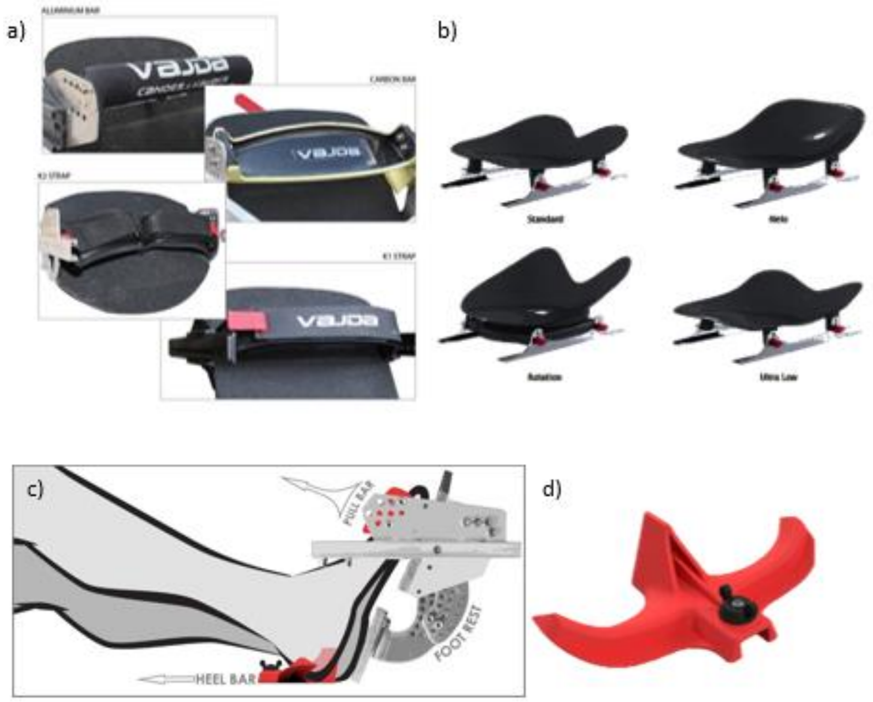


Figure 2.12: examples of the commercially-available attachments between the athlete and the boat via: a) footplate and pull bar (Australian Paddle Sports, www.australianpaddlesports.com.au), b) seat (Nelo Australia, www.neloaustralia.com.au) and c & d) heel bar designed by Olympic Champion Liam Heath.

Tornberg et al. (2019) recently investigated the force output at the seat, footrest and paddle across three athletes of different ability levels, concluding that power and force at the paddle were similar across athletes, while footrest forces displayed large differences (Figure 2.13). Footrest pushing force demonstrated the largest differences between junior and international senior, while the largest difference between international senior and national level senior was in pulling forces, highlighting the importance of both directional forces.

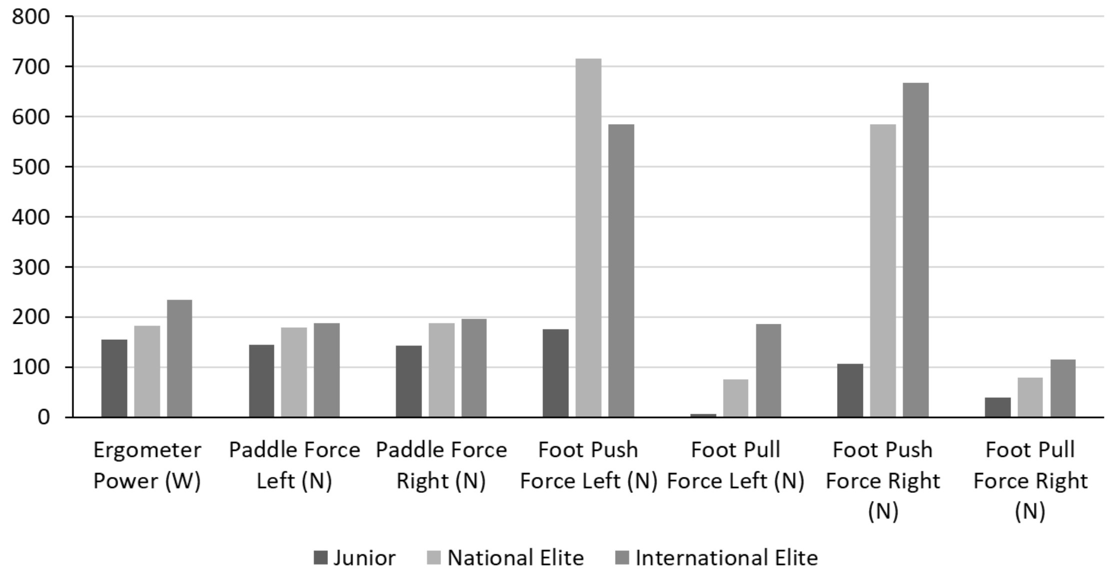


Figure 2.13: force and power measurements from kayakers of different levels of performance measured on an instrumented ergometer (Tornberg et al., 2019).

Begon et al. (2009) also measured foot forces on an ergometer and found similar values and a considerable amount of inter-individual variability in force production (n = 10; footrest forces = 322-815 N). Tornberg et al. (2019) considered the timing of the application of force at the footrest to be of importance, an idea supported by Jahn et al. (2016) who found footrest force to begin slightly earlier than paddle force when testing elite athletes on an ergometer. An on-water force measurement system found that restricting leg movements (ascertained with a goniometer across the knee joint) dramatically reduced footplate force and resulted in a decrease in both paddle force and kayak velocity (Nilsson & Rosdahl, 2016), in agreement with Brown et al. (2010) who detailed the importance of the lower limbs to kayak performance.

Swivel seats have been investigated with the idea that they may enhance the athlete's connection with the boat for better power transfer, reduce the energetic cost of paddling or increase hip and trunk rotation. Physiologically, Michael et al. (2010) found use of the swivel seat resulted in an increased power output (swivel: 299.1 ± 24.9 W; fixed: 279.8 ± 19.2 W). Swivel seats were also found to result in higher trunk muscle activation, higher paddle displacement and an increase in knee range of motion (López-Plaza Palomo, 2013). Investigating the paddle and foot forces, Lok et al. (2016) found the swivel seat to increase paddle force, foot force and SR in a sub-elite athlete and to increase foot force in an elite athlete. Despite these positive research findings, the swivel seat has not been adopted by elite paddlers. This may be due to differences in kinematics necessitating re-learning the skill and therefore likely an initial decrement to performance, or through an increase in non-advantageous boat movement increasing drag and therefore negate the potential benefits.

2.6.2 Hydrodynamics of the boat

Kayak design, including maximum length and minimum mass, is restricted by the ICF regulations (ICF, 2019; page 24). Total drag on the kayak hull is made up of drag arising from three components (Gomes et al., 2015; Pendergast et al., 2005): friction between the hull and the water (friction drag; $Drag_{Fr}$), pressure drag as the water separates to allow the kayak hull through (pressure drag; $Drag_{Pr}$) and the drag created by waves resulting from accelerating water away from the hull (wave drag; $Drag_{W}$).

$$Total\ drag = drag_{Fr} + drag_{Pr} + drag_{W} \qquad \text{(Equation 2)}$$

Gomes et al. (2015) investigated the contribution of each of these forms of drag relative to velocity and mass by towing an athlete in a kayak using a specially-designed system. Friction drag was found to be the highest contributor, making up 59-67% of the total drag dependant on weight and velocity (Figure 2.14). Pressure drag accounted for 21-25% and wave drag for 9-19%. Increasing the mass of the system by adding weight increased both the wetted surface area and the frontal submerged area, having a larger increase at higher speeds. This mass-related effect of speed was highest for wave drag (Figure 2.14b). The towing system used constant velocity and therefore the effect of velocity fluctuations within strokes is not clear.

Drag factors can be minimised by reducing additional boat movement in directions other than forward motion. Additional movement will increase the wetted surface area and therefore increase drag, an effect also found in rowing (Hill & Fahrig, 2009). Ong et al. (2006) recorded boat movement and reported 'minimal' movement within their three participants of 0.5° yaw, 1.7° pitch and 1.3° roll when paddling on-water. Full results on boat movement are not presented and additional boat movement was not linked to performance, but two athletes were noted as having higher roll movement, once again indicating the importance of inter-individual variability. The accuracy of these data, based on calibrated, manually-digitised footage at 50 Hz, needs assessing.

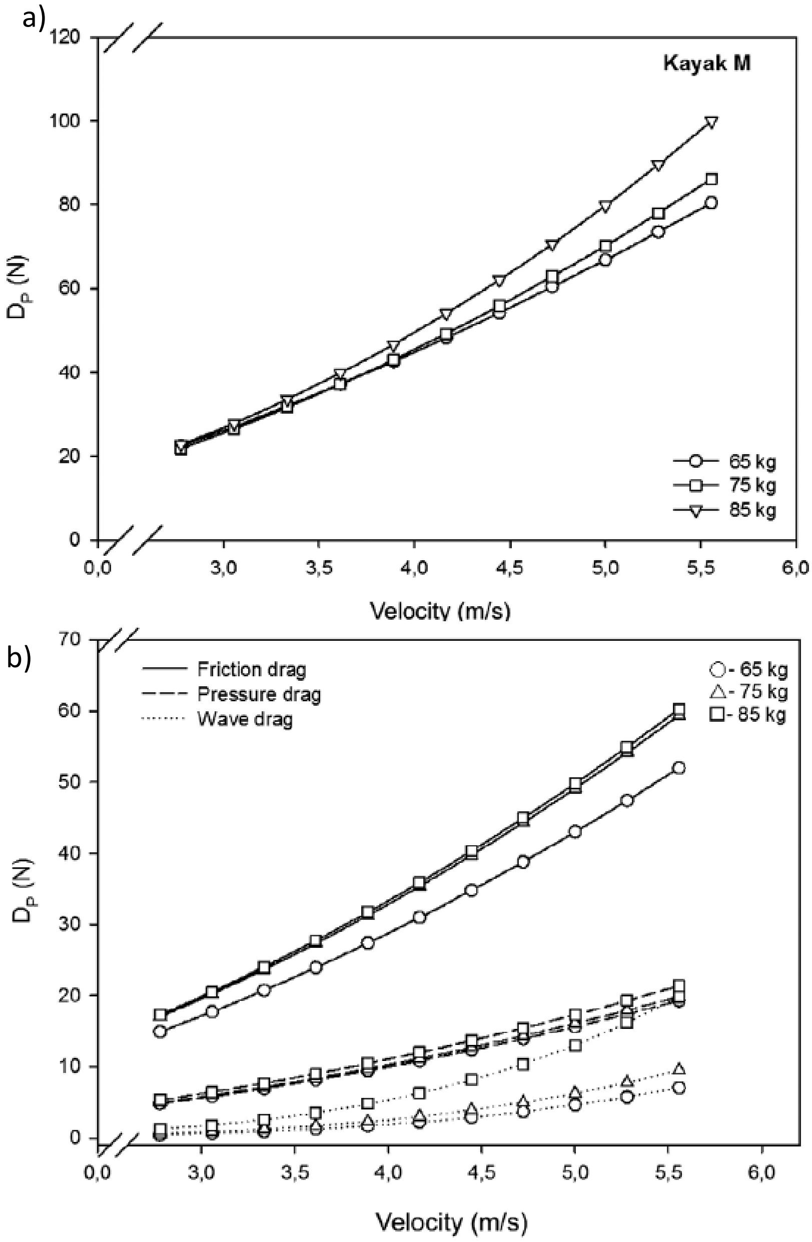


Figure 2.14: a) total drag force on sprint kayaks of different mass being towed across a range of velocities with b) contribution from components of drag (Gomes et al. 2015).

A Minimax B4 unit containing GPS and IMU (Catapult, Australia) placed on the centre of the back deck along with an instrumented paddle were used to find that lower times (and therefore better performance) were correlated positively with paddle torque (r^2 = 0.76) and forward boat acceleration (r^2 = 0.64), as well as negatively with boat pitch (r^2 = -0.56) and boat roll (r^2 = -0.51) across the eight national-level and club paddlers tested (Fisher, Karpul, Tam, Tucker, & Noakes, 2013). Those who produced high boat acceleration also produced more boat roll and pitch, but it would be logical to assume the acceleration to be the aim and the roll/pitch as an undesired outcome.

2.6.3 Environment

The environmental conditions during kayak races are not controllable but can have a large effect on boat velocity via the determinants of drag (Figure 2.15). From wind tunnel and on-water experiments focusing on aero-dynamics, Barber (2018) showed that a kayaker's coefficient of aerodynamic drag is mainly described by relative air velocity, with turbulence having little effect. A theoretical 10% reduction in the coefficient of air drag was found to result in a decrease in finish time of a men's K1 200 m of 0.1 s, while headwinds of 2 to 10 $m \cdot s^{-1}$ increased finish time by 0.8 to 8 s.

Although there are models which have been created to allow coaches to compare race times hypothetically free of environment influence, no published studies or validations could be found. Guilbaud and Durand (2006) described a model using wind tunnel data in a short abstract, and British Canoeing and the German Canoe Federation are both known to monitor environmental conditions at races, including wind speed and water temperature, and to have methods of longitudinal comparison. The British Canoeing model is based on the mechanical equation for drag (Equation 1) to measure both aero- and hydro-dynamics and compare the measured environmental conditions to datum with no wind and standardised water conditions (still and warm). These models over-simplify conditions, applying average conditions over the time period and not taking into account any fetch (the distance wind travels over open water) or lane effect or any fluctuations in boat velocity. Despite these limitations, quantifying even some of the effect of environmental conditions will allow for an improvement in comparison between trials or dates.

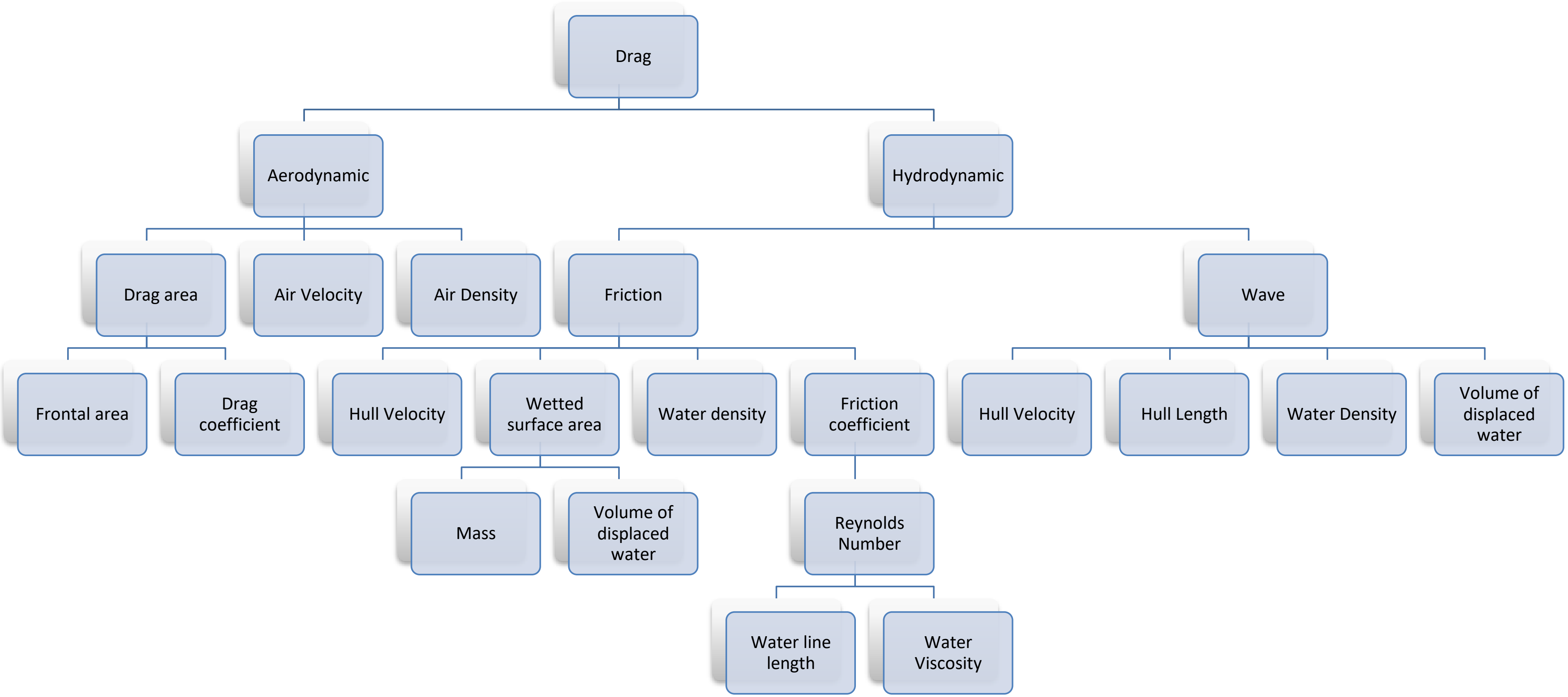


Figure 2.15: Schematic breakdown of causes of drag force experienced by a sprint kayak, based on Jackson et al. (1992)

The ICF canoe sprint level 2 and 3 coaching manual (ICF, 2014; page 32) cites that hydrodynamic drag makes up 93% of the total drag experienced by a kayak athlete. Although no reference was listed, this figure could be taken from Jackson (1995) who reported values from towing tank experiments by Toro (1986), that listed aerodynamic drag to account for 5.6 N of 80.6 N of total drag, equivalent to 7%, when there is no wind. Measurement of aerodynamic drag uses the same equations as hydrodynamic drag (Equation 1), with different values arising from air density, drag coefficient and frontal surface area- which would relate to the area of the athlete and the portion of the boat above the water line. From Equation 2 and Figure 2.15, the effect of environmental conditions such as water and air temperature (through changes in viscosity and density), wave size and wind speed will influence drag. While the effect of boat velocity can be estimated using models, it is not possible to use the same calculations for the influence on SR. Models also do not specify how an individual reacts to these conditions, for example a less stable athlete may struggle more in choppy water, which cannot be quantified easily.

As with paddle movement, the causes and consequences of boat movement are more complex than might first be thought and an athlete's technique is not limited to how they move the paddle. The effects of the weather have been shown to be large and so it is important to account for these in measurements of performance, something which is not often done in sprint kayak research.

2.7 Athlete variability

Traditionally, variability in movement within (intra-individual) or between (inter-individual) athletes has been seen as a negative, with the underlying idea that sporting performance conforms to a specific ideal movement and anything outside of this is 'noise' of the system and is to be avoided (Schmidt, 1975). Bernstein (1967) originally outlined the "degrees of freedom problem" whereby the human system has multiple options to perform a movement.

Over the last two decades, a significant amount of research has been conducted looking at how and why athletes vary in performance. Reviewing the literature available in golf, Glazier and Lamb (2018) found that while in the coaching literature a single optimal technical model of performance is often recommended, studies have shown high levels of inter- and intra-athlete variability at all levels of performance, although there is some disagreement in the literature reviewed. Co-ordination variability in triple jumping has been found to be low in intermediate level athletes and higher for most and least skilled, thought to indicate high variability during the early stages of learning followed by a reduction in variability and finally a flexibility to adapt to perturbation as skill level increases (Wilson, Simpson, Van Emmerik, & Hamill, 2008). As there were only five participants in this study, all of whom were classed as 'elite', the authors postulated that the lower skill level athlete could still be considered in the early phase of learning due to the complexity of the task. MacPherson, Collins and Morriss (2008) demonstrated that when mental effort is focussed on one aspect of skill, biomechanical variability in that element is decreased, while variability in other areas is increased, highlighting the role of focus of attention in movement variability and a potential mechanism for differences seen between performance levels, or individuals. This interaction between focus and technical performance has been postulated to be a useful tool for coaches to develop skill (Carson, Collins and Richards, 2014). Even in relatively 'simple' skills, such as a back squat, significant quantities of inter- and intra-athlete variability have been reported (Kristiansen, Rasmussen, Sloth & Voigt, 2019). By comparing the whole trace of a lifting movement through statistical parameter mapping, rather than key metrics, additional differences could be identified. Kristiansen et al. (2019) concluded that successful back-squat performance can be achieved with variable lifting strategies.

Bartlett and colleagues (2007) published an overview of variability in sport biomechanics, focusing on data from javelin and discus throwing and basketball shooting. From computer simulation modelling and experimental research of performers across levels, including elite performance, they surmised that "outcome consistency does not require movement consistency" (p. 229) and emphasised the value of between-individual studies alongside group level research: "it makes no sense to try to copy specific details of a successful athlete's technique" (p. 240).

Glazier and Mehdizah (2019) wrote that the identification of athlete-specific optimum technique is the 'holy-grail' of sports biomechanics research but is unlikely to be achieved in the near future as attention needs to be paid to the likelihood of the athlete achieving this change in technique and measuring the complex combination of intrinsic and extrinsic dynamics needed to create a mathematical model is not currently viable.

2.7.1 Single subject research

The ideas of inter- and intra-individual variability are directly linked with those which underpin single-subject design research. Parametric inferential statistical methodologies were developed around the finding that data follow a normal distribution around an average, with group approaches' removal of individual variability and noise through averaging considered advantageous (Bates, 1996). However, there is now a body of evidence indicating that group level conclusions are not representative of any of the participants' data and therefore mask individual differences (Bates, 1996; Chapman, Stray-Gundersen, & Levine, 1998; Dufek, Bates, Stergiou, & James, 1995). Inter- and intra-athlete variability will also affect reliability and statistical significance of output in group level research, as highlighted by Mullineaux, Bartlett and Bennett (2001). Bates, Dufek and Davis (1992) ran simulation studies and found significance was considerably harder to attain from single subject research compared to group level. Single subject design has been advocated for elite sports research due to the small participant numbers and a level of flexibility which allows easier integration into coaching practice (Kinugasa, Cerin, & Hooper, 2004; Kinugasa & Taisuke, 2013).

2.7.2 Kayak variability

Therrien et al. (2012) investigated how changes in stroke rate influence paddle tip path in ergometer kayaking. Intra-participant paddle tip path was consistent at increasing stroke rates as quantified using multiple correlation coefficients, but visual assessment of the paddle paths shows considerable differences between participants. The differences between athletes were not quantified so cannot be objectively assessed but are visually clear. The main limitation with this study is the use of an ergometer for detailed kinematic analysis which places more constraints on the paddle stroke path as the paddle is connected via rope and bungee to the front of the machine; this limitation might be expected to reduce inter-athlete variability and so the individual differences found are of greater significance. Ergometer use takes out the above-mentioned changes in environmental conditions, which would be likely to affect stroke-to-stroke variability as well as larger differences likely in different places or on different days. This is similar to other sports, for example in running, where variability on a treadmill is lower than over ground running (Wheat, Milner, & Bartlett, 2004). While the environmental constraints reduce the value of a kayak ergometer for analysis of variability in detailed kinematics, it does not diminish its value for measurement of power or force variables.

Wainwright, Cooke and Lowe (2015) applied Wainwright's (2014) deterministic model to a group of international standard kayakers and looked at individual regression analyses based on data collected on-water. They found inter-athlete variation to be high, stating that "each athlete used an individual style to create velocity" (p. 4), although this was not quantified. In agreement with this, Sanders and Baker (1998) discuss data from an unpublished report of elite kayak athletes, stating that the paddlers "varied considerably in their techniques" (p. 72) including paddle path and blade orientation, although again no supporting data was provided.

Many kayak studies have not directly measured inter-individual variation but have reported it within their results for many factors: Mann (1978) found segmental velocities and accelerations varied between participants, stating these differences were due to the way the paddle is held; Michael et al. (2012) found individualised results within paddle force measurement; Begon et al. (2009) reported large differences in foot forces and Ong et al. (2006) reported differences in boat movement.

2.7.3 Competition variability

As kayak velocity is the product of distance per stroke (DPS) and stroke rate, individual athletes may have different strategies for maximising velocity. In athletics, sprinters have been classified as being either stride rate or stride length dominant, with this dominance considered to vary between athletes (Salo et al., 2011). The relationship between stride length and stride rate throughout a 100 m sprint is well documented in sprinting, with the early steps shorter in length and longer in duration to ensure the best orientation of highest possible impulse (Debaere et al., 2013). However, in kayaking, little is known about phase differences in stroke characteristics and in many analyses the initial acceleration is not analysed. McDonnell et al. (2013b) investigated the stroke rate (SR) pattern and place time consistency of international 200 m races between 2006 and 2011. Using times from 17 international events, they found the time needed to win the 200 m at World Championship events was consistent, with a range of only 0.7%. Analysis of SR was limited to seven male and five female medallists due to video quality and stroke visibility, but the race winners did not always have the highest SR. Stroke rate profiles were discussed but not shown, and were described as decreasing throughout the race, although the initial five seconds of acceleration are not included. The authors noted this decrease appears to be becoming smaller from 2006 to 2011. Figure 2.16 demonstrates the combinations, and large variability of SR and DPS, that can be used to achieve the required medal-winning velocities as taken from McDonnell et al. (2013b). The use of only an average to calculate recommended SR ranges, despite documented evidence of changes in SR pattern, limits the applicability of these figures.

Displacement pre stroke (m)

Stroke Rate (spm)	1.78	1.82	1.86	1.90	1.94	1.98	2.02	2.06	2.10	2.14	2.18	2.22	2.26	2.30	2.34	2.38	2.42	2.46	2.50	2.54	2.58	2.62	2.66	2.70
108	3.20	3.28	3.35	3.42	3.49	3.56	3.64	3.71	3.78	3.85	3.92	4.00	4.07	4.14	4.21	4.28	4.36	4.43	4.50	4.57	4.64	4.72	4.79	4.86
112	3.32	3.40	3.47	3.55	3.62	3.70	3.77	3.85	3.92	3.99	4.07	4.14	4.22	4.29	4.37	4.44	4.52	4.59	4.67	4.74	4.82	4.89	4.97	5.04
116	3.44	3.52	3.60	3.67	3.75	3.83	3.91	3.98	4.06	4.14	4.21	4.29	4.37	4.45	4.52	4.60	4.68	4.76	4.83	4.91	4.99	5.07	5.14	5.22
120	3.56	3.64	3.72	3.80	3.88	3.96	4.04	4.12	4.20	4.28	4.36	4.44	4.52	4.60	4.68	4.76	4.84	4.92	5.00	5.08	5.16	5.24	5.32	5.40
124	3.68	3.76	3.84	3.93	4.01	4.09	4.17	4.26	4.34	4.42	4.51	4.59	4.67	4.75	4.84	4.92	5.00	5.08	5.17	5.25	5.33	5.41	5.50	5.58
128	3.80	3.88	3.97	4.05	4.14	4.22	4.31	4.39	4.48	4.57	4.65	4.74	4.82	4.91	4.99	5.08	5.16	5.25	5.33	5.42	5.50	5.59	5.67	5.76
132	3.92	4.00	4.09	4.18	4.27	4.36	4.44	4.53	4.62	4.71	4.80	4.88	4.97	5.06	5.15	5.24	5.32	5.41	5.50	5.59	5.68	5.76	5.85	5.94
136	4.03	4.13	4.22	4.31	4.40	4.49	4.58	4.67	4.76	4.85	4.94	5.03	5.12	5.21	5.30	5.39	5.49	5.58	5.67	5.76	5.85	5.94	6.03	6.12
140	4.15	4.25	4.34	4.43	4.53	4.62	4.71	4.81	4.90	4.99	5.09	5.18	5.27	5.37	5.46	5.55	5.65	5.74	5.83	5.93	6.02	6.11	6.21	6.30
144	4.27	4.37	4.46	4.56	4.66	4.75	4.85	4.94	5.04	5.14	5.23	5.33	5.42	5.52	5.62	5.71	5.81	5.90	6.00	6.10	6.19	6.29	6.38	6.48
148	4.39	4.49	4.59	4.69	4.79	4.88	4.98	5.08	5.18	5.28	5.38	5.48	5.57	5.67	5.77	5.87	5.97	6.07	6.17	6.27	6.36	6.46	6.56	6.66
152	4.51	4.61	4.71	4.81	4.91	5.02	5.12	5.22	5.32	5.42	5.52	5.62	5.73	5.83	5.93	6.03	6.13	6.23	6.33	6.43	6.54	6.64	6.74	6.84
156	4.63	4.73	4.84	4.94	5.04	5.15	5.25	5.36	5.46	5.56	5.67	5.77	5.88	5.98	6.08	6.19	6.29	6.40	6.50	6.60	6.71	6.81	6.92	7.02
160	4.75	4.85	4.96	5.07	5.17	5.28	5.39	5.49	5.60	5.71	5.81	5.92	6.03	6.13	6.24	6.35	6.45	6.56	6.67	6.77	6.88	6.99	7.09	7.20
164	4.87	4.97	5.08	5.19	5.30	5.41	5.52	5.63	5.74	5.85	5.96	6.07	6.18	6.29	6.40	6.51	6.61	6.72	6.83	6.94	7.05	7.16	7.27	7.38
168	4.98	5.10	5.21	5.32	5.43	5.54	5.66	5.77	5.88	5.99	6.10	6.22	6.33	6.44	6.55	6.66	6.78	6.89	7.00	7.11	7.22	7.34	7.45	7.56
172	5.10	5.22	5.33	5.45	5.56	5.68	5.79	5.91	6.02	6.13	6.25	6.36	6.48	6.59	6.71	6.82	6.94	7.05	7.17	7.28	7.40	7.51	7.63	7.74
176	5.22	5.34	5.46	5.57	5.69	5.81	5.93	6.04	6.16	6.28	6.39	6.51	6.63	6.75	6.86	6.98	7.10	7.22	7.33	7.45	7.57	7.69	7.80	7.92
180	5.34	5.46	5.58	5.70	5.82	5.94	6.06	6.18	6.30	6.42	6.54	6.66	6.78	6.90	7.02	7.14	7.26	7.38	7.50	7.62	7.74	7.86	7.98	8.10

Figure 2.16: stroke rate – distance per stroke matrix with resultant velocity in $m \cdot s^{-1}$ calculated as (SR/60) x DPS. Shaded boxes are velocities of international female (light grey) and male (darker grey) medallists, taken from McDonnell et al. (2013). Outlined boxes are the SR range recommended by McDonnell et al. (2013).

2.7.4 Applied measurement

Understanding when differences between athletes or between groups is of practical significance is of huge importance to the application and impact of research in sport science. Traditional testing between groups of data has involved hypothesis testing. By testing the 'null hypothesis' that there are no differences between groups, hypothesis testing produces a p-value, which indicates the likelihood that a difference would be found if the null hypothesis were true. A significance level, or alpha value, is commonly set at 0.05, indicating a 5% chance of falsely rejecting the null hypothesis. These statistics have been commonly, and increasingly, used in sports biomechanics research (Vagenas, Palaiothodorou, & Knudson, 2018). However, this form of significance testing has resulted in over-reliance on 'significant' results which may be, in a practical sense, meaningless (Knudson, 2009). In order to understand whether difference between groups or individuals have useful meaning, effect size calculations have been recommended (Fritz, Morris, & Richler, 2012; Knudson, 2009; Mullineaux et al., 2001; Vagenas et al., 2018). Cohen's d (Cohen, 1988) is one of the most commonly used measures of effect size (Fritz et al., 2012; Vagenas et al., 2018), and provides a measure of the difference between means, in units of standard deviations of the population, with values of 0.2 considered a small effect, 0.5 a medium effect and above 0.8 a large effect. Use of effect size has increased following a quadratic function since the 1990s (Vagenas et al., 2018). Use of effect sizes also provides easier understanding of outcomes for those who have little or no experience with statistics.

Despite the importance attributed to single subject research and the frequent reporting of variability within or between athletes (e.g. Bates et al., 1996; Kinugasa et al 2004; Kinugasa & Taisuke, 2013), few researchers have clearly quantified inter- or intra-athlete variability. Standard deviations and ranges have been reported in biomechanics research, but this has primarily been for statistical power purposes rather than as a feature of for investigation (Glazier & Lamb, 2018). Quantification of variability has made use of standard statistics such as coefficient of variation (Legg et al., 2017), Pearson correlations and ANOVAs (Kristiansen et al., 2019). This indicates it may be the reporting and emphasis, more than the analysis methods, which need adapting to create impactful research for elite populations.

It is clear that inter- and intra-individual differences in sport performance exist in many sports, including in sprint kayaking. It is therefore highly important when conducting research, and particularly in research with an applied aim, that individual responses are measured and considered alongside group level conclusions as otherwise highly valuable information may be lost. The optimum way for analysing individual data is not immediately clear but for practical inferences, effect sizes have clear value.

2.8 Physiological/Mechanical determinants

It might be expected that some of the variability between athletes stems from their physiological and mechanical capabilities. The following section provides an outline of some of the key physiological and mechanical factors relating to sprint kayaking.

As kayakers compete over different distances and over different time frames (Table 2.1), there are different contributions of energy systems to performance (Zouhal et al., 2012). Van Someren and Howatson (2008) investigated the influence of various anthropometric and physiological aspects on performance in each of the distances raced. By correlating performance time for each event (during racing) with these aspects, they highlighted the similarities and differences between events (Table 2.6). Measurements of power and work were conducted on an ergometer within three weeks of race performance.

Table 2.6: Statistically significant correlations between race time and ergometer measured physiological measures in the three race distances from van Someren & Howatson (2008).

Distance	Significant physiological correlates	R values
200 m	- Peak power	-0.68
	- Work done in 30 s	-0.74
	- Fatigue index in 30 s	-0.54
	- Peak isometric function	-0.47
	- Peak isokinetic function	-0.57
500 m	- Peak power	-0.84
	- Work done in 30 s	-0.87
	- Fatigue index in 30 s	-0.52
	- Work done in 2 minutes	-0.74
	- Peak isometric function	-0.60
	- Peak isokinetic function	-0.66
1000 m	- Peak power	-0.65
	- Power output at lactic turn point	-0.51
	- Work done in 30 s	-0.74
	- Work done in 2 minutes	-0.83

Fry and Morton (1991) previously undertook a similar study looking at the performance of 38 male kayakers over 500, 1000, 10,000 and 42,000 m and created multiple regression equations for the variables tested with each race distance. The first five inputs into the regression equation for the 500 m event were: maximum ventilation, $\dot{V}O_{2max}$ ($l{\cdot}min^{-1}$), work done in 60 seconds, force generated during $120s°{\cdot}s^{-1}$ movement on a dynamometer (described as simulating a kayak stroke, with no further detail) and forced vital capacity. For 1000 m, the first five variables were: time to exhaustion, $\dot{V}O_{2max}$ ($l{\cdot}min^{-1}$), $\dot{V}O_{2max}$ ($ml{\cdot}kg^{-1}{\cdot}min^{-1}$), force generated during $30s°{\cdot}s^{-1}$ movement on a dynamometer and chest girth. These equations were found to result in r^2 values of 0.83 and 0.92 respectively. No mention of testing of the assumptions of normality, linearity, homoscadacity or multi-collinearity means these results must be interpreted with caution.

Looking at the shorter distance of 200 m, which was only introduced into the Olympic programme in 2012, van Someren and Palmer (2003) found anthropometric and anaerobic characteristics to differentiate between performance levels, while no aerobic measures had significant differences. Multiple regression analysis resulted in only the total work during a 30 second all-out Wingate test predicting 200 m performance across all athletes. In opposition to this, well-trained junior athletes' 200 m performance has been found to correlate strongly with physiological variables, including $\dot{V}O_{2max}$ (Oliveira Borges, Dascombe, Bullock, & Coutts, 2015). These differences may be due to maturity status, or training focus; young athletes are unlikely to have specialised while the international group in van Someren's (2003) research had already competed internationally in 200 m racing and are therefore likely to have heavily focused on this during training.

2.8.1 Anthropometrics

Four papers could be found that have directly investigated the relationship between anthropometric factors and performance (Table 2.7). None of the parameters are significantly linked to performance by all authors, although the size of the upper arm is significant in all papers from different measurements: skeletal (humerus breadth) and muscular (bicep/upper arm girth). Height, sitting height and body mass, along with other variables, displayed contradictory findings between research papers. This may be due to differences in cohort or statistics employed: van Someren and Howatson (2008) used correlations across a group of club and international paddlers; Fry and Morton (1991) created an intercorrelation matrix and t-tests to compare between state and non-state team members, and Aitken and Jenkins (1998) directly compared ‘elite’ kayak athletes with recreationally active volunteers. Correlations are undoubtedly interesting but a large spread of data in one dimension (such as combining participants of different abilities or genders) can artificially inflate the strength of a correlation value due to the reliance of the commonly calculated ‘r’ statistic on mean and standard deviations (Altman, 1991).

Table 2.7: Summary of anthropometric parameters considered to relate to sprint kayaking performance from previous literature.

Paper	Distances	Participants	Anthropometric parameters	
			Linked with performance	**Not linked with performance**
Van Someren & Howatson (2008)	200 m 500 m 1000 m	18 males; 10 international, 8 club level	Chest circumference Humerus breadth (200 m and 500 m only)	Body mass Height Sitting height Arm span Body fat Lean body mass Arm circumference Femur breadth Morphology
Van Someren & Palmer (2003)	200 m	26 males; 13 international, 13 national level	Upper arm circumference Lower arm circumference Chest circumference Humerus breadth Mesomorphy	Body mass Height Sitting height Arm span Sum of skinfolds Body fat % Lean body mass Calf circumference Femur breadth
Fry & Morton (1991)	500 m 1000 m	38 males; 16 state team member, 22 non-state team members	Sitting height Body mass (1000 m only) Bicep girth Forearm girth Chest girth Biacromial width Sum of skinfolds	Height
Aitken & Jenkins (1998)	Unknown	25 males, 25 females; 20 elite, 30 recreationally active	Body mass Bicep girth Upper arm length Forearm length Thigh length Lower leg length Biacromial breadth	Height Sitting height Sum of skinfolds Arm span Bi-illiocristal breadth Thigh girth

Figure 2.17 (Ackland, Ong, Kerr, & Ridge, 2003) compares the size of athletes across various measurements with a 'Phantom Z-score' which provides a measurement of relative magnitude of variables compared to the population. Kayak athletes were found to differ from the general public via lean composition (i.e. skinfolds; Figure 2.17) and large upper body girths (i.e. arm and chest girths; Figure 2.17). Comparing young paddlers to Olympic-level kayak athletes found larger upper body girths of the latter (Alacid, Martínez, López-Miñarro, & Muyor, 2014), indicating the influence of maturity and training focus on the dimensions of high-level kayak athletes.

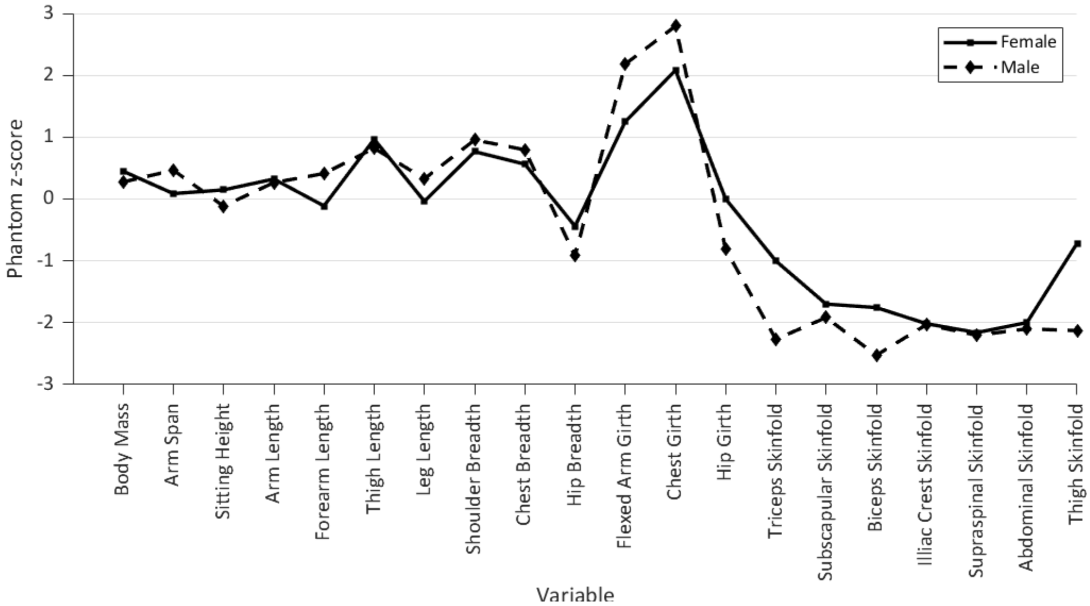


Figure 2.17: Anthropometric measures of male and female Olympic sprint kayakers relative to an average population via a phantom z-score, adapted from Ackland et al. (2003).

As well as the potential for understanding inter-athlete variability, the link between anthropometric factors and performance is important to determine when data need to be normalised to compare across a group. A standardisation of normalisation of physical performance tests has been proposed (Jaric, Mirkov, & Markovic, 2005) so that comparison across groups and sports can more readily be made. The authors proposed allometric scaling to body size (variable divided by mass$^{0.67}$) for measures of force and power; although this uses an assumption of geometric similarity, it would be beneficial when specific normalisation (i.e. limb length) is too logistical a challenge for data collection. Allometric scaling to the factor 0.67 is based on the idea that muscle force has been shown be proportional to muscle cross sectional area (CSA; Maughan, Watson, & Weir, 1984; Tavares et al., 2017) and CSA is proportional to volume to the power 0.67, therefore force can be considered proportional to mass to the power 0.67 (Mullineaux, Milner, Davis, & Hamill, 2006). Mullineaux et al. (2006) compared methods of normalising ground reaction force and concluded that ratio normalisation (force divided by bodyweight) removed the effect of mass from results more effectively than allometric scaling to the power 0.67. For ground reaction forces, where the acceleration of gravity will always apply vertically downwards on mass, this might be expected, with Newton's second law underpinning the theory. It is not clear if the same relationship is true when the force applied is in a different direction from that in which gravity acts on mass, such as in kayaking.

It is not known if anthropometrics affect technical factors such as SR, forward reach, lateral blade movement or any of the other technical factors highlighted in the 'athlete movement' section although in running, naturally-chosen stride length and stride frequency have not been found to relate to anthropometric measures (Cavanagh & Kram, 1989).

Anthropometrics could also be of value for equipment setup. Barrett and Manning (2004) stated that in rowing, setting up the rigging to match a rower's 'strength and size' is vital to maximising performance. In kayaking, anthropometric measurements have been found to correlate with paddle set-up (Diafas et al., 2012; Ong et al., 2006). Based on regression equations as opposed to mechanical theory, Ong et al. (2006) changed paddlers' set-up and investigated the effect on performance. Changing to the predicted set-up led to reductions in kayak velocity. As seat-foot bar distance and grip width were changed simultaneously, it is not possible to differentiate between cause. In addition, although based on other elite performers, the equation used had no basis in mechanical theory and therefore it is unclear what underpinned the negative change to performance and no practice time was given for the change in set-up.

2.8.2 Force-velocity

Anaerobic variables such as force and power have been shown to strongly correlate with performance of the shorter sprint kayak events (Mononen & Vitasalo, 1995; van Someren & Palmer, 2003). As power is the product of force and velocity, the relationship between these two factors is potentially highly important to sprint kayak performance.

The force-velocity relationship of isolated muscle was originally documented by Hill (1938) showing a hyperbolic decrease in force production at increasing velocities and is thought to be due to reduced time for formation of actin-myosin cross bridges, commonly known as the sliding filament theory (Huxley & Simmons, 1971). Martin (2007) reviewed the factors affecting muscular force in humans and summarised the relationships between them (Figure 2.18).

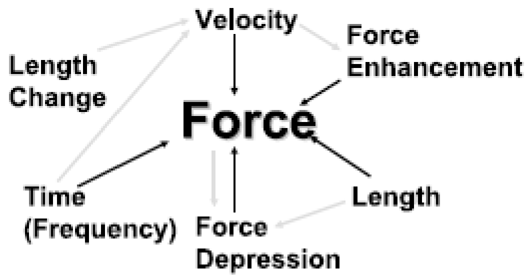


Figure 2.18: Schematic representing interplay between the factors affecting muscle force production in humans (Martin, 2007).

Highlighting these inter-relationships, Kawakami and Fukunaga (2006) looked at human muscle function and found peak knee extension torque to occur at increasing joint angles when operating at increasing joint velocities. This indicates the importance not only of the interaction between force-length and force-velocity relationships, but also the use of the muscle tendon unit (MTU), as the elastic component (the tendon) elongation also influenced torque.

Multi-joint human movement has consistently been found to exhibit a linear force-velocity profile (Jaric, 2015). This is thought to be due to segmental dynamics as modelling has shown the hyperbolic muscular force-velocity output is maintained but 'buffered' by the joint movement, resulting in a linear external force-velocity relationship (Bobbert, 2012), although it has also been attributed to activation dynamics of the muscle (Bobbert, Casius & van Soest, 2016), and to neural mechanisms (Yamauchi, Mishima, Fujiwara, Nakayama, & Ishii, 2007). In support of the segmental dynamics proposal, eccentric and concentric cycling at different cadences using a recumbent bicycle has been found to result in linear relationships for both contraction types, leading the authors to suggest that the linearity is caused by a technique-dependent factor rather than an intrinsic muscle property (Green et al., 2018).

Zivkovic et al. (2017) investigated the fit of a second-order polynomial in comparison with a linear model, across four different movement types (vertical jumps, cycling, press throw and bench pull) and found correlation coefficients of all profiles of above 0.98 with linear relationships never outside the 95% confidence intervals of the polynomial correlation values. Visual assessment of the graphs provided also confirms a linear relationship. In a similar study isolating the knee joint, Iglesias-Soler et al. (2019) found the F-V profiles of 24 students to be well fitted by linear, quadratic and exponential models (r^2 > 0.964). By comparing the power calculated from the resulting F-V equation with that measured during movement, Iglesias-Soler et al. found linear models to most accurately estimate maximum power and therefore recommended this model. In a review of F-V profiling, it was suggested that the linear relationships found in multi-joint movement may be as a result of a reduced range of measurement, with hyperbolic qualities measurable if very low or very high velocities are investigated (Alcazar, Csapo, Ara, & Alegre, 2019).

As with functional movement, the force-velocity (F-V) relationship in sporting movements has been found to be linear, mathematically and empirically resulting in a quadratic relationship between velocity and power (P-V; $P = F \cdot \mathrm{V}$) in sports such as cycling (Martin, Wagner, & Coyle, 1997), rowing (Sprague, Martin, Davidson, & Farrar, 2007), kayaking (Schofield, 2015) and all sports backgrounds tested by Giroux and colleagues (2016; cycling, fencing, taekwondo and athletic sprinting, n = 95). The gradient of the F-V relationship differs between sports at elite level (Bozic & Bobana, 2018; Giroux, Rabita, Chollet, & Guilhem, 2016; Haugen, Breitschädel, & Seiler, 2019), although the relationship of a negative slope was consistent. A steeper gradient value indicates a sharper drop off, so for a given gain in velocity, the decrease in force production is larger and the profile is considered '**force orientated**'; the opposite is also true, a lower gradient represents a shallower profile, which can be considered '**velocity orientated**' (Samozino et al., 2012; Figure 2.19). Extrapolating the best-fit line as far as the axes results in a theoretical maximum force at zero velocity (**F0**) and a theoretical maximal velocity at zero force (**V0**).

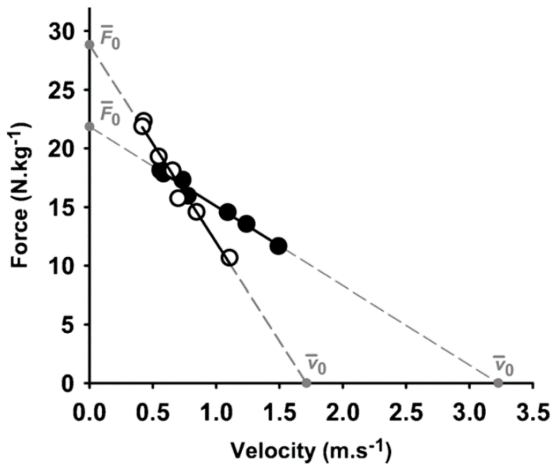


Figure 2.19: Examples of two athletes' F-V profiles from inclined maximal lower limb push-offs (Samozino et al., 2012). Profiles defined by the authors as force-orientated (unfilled circles) and velocity-orientated (filled circles).

Previous activity can influence F-V profile (Jiménez-Reyes et al., 2014; Komi & Bosco, 1978) and therefore for sports involving cyclical motion, the test used to create F-V profiles should also involve cyclical motion. Using three maximal 6 s sprints on a cycle ergometer at loads of 7, 9 and 11% of body weight to caputure F-V profiles, Bozic and Bacvarvic (2018) found strong linear F-V relationships ($r > 0.95$) across groups of combat sports, athletic sprints, team sports and physically active ($n = 111$). Combat sport participants exhibited a more force-orientated profile, sprinters and team sports participants' profiles were more velocity-oriented, and a more balanced profile was reported for the physically active participants. The relevance of the cycle ergometer to each sport, and its training methods, would vary, and no individual values were reported. In addition, a linear regression was used to model the F-V relationship with only three data points (one per trial) which is not enough for statistical use of a linear regression (Nunnally, 1967) and is lower than the six measurements suggested as a minimum by Morin and Samozino (2016) for practical F-V and P-V profiling of athletes. Haugen et al. (2019) also compared F-V profiles of elite athletes from different sporting backgrounds, testing 566 athletes from 23 different sports using a 40 m sprint, and concluded that profiles are more specific to the individual than they are to a specific sport.

The importance of using an appropriate movement pattern to assess an athlete's F-V and P-V is highlighted by differences in these relationships within gym exercises which are thought to work the same muscle groups. The F-V relationships of 75 resistance trained athletes in prone bench pull showed consistent differences relative to the profiles generated in bench press, with the bench pull demonstrating a more velocity-orientated profile, considered by the authors to be due to differences in moment arm and muscle architecture (Sánchez-Medina, González-Badillo, Pérez, & Pallarés, 2014). Supporting this, Jimenez-Reyes et al. (2018), compared vertical F-V and P-V profiles created from squat jumping with horizontal profiles generated from linear sprinting and found low correlations coefficients of -0.12 to 0.58 for theoretical maximal force production (F0), -0.31 to 0.71 for theoretical maximal velocity (V0) and -0.10 to 0.67 for maximum power, highlighting the difference in values typically found between techniques and the importance of the measurement type used.

Measuring the force and velocity of the activity as directly as possible would appear to be the best way to get sport-specific F-V profiles. However, by doing so researcher control is reduced and the recommendations by Alcazar and colleagues (2019) for F-V profiling (controlling movement parameters, activation and joint angles) cannot be met. While this means the underlying muscle mechanics cannot be clarified from applied F-V profiles, it does not diminish their value in the sport environment.

Morin and Samozino (2016) have developed easy-to-use systems and tools to identify differences between individuals and to tailor training. They reported that this can optimise training, by working on a relative weakness from an 'imbalance' in F-V, and reduce injury risk by reducing high velocity stimulus to velocity dominant athletes. The idea of an imbalance is based on an individually generated 'optimal' relationship using a participant's push off distance, body mass and maximum power. The complexity of the mechanical underpinnings of the F-V supports the likelihood of individual differences but the proposition of a single 'optimal' profile for each person may limit experimentation and improvements.

The F-V profile can be used by practitioners to improve sporting performance. Gym-based training interventions have been found to be effective at targeting either F0 or V0 (García-Ramos, Torrejón, Pérez-Castilla, Morales-Artacho, & Jaric, 2018), an effect which improves jumping performance when targeting is based on the 'imbalance' mentioned above (Jimenez-Reyes et al., 2017). Longer term, changes in F-V have been recorded in bob-skeleton athletes over an 18-month period (Colyer, Stokes, Bilzon, Cardinale and Salo, 2017). Heavy strength blocks were found to result in increases in F0, while competition season, where focus is on speed, showed increases in V0 and decreases in F0. These effects were stronger with less highly trained individuals. In addition to this direct research, Bezodis, Kerwin, Cooper and Salo (2018) postulated that changes in stride length and stride frequency seen over a five month period, covering heavy strength training and speed focussed block, could be attributed to changes in F-V although this was not measured directly.

Sprint kayakers tend to have different anthropometrics to the average population (Ackland et al., 2003), although these have not been strongly linked to performance and it is not clear if or how anthropometrics affect technique. Anthropometric factors such as muscle mass, however, are known to influence force and power generation as well as relating directly to kayak performance. It is therefore important that F-V and P-V profiles are normalised if they are to be compared across a group. Understanding F-V profiles has had a positive impact in a number of sports and investigating these profiles in a sport-specific manner in sprint kayaking would valuable to practitioners and researchers.

2.9 Summary

Biomechanics research in sprint kayaking has mostly involved limited on-water capture or more detailed ergometer capture. Ergometer kayaking does not perfectly replicate the kinematics of on-water paddling and therefore should not be used to assess the technique of paddlers. However, accurate data are considerably easier to obtain with ergometers compared to when on-water paddling and data measured using ergometers (e.g. work, force, power) have shown strong relationships with on-water performance. Ergometers require multi-joint movements and similar timing strategies and have comparable force outputs, indicating there is considerable value to ergometer research and use in applied practice, providing the context is thoroughly considered.

The difficulties involved in on-water measurement mean there is limited information available related to paddle path and hydrodynamics of the blade. Researchers have not yet accurately quantified paddle path and forces in 3D, which limits current understanding. There have been measurements of force limited to one or 2D, or ergometer studies, which have indicated the importance of force and power to performance. Combining force measurement with anthropometrics could lead to additional insight into the cause of variability and understanding athlete individuality.

The development and use of F-V profiles in sport settings has led to first sport-specific then athlete-specific differences emerging. Gaining an insight into how athletes generate power through individual F-V profiles, and tailoring training based on these has been used effectively in athletics, although it is not clear how these physiological capacity measures link to performance. These profiles have also been used to suggest equipment modifications in sports such as kayaking (Sprigings et al., 2006) and cycling (Barratt et al., 2011).

Despite its importance in transmitting force, there has been little research into the paddle set-up in kayaking. Many paddles have the functionality to change length and angle, as well as grip position, but no clear evidence has been found to clarify how best to choose paddle set-up for a given athlete, potentially due to the open nature of the skill.

Chapter 3: Sprint kayak coaches' knowledge

3.1 Introduction

Coaches' careers can be dependant on their understanding of the sport they work in, but this experiential knowledge is often overlooked by researchers as it is difficult to document and validate and is traditionally not as highly valued by quantitative researchers. As highlighted in the literature review, there are a number of areas of sprint kayaking in which researchers could be guided by coaches to run more impactful studies.

Researchers frequently identify ways in which specific biomechanical variables (Michael, Smith, & Rooney, 2009), or biomechanics as a discipline (Luhtanen, 1997) may aid coaches' practice, however it is not clear how often these research findings transfer to practice. Elliott and Bartlett (2006) tried to establish if and how biomechanics research has informed coaching practice through identifying technical changes in throwing sports and associating them with their research outputs and experiences with coaches. While this does highlight the role biomechanics *can* play in technical development, the paper focuses on a few specific aspects rather than a comprehensive knowledge of the sport.

Comparing coaching knowledge, empirical evidence and mechanical theory is a form of triangulation (Figure 3.1) defined by Denzin (1978, p. 291) as "the combination of methodologies in the study of the same phenomenon" and highlights specific areas of interest for coaches and researchers. In the overlapping areas this can help validate each to the other, while coaches' areas of interest not reflected in literature are areas for additional exploration, allowing the common barrier for research impact of inappropriate research questions (Fullagar et al., 2019) to be overcome. In a sport such as kayaking

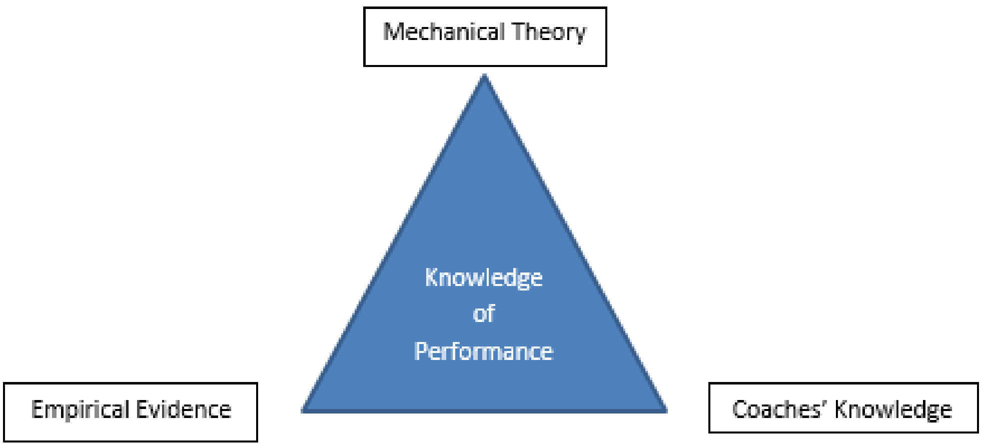


Figure 3.1: Schematic highlighting the combination of the three main sources of knowledge used in this study, to enhance understanding of performance in sprint kayaking.

where it is currently difficult to measure many factors accurately (for example, the boat-water interaction), documenting the knowledge of expert coaches becomes of even higher importance. The collation and analysis of this experiential knowledge will help in understanding the nuances of sprint kayaking, optimising equipment and bringing coaches into the research process, which may help to encourage their support in future research.

Much of coaching knowledge is formed from experience or passed down from other coaches and is therefore subjective and will be highly dependent on the specific athletes or mentors with whom a coach has worked or, often, their experience from being an athlete themselves. While this does not undermine the value of the data gained, it does highlight the importance of the context in which it is gained. Previous research has investigated coaches' experiential technical knowledge of sports such as golf (Smith, et al., 2015), gymnastics (Cote & Salmela, 1995), wheelchair racing (Bundon, Mason, & Goosey-Tolfrey, 2017; Stone, Mason, Bundon, & Goosey-Tolfrey, 2019) and sprinting (Jones, Bezodis, & Thompson, 2009; Thompson, Bezodis, & Jones, 2009). While these papers sought to document knowledge, some also had additional aims such as ascertaining the origin of knowledge (e.g. Thompson et al., 2009) or to guide future research and develop useful technologies (Bundon et al., 2017; Smith et al., 2015).

In qualitative research, interviews are often defined as structured, semi-structured or non-structured (for details see Smith & Sparkes, 2016). Semi-structured interviews are considered to allow participants to express opinions, ideas, feelings and attitudes more than in structured interviews. This type of research is inductive, meaning themes emerge from the data, rather than being pre-defined and tested, as with typical deductive hypothesis testing in quantitative research. For qualitative researchers, their epistemology (relationship between the researcher and what is being researched) and ontology (the nature of reality) are important considerations (Sparkes & Smith, 2016). Qualitative researchers often use a process described as grounded theory, coding one line at a time to be immersed in the data while maintaining analytical thinking (Corbin & Strauss, 2015). Portions of data or 'meaning units' can be identified at this point with a single idea isolated; the meaning units are then subsequently assessed for common themes and categorised (Tesch, 1990).

Jones et al. (2009) conducted semi-structured interviews with seven expert coaches to gain insight into their knowledge of the phasing and technical constructs of athletics 100 m sprinting. While three topic areas were defined, and an interview guide created, this format allowed them to explore subjects raised by coaches through probing questions. The authors found that, while division of the race into phases is broadly utilised in the same way in research and training, the importance of posture to the coaches was not reflected in the scientific literature, indicating a clear divide between researchers and coaches and highlighting an area for research which may not have become apparent using a different methodology.

There is a paucity of data in sprint kayaking and although there are technical models of performance (Wainwright et al., 2013; McDonnell et al., 2012; Gomes et al., 2015), it is not clear how well these reflect the factors that are important to coaches, limiting their value in directing impactful research. Interviewing coaches directly would like result in suggestions for future empirical research, as has been found previously (Bundon et al., 2017).

Four areas were chosen deductively from areas of literature which warrant future investigation: technique, feedback, paddles and crew boats. The first area of technical sprint kayak performance will direct further research through highlighting important applied variables. In addition, questions on feedback will be useful for sport scientists to understand how coaches interact with data and with athletes in order to improve communication and provide relevant data. The distinct lack of empirical evidence to support choices regarding paddle setup parameters make this a highly valuable area to understand applied practice and direct impactful research. There is also a paucity of published research on crew boats, likely due to the difficulties in measurement being emphasised when multiple athletes are included, but as crew boats represent 50% of the medal events in the Olympic games, documentation of factors of value would be useful.

3.1.1 Aim & Research Questions

The aim of the current study was to explore expert coaches' knowledge of sprint kayaking across four topic areas. This will build a picture of the important constructs underpinning sprint kayaking and develop the relationship between coach and researcher, allowing each to better support the other. The secondary aim was to compare the experiential knowledge to existing empirical evidence and inform future research for this dissertation.

Research Question 3.1: *What are the key determinants of performance according to expert sprint kayak coaches?*

Research Question 3.2: *How does expert coaching knowledge compare to existing biomechanical research in sprint kayaking?*

3.2 Methods

Twelve coaches took part in this study. Purposive sampling was used to recruit participants who were expert coaches, as defined by their meeting at least two of the following criteria:

- 10 years coaching experience
- Having coached two international level athletes
- Current or previous national coach
- Level three qualified coach (highest available in the country at the time of the interviews)

These criteria are similar to those used in previous research in other sports (e.g. Cote & Salmela, 1995; Thompson et al., 2009). All participants were currently coaching and living in the country of research but four were originally from different countries, where part of their coaching experience was gained. Participants ranged from 32-64 years old and 11 were male and one female. All participants volunteered and provided informed consent. Ethical approval was gained from University of Lincoln School of Sport and Exercise Science Ethics Committee.

Participants took part in semi-structured interviews, standardised to ensure cover of the four topic areas - technique, feedback, paddles and crew boats - using a question guide (Appendix 1). The topic areas were selected by the principle researcher as being of most value to the performance environment based on the review of literature and the interviewer's own experience of working in the sport. All interviews were conducted at a location of the coach's choosing, ensuring the coach was comfortable talking at length and in detail. The interviewer was previously known to all interviewees, having worked alongside them as a sport science practitioner for the previous 12 months. Prior to this, the principle researcher did not have a background in sprint kayaking. Interviews lasted on average 63 minutes with a range from 29 to 100 minutes. All interviews were audio recorded and transcribed verbatim by the principle researcher. A member checking process was used, where all interviewees were given full transcripts of the interviews to check them for error or understanding (Friesen & Orlick, 2010). No changes were requested following member checking.

A thematic analysis was conducted using a combined deductive and inductive approach based on grounded theory, as used in previous research documenting coaching knowledge (Jones et al., 2009; Smith et al., 2015), with data first broken down into 'meaning units'. These were subsequently combined to create sub-themes which were then further combined to create main themes. Data were coded into these 'meaning units' and themed using N-Vivo 10 (QSR International, Australia).

3.3 Results/Discussion

From the four pre-defined topics, seven main themes emerged from the analysis of the transcripts (Table 3.1): mechanics, distance, race phases, other disciplines, paddles, crew boats and feedback. Direct quotes from coaches that are used in this discussion are highlighted by italicising.

Table 3.1: Themes, sub-themes and meaning units emerging from interviews relating to sprint kayak coaches' perceptions on performance. Bold indicates meaning units that were emphasised by 6 or more coaches.

Main themes	Sub themes	Meaning units
Mechanics	Water Interaction	• **Athlete feel** • Forward blade entry • Minimise slip • Pressure on the blade • Dynamic catch • Recover between strokes • Sharp blade exit • **Mechanical efficiency** • Rhythm
	Boat connection	• Boat passed blade • Power transfer • Boat movement • **Strong core**
	Force/Power	• Strength • Ballistic force • Momentum • Downward force • Pulling

Table 3.1 continued

Main themes	Sub themes	Meaning units
	Specific kinematics	• Low top hand • Leg drive • **Rotation** • Little elbow bend • Still head
	SR/DPS	• **Highly individual** • Anthropometrics • Strength/power • Aerobic capacity • Paddle size
	Weather	• SR • Transition position • Time context
Distance	200 m	• Max speed • All-out profile • High SR
	500 m	• Speed • Transition
	1000 m	• Glide • Pacing • SR pick-ups • Endurance
Race phases	Start	• Pulling • Strength • **Lock/grip/hold** • Athlete feel • Deep blade • Short stroke
	Acceleration	• Continuous change • Lengthen stroke • Increase SR
	Transition	• Continuous cycle • Race pace SR • Increase glide
	Maintenance	• Race plan • Pacing • Pick-ups • Fatigue

Table 3.1 continued

Main themes	**Sub themes**	**Meaning units**
Other disciplines	Physiology	• Anthropometrics • Muscle fibre type • Strength • Power • Fatigue • Technical breakdown
	Psychology	• Motivation • Ownership
Paddles	Paddle length	• **Anthropometrics** • Seat height • Strength • Paddle distance • Comfort • Naturally optimised • Folk lore • SR
	Blade size	• Athlete feel • Availability • **Strength** • Power • Gender • Anthropometrics • SR
	Feather angle	• Blade square to boat • Comfort • Elite example
	Blade shape	• Manufacturers guide • Focus phase of stroke (e.g. catch)
Crewboats	Technique	• Faster • Higher SR • Turbulent water • Stable platform • Compatibility
	First seat	• Confidence • Consistency • Athlete feel • Rhythm • SR setter

Table 3.1 continued

Main themes	Sub themes	Meaning units
		• Tactical
	Second seat	• Technical • Strength • Tactical
	Third seat	• Strong • Larger • Power
	Fourth seat	• Athlete feel • Turbulent water • Fast
	Synchronicity	• Visible reverse offset (4-3-2-1) • Power application matched • Leg drive • Comfort
	Crew boat paddles	• Longer paddle in 3 & 4 • Bigger blade
Feedback	Individual	• Athlete level • Rapport • Goal setting • Over-thinking
	Verbal	• Immediate • Limit • Key messages • Trigger words
	Video	• Evidence • Technical sessions
	Proprioception	• Talented athletes • Intangible
	Data	• Evidence • GPS • SR/DPS • Paddles

3.3.1 Limitations & Delimitations

Although 12 participants do not constitute a large-scale study, this cohort represented the entirety of the senior international and high-level development coaches in the country at the time. Alongside the in-depth level of analysis, this number of participants was considered sufficient to meet the study aims. Some qualitative researchers cite that enough participants should be used to achieve ‘theoretical saturation’ where data from additional interviews do not add new information (Glaser & Strauss, 1999) but this was not considered necessary due to the level of coaches and the highly specific environment they work in.

The interviewer was known to all interviewees beforehand, which might be considered to have affected the answers provided by coaches: ‘insider’ researchers have a better understanding of the culture, do not interrupt the flow of social interaction and have a recognised level of familiarity (Bonner & Tolhurst, 2002). On the other hand, this may mean assumptions are made, or fewer probing questions asked (DeLyser, 2001). Qualitative researchers have found that researchers being embedded in the environment they are researching increases rapport between interviewer and interviewee (Spradley, 1979) and the ‘worker-researcher’ has been found to produce rich data (Campbell & Clarke, 2019). It is not possible to ascertain exactly the influence of a known interviewer conducting the research but, based on the literature, it would appear that there are more advantages than disadvantages.

Some of the ideas presented in this study may not be limited to one theme and therefore grouping of the themes could be open to further interpretation. This is inherent in qualitative research and it has been recommended that researchers view themes while considering theory and previous research (Lincoln & Denzin, 2018), which has been done in the current study. It is accepted within qualitative research that the researcher’s observations and conclusions will be shaped by factors such as their age, gender, ethnicity, experiences and many other factors but this is not considered as a negative or a bias, and is “just how it is” (Smith & Caddick, 2012, p. 62).

In gymnastics, researchers separated coaches according to whether they coach male or female athletes (Cote & Salmela, 1995) due to the differences perceived in task characteristics and physiology of athletes and previous reporting of different behaviours exhibited by those coaching male and females (Salmela, Petiot, Halle, & Regnier, 1980). As this study was an investigation of knowledge, rather than behaviour, and there are not differences between the task characteristics for males and female in sprint kayak (Baker et al., 1999), no such separation was done.

3.3.2 Mechanics

The key mechanical components will be discussed first as these ideas underpin the later categories and formed the majority of the interviews. Six sub-themes were defined from the meaning units coded directly from interviews (Table 3.1). Five of the six themes can be seen to reflect factors in the models of both Wainwright et al. (2013) and Gomes et al. (2015), although McDonnell's (2013b) model can be seen to only relate directly to two of the factors (SR/DPS and water interaction). The interpretation of coaches' words into mechanical theory is difficult but is cited by Lees (1999) as the 'duty' of the biomechanist. Table 3.2 shows how the comparisons have been made relative to the overall models available for kayaking in the published literature.

Table 3.2: Mechanical sub-themes from coaching interviews compared with the hierarchical model by Wainwright et al. (2013) and Gomes et al. (2015).

Sub-theme	Wainwright's model- Related factors	Gomes' model - Related factors
Water interaction	- Forward reach - Blade slip - Propulsive impulse	- Paddle force - Orthogonal and transverse blade force - Slip
Boat connection		- Seat force - Footrest force
Force/power	- Propulsive force - Max velocity	- Paddle force - Instantaneous velocity
Kinematics	- Forward reach - Backward reach	
SR/DPS	- Stroke distance - Stroke time	- Stroke rate - Stroke length
Weather	- Passive drag - Water temperature	- Aerodynamic drag - Hydrodynamic drag

3.3.2.1 Water interaction

An athlete's interaction with the water, as might be expected, was an important concept from all interviews. Since the terminology used by coaches can be understood by those who are involved in kayaking but may not have a clear meaning to those outside the sport, each of the meaning units highlighted above (Table 3.1) will be clarified and discussed with reference to the literature below.

Many coaches emphasised the importance of athlete 'feel', an abstract concept linked to further descriptions such as 'grip' and 'lock' regarding the connection between the paddle blade and the water. Many of the coaches discussed this concept as naturally occurring:

> *It's that natural instinctive feeling, or intuition, or an awareness of the feel of the blade in the water, and transferring that power, in much the same way swimmers do, they have that feel and they can grip the water*

This idea is echoed by online coaching guidelines such as "Training in Paradise" (Župančič, 2018), which describes the paddle grip on the water as "both inborn and developed with training." This 'grip' or 'feel' is very hard to define, measure or quantify and therefore cannot be compared accurately to any empirical literature, although 'grip' could be considered to involve minimal blade movement and/or maximal force between the blade surface and the water. As apparent from the quote above, similar comparisons have been made in swimming, with these same terms commonly used by coaches and researchers finding force output linked to propulsion (van Houwelingen, Schreven, Smeets, Clercx, & Beek, 2017; Morouço, Barbosa, Arellano, & Vilas-Boas, 2018).

Coaches mainly view kayakers from the bank in the sagittal plane and therefore the concept of a 'fixed' blade is likely to refer to a lack of apparent motion in the anterior-posterior direction only. As highlighted in the literature review of this thesis (Chapter 2), there is considerable movement in the lateral direction during a stroke, the magnitude of which positively correlates with performance (Kendal & Sanders, 1992), but this is only highlighted when displayed in an external reference frame or global co-ordinate system (Figure 2.9). Digitised data from an overhead television camera moving with the athlete used during the 2012 Olympics (Figure 3.2) also highlight the importance of the reference frame used: the paddle moves considerably further backwards relative to the boat (internal reference frame), which visually reduces the importance of lateral movement. This video is low quality and would not be recommended for biomechanics research but highlights important differences in visual data which would be available to coaches, compared to research.

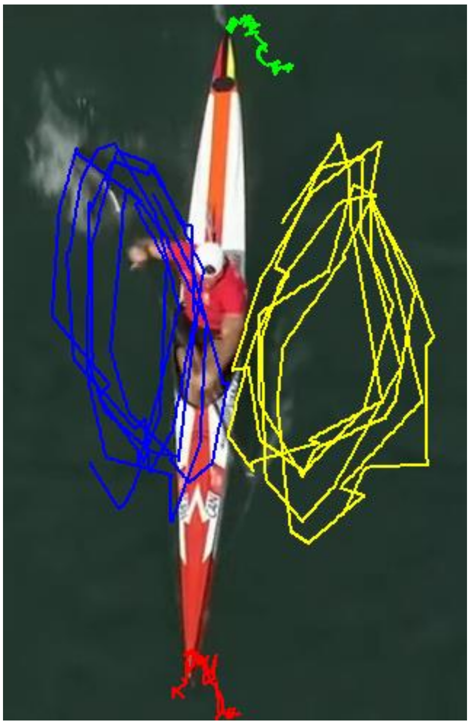


Figure 3.2: digitised overhead footage showing the paddle path of an elite sprint kayaker from London 2012 (Olympic, 2012).

Higher paddle forces have also been found to correlate with better performances (Mononen & Vitasalo, 1995; Brown et al., 2011), which may be expected due to Newton's second and third laws with the unchanging mass of the kayak-athlete-paddle system. The direction of this force is important and remains an under researched area due to the complexities of in-situ force measurement and unsteady flow dynamics (see the literature review in Chapter 2 for additional information on hydrodynamics).

Linked with the idea of athlete feel is that of minimising slip. Slip is the opposite of grip: movement of the paddle that does not result in boat movement.

> *If someone is putting the blade in, it's not locking, there's a lot of splashing, they're grabbing back, they're bending the arm too soon, is an indication that they're just kind of pulling and slipping the blade through the water, rather than locking the blade on and coming past the blade with the shoulder and the hip.*

Kendal and Sanders (1992) measured blade slip of 7-22 cm in elite kayakers but did not find it to be linked to performance. Wainwright (2014), however, found increased blade slip to be linked with lower performing athletes. How the researchers define the blade slip is important to its measurement: for Kendal and Sanders it was defined as the backward movement of the blade tip in the global reference frame and was measured via video, whereas Wainwright et al. (2013) defined it as the horizontal distance moved by the paddle, minus the horizontal distance moved by the boat, both during the pull phase. Wainwright's measurement encompasses two different reference frames, with paddle movement measurement relative to the internal reference frame of the kayak, and the kayak movement measured from the double integration of the acceleration data. Error in either of these would result in errors in slip. The low frequency of the cameras used (50 Hz) and the uniaxial nature of the accelerometer - whereby any pitch of the boat would influence the acceleration by incorporating gravity - means error is likely to have been introduced in both. While these issues do not mean slip is not important to performance, they do highlight the difficulty of measuring it. The theory underpinning the value in reducing slip is the same as that used to show the value of increasing 'grip' as above.

The meaning unit 'pressure down the blade' was mentioned numerous times and appears to refer to the athletes directing the force down the paddle shaft which was thought to improve the 'lock' or connection with the water. Phrases used included:

claw, don't slap

push down the blade

Nothing could be found in the literature relating to this idea. It may be that the idea of pushing 'down' the blade combined with a forward entry and rotation, is a coaching reference that results in athletes moving the blade more laterally to make use of the lift forces (Kendal & Sanders, 1992) or that the 'spoon' of the blade surface directly creates a drag force acting parallel to the paddle shaft, or that it encourages an increase in velocity of the blade, which would in turn increase drag on the blade. A better understanding of three-dimensional paddle kinematics and hydrodynamics would improve understanding of this coaching point. The equation for drag force (equation 2.2, Chapter 2) also highlights the importance of additional factors- namely surface area and velocity- that link this idea of 'feel' to other concepts including 'dynamic catch' and paddle blade size.

Catch typically refers to blade entry, but there were nuances between the coaches interviewed, with some considering the 'catch' to be a single instant, while others considered it a phase, from water entry until (again, ambiguously) 'locked-on.' The discrepancies among coaches are reflected by the literature: McDonnell et al. (2012)

highlighted the differences in position and phase definitions within kayak literature (Figure 3.3) and subsequently defined a four-phase observational model where 'catch' was defined as the instant of the blade entering the water and marked the beginning of the 'entry' sub-phase which makes up one of three sub-phases of the 'water' phase. The newly created model was based on ease of measurement rather than existing protocol; in Figure 3.3, 'C' represents McDonnell's definition of 'catch' where the blade tip is touching the water, while 'D' represents blade immersion which might be considered to reflect 'lock' and as can be seen, none of the papers collated in Figure 3.3 use solely C-D as their description of the catch phase (phase 1). While the above paper gives clear guidelines for researchers, the ambition of the study was to 'improve communication and application of research to practice.' While this may have occurred in the authors' native countries, the definitions in the paper do not match those highlighted by the coaches interviewed in this study.

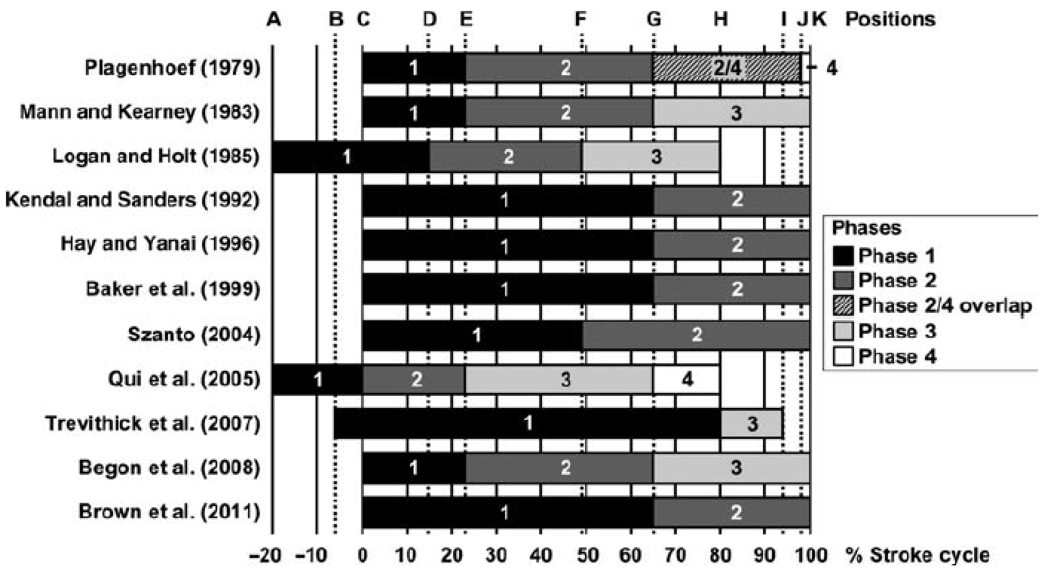


Figure 3.3: Overview of how previous literature has broken down sprint kayak strokes into specific phases (McDonnell et al., 2011). Phase-defining positions: A = left (paddle) horizontal; B = right most forward (quarter shaft); C = right (blade) catch; D = right (blade) immersion; E = right (paddle) vertical; F = right (blade) extraction; G = right (blade) release; H = right (paddle) horizontal and right most backward (quarter shaft); I = left most forward (quarter shaft); J = left (hand) greatest forward reach; K = left (blade) catch.

The idea of a 'dynamic catch' was raised by coaches, particularly in reference to 200 m sprinting, indicating a fast movement to get the paddle into the water.

whole blade in as quickly as possible

As described above, the equation for hydrodynamic drag supports the idea of a fast blade entry, where it can be seen that velocity has a large influence (due to being squared in the equation) so increasing contact velocity will increase the drag force, which is likely in turn to increase boat acceleration. This meaning unit may also simply refer to the idea of submerging the whole blade quickly in order to start the pull phase earlier and to ensure energy is not wasted due to only part of the blade being in the water. McDonnell et al. (2011) showed the phase from catch to immersion as taking 15% of the stroke (Figure 3.3), but no studies could be found that quantified the time of this phase or linked it to performance. Wainwright et al. (2013) divided the stroke but the early phase was from 'catch' to 'paddle vertical' and therefore the 'catch' alone cannot be assessed.

One of the more easily understood meaning units which resulted from this analysis is that of 'forward blade entry' referring to the position of the blade relative to the boat.

> *the blade needs to go in the water a long way forward, but it's got to be locked on there.*

> *The key for them is get the blade in by your feet. By the time you're connecting it might be further back than that, but it is a long way far forward rather than by your knees.*

This concept is supported by some academic literature which has shown a significantly longer forward reach in international level paddlers compared to national level paddlers (Brown et al., 2011). However, this conclusion is not unanimous as Kendal and Sanders (1992) found no differences in forward or backward reach between participants of different performance levels. It seems likely that reach would be highly linked with both anthropometrics and technique and is also likely to be affected by paddle set-up and weather conditions. Those with longer arms or a technique with a large amount of rotation may be expected to exhibit a further reach, while rough water conditions or strong winds may reduce stability and therefore reduce reach in an effort to reduce the distance of the stroke from the base of support. Similarly, a longer paddle may increase reach with no technical change. No research could be found that has investigated the stability of sprint kayaks or explored how weather conditions or paddle set-up affect technical performance.

The recovery phase, defined by coaches as the time in which no force is being applied by the paddle to the water, is also known as the 'aerial phase' (McDonnell et al., 2011). This phrase was mentioned as important for all race distances to maximise DPS and allow muscles to 'recover'.

then the ability to recover when both blades are in the air so let the boat glide and feel be able to recognise where, when is the time to put the next stroke in, you know, in order to get another power transfer.

Even with the 200 m guys, the sprinters, it's a massive job to teach them to be able to recover, within a very short time because otherwise within one minute all the athletes die.

Increasing stroke rate leads to a decrease in absolute duration of both water (pulling) and aerial (recovery) phases but the percentage of recovery decreases: from 41.7% at a stroke rate of 60 spm to 29.5% at 100spm and 27.5% at race pace (Gomes et al., 2015). Similarly, Brown et al. (2011) found higher SR and lower recovery percentages when comparing elite with club paddlers, although the values used for 200 m SR seem unusually low (60.5 vs 50.2 spm) and it is not clear how the authors defined strokes or glide time. During the aerial phase the major force acting on the kayak is that of hydrodynamic drag force on the hull, slowing the boat down and it is therefore crucial to boat speed to maximise the percentage of effective force application. For longer distances where physiological efficiency is paramount, lower rates with higher non-active percentages may be preferred, Sundberg & Bundle (2015) found that higher percentage duty cycles, as found during high SRs, result in much faster degradation of force and power production.

A fast or 'sharp' blade exit was another parameter coaches deemed important, outlined with statements like:

get the blade out as quick as you can

you just have to pull harder and release back end, it's very important to release boat easier, quicker back end

In agreement with this, Wainwright (2013) constructed a deterministic model of performance (see Figure 2.2 in literature review Chapter 2) and he concluded that the highest priority coaching recommendation was to remove the blade from the water as soon as possible after paddle vertical. Wainwright broke the water-phase down into three further phases, one of which ran from maximum velocity until paddle exit. During this phase, smaller vertical and horizontal impulses were associated with higher boat velocity and efficiency, thought to be through an decrease in active drag due to decreased pitching of the boat. To remove the blade from the water, it must be raised. The position of the blade as it is raised out of the water is important for the vertical impulse described by Wainwright: if the blade is lifted facing upward, the acting resultant force on the paddle, and therefore athlete and boat, will be downward, thereby lowering the boat in the water and increasing the resistive drag force acting on the kayak.

3.3.2.2 Boat connection

The idea of 'moving the boat past the blade', rather than the blade past the boat encompasses both the 'locking' of the blade, which has already been discussed, and the connection between the athlete and the boat. While the phrase "moving the boat past the blade" is so commonly used by coaches (particularly when discussing ergometers) that it warranted its own meaning unit, the ideas will be discussed relative to power transfer and boat movement. The combination of these two ideas is summarised in the quotes below:

> *how the boat is running as well really, so whether it's jumping up and down or it is running smooth, that'll give an idea of how the power's connected to the boat.*

> *everything that they do, from a physical perspective, has to be transferred down the chain, through the core and into the boat, and to the point where, if somebody is really paddling well, they look like they're actually wearing their boat, like a mermaid, there's just that strong a connection and you can see the reaction of the boat to the actions of the arms and hands*

The transfer of power into the kayak occurs via the athlete's connection to the boat at the seat and footplate, but there is a paucity of research in this area. Nilsson and Rosdahl (2014) created a system to measure the force at the seat and footrest points during on-water kayaking but, despite limiting the system to measuring horizontal force at the seat and force perpendicular to the footplate, the system weighed 4.65 kg (almost 40% of the kayak mass), highlighting the difficulties involved in on-water measurement. Using this system to investigate contribution of leg musculature, they found restricting the legs via fixed knee angle resulted in a large decrease in footplate force, contributing to a 16 and 21% reduction in paddle force and kayak speed respectively. Ergometer studies have shown differences between athletes at the seat and footrest (Begon et al., 2009; Tornberg et al., 2019). Although Tornberg et al. linked higher footplate forces with higher performance, the use of only three athletes limits this interpretation.

As described in the literature review chapter, kayakers must overcome hydrodynamic pressure drag, a portion of which is due to the wetted surface area of the kayak (see equation 2.1). Roll, pitch and yaw refer to movements around the sagittal, transverse and vertical axes respectively and movements in any of these planes are likely to increase the wetted surface area of the boat, thereby increasing resistance and decreasing the efficiency of the stroke. Coaches are aware of this as terminology such as 'running smooth' and 'staying upright' was used frequently around boat movement. Kayak research has typically looked at drag during passive movement of the kayak as this is much easier to measure (e.g. Jackson, 1995), but research in slalom indicates much higher active drag is created by novice paddlers, who are likely to have much more boat movement, when compared with elite paddlers (Pendergast, Bushnell, Wilson, & Cerretelli, 1989). Additionally, a four-year training period with collegiate paddlers was found to decrease the kayak's active drag by as much as 50% (Pendergast et al., 2005). A longitudinal study of this duration is logistically complex to carry out and it is not clear what level the kayakers were at or how much they changed over the period investigated. Research investigating boat movement using IMU technology has been conducted in rowing, with yaw and roll found to have a large, negative influence on boat velocity, thought to be due to a larger increase in wetted surface area (Loschner, Smith, & Galloway, 2000; Wagner, Bartmus, & De Marees, 1993). The minimum length of a rowing boat is 7.2 m (World Rowing, 2017), while the maximum length for a kayak is 5.2 m; the increased length, and therefore larger moment of inertia around the transverse axis, of a rowing boat makes it less susceptible to pitch movements which may be important to kayak performance.

In between the paddle and the kayak, the athlete forms the middle of the closed kinetic chain created. The importance of the athlete's core strength was mentioned by all coaches interviewed.

> *it's that terrific core strength that holds his boat upright*
>
> *if they've got a strong core, they can transmit the power*

Brown et al. (2010) looked at the contribution of the trunk and legs to kayak performance and found significant correlations between muscle activation of the contralateral rectus abdominis and external oblique abdominal with paddle force, which was in turn linked to boat velocity, leading them to conclude that these muscles are important in the application of power, in support of coaches' ideas. Similarly, Steeves et al. (2019) measured seven trunk-strength scores and found the sum of these to correlate with 200 m performance. Additional training of the core based on a dynamic neuromuscular stabilisation approach was reported to increase club level kayakers' force production measured on a kayak ergometer compared to a control group (Davidek, Andel, & Kobesova, 2018) but on further examination, it appears the control group decreased force more than the intervention group increased (5% increase for intervention group, 7% decrease for control group).

Further highlighting the importance of the multitude of connections and the generation and transfer of power, all twelve coaches referred to 'connections' in some form.

> *It's a locked in circle of all. When you lock in the blade, you're already pushing on the footrest on the same side as the stroke and once you're locking the shoulder down, that's where your lats and abs start locking in as well and pushing the boat forward. So basically, you're locking it in through the arm, through the leg, through the core. It's a circle.*

Statements such as the one above emphasise the coaching belief of importance of using the whole body in the movement and not isolating any one limb or muscle group, and reinforce the difficulty faced by biomechanists in trying to quantify optimal performance of this three-dimensional, multi-segment closed-chain movement.

3.3.2.3 Kinematics

There was some disparity between coaches in terms of the importance of some of the specific body movement factors. Most coaches observed that there is not one set kinematic movement pattern that needs to be followed precisely.

> *You're still trying to achieve the same thing in the water, and you can throw all the shapes you want around it, as long as you're achieving that grip and that movement, being efficient and that power.*

However, having emphasised the importance of the interaction with the water, there were numerous mentions of specific movements (Table 3.3).

Table 3.3: specific desirable or undesirable kinematics in sprint kayaking which emerged from elite coach interviews.

Body Part	Advised movement	Undesirable movement
Arms	• Small amount of elbow bend • Move down through the body to the opposite hip • Locking shoulder down	• Top hand shooting up • Punching • Too low • Travelling too quickly • Elbow bending
Trunk	• Rotating far forward • Locking in the lats and abs • Sitting upright	• Collapsing shoulder to hips
Legs	• Legs drive pelvis rotation • Pushing on same side footrest prior to blade lock • Pull opposite hip forwards	

Three-dimensional kinematics of sprint kayaking have been studied both on an ergometer (Fleming et al., 2012; Michael et al., 2012) and on-water (Baker et al., 1999; Begon et al., 2008). Baker et al. (1999) compared the upper body technique of elite males and females and found no significant differences, despite higher boat velocities for males. Greater stroke width, forward reach, trunk rotation and leg motion were found to differentiate elite kayakers from club paddlers when assessed via notational analysis with kinematic factors subjectively graded (Brown et al., 2011). Trunk rotation in particular was mentioned by all of the coaches as being important for performance; this movement may help athletes to 'move the boat past the blade' without creating additional unwanted boat movement, or support the lateral movement of the blade relative to the boat through the fixed arm. The trunk and legs also play an important role in transferring paddle force through to the boat (Brown et al., 2010). During ergometer paddling, researchers have found peak footrest forces to occur fractionally before peak paddle forces (Jahn et al., 2016), in agreement with the coaching points above (Table 3.3). In addition to ergometer work, Begon et al. (2010) modelled lower limb contributions and found it to both enhance propulsive impulse and reduce mechanical work.

Nine coaches mentioned the importance of looking at the paddler overall. Elite performers were described with words such as: *effortless*, *efficient*, *rhythmic*, *fluid*, *relaxed* and *seamless*. Despite the importance of this impression on coaches, this concept is difficult to quantify. It could potentially be compared to efficiency of movement, which was also proposed by a number of coaches as important to performance.

> *…that efficient transition from one stroke to the next, carrying the power without over rating, so that there's an efficient powerful movement that's maximising travel per stroke, distance per stroke.*

> *Those things just relate more to efficiency, and the simply physics of it, in terms of the blade being in the best position to deliver power or to deliver the ability to pull the boat, or push the boat passed the paddle.*

Mechanical efficiency is an indication of the resultant output compared to effort going in. It could in theory be measured by looking at the force being output by the athlete on the paddle, footrest and seat, and comparing it to the resultant boat movement, but the technology does not yet exist to do this accurately, reliably and affordably. Sprigings et al. (2006) compared the forward forces with the total force in ergometer trials to attempt to give a measure of 'efficiency' and found values of around 80-83%, however the fundamental assumption that forward forces are the only desirable ones is inaccurate, therefore the findings have little bearing on performance. Despite reported similarities in technique on an ergometer when compared with on-water kinematics (Begon et al., 2008; Fleming et al., 2012), efficiency measured on an ergometer gives little insight into the on-water equivalent due to the mitigating differences in technique, balance and equipment.

3.3.2.4 SR & DPS

Stroke rate and distance per stroke were mentioned by the coaches in a number of contexts, including when discussing differences between race distances, paddle set-up and crew boats. For most of the coaches, SR was considered to be highly individual. Follow up questions revealed that many attributed those individual differences to anthropometrics, strength, aerobic capacity or paddle set-up.

> *you have to control the stroke rate and adjusting the paddle for the optimum stroke rate, optimum stroke rate is quite individual but still, there are established norm. You have to play with the length of the paddle and size.*

It's again very individual and it depends on the physiology of the athletes as well as how big they are. It's very individual.

[Athlete A] *could hold a slightly higher SR than* [Athlete B] *on a 1000 but he wasn't quite as strong and as powerful so all those different parameters, feed in to a person's natural rhythm, natural cadence.*

As seen above, force and power characteristics were raised by coaches when referring to SR and DPS for each athlete, with those seen as stronger or more powerful generally considered to have a longer stroke and higher DPS, while those who are smaller, lighter or with more endurance capacity generally considered to have a higher SR. While research has shown higher SR by elite when compared to club paddlers (Brown et al., 2011), differences have also been found between athletes' SR within the elite level (McDonnell et al., 2013b) supporting the belief of coaches that it is individual. No research could be found that has investigated the cause of the differences between individuals.

3.3.2.5 Weather

Weather and environmental conditions were raised with reference to SR, the context for data feedback, race phases and paddle set-up. As has been discussed in the introduction, the water temperature, wind speed and direction, air temperature and pressure and humidity have an impact on performance through their influence on the hydro- and aero-dynamic drag experienced by the athlete. Coaches expected headwinds to reduce boat speed via a lower SR while a tailwind might lead to a shorter acceleration phase or may allow an athlete to reach race pace and SR earlier, although no research could be found that has investigated this effect.

1.1.1 Mechanics summary

For some coaching points, there are clear links with mechanical laws. However, the terminology used does not always make this easy to identify. Often research looking at mechanical specifics relating to kayaking is not ecologically valid as it is not yet possible to measure the factors directly and therefore findings are limited. The key areas raised by coaches were: water interaction, boat connection, kinematics, force/power, SR/DPS and influence of weather.

Of these key areas, there are a number of areas lacking research, for example:

- **Basis of individual SR choice**
- Variation in kinematics
- Effect of weather on technical performance
- Effect of stability on performance
- The orientation of the blade through the water
- Three-dimensional force on the blade
- Three-dimensional kinematics.

Research in these areas, while challenging, could improve technical understanding, give insight for improving equipment set-up, better tracking of changes to performance and allow for individualised and more efficient training.

3.3.3 Race phases

Unlike Jones et al. (2009), who found coaches to largely agree on the phases in a track sprint race, there was some discrepancy between coaches as to the phasing of a canoe race. Figure 3.4 demonstrates the differences found between coaches, in both terminology and philosophy of race phasing.

While most agree on the existence of a ‘Start’ phase, this was considered as anywhere between 2 strokes and 100 m. Some incorporated an ‘Acceleration’ phase into the start, while others considered the first few strokes alone to be the start due to the large technical differences found in moving the boat from stationary. Even within these differences, the first ‘few’ strokes were reported as 2, 4-5, 6, 6-7, 12 or 15-20 strokes depending on which coach was asked. No literature could be found which has looked at different phases of a sprint kayak race, although the 'start' first five seconds have been disregarded in race average calculations of SR and velocity by McDonnell et al. (2013b), indicating perceived differences.

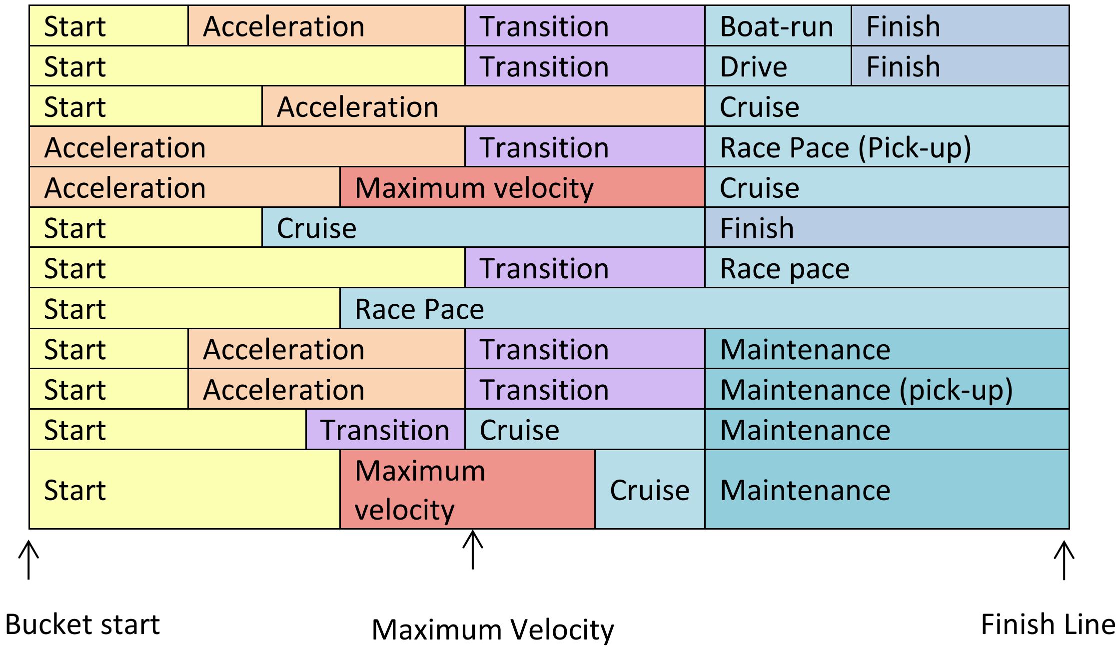


Figure 3.4: illustration of sprint kayak race phase breakdown provided by each of the coaches interviewed

The early strokes of a sprint kayak race were considered to involve more of a 'pulling' action, with the paddle blade deep in the water. The importance of the 'lock' or 'grip' or 'hold' on the water was also emphasised as important to start performance. Strength was mentioned numerous times, with indications that stronger athletes and those with better 'feel' who could get a better 'grip' of the water were those who would start best. The first stroke was considered to be generally shorter and slower than the later ones, in similarity with athletics sprinting (von Lieres Und Wilkau, Irwin, Bezodis, Simpson, & Bezodis, 2018), and with kayak research (lowest SR in first 10 strokes; McDonnell et al., 2013b).

The definition of 'Acceleration' and 'Transition' phases were somewhat blurred but, regardless of terminology used, a period of acceleration followed by a change into a more 'steady state' period was often described. The early acceleration was mostly categorised by lengthening the stroke simultaneously with increasing SR as boat velocity increased. The transition phase was then generally considered a technique change from accelerating to maintaining steady speed via a reduction in stroke rate and an increase in the 'glide' or run of the boat along with a more continuous stroke cycle. A transition phase was considered to occur for 500 m and 1000 m races but not for 200 m racing. No research could be found that has looked at the kinetics or kinematics of kayak performance across a competition distance or compared different race phases. A consensus around a defined model – likely to include start, acceleration, transition and maintenance phases – would improve athlete understanding and enable focussed research.

In the longer races, following a transition or acceleration phase, most coaches referred to a steady-state phase in some way, often referred to as 'race pace.' Some coaches included the idea of 'pick-ups' where an increase in SR was considered to counteract the effect of decreasing DPS:

> *…doing your pick-ups, you've got to increase that rate, you've got to have a higher stroke rate to compensate for the lack of power.*

These pick-ups were considered to form part of an athlete's race plan, a set of pre-decided strategy of how the race would be performed and paced. The pick-ups often seemed to be linked with ideas of increased effort or exertion to try and mentally overcome the inevitable fatigue but were not generally considered to increase the speed of the boat. An ergometer research study indicated that an all-out pacing strategy results in better performance for kayakers when compared with an even paced strategy (Bishop, Bonetti, & Dawson, 2002). Although no literature could be found that has investigated the phase breakdown of a sprint kayaking race, the pacing strategies at World Championships were investigated by Borges, Bullock and Coutts (2013) from published 250 m splits and a 'reverse J' shape profile was found across levels and crew size (1, 2 and 4). This 'reverse J' is described by the first 250 m split being the fastest, with speed decreasing from then on in the 500 m and a decrease in the middle followed by an increase in speed in the last 250 m in the 1000 m event. This fast start strategy has also been found in rowing (Garland, 2005) and was speculated by the authors to avoid the detrimental effects of wash (the additional wave drag caused by other boats' movement through the water nearby). McDonnell et al. (2013b) reported a decrease in SR through World Championship level races, matching what would be expected by this cohort of coaches from the transition.

Differences in coaches' definitions of race phasing may be due to the different focus of their typical athlete group. The 200 m event is typically seen as having an 'all-out' pacing strategy, with maximum speed of high importance to performance, while the 500 and 1000 m are considered to have transition phases, to include more 'glide' within the strokes and to require more pacing and endurance capacity.

Race phases summary

The language used by coaches around race phases was not consistent. Despite the use of start, acceleration and race pace phases mentioned by almost all coaches, the distances each phrase referred to was different. Athletes would likely benefit from a consistent model, particularly as they move up the development pathway towards being an elite athlete. The start and transition were areas that many coaches highlighted but there was not universal clarity on what success looks like for these phases.

Coaches discussed nuances in kinematics of the different race phases, empirical evidence of which would allow better targeted training. In particular, a better understanding of start technique and changes due to fatigue for specific athletes would improve performances.

To account for differences, research should focus on a specific area rather than take average for whole efforts- start, acceleration, transition and steady state (or 'race pace') phases with clear definitions are recommended.

3.3.4 Paddle set-up

Many coaches acknowledged paddle set-up is not necessarily optimised, primarily due to practical considerations of what an athlete can afford/has available to them and what they are used to/comfortable with. However, the predominant view was that athletes are able to 'feel' what is right for them with a reasonable accuracy:

> *So much of it is kind of feel, and what they're used to… It's what they're comfortable with and how they do it so changing is quite difficult*
>
> *Every athlete adapts to what they're using, and they make it work for what they've got*

Coaches' consideration of the paddle length and grip positions was based on athletes' physical characteristics, observation or conventional wisdoms. When asked how they would advise their athletes on paddle set-up, statements such as the two below exemplify the information around length and hand position.

From the very old times the length of the paddle is, if the athlete stretches out their arms above their head, and from there puts their paddle down to the floor, somewhere in the middle of the palm or the beginning of the fingers, is the basic length.

if you've got 90 degrees at the elbows and your head's in the middle, you're about right. And as long as you're not overhanging the length of the blades and you've probably got an inch or two at the bottom, on the outside of the hands, some are a bit closer, maybe an inch, then you're about the right sort of set-up

These typical set-up parameters are used for novices when selecting a paddle for the first time but are often not challenged or changed as the athlete grows or develops in skill. While the basic idea is clearly based on anthropometry, no rationale could be found for these measurement choices in the literature. Ong et al. (2005) investigated anthropometrics and equipment set-up and found significant relationships between body size and both paddle length and blade length in 31 male and 11 female elite sprint kayakers, although the details were not provided. The authors described "sizeable differences" in foot-seat distance, paddle length and blade length but blade width and seat height were found to have little variation. Overall, variation in standing height was found to predict 59% of the variance in foot-seat distance, and 54% of grip width distance.

Paddles are designed for the entirety of the blade to be submerged, while none of the shaft is, and therefore an estimation could be made from anthropometrics (e.g. arm span) and the athlete's height above the water level (incorporating sitting height, height of the seat and depth of the kayak in the water), but technique will cause a large discrepancy with this, in particular the lateral distance between the paddle and the kayak. As described earlier, no research has been found to describe the paddle path on-water; it seems likely this varies between individuals as it does on ergometers, which are considerably more constrained (Therrien et al., 2012). Considered purely from the sagittal plane, changing the paddle length while maintaining grip width changes the lever arm over which the force must act. This means that to produce the same rotational force around a pivot, a longer paddle would need a lower force. However, this would be a gross simplification of the paddle movement as much of the movement is translational while the paddle is vertical. Linked to the ideas discussed above, there may be differences in paddle optimisation for the race distance being paddled, with maximising force and power more important for the shorter races and energy efficiency of higher importance to the longer distance races.

Blade size was predominantly linked by coaches to an athlete's strength and their chosen stroke rate (SR). While it seems clear from a theoretical perspective that, based on the muscle force-velocity relationship, a larger blade will increase the resistance and thereby reduce the speed at which the blade can be moved and decrease the SR, it is not clear if this is necessarily advantageous to athletes. Sprigings et al. (2006) looked at athletes' power profiles while paddling on an ergometer and calculated an optimised blade size for each athlete by rearranging the drag equation for surface area (C_D, Equation 1) and inputting the force and velocity at which peak power was achieved. An increase in blade size for optimal power production for five of the 12 participants was subsequently proposed. However, the measurement time of 10 seconds on an ergometer at "estimated 500 m race pace and SR" is not representative and indeed, the authors noted it is unlikely that the selected pace could be sustained for the entire race. Additionally, the calculations make a number of assumptions (e.g. replicable paddle path, lack of importance of blade shape, density of the water) which would likely greatly reduce the ecological validity and no subsequent performance testing was conducted.

Coaches were not asked explicitly about blade shape and the six who mentioned it primarily attributed choices to athletes' feel and preference. The shape of the blade was referred to by coaches as being either suited to optimising catch (the initial increase in force on the blade) due to a teardrop shape blade or to optimising force through the whole stroke due to a more rectangular blade, matching the manufacturer's descriptions (Brača, 2017; Jantex, 2019) and likely acquired directly from one of the two manufacturers, who are present at most international level competitions. No studies could be found that have investigated the differences in modern blade shapes, but Sumner et al. (2003) tested conventional, Norwegian and turbo blades and a flat plate in a wind tunnel in steady state conditions to investigate the drag associated with each shape (Figure 3.5). They found no differences in drag coefficient for any of the blades at 0° or while varying yaw by ±20° and a large difference between the three blades when compared against the flat plate when varying pitch. As kayaking is a highly dynamic, 3D movement, steady state flow is an oversimplification and therefore these results should be applied with caution.

Four of the coaches mentioned that the feather angle (between the left and right blade) should be between 60 and 75°. Only one study could be found that has experimentally investigated the effect of feather angle: Lee (2013a) compared a 90° angle with a 0° angle and found SR to be significantly higher in the 90° condition but distance per stroke (DPS) to be significantly lower. No other angles were used, and it appears that an inflatable kayak was used, undermining the value to sprint kayaking.

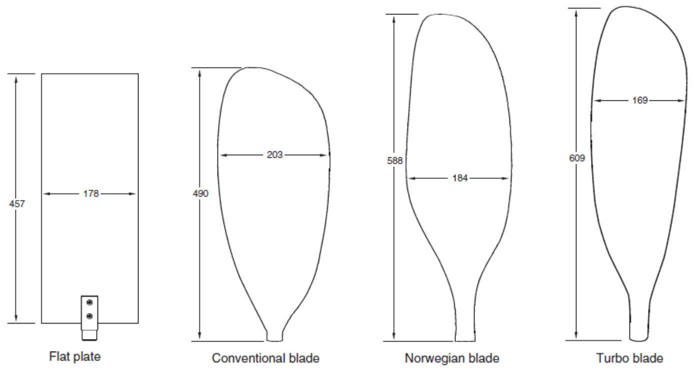


Figure 3.5: Diagrammatic representation of blade shapes investigated in wind tunnel testing from Sumner et al. (2003).

> **Paddle set-up summary**
>
> Coaches generally believe that variation in paddle set-up is largely explained by height, strength and SR choice and that athletes naturally choose a paddle that allows them to perform well, although most acknowledge that this is an under-researched, under-considered area which could lead to improvements in performance. The vast majority of coaching knowledge is based on observation, experience and athlete's subjective opinions.
>
> Published literature available in the area is currently limited in quantity and methodology and objective evidence to help advise both coaches and athletes towards optimising their set-up, has large potential gains in performance as a result. **Paddle length**, blade size, blade shape and feather angle all contribute to paddle set-up and would all benefit from additional research. Paddle length is the logistically easiest factor to investigate as most commercially available paddles have a 10 cm range when purchased and so any conclusion can be affected immediately.

3.3.5 Crew boats

Coaches cited technical differences when paddling in crew boats compared with individual boats. These differences stemmed from the increase in speed of the boat movement and the importance of a 'quick catch' due to the shorter water phase as a result of an increase in SR.

> *K4, technique is different again…because the speed is much higher, the boat glides much more. K1 technique is not good enough for K4, so you have to teach the athletes to run the boat for longer, because speed comes from different level, what is called power stroke, for K4 it's just a normal stroke*

Publicly-available data from the Rio Olympic games (Table 3.4) show that on average SR and velocity increase from individual to crew boats, corroborating coaches' views. Gomes (2015) compared paddle force and boat acceleration in K1 and K2 boats and concluded that paddle entry should be "faster and more powerful to compensate for the faster moving water" (p. xxii), in direct agreement with coaches.

Table 3.4: average and peak SR and velocity data for the women's sprint kayak A final races during the Rio Olympic Games in 2016. Velocity data for women's K4 not available (ICF, 2016).

Event	Average SR in SPM (± SD)	Average Velocity in $m \cdot s^{-1}$ (± SD)	Peak SR in SPM (± SD)	Peak Velocity in $m \cdot s^{-1}$ (± SD)
WK1 500 m	119.6 (± 4.1)	4.4 (± 0.1)	133.3 (± 8.0)	4.8 (± 0.1)
WK2 500 m	125.6 (± 4.9)	4.8 (± 0.1)	139.9 (± 8.0)	5.3 (± 0.1)
WK4 500 m	127.6 (± 3.8)		132.3 (± 4.6)	

Athlete 'compatibility' was also discussed by some coaches as being highly important, although it is not always clear what is meant by the term.

> *In top boats, everything should be compatible, psychology, physiology and technique also*
>
> *there are people who are compatible and there are people who are absolutely not. Not always the first four people that finish the race will be the fastest K4.*

Half of the coaches emphasised that athletes ought to have similar technique to each other, underpinned by the idea that moving differently *throws the boat out*. On the other hand, two coaches observed that you can *get away with more* in a crew boat as the increased weight and other athletes lend stability to the platform. Seven coaches stated that the most important factor was to have the power application to the water synchronised; some expected this to require synchronised movement timing, others felt this requires a back-forwards timing (for example in a K4, seat four would be fractionally before seat three and so on) and the remainder felt the movement was unimportant so long as the power application was timed. The back-forwards pattern is supported by the only research which could be found comparing force profiles in a crew boat: Gomes (2015) found paddlers at the stern to start the water phase an average of 0.034 s (SD = 0.016 s) earlier than the bow paddler. They studied 11 elite male (n = 6) and female (n = 5) athletes who each paddled 150 m at 110 spm in a K1 as well as in both the bow and stern positions in a K2. The primary aim of the research was to investigate how an athlete's stroke force profile changes from K1 to K2 and the crews had not necessarily paddled together before. The controlled SR and lack of reporting of boat speed means the synchronicity cannot be compared to performance, but the consistent earlier timing of the stern paddler is interesting. Tay and Kong (2018) investigated kinematic synchronicity using video and found differences between boats were not explained by performance, indicating a universal optimum does not exist. Insight can be drawn from rowing due to the similar environment: increased synchronicity was found to improve rowing performance (Baudouin & Hawkins, 2002; Wing & Woodburn, 1995) but also to increase pitch, surge and heave (Cuijpers et al., 2017) indicating increased synchronicity reduces mechanical efficiency but improves overall power production. There were also differences in opinion on the role of the athlete in each seat in a crew boat and Table 3.5 displays some examples of attributes considered important for each seat.

Table 3.5: key performance variables for sprint kayak athletes in each seat of a crew boat, according to elite coaches interviewed. Count indicates number of mentions by all coaches. Tactical aspects are reported in bold, technical aspects are underlined in dotted style and physiological aspects are underlined in solid style.

Seat 1 (driver):	Count	Seat 2:	Count
Strong mentally / Cope under-pressure / Focused	4	**Ability to follow**	3
Get the most out of the crew	1	**Boat aware**	3
Tactically aware	4	**Tactically aware**	1
Control rate/pace	5	Feel	1
Best in K1	3	Rhythm	2
Consistent	4	Technically good	1
Good feel	4	Quicker on the catch	1
Good rhythm	5	Fit	2
Fast	1	Fastest	1
Fit	2	Strong / Powerful / Engine	7
Strong / Powerful	2		
Seat 3:		Seat 4 (back):	
Ability to follow	3	**Ability to follow**	2
Bigger	3	Able to maintain higher SR	1
Fit	2	Bigger	2
Strong / Engine	13	Fast	1
		Fastest	2
		Strong / Engine	7

These factors could be considered to fall into **tactical**, technical or physiological aspects and have been formatted to show this. It appears that coaches believe the tactical and technical aspects of performance are more important for the front two paddlers, while physiological aspects are the most important for the third and fourth seat positions. In terms of speed, there were some discrepancies, with one coach stating that the fastest paddler should be in the second seat and two more saying the fourth seat should be fastest. While most coaches felt the driver was the most important for setting the rhythm and race plan of the athletes, one felt this was the role of the second seat position, this could potentially be due to exposure to different specific crews and what has worked well in the past. There is currently no literature that has investigated the relative importance of different factors to seat positions in crew boats.

The majority of coaches referred to the paddlers in seats three and four requiring bigger paddles, either via length or blade size. However, almost all the coaches mentioned a lack of clarity, knowledge or evidence for changes. Three coaches cited how traditionally, three and four had longer paddles due to the boat becoming wider further back, which is no longer the case. Two more coaches mentioned changes in boat set up from K1 to K4 as a reason for changing paddle set-up, but were unclear on why differences in boat set-up should occur either, and three coaches cited increased boat speed as a reason for increasing size due to an *easier grip on the water*. One clear rationale for difference in paddle set-up was given: the distance moved by the boat between strokes is often not long enough for the athlete in the fourth seat to put their paddle in past where the first athlete's paddle left the water. This would result in an increase in water turbulence for the fourth seat paddler which in turn, would decrease the drag force on the blade, making it harder to 'grip' the water. Increasing the blade size conversely increases the drag force and therefore may mitigate this factor. Alternatively, increasing shaft length may allow the blade to go deeper or further out into the water, meaning it is more likely to find still water. At lower rates, where there is more time between strokes and the boat often moves further between strokes, this may not be an issue.

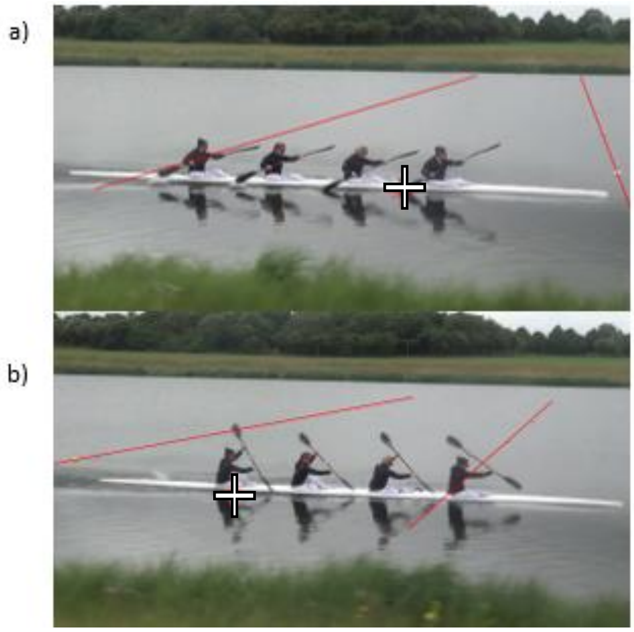


Figure 3.6: a K4 stroke shown from a) blade exit to b) subsequent blade entry of the same side. The cross allows comparison of the first paddler's blade exit with the fourth paddler's blade entry. Lines are for calibration using the buoys positioned 10 m apart.

This idea of increased water turbulence for paddlers in the back of the K4 may also provide rationale for choosing certain athletes for certain positions: at high speeds and stroke rates, all of the athletes have to produce and apply force to the water in a very short time period (this could be as low as 0.1s) but, with the added difficulty of turbulent water, the athlete in seat four in particular needs to be able to optimise drag force (grip) as efficiently as possible.

Crew boat summary

There were a number of discrepancies between coaches in terms of which characteristics were most important between seats. The first seat athlete was often considered to be technically the best to set the rhythm, while seats three and four were typically seen as strong and powerful “engines”. Coaches considered synchronicity of power application to be important, to a larger extent than synchronous kinematics. Some felt this should be in a stern-bow order, supported by the only crew boat force analysis available (Gomes, 2015), while some felt peak force should occur at the same moment. More research is needed to understand how force profiles in crew boats relate to performance.

There is very little research focused on crew boats and understanding the synchronicity of footplate and/or paddle force would add value to current coaching. The logistical challenges in measuring performance of multiple athletes in this environment likely explain the paucity of research in the area.

3.3.6 Other disciplines

Athlete’s physiological characteristics were linked to technique and performance by coaches: height, sitting height, strength, power production, fitness, muscle mass, flexibility, arm length, power to weight ratio, local muscle endurance, co-ordination, stability and speed endurance were all mentioned as influencing sprint kayaking. A review of how physiological and anthropometrical factors have been found to influence sprint kayak performance has been conducted in the literature review in Chapter 2 (for summary see Table 2.7).

Using phantom z-scores as a measure of the comparative size of a physical characteristic, Ackland et al. (2003) found Olympic sprint canoe and kayak paddlers to have larger shoulder and chest breadth, arm and chest girth and low skinfold scores relative to average. It is not entirely clear which 'average' the study is comparing to in order to create their z-scores, the methods cite the physical characteristics are compared to stature but it is not clear how z-scores would be created if only compared to their own (single measurement of) height as standard deviations are needed; reference data from the Australian Anthropometric Database are cited as a later comparison and could be used to calculate z-scores. In agreement with Ackland et al.'s conclusions, van Someren and Howatson (2008) found upper body dimensions to correlate to 500 m and 200 m performance although not 1000 m performance. None of mass, height, sitting height, arm length or arm span were found to be any higher than the average population (Ackland et al., 2003) or to differentiate between performance levels (van Someran & Palmer, 2003). These breadth and girth scores are influenced by muscle mass and this could therefore be indicative of training influencing anthropometrics, rather than any in-built anthropometric advantage.

When researchers have compared gym-based measures, bench pull maximum power was found to correlate with on-water performance but no significant correlations were found between on-water performance and flexibility or other strength measures (McKean & Burkett, 2010). Van Someran and Palmer (2003) described a kayak-specific strength test involving an isokinetic dynamometer positioned to 'simulate a kayak stroke' which was found to differentiate between national and international standard paddlers- with considerably higher torque and power in the latter group- although the design of this test and contribution of muscle groups is not clear.

Physiologically, 1000 m performance has been significantly correlated with work done in 2 minutes, work done in 30 seconds, power output at lactic turn-point and peak power (Van Someran & Howatson, 2008). For 200 and 500 m, these same variables were correlated with performance and additionally, 30 second fatigue index and strength measures from a dynamometer.

While the focus of these interviews was clearly heavily on the technical side, some psychological constructs were mentioned as important, in particular motivation, ownership and teamwork. While a review of all sport science topics is outside of the scope of this thesis, these areas brought up directly by coaches working at the highest levels of sprint kayak performance could be used by psychologists to focus research efforts on areas of direct impact.

Other disciplines summary

Many of the physiological and anthropometric characteristics mentioned by coaches as relating to performance have been supported by the academic literature, in particular strength, power and muscle mass related factors. Skeletal measures of anthropometrics have not been found to differ significantly from the general population, or between performance levels, but these factors are likely to influence technique and equipment selection. **Strength and power characteristics** correspond strongly to performance when measured in kayak-like movements and less strongly when measured in isolated movements (e.g. in a gym), highlighting the importance of specified measurement.

A greater understanding of power and force generation and how they related to performance could lead to more focused and **individual specific training** while the development of technologies to measure these factors on water could also be used for biofeedback and improve training efficiency.

3.3.7 Feedback

Although a full review of the coaches' views on feedback and how they agree with pedagogical literature is outside of the scope of this thesis, a brief summary of the key points follows. All coaches agreed feedback is important and for seven of the 12 coaches, the predominant idea was that of the importance of getting the right feedback for the athletes as individuals, which was often linked in with the idea of the coach-athlete relationship.

> *[feedback is] critically important, as long as the coach and athlete are on the same wavelength. Because it's all got to be driven by the athlete, the needs of the athlete, some athletes are very direct, and some are just "…let me just work it out for myself"*

> *there are people who like data more than anything and there are people who actually want to see a video, and see the race so it's again very individual but in order to improve, feedback, I feel, is important*

In general, researchers have found performance in movements with multiple degrees of freedom to improve with feedback, particularly when knowledge of results along with error-correcting 'transitional' information, or attention-focusing cues are provided (Kernodle & Carlton, 1992). As well as directly impacting performance, feedback has been found to positively impact competence satisfaction and autonomous motivation in a non-skilled sport task (Mouratidis, Vansteenkiste, Lens, & Sideridis, 2008).

The coach-athlete relationship has been the subject of a large amount of psycho-social research and is considered by researchers in the field to form a significant part of coach effectiveness (Jowett & Poczwardowski, 2007; Jowett, 2017). The idea of the athlete determining how feedback occurs is also supported by research, with Janelle, Kim and Singer (1995) finding that athletes controlling feedback is a better learning tool than being passively provided with feedback.

Relating to individualisation, there is a paucity of research looking at the development of motor skills through matching feedback with learning preference; the only paper which could be found on the subject is that of a undergraduate thesis focused on darts with visual or auditory feedback which concluded that learning preference did not influence skill development (Alvine, 2015). Pashler, McDaniel, Rohrer and Bjork (2008) reviewed the literature from the academic sphere and stated that evidence shows individuals demonstrate both a preference for feedback type, and an aptitude for processing information in a certain way. However, they concluded there is not sufficient evidence to support the idea that a specific instructional method is more effective for a given learning style.

For some of the coaches interviewed, the most important factor was stage of learning, with juniors considered to need more external and elite athletes considered to have developed adequate internal feedback.

> *fundamental difference between the top athletes and club athletes is in feeling, the main difference. So feedback is very important 'til they form something.*

> *everybody likes feedback, especially when you're a junior. Some of them do need technical feedback and some of the guys need more data feedback*

I think the really good athletes are able to find their own methods of internal feedback, they have a good sense, they feel through their muscles

Much of the research investigating the effect of feedback does so on those who have no previous experience of the task and no studies could be found that have investigated the influence of feedback or feedback type on elite level athletes in kayaking.

Feedback summary

Coaches interviewed were highly aware of the overall value of feedback, with emphasis placed on individuality and experience of the athletes to dictate the coaches' use of different types and frequencies.

The ideas presented about internal feedback and the level of athlete determining the amount of feedback needed, as well as individual variation, could be topics for future research, which could help in skill-development and coaching practice across levels of performance.

3.4 Overall Summary

The key components of performance outlined by coaches are summarised in Table 3.1. The key technical determinants identified were water interaction, boat connection, kinematics, force/power, SR/DPS and influence of weather. Models of sprint kayak performance in the literature on the whole match well with these overarching categories, but investigating each factor directly reveals there are very few pieces of empirical evidence that are not an oversimplification of kayaking to suit mechanical principles. Little is known about paddle movement and the hydrodynamics of paddling due to the difficulties in on-water measurement and therefore direct measurement and modelling approaches to date have been extremely limited.

Other areas revealed discrepancies in coaching beliefs and language and reaching a consensus combining coaching knowledge with existing models could be a direction for future research. In phase identification, a start, acceleration, transitions and race pace were commonly detected, but the same definition or order was not always present. A distinct and clear identification of which phase is being researched would allow ease of transfer of research conclusions. Crew boat selection also displayed discrepancies among coaches, with different elements seen as of primary importance to each seat and differences in beliefs regarding synchronicity. The paucity of research in crew boats is understandable due to difficulties in data collection but could have large impact on performance. Paddle set-up is also an area with a lack of reliable empirical evidence and one which coaches acknowledged as important but with very few ideas on how to optimise, making it another possible area for impactful research.

Among many potential research areas highlighted by coaches and not reflected in the literature, some that stand out as both measurable and valuable are: **stroke rate**, **distance per stroke**, **force production** and **power production**. In particular, **individual differences** in these simple metrics and **paddle set-up** are under-investigated and would add value. Force and power- velocity profiling have long been used in cycling to investigate bike set-up and to calculate optimal cadence (e.g. Dorel et al., 2005), understanding these metrics in sprint kayakers in a sport-specific manner could greatly enhance our understanding of the demands of the sport in a controlled manner. Understanding how and why athletes differ in simple performance measurements and how these individual differences can be used to support paddle choice, could result in individualised training and improve paddle set-up leading to improvements in performance.

Chapter 4: Power and force-velocity profiling of sprint kayak athletes

4.1 Introduction

As described in the previous chapter, force and power are directly important to coaches, in previous deterministic models (Gomes, 2015; Wainwright, 2013) and as being concepts that underpin many of the mechanical aspects to sprint kayak performance, such as water interaction and boat connection. Understanding how force, velocity and power interact in elite kayakers will therefore support and expand coaches' understanding of important aspects to technique, as has been done in other sports (Dorel et al., 2005; Colyer et al., 2017).

In cyclical movement sports, resultant movement velocity (e.g. of the bike, boat or human) is the product of cycle frequency and cycle distance. Logically, assuming all else were maintained, increasing force will increase cycle distance and increasing cycle velocity (via a decrease in cycle time) will increase frequency. Clearly then, there are large advantages to increasing both aspects of the force-velocity profile.

The literature review section of this thesis has provided a background and critique of force-velocity (F-V) relationship and has highlighted some research demonstrating the consistency of the linearity of the relationship across sports (e.g. Giroux et al., 2016) and the subsequent individuality of athletes (e.g. Samozino et al, 2012). This chapter introduction will review how F-V profiles have been useful in elite sports and the methodologies that have been used.

4.1.1 F-V, P-V and performance

Across 12 elite sprint cycling athletes, maximum power has shown a strong correlation with 200 m sprint performance when normalised for frontal surface area (Dorel et al., 2005). When comparing torque and angular velocity (the angular components that make up power), maximal torque and torque at maximal power were found to significantly correlate with maximal power ($r = 0.92$ and $r = 0.91$ respectively), but neither maximal cycle frequency, nor cycle frequency at maximal power showed significant relationships with maximal power. This would indicate that **at group level in cycling, differences in**

power are coming predominantly from changes in force generation rather than cadence.

In opposition to this, time needed to generate force rather than capacity to generate high magnitude of force has been found to be the limiter to human track sprinting; Weyand Sternlight, Bellizzi, and Wright (2000) investigated maximal running and hopping to see whether human locomotion is limited by maximal vertical force production or the time taken to generate this force. The study found hopping forces to be over 50% of a bodyweight higher than in maximal running with considerably longer contact times, indicating maximal force does not limit sprinting. In agreement, Morin et al. (2012) found **power and theoretical maximal velocity (V0) to be related to 100 m sprint performance, while theoretical maximal force (F0) was not** (see Figure 2.19 for graphical example). However, Marcote-Pequeño et al. (2019) looked at the key parameters in F-V profiling that were most strongly linked to 20 m sprinting and vertical jumping performance. Their research found high correlations with maximum power but not with V0, F0 or the F-V slope, with the authors concluding that the individual nature of the profile removed significance from group level conclusions. The importance of F-V and power-velocity (P-V) profiles in athletes is therefore not clear cut, with these studies indicating **high individual variation**, and the potential of different, preferable profiles for short accelerations of 20 m when compared to 100 m maximal sprinting.

In rowing, Giroux and colleagues (2017) compared F-V profiles created using bench pull and squat jump exercises to a 1500 m effort on an ergometer and found bench pull peak power, F0 and V0 as well as squat jump max power and F0 to all significantly relate to rowing ergometer performance, providing useful information for practitioners working in rowing. Additionally, in a review of the biomechanical factors affecting rowing performance, Baudouin and Hawkins (2002) highlighted the importance of a rower's torque-velocity characteristics in application of power to the water and in boat set-up, stating that a mechanically optimised SR should be possible from F-V relationships.

4.1.2 F-V Methodologies

Sprint cycling has often been at the forefront of F-V research in sports biomechanics research due to the measurable, controllable nature of much of the environment. Data for F-V profiles were originally collected using repeated exercise bouts (Vandewalle, Pérès, Heller, & Monod, 1985) but more recently, equipment has been designed to capture the whole F-V profile, in an appropriate sporting movement, in a single bout to avoid fatigue (Martin et al. 1997). Martin and colleagues developed the iso-inertial method, whereby the fan flywheel of an ergometer was replaced with a disc weight of known moment of inertia, the movement of which was accurately measured, through use of a photodiode, allowing torque applied to the disc to be calculated through the angular equivalent of Newton's second law ($T = I \cdot \alpha$). This method was designed to allow instantaneous measures without requiring multiple bouts and allows the whole profile to be created in a matter of seconds as a stationary start is followed by cycles of increasing speed, in a sport specific movement which makes it appealing to applied practitioners, bridging the gap between non-sport specific work in the gym and the competition environment.

Having applied their iso-inertial method in cycling ergometry, described above, Martin and colleagues went on to develop this technique for increased understanding of the water-based sport of rowing (Sprague, Martin, Davidson, & Farrar, 2007). This meant rowing F-V profiles could be measured without the influence of fatigue which would undoubtedly influence other measurement techniques. While not directly representing on-water performance, this measure of fatigue-free power and F-V relationship allows insight into transferability of land (strength and conditioning) training as well as technical insight as highlighted above by Baudouin and Hawkins (2002). In rowing, the stroke cycle can be broken down and power, force and velocity values can be taken as: instantaneous output, averaged over the pull phase of a stroke or averaged over the entire stroke. Sprague et al. (2007) found linear F-V and quadratic P-V profiles were well defined for each of these breakdowns in male college level rowers (n = 11), with optimum velocity for maximising power occurring at different points (instantaneous power 3489 W occurring at 3.43 $m \cdot s^{-1}$, pull power 1995 W at 3.25 $m \cdot s^{-1}$ and stroke power 812 W at 2.04 $m \cdot s^{-1}$). The ratio of pull to recovery time is not consistent in rowing, known as an 'unconstrained duty cycle' this means velocities are not synonymous with a stroke rate, and additional research would be needed to understand the relationship between SR and power.

Force-velocity profiles have frequently been found to be linear across sporting movements (Bozic & Bobana, 2018; Giroux et al., 2016; Haugen et al., 2019), thought to be due to segmental dynamics (Bobbert, 2012; see Section 2.8.2 for further discussion), although it is not always clear if other relationships have been investigated. Researchers who have directly investigated other fits have found polynomial, exponential and linear fits to all result in high correlation values, with linear recommended due to improved accuracy in power calculation (Iglesias-Soler, Fariñas, Mayo, Santos, & Jaric, 2019; Zivkovic, Djuric, Cuk, Suzovic, & Jaric, 2017).

Differences have been found in profiles created between maximum and average values and the point of maximal force occurs at a different moment in the stroke to that of maximal velocity (Zivkovic et al. 2017). In a review of F-V profiling within strength and conditioning (S&C) research, Picerno (2017) cited that all papers found used the average for force and velocity for correlation, citing the reason for this to be to remove the effect of the non-linear velocity during a lift that occurs due to advantageous muscle moment arms during specific parts of the movement. These maximum and average values represent different capacities and therefore may both be of value in an applied setting, provided context is available. While a maximum may better represent a true capacity measure, it is not directly relevant to power if maximal force and velocity are taken at separate instances. In addition, an instantaneous maximum is also more susceptible to noise or error in the measurement and therefore less reliable.

4.1.3 F-V in Sprint Kayaking

Peak power as measured on a kayak ergometer has been found to be highly related to on-water 200 m performance (van Someren & Palmer, 2003). The authors compared 13 international level with 13 national level 200 m kayakers and found international athletes to have: significantly higher peak power (615 ± 81.5 W vs 476 ± 72.3 W), higher total work in a 30 second all-out test and higher isometric force and isokinetic power from an isokinetic dynamometer. The accuracy of the measurement cannot be determined as the sample rate and peak detection methods are not clearly described. While the use of a 30 second test reflects the duration of a race, it would be too long to document a 'true' maximal effort and does not give insight into how the power is created; the additional calculation of F0 and V0 in F-V profiles created from maximal efforts allows coaches and S&C coaches insight into how they can influence and increase power.

Similar values of maximal power have been attained for elite athletes (males, n = 6; females, n = 4) from air braked kayak ergometers (610 ± 65 W males, 359 ± 33 W females, Bjerkefos et al., 2018). A maximal intensity effort of 20 strokes was completed as the final stage of an incremental step test, and maximal power was taken as the average from 10 strokes. As a stroke average, these values are considerably lower than those achieved by rowers, but this may be explained by the use of a 10-stroke average alluding to a sustainable, rather than peak, stroke power.

Schofield (2015) directly investigated the F-V and power velocity relationships of 12 elite kayakers using an iso-inertial ergometer based on the design of Martin's (1997) cycle ergometer and compared 200 m and 1000 m paddlers. Peak stroke power was found to correlate with a more force-orientated profile (ratio of F0 to V0) across the cohort, while the 200 m group had higher values for stroke power (from catch of one hand to catch of the other; 687 W vs 613 W), stroke force and velocity. As this group included three Olympic medallists, compared to non-medallists in the 1000 m group, it is not clear whether these differences are the result of the distance focus training, or the higher relative level of the athletes, therefore highlighting an area for valuable research.

The differences in ergometer design, variable measurement, stroke breakdown and lack of normalisation within the above studies make them difficult to compare directly to each other. Furthermore, **no studies could be found that have investigated the F-V profile of athletes of different levels in sprint kayaking**, resulting in an opportunity for impactful research.

4.1.4 Trainability of F-V

Short term resistance training interventions have been found to produce changes in the F-V profile in physically active participants, with high resistance and therefore low velocity training causing increases in F0, and low resistance, high velocity training inducing higher V0 post training intervention (García-Ramos, Torrejón, Pérez-Castilla, Morales-Artacho, & Jaric, 2018). As the participants in this study were not highly trained, it would be expected that larger changes could be achieved in a relatively short space of time, but it is not clear if the same changes would occur in elite or highly trained athletes.

Colyer et al. (2017) profiled 12 bob-skeleton athletes over the course of almost 18 months to investigate how a training cycle, as defined by the S&C coach, might influence the F-V profile of athletes. Profiles were created from a pneumatic resistance horizontal leg-press, measuring force and velocity at a sampling rate of 400 Hz. While this methodology is subject to some of the limitations mentioned previously (e.g. different movement pattern, influence of fatigue, approximation of linear trend), the measurements were consistently done at least seven times across the time period, so could be directly compared. As might be expected, the authors found increases in maximal force generation were high in strength-heavy training blocks, while decreases in this same parameter and increases in maximum velocity were found during the winter (competition) period. Although individual adaptations are not reported, there was a differentiation made between elite athletes, and those relatively new to the sport, with new athletes demonstrating the same trends but with larger increases in maximal force generation.

4.1.5 Individuality in F-V profiles

Most of the research above has focused on group means, but some researchers have investigated the differences that exist between individuals. Samozino et al. (2012) described large differences in F-V profile within one cohort and outlined an 'optimal profile' (i.e. an optimal gradient of the profile) for vertical jump performance (Figure 4.1). Working from a theoretical approach outlined in a previous paper (Samozino, Pierre, Morin, Hintzy, & Belli, 2010), which in turn worked from defined mechanical laws such as equations for constant acceleration, mechanical work and energy, to create an equation determining the relationship between force, velocity and jump height, the authors investigated the influence of power and F-V profile shape on jump height and derived the following equation for maximal take off velocity, v_{TOmax}:

$$v_{TOmax} = h_{PO}\left(\sqrt{\frac{S_{FV}{}^2}{4} + \frac{2}{h_{PO}}\left(2\sqrt{-\bar{P}_{max}S_{Fv}} - gsin\alpha\right)} + \frac{S_{Fv}}{2}\right) \qquad \text{Equation 2}$$

Where h_{PO} is the distance moved by the centre of mass during push off, S_{Fv} is the slope of the force velocity curve ($S_{Fv} = -\frac{F_0}{v_0}$), α is the angle of inclination and $\bar{P}_{max}$ is the maximum power produced. From this they surmised that an individual optimal profile for

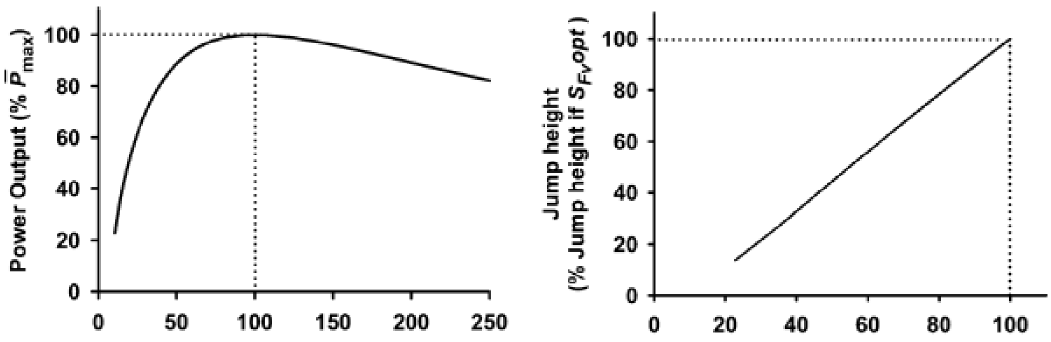


Figure 4.1: a) relationship between the F-V gradient (S_{FV}) and power output during jumping and b) power output relationship with jump height. Dotted lines indicate 'optimum' profile (Samozino et al., 2012).

ballistic performance is dependent on maximum power production, limb extension range and on the inertia and inclination of the movement. Figure 4.1 demonstrates how changing the S_{Fv} for an individual creates a decrease in power output (a) that directly results in lower performance (b; jump height). The resultant power output decrease is much starker as profiles become more velocity-orientated compared to a move towards a more force-orientated profile (see Figure 2.19 in the literature review for example of different profile orientations).

In a training study, Jimenez-Reyes et al. (2017) profiled 84 athletes and for the intervention group, prescribed training according to how their profile compared to their theoretical optimal for maximising vertical jump (outlined above). Those who exhibited a force or velocity ‘deficit’ (i.e. their profile showed a different gradient to their theoretical optimal) were classified accordingly and underwent a nine-week training programme aimed at decreasing this deficit. The training reduced the so-called ‘imbalance’ and resulted in greater increases in jump height when compared to a those who had undergone a traditional training programme.

4.1.6 Literature Summary

Power has been strongly linked to successful sprint performance in a variety of sports and as power is the product of force and velocity, researchers have tried to identify if maximum power production is based more on one of these variables than the other. Understanding how maximum power is generated in kayaking with different levels of performance through a fatigue-free measurement will allow coaches to focus training for efficient development.

4.1.7 Aim & Research Questions

The aim of the current study was to investigate and compare the F-V and P-V profiles of elite, sub-elite and club level sprint kayakers in order to increase understanding of performance in kayaking and the extent of the individuality of F-V and P-V profiles.

Research Question 4.1: *do power and force-velocity relationships explain differences in performance level in sprint kayakers?*

Research Question 4.2: *do group level average profiles represent the individuals in the group?*

4.2 Methods

4.2.1 Participants

Thirty-nine athletes (Table 4.1) volunteered for the study. These athletes were categorised as 'club', 'sub-elite' or 'elite' according to their competition level (Table 4.2).

Table 4.1: Group level participants' characteristics for each gender (group mean ± SD)

Gender	N	Level	Age (years)	Mass (kg)
Female	2	Club	29.9 ± 18.3	63.2 ± 12.9
	8	Sub-elite	22.6 ± 3.4	71.9 ± 7.1
	4	Elite	25.2 ± 4.4	70.7 ± 6.1
		Mean	**25.9**	**68.6**
Male	9	Club	20.2 ± 10.6	76.7 ± 4.7
	7	Sub-elite	21.1 ± 2.1	80.5 ± 4.3
	6	Elite	23.4 ± 5.0	81.8 ± 3.3
		Mean	**21.6**	**79.6**

Table 4.2: Performance level classification description

Classification	Description	Competition Level
Club	Member of a British Canoeing registered club	National regatta
Sub-elite	Part of the national governing body podium potential squad	International event
Elite	Part of the national governing body podium squad	Regularly compete on international circuit including World/European Championships

All participants provided informed consent and took part in a minimum of two familiarisation sessions and one testing session. A sub-group of 18 elite and sub-elite athletes took part in additional testing between the March and August of one competitive season with a minimum of three testing sessions. All participants were injury and illness free and had been cleared to participate by medical practitioners (elite and sub-elite athletes), or through assessment of a pre-test questionnaire (club athletes). Participants aged between 16 and 18 years provided informed assent, with informed consent from a parent or legal guardian. Ethical approval was gained from the University of Lincoln School of Sport and Exercise Science ethics committee.

4.2.2 Isoinertial ergometer

The ergometer used was an adapted Dansprint model (Dansprint, Hvidovrere, Denmark), as used and described in previous sprint kayaking research (Schofield, 2015), with additional modifications described below. The ergometer was fixed to the gym floor foundations via screws with a floor covering of 10 mm layer of dense rubberised matting. A standard Nelo (Nelo, Vila Do Conde, Portugal) seat and footrest were attached with fully adjustable settings. The ergometer paddle shaft length was set to match that used by the athlete on-water, with the ropes connecting to the end of the ergometer shaft representing the assumed centre of pressure of 20 cm from the end of the blade of the athlete's normal paddle length (Figure 4.2a).

The original flywheel was replaced with disc weights to create an isoinertial load, where the only resistance of the flywheel is provided by its inertia. The position of the flywheel was measured via a slotted reflective surface with 15 segments. The surface (Figure 4.2c) reflected the light from a photodiode, which was received by an optical sensor. The time between each slot was recorded by an Arduino microprocessor (Arduino micro, Atmel Corp. San Jose) with the timestamp output each time a non-reflective section moved passed the photodiode. The 15 non-reflective segments were machine cut with π/8 radians between them, with the exception of an index slot to identify a full rotation of the flywheel, which was cut with a gap of π/4 radians. As the radius of the sprocket was 0.03285 m, this resulted in a measurement every 0.0129 m of rope (and therefore paddle) movement. This method of force calculation has been used previously in both cycling (Martin et al., 1997) and rowing (Sprague et al., 2007) and the kayak ergometer in this form has been used in previous F-V research (Schofield, 2015). Pilot testing established good levels of within-athlete reliability (2.6-6.2%).

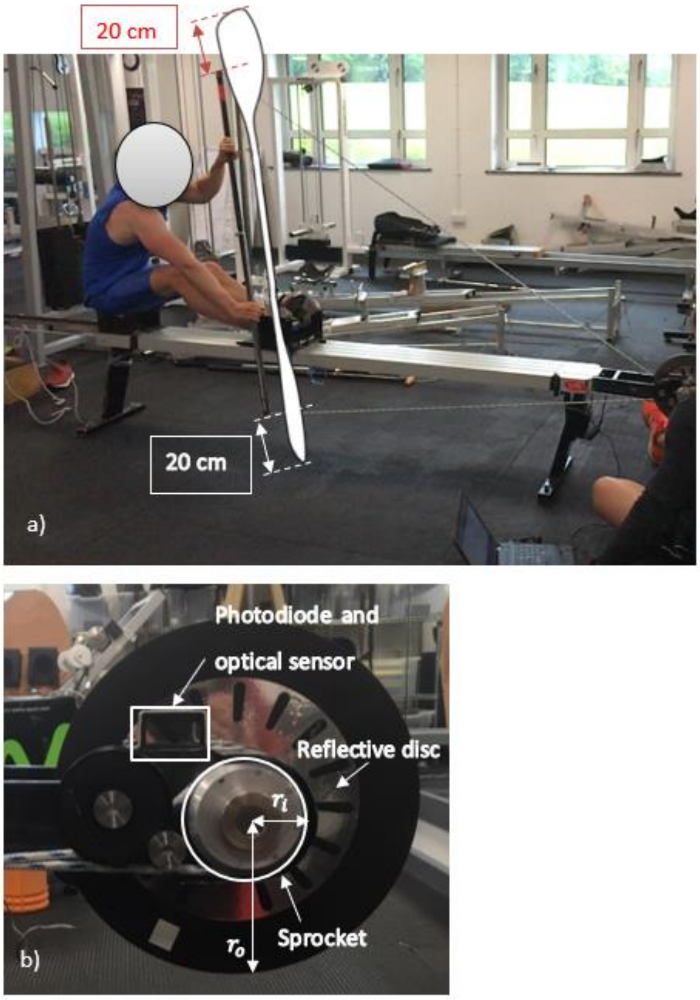


Figure 4.2: a) photo of paddler on the isoinertial ergometer and comparison to on-water paddle set-up diagram b) labelled ergometer disc flywheel with reflective surface.

Following pilot research which demonstrated that changing bungee tension influenced the power output (Shin, Willmott, Mullineaux, & and Worsfold, 2017), a steel bracket and load cells were added, through which the bungees are attached, allowing the force applied to the bungee to be included in calculations. The load cells were linked to the Arduino microprocessor to output force data alongside timestamp data outlined above.

The moment of inertia of the flywheel was set individually per athlete, by adding or removing discs with a resultant disc mass range for the group of 3-7 kg and an inertial load range of 0.036 to 0.077 kg·m^2. Selection was made from pilot data based on the highest peak power, strongest coefficient of variation and reaching peak power midway through the effort (~stroke 6). Due to the parabolic nature of the P-V relationship, it is important for peak power to occur near the midpoint of the test in order that it can be clearly identified.

4.2.3 Test protocol

As many of the athletes were full time athletes, it was not possible to control training prior to testing, or between sessions for the sub-group. For these athletes, to reduce the effect of fatigue or previous training load, data collections were included in training plans in the morning and, where possible, this was done following a rest day with no training. The timing of these testing sessions for the sub-group was not consistent as athletes were part of different training groups. Sub-group data for whole group analysis were taken from the date nearest the highest-level competition the athletes entered that year (e.g. world championships, junior world championships, international regatta etc.).

The two familiarisation sessions were completed separately within the four weeks preceding the first testing session and consisted of five trials of 14 maximal effort strokes with three minutes passive recovery between trials (Hoianaski, Franchini, Matsushigue & Schneck, 2007; Toubekis, Douda & Tokmakdis, 2005). Athlete were asked to paddle in as close an approximation of on-water paddling as they were able to. In order for the rope to retract at a high enough rate to handle the high-velocity end of the data collection, bungee tension was generally set higher than the athletes would typically use on an ergometer, which may have slightly affected kinematics and highlighted the need for two familiarisation sessions.

Athletes completed the same standardised gym warm up (Appendix 2) with an additional minimum of 5 minutes of ergometer paddling, inclusive of one sprint effort of approximately five second duration. The gym warm-up was approximately ten minutes in duration and was devised by the S&C coach and physiotherapist to increase heart rate and activate appropriate muscles. Paddlers were given approximately one minute of re-familiarisation time on the inertial load ergometer prior to testing commencing, or more if they wished. Participants completed a total of five trials with three minutes of recovery between trials, in line with previous research (Schofield, 2015). The first trial for all athletes was regarded as a re-familiarisation trial and was not included in subsequent analysis. Each trial consisted of 14 maximal effort strokes, of which the first 12 were included in the analysis, in order for maximal effort to be ensured across all strokes. Trials were started with the paddle forward on the side the athlete would usually use for starting on water, in a position reflective of that used in a standing start during a race (Figure 4.2a). The flywheel was then rotated so that the index ‘slot’ was positioned level with the photodiode and held there, being released after a three second verbal countdown ending in a 'go' command, upon which point the trial started. Verbal encouragement was given throughout to encourage maximal effort. The design of this ergometer with high inertia creates a slow, high force first stroke, with each consecutive stroke increasing in speed. The researcher counted the strokes and gave a clear shout of 'stop' after 14 strokes had been completed.

4.2.4 Calculations

All calculations were conducted in Microsoft Excel (2010). The flywheel moment of inertia was the sum of the components, which included the spacers, freewheels, bolts, weighted discs, and the axle. Moment of inertia (I) of the discs was calculated from the mass (m), inner radius (r_i) and outer radius (r_o) as outlined in the equation below:

$$I = \frac{m({r_i}^2 + {r_o}^2)}{2} \qquad \text{Equation 3}$$

The bolts were treated as a point mass, where $I = mr^2$, where r is the distance from the centre of the bolt to the axis of rotation. The inertia of the flywheel (I_F) was modified for individual athletes based on pilot work as mentioned above.

Angular velocity of the flywheel (ω) was calculated as change in angle (θ) divided by the change in time (t). Angular velocity data were second-order low pass Butterworth filtered at a visually selected frequency of 6 Hz and the following calculations conducted:

Angular acceleration (α):	$\alpha = \frac{\Delta\omega}{\Delta t}$	Equation 4
Torque (T):	$T = I_F \cdot \alpha$	Equation 5
Force (F):	$F = \frac{T}{r_s}$	Equation 6
Power (P):	$P = T \cdot \omega$	Equation 7
Paddle tip velocity (V_P):	$V_P = \omega \cdot r_s$	Equation 8

All calculations were conducted for the entire duration of the trial and the pull portion of strokes was subsequently detected using a threshold power of 10%. Each stroke was used to calculate SR throughout the trial:

$$SR = \left(\frac{1}{stroke\ duration}\right) * 60 \qquad \text{Equation 9}$$

In line with previous ergometry studies with water sports (Schofield, 2015; Sprague et al., 2007) averages were then calculated per stroke across the pull phase and across the stroke cycle (including recovery time) in addition to the instantaneous values (Figure 4.3 & Figure 4.4). This resulted in a 12 x 15 matrix of stroke number by variable.

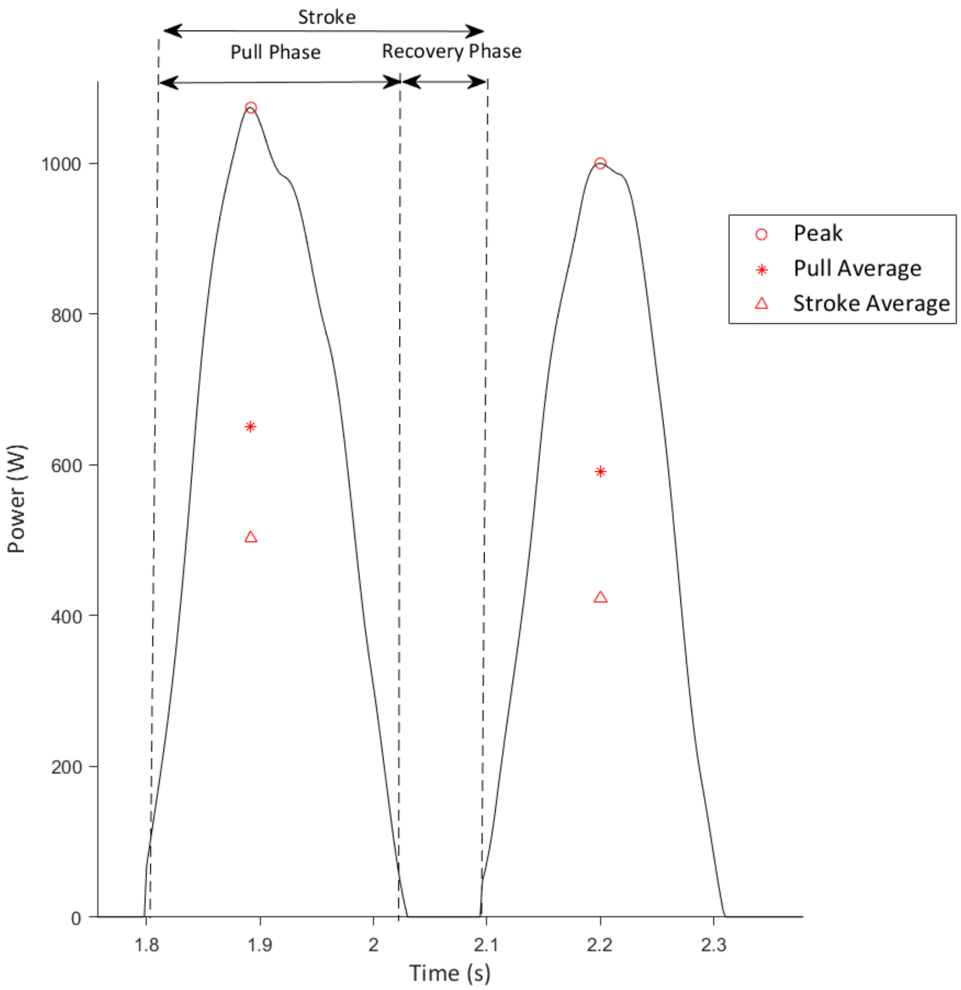


Figure 4.3: Example power-time curve from the ergometer for two strokes denoting pull and recovery phases and stroke definition. Calculated pull and stroke averages and peaks are marked.

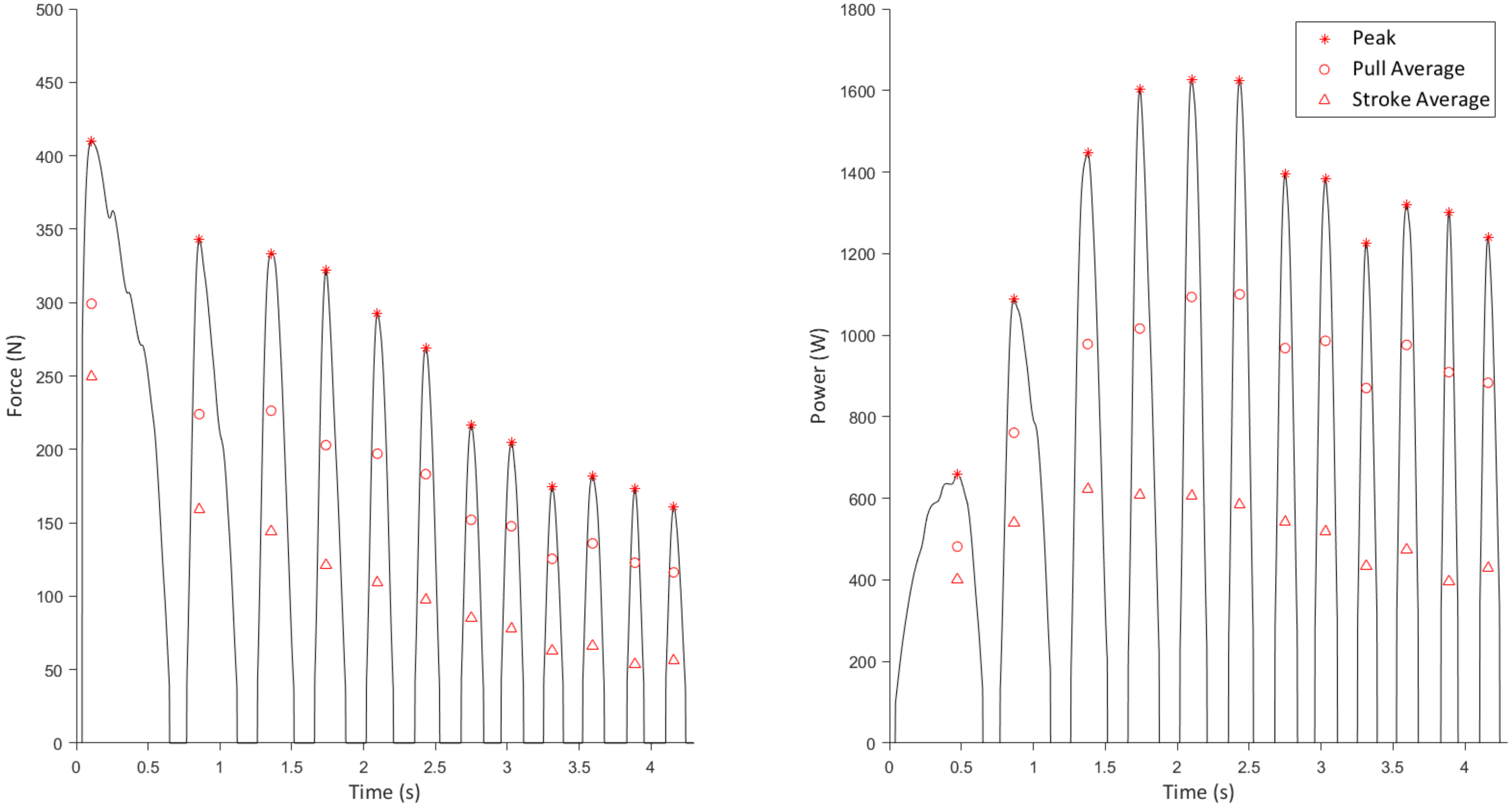


Figure 4.4: Example data from one ergometer trial. Calculated force-time and power-time curves for all 12 strokes. Calculated pull and stroke averages and peaks are marked.

Test maximums and averages (across all strokes) were then identified and calculated for each trial. Force and power were then normalised using allometric scaling, dividing by body mass$^{0.67}$ (Jaric et al., 2005; Jaafar, 2017; see Sections 2.8.1 and 4.4.1 for discussion).

Three F-V profiles were created from 12 strokes per trial using each of: values for instantaneous maximum or 'peak' force per stroke and the velocity at which it was created; average values across the pull phase and average values across each stroke. Figure 4.5 shows examples of each of these profiles for one trial, along with their linear fit and regression equations.

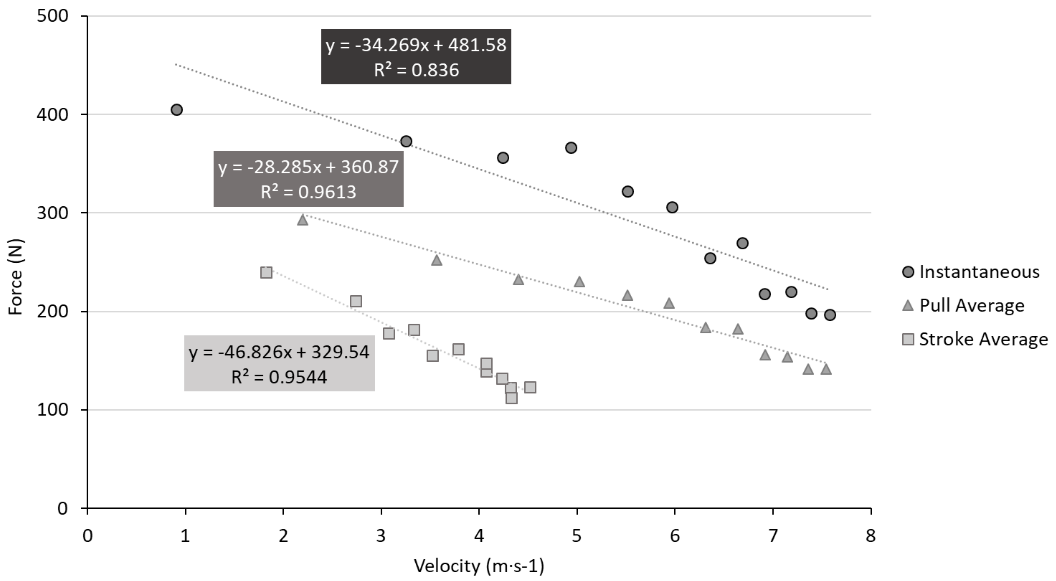


Figure 4.5: an example of the peak instantaneous, pull average and stroke average F-V profiles created from the ergometer for one trial with the linear trend line, its equation and r² value shown for each.

Distinct differences were apparent, in line with previous research (Schofield, 2015). Using one finite moment in time in the instantaneous data is more susceptible to variability within a given stroke or noise within the measurement and, although the linear fit was strong, high variability was also present across the group ($r^2 = 0.88 \pm 0.13$). The stroke average values show a weaker linear trend ($r^2 = 0.77 \pm 0.18$), again with high variability across the group. Stroke averages include the 'recovery' phase of a stroke where no active force is being applied to the ergometer and so may have reduced relevance for maximal capacity, although this could be countered by considering the increased ecological validity. The F-V created from pull averaged values demonstrated high linearity and high consistency ($r^2 = 0.92 \pm 0.05$). Therefore, all subsequent analysis of F-V profiles used force and velocity were averaged across the pull phase. Using averages across the active phase also allows for valid comparison to F-V profiles created from gym exercises

(Picerno, 2017), which provides context for this new testing methodology within the multidisciplinary team.

The slope of the F-V profile ($S_{F\text{-}V}$) was calculated as the slope of the linear regression, as in previous research (Samozino et al, 2012; Schofield, 2015). From this profile, extrapolation across the axes allowed calculation of F0 (force generated at hypothetical zero velocity) and V0 (velocity at hypothetical zero force). While categorisation into force-orientated or velocity-orientated did not occur, these terms were used as relative descriptors, with more force-orientated indicating a steeper F-V and therefore a higher $S_{F\text{-}V}$, in line with Samozino et al. (2012).

Power-velocity (P-V) profiles for each aggregation level were created using a second order polynomial regression of power with velocity, with maximal power (P0) calculated as the apex of the curve (e.g. Dorel et al., 2005; Sprague et al., 2007). In total, nine possible measures of power were created with which to summarise a trial (Table 4.3). As force is a component of power, the values calculated for peak and stroke are subject to the same limitations as cited above and the values relating to pull power only were used for this study. All three power variables for pull power (trial mean, trial maximum and theoretical maximum) were all calculated and taken forwards for analysis.

Table 4.3: Power variables calculated within and across strokes

		Within stroke:		
		Peak	Pull	Stroke
Within Test:	Mean	$PeakPower_{mean}$	$Power_{pull,ave}$	$Power_{str,ave}$
	Maximum	$PeakPower_{max}$	$Power_{pull,max}$	$Power_{str,max}$
	Theoretical	$P0_{peak}$	$P0_{pull}$	$P0_{stroke}$

Force-SR (F-SR) and power-SR (P-SR) profiles were created using SR along with both pull and stroke averages per stroke for force and power. From these, stroke rate at maximum power ($SR_{opt,pull}$, $SR_{opt,str}$) were calculated. The latter was conducted as stroke rate incorporates the recovery time and therefore is of more direct contrast to the stroke averages than with the pull averages.

4.2.5 Statistical analysis

Data were analysed using SPSS (IBM SPSS Statistics for Windows, Version 22.0., IBM Corp., Armonk, NY) and Microsoft Excel (2010, etc). For each athlete, the average values for F0, V0, $Power_{pull,ave}$, $Power_{pull,max}$, $P0_{pull}$, $S_{F\text{-}V}$ $SR_{opt,str}$ and $SR_{opt,pull}$ were calculated from the final four trials to input into statistical calculations. Significance was set at $p < 0.05$.

4.2.5.1 Group analysis

Normality of the data distribution was checked using the Shapiro-Wilk test. At group level (club, n = 11; sub-elite, n = 15; elite, n = 10), all data were normally distributed ($p \geq 0.299$) except for V0 ($p = 0.024$). Between groups one-way ANOVAs were used for all variables. While ANOVAs have been found to be robust to violations in the assumption of normality (Schmider, Ziegler, Danay, Beyer, & Bühner, 2010), a comparison of ANOVA results with the results of a non-parametric Kruskal-Wallis ranks test was conducted for variables that violated the normality assumption (at group level, only V0).

Cohen's *d* was calculated as a measure of effect size for group level analyses for all variables (F0, V0, $Power_{pull,ave}$, $Power_{pull,max}$, $P0_{pull}$, $S_{F\text{-}V}$, $SR_{opt,str}$ and $SR_{opt,pull}$). The equation for Cohen's d is below:

$$d = \frac{|M_{exp} - M_{Cont}|}{SD_{pooled}} \quad \text{Equation 10}$$

Where M_{exp} is the mean of the experimental group, M_{Cont} is the mean of the control group and SD_{pooled} is the average standard deviation of the two data sets. As the absolute value of the numerator is taken, it is not important which group is considered the 'control' or 'experimental' group in this study.

To investigate gender-specific group level differences, data were first split according to gender and same the analyses run. The female club group only included two athletes and therefore non-parametric Kruskal-Wallis testing only was conducted for female group comparisons. All data were normally distributed for both genders ($p \geq 0.185$) with the exception of V0 for males ($p = 0.003$). One-way ANOVAs were therefore run on all variables for male athlete data, with an additional Kruskal-Wallis test on the male V0 data.

4.2.5.2 Individual analysis

For individual level analysis, F0 and V0 were correlated against $Power_{pull,ave}$ for each athlete's set of data, using one value for F0, V0 and stroke power per trial resulting in between 12 and 26 data points per athlete. Tests for assumptions of normality, linearity and homoscedacity revealed violations and therefore correlations were conducted using Spearman's rank order test. Visual assessment of linearity was conducted and subjectively categorised into: clear strong linear pattern ('Strong'), apparent linear trend ('Medium'), potential linear trend ('Low') and no linear trend ('None'), examples of each of these can be seen in Appendix 3. As r^2 values are considered a measure of size of effect (Knudson, 2009) no additional calculations were conducted.

4.3 Results

For data that violated the normality assumption, neither the ANOVA nor the Kruskal-Wallis showed significant differences in V0 between groups, although the Kruskal-Wallis test neared significance (ANOVA $p = 0.257$; Kruskal-Wallis $p = 0.051$). For male athletes, significance of V0 was not affected by test used, with non-significant differences between groups with both tests (ANOVA $p = 0.630$; Kruskal-Wallis $p = 0.350$).

The three measures of power resulted in the same overall trends, with highest values for the elite athletes, followed by sub-elite and then club (Table 4.4). However, statistical significance was not the same for the three different measures of power. For male athletes $Power_{pull,ave}$ and $Power_{pull,max}$ were significantly higher for both the sub-elite ($p < 0.001$) and elite ($p < 0.001$) groups relative to club but the difference between sub-elite and elite athletes did not reach statistical significance. For $P0_{pull}$, the difference between club and sub-elite did not reach significance either. For female athletes, the same increasing trend with level was seen with statistical significance between club and elite in $Power_{pull,ave}$ and between club and both elite and sub-elite for $P0_{pull}$.

For F0, significant differences between male and female club athletes and those at elite level was found, but no significant differences between club and sub-elite or between sub-elite and elite. There were no significant differences in V0 between any group, but it was highest for sub-elite in both male and female athletes. Despite graphically visible differences between groups (Figure 4.6a), the only statistically significant differences in the gradient of the S_{F-V} was between elite and club males.

Using Cohen's (1988) definitions, effect sizes were 'large' (> 0.8) for all measures of power and for F0 when elite and sub-elite were compared to club athletes after separating for gender (Table 4.5). Large effect sizes were also apparent comparing female elite and sub-elite athletes with club athletes for V0 and $SR_{opt,pull}$. When comparing male elite to sub-elite athletes, large effects were apparent in maximum and average pull power, F0, V0, S_{F-V}, $SR_{opt,pull}$ and SR0. Large differences are apparent when effect sizes were calculated on grouped relative to gender-split data.

Table 4.4: Normalised power, normalised force, velocity, slope of the F-V profile and maximum SR for club, sub-elite and elite athletes. * indicates significant difference from elite at p < 0.05 level. Δ indicates significant difference from sub-elite at p < 0.05.

Variable	Group	Mean	SD	Male Mean	SD	Female Mean	SD
$Power_{pull,mean}$ ($W \cdot kg^{0.67}$)	Club	38.88*	1.93	41.37*^{Δ}	3.83	27.65	9.29
	Sub-elite	40.98	1.74	49.98	2.26	37.12	5.89
	Elite	48.49	2.70	54.76	4.39	39.55	4.49
$Power_{pull,max}$ ($W \cdot kg^{0.67}$)	Club	46.06*	8.58	49.24*^{Δ}	3.99	31.77*	10.42
	Sub-elite	49.02	8.99	59.58	1.48	44.50	6.40
	Elite	56.89	10.58	64.16	5.97	46.51	5.61
$P0_{pull}$ ($W \cdot kg^{0.67}$)	Club	42.39*	13.34	46.97*	9.60	21.78*^{Δ}	1.87
	Sub-elite	46.73	10.41	59.35	5.91	41.31	6.09
	Elite	53.81	10.70	61.00	6.60	43.53	5.52
F0 ($N \cdot kg^{0.67}$)	Club	14.21*	1.93	14.80*^{Δ}	1.47	11.58*	1.66
	Sub-elite	14.45*	1.74	15.95	0.61	13.80	1.67
	Elite	17.62	2.70	19.52	1.47	14.90	1.24
V0 ($m \cdot s^{-1}$)	Club	12.04	0.38	12.42	1.29	10.34	2.17
	Sub-elite	12.64	0.04	14.35	1.27	11.90	0.99
	Elite	12.10	0.37	12.43	1.54	11.63	0.90
S_{F-V}	Club	-21.45*	3.89	-1.20*	0.20	-1.13	0.08
	Sub-elite	-20.88*	3.18	-1.35*	0.25	-1.16	0.15
	Elite	-27.04	6.07	-1.65	0.33	-1.38	0.09
$SR_{opt,str}$ (spm)	Club	150.74	15.88	150.89*	16.61	150.07	17.69
	Sub-elite	150.59	50.08	170.47	4.49	140.65	8.25
	Elite	167.07	17.84	173.86	15.88	157.38	16.84
$SR_{opt,pull}$ (spm)	Club	187.02	98.81	208.86	54.75	110.58	86.01
	Sub-elite	213.43	41.14	251.63	27.42	197.06	35.30
	Elite	204.08	32.86	210.61	34.35	194.75	30.61
SR0	Club	346.45	42.97	346.56	47.24	345.97	24.78
	Sub-elite	360.29	51.10	403.47	27.93	341.79	48.22
	Elite	366.41	29.63	372.76	36.11	357.34	14.87

Table 4.5: Effect sizes across the whole group and gender specific groups. Grey shading indicates 'large' effect size according to Cohen's (1988) effect sizes.

Group	M_{exp}	M_{cont}	$Power_{pull,ave}$ ($W{\cdot}kg^{0.67}$)	$Power_{pull,max}$ ($W{\cdot}kg^{0.67}$)	$P0_{pull}$ ($W{\cdot}kg^{0.67}$)	F0 ($N{\cdot}kg^{0.67}$)	V0 ($m{\cdot}s^{-1}$)	$S_{F\text{-}V}$	$SR_{opt,str}$ (spm)	$SR_{opt,pull}$ (spm)	SR0
All	Elite	Sub-elite	0.90	0.80	0.67	1.43	0.37	1.33	0.49	0.25	0.15
	Elite	Club	1.20	1.13	0.95	1.47	0.04	1.12	0.97	0.26	0.55
	Sub-elite	Club	0.28	0.34	0.37	0.13	0.38	0.16	0.00	0.38	0.29
Male	Elite	Sub-elite	1.44	1.23	0.26	3.44	1.37	1.98	0.33	1.33	0.96
	Elite	Club	3.26	3.00	1.73	3.21	0.01	1.79	1.41	0.03	0.63
	Sub-elite	Club	2.83	3.78	1.60	1.11	1.52	0.21	1.86	0.65	1.51
Female	Elite	Sub-elite	0.47	0.34	0.38	0.75	0.28	0.54	0.47	0.07	0.49
	Elite	Club	1.73	1.84	5.88	2.30	0.85	1.30	0.42	1.44	0.57
	Sub-elite	Club	1.25	1.51	4.91	1.34	0.99	0.69	0.26	1.43	0.11

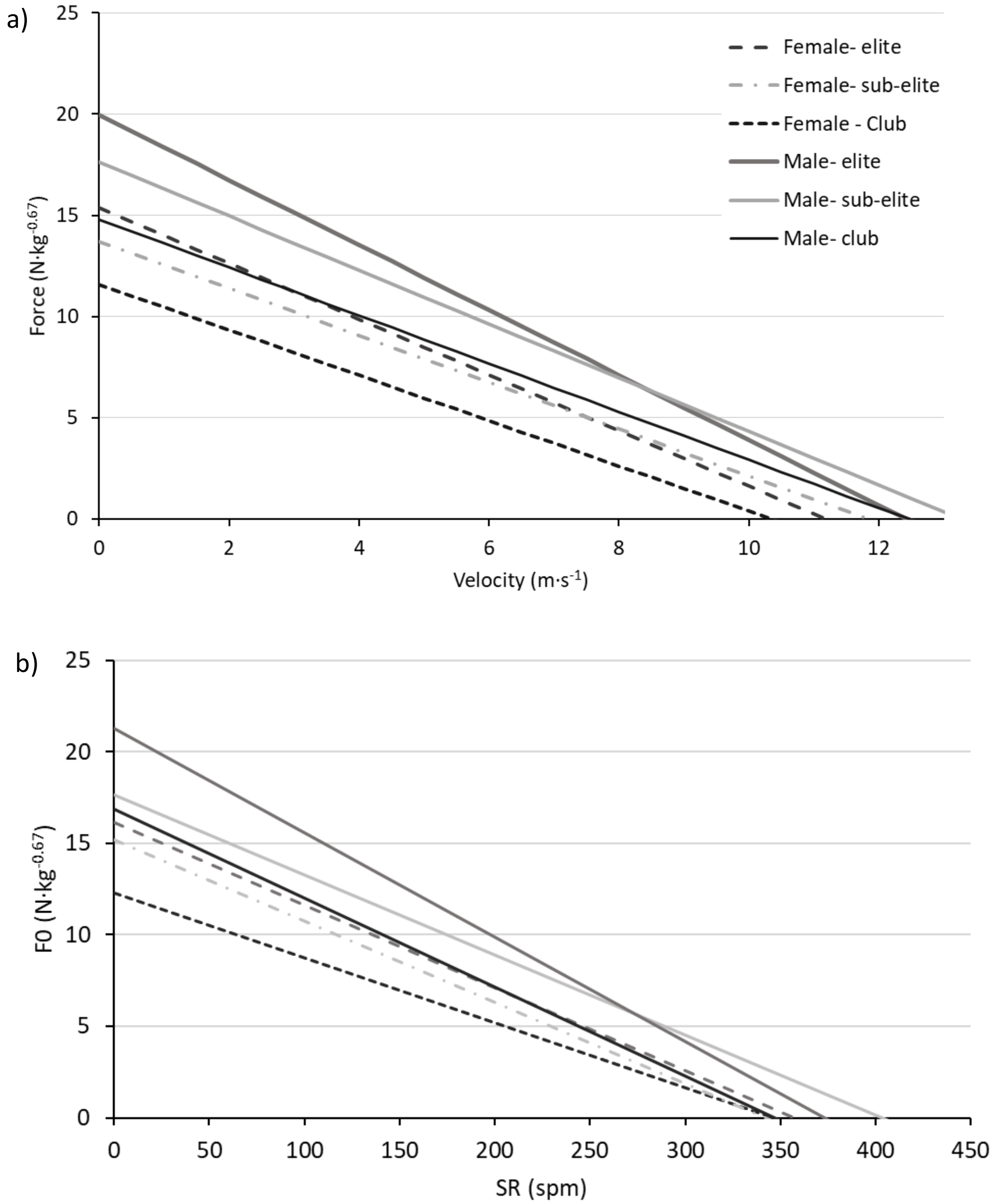


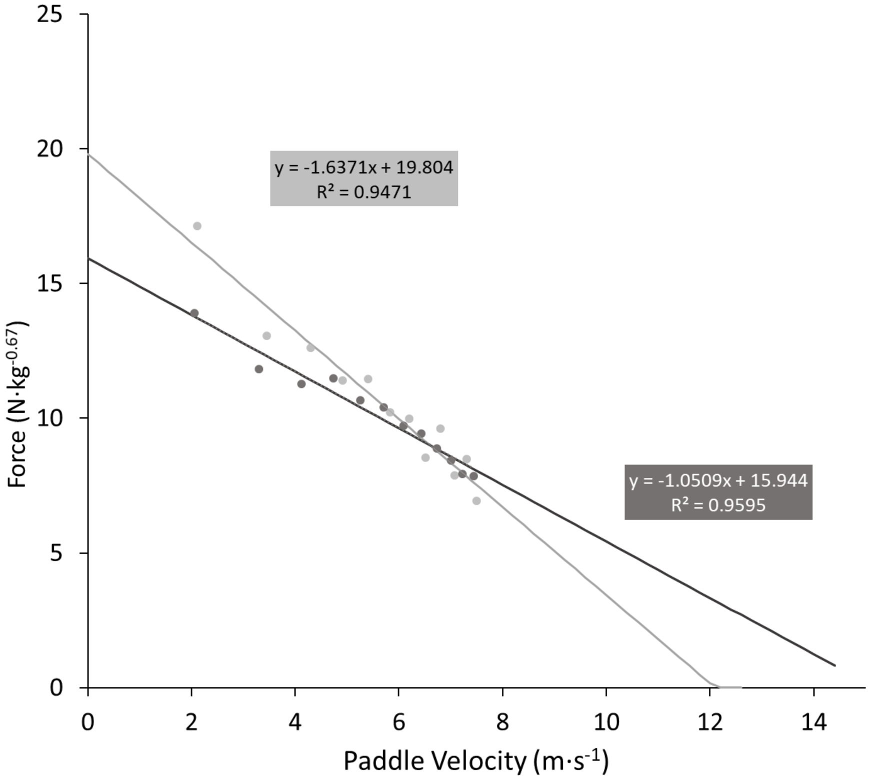
Figure 4.6: a) Force-velocity profiles and b) Force-SR profiles for group means of elite, sub-elite and club, male and female athletes.

Individuals were found to exhibit differences in both the strength and direction of their correlations (Table 4.6). For eight athletes, F0 was found to correlate positively and significantly with stroke power, indicating F0 is the stronger determinant of power for those athletes. Five of these eight displayed 'medium' or 'strong' linear relationships, increasing the applied value of the statistical relationship. On the other hand, six athlete exhibited negative relationships between F0 and stroke power, although only one reached significance. Five athletes were found to have a significant, positive and 'strong' linear correlation between V0 and stroke power, with three further exhibiting negative correlations.

Table 4.6: Individual athlete correlations of F0 and V0 against stroke power. *denotes correlations with p-values lower than 0.05.

Athlete No.	Gender	Level	$Power_{pull,ave}$ - F0 r	P-value	Linearity	$Power_{pull,ave}$ - V0 r	P-value	Linearity
2	F	Elite	-0.07	0.84	Low	0.35	0.26	Low
31	F	Elite	0.12	0.66	Medium	-0.01	0.97	Medium
33	F	Elite	0.68*	0.02	Strong	-0.41	0.18	None
3	F	Sub-elite	0.01	0.96	None	0.74*	<0.01	Strong
7	F	Sub-elite	0.59*	0.02	Medium	0.19	0.47	Low
15	F	Sub-elite	-0.07	0.77	None	0.81*	<0.01	Strong
24	F	Sub-elite	-0.09	0.73	Medium	0.37	0.16	Medium
28	F	Sub-elite	0.88*	<0.01	Medium	0.31	0.18	Medium
36	F	Sub-elite	0.59*	0.01	Low	0.81*	<0.01	Strong
1	M	Elite	-0.11	0.69	Medium	0.22	0.42	Strong
5	M	Elite	0.38	0.23	None	0.51	0.09	Low
11	M	Elite	0.46	0.14	None	0.54	0.07	Strong
12	M	Elite	0.62*	0.01	Low	0.30	0.25	Low
20	M	Elite	0.73*	<0.01	Strong	-0.41	0.12	Low
30	M	Elite	-0.56*	0.02	Low	0.83*	<0.01	Strong
4	M	Sub-elite	0.47*	0.04	Low	0.53*	0.02	Strong
9	M	Sub-elite	-0.21	0.61	Low	0.41	0.32	Low
16	M	Sub-elite	0.49*	0.03	Medium	-0.05	0.84	Medium

a)



b)

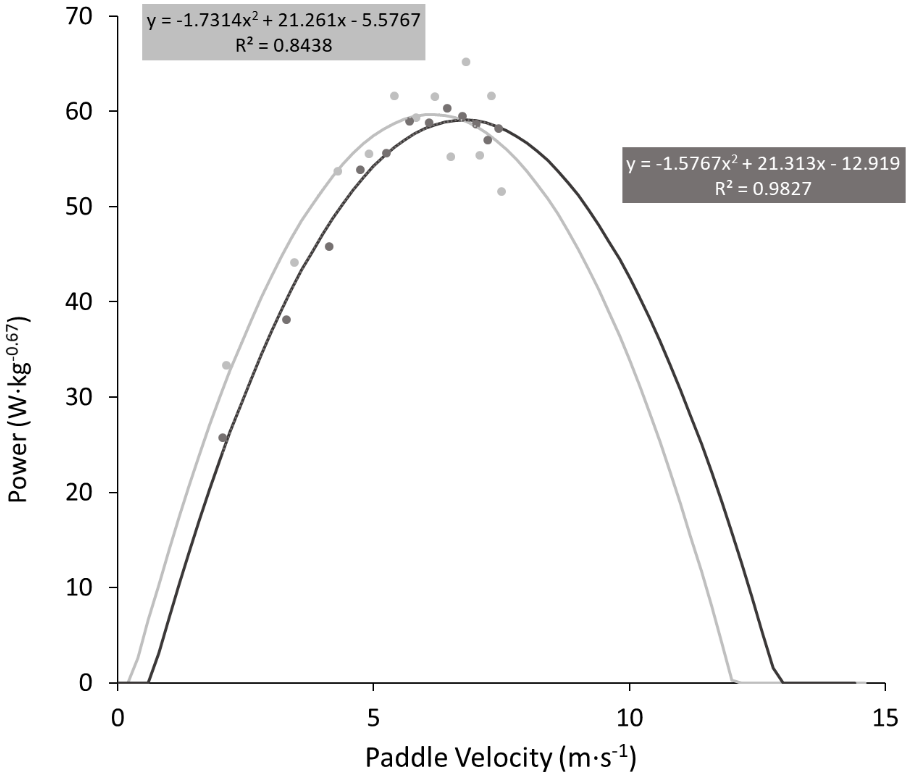


Figure 4.7: a) example force-velocity profiles for two athletes- one displaying a more force-orientated profile (light grey) and the other a more velocity-orientated (darker grey) and b) the respective power-velocity profiles created by the same athletes. The filled circles represent each of the strokes.

4.4 Discussion

Normalised power increased from club, through sub-elite to elite paddlers (Table 4.4, Figure 4.6), regardless of which measure of power was considered. The demonstration that higher levels of performance are linked with higher power is not surprising for a sprint-based sport, with other sports such as cycling, jumping and sprinting showing a link between maximum power and sprint performance (Dorel et al., 2005; Marcote-Pequeño et al., 2019). The lack of statistical significance between consecutive groups in some measures may be due to the range of performance levels within those groups or the difference in level between groups; high standard deviations can be seen, in particular for the club group (Table 4.4), and the difference in performance from elite to sub-elite may be smaller than from sub-elite to club.

Differences in statistical significance were found when using different measures of power. For male athletes, $Power_{pull,ave}$ and $Power_{pull,max}$ had greater significance than $P0_{pull}$, but the opposite was true for female athletes. The different measures of power quantify different things: $Power_{pull,max}$ is a maximal single output; $Power_{pull,ave}$ is a capacity across 12 strokes and $P0_{pull}$ is a modelled estimate of the single maximal from the 12 strokes. These slight differences effect the variances between performance levels, and although they do not indicate which may be more useful, highlight the importance of understanding the mechanical relationship being investigated prior to comparing to literature or making applied conclusions. While 'power' has consistently been related to performance, studies typically only report one calculation of power. In F-V research, this is commonly reflective of the $P0_{pull}$ used in this study (Dorel et al., 2005; Marcote-Pequeño et al., 2019; Samozino et al., 2012), while in other kayak research, power calculation has included the averages across multiple strokes (Bjerkefors et al., 2018) or time periods (van Someren & Palmer, 2003) or multiple measures have been reported (Schofield, 2015). The effect sizes also show differences in power measures between gender, with males again showing the largest effects between performance levels in $Power_{pull,ave}$ and $Power_{pull,max}$ and females in $P0_{pull}$. These values give more insight into the size of differences rather than categorising according to a single value as in standard statistical tests.

The extrapolated maximum pull force (F0) produced by athletes follows the same trend as the power, with highest forces produced by elite, followed by sub-elite and club, with significant differences and large effect sizes in F0 between groups on both the male and female sides (Table 4.4), as it has found to be in sprint cycling (Dorel et al., 2005) and rowing ergometry (Giroux et al., 2017). These data seem to contradict previous research that has indicated strength is not a significant determinant of performance in sprint kayaking (McKean and Burkett, 2010). However, the strength measures in McKean and Burkett's study were bench press and pull-up, with the differences highlighting the importance of sport-specific strength assessment. This is corroborated by recent research that found very weak correlations between vertical and horizonal F-V profiles of the same athletes (Jimenez-Reyes et al., 2018). The multi-joint co-ordination necessary for force-production on the ergometer in the current study more closely replicates the movement of kayaking, indicating that it is kayak-specific force generation, rather than raw strength, which is linked to better performing groups. Strength and conditioning coaches should consider the information from these profiles alongside standard strength measures for the applicability and transfer of their training plans for kayakers.

Maximal velocity (V0) does not follow the same relationship as maximal force and power. For both males and females, the sub-elite group achieved the highest maximal velocities, followed by the elites and then the club paddlers. Although this finding was not statistically significant, large effect sizes were apparent between the sub-elite and other two groups of male paddlers and between the sub-elite and club female paddlers. This indicates maximal velocity of paddle movement is not an underpinning characteristic of elite-level sprint kayak performance, the opposite to the findings of Morin et al. (2012) in sprinting. The highly technical nature of kayaking may explain this difference; as outlined in Chapter 2, the paddle path (and therefore direction of force application) and hydrodynamics around the paddle blade are complex and little-understood which mean paddle velocity may not directly correlate with boat velocity. In addition, Chapter 3 demonstrated that elite coaches emphasise the value of 'not travelling too quickly' or 'rushing the arms' and take time to build up the power in a stroke, before increasing the rate at which that stroke is applied. This idea is supported by comparing the F-V profile with the F-SR profile (Figure 4.6). This shows that although sub-elite athletes are creating the highest paddle velocities, they are not creating the highest SR and therefore are utilising longer recovery times between strokes.

The findings of this study indicate that, at group level, elite athletes have a more force-oriented profile than sub-elite and club paddlers, with these differences both statistically significant and with large effect sizes among male paddlers. Female paddlers appear to follow the same trend although only the effect size between elite and club is 'large' and no statistical significance was reached. Previous research found the ratio between F0 and V0 (equivalent to $S_{F\text{-}V}$) was not significantly correlated with pull power (Schofield, 2015). The differences between elite and sub-elite $S_{F\text{-}V}$ points towards the complexity of excelling in sprint kayak performance; it is not merely a case of becoming stronger or faster, but rather applying the force generation capacity effectively at high velocities with appropriate angles through complex movements.

When comparing the F-SR profile of athletes at different levels (Figure 4.6b), the maximal SR attained is much more similar between groups than the maximal velocity, with four of the groups' SR0 falling within 16 strokes per minute and only the male sub-elite and elite athletes exceeding this. These SRs are more than twice what would be seen on water (McDonnell et al., 2013b) but represent an extrapolated, theoretical physiological maximal at zero force. In kayaking and rowing, a cycle is made up of a water and recovery phase and the relationship between these two (known as the duty cycle) is unconstrained: the percentage of pulling (water phase) has been found to decrease with increasing SR (e.g. Sprague et al., 2007; Schofield, 2015), which can be inferred to be happening to a higher extent in the sub-elite than elite group, as mentioned above.

Despite a lower strength of relationship when power is compared again SR rather than velocity (P-SR r^2 = 0.38, P-V r^2 = 0.98), Sprague et al. (2007) found maximum stroke power to occur at around 40 strokes per minute, similar to the 35-50 spm found to be used by Olympic rowers (World Rowing, 2019). The elite athlete data in this study returned a higher $SR_{opt,str}$ than that found in Schofield's research (158 spm), which exactly matched the average value of K1 200 m World Championship medallists (McDonnell et al., 2013b). This would appear to indicate that as a group, the athletes in this study should use an average higher SR than those in Schofield's study in order to be utilising their maximum power capacity. Comparing $SR_{opt,str}$ with $SR_{opt,pull}$, the latter returned values which are considerably higher than those seen on water and the difference in duty cycle is again apparent as the differences between groups are not the same between these two measures of optimum SR.

Looking at the data on an individual basis gives another layer of insight. While at group level it did not appear that S_{F-V} described performance level, the proportionately large SD indicated there were differences between individuals. Figure 4.7 and Table 4.6 show the large range between individuals, with 12 athletes showing a positive trend between F0 and power (eight statistically significantly) and six showing a negative trend (one statistically significantly). For V0, 14 athletes exhibited a positive correlation with power (five statistically significantly), and four a negative correlation (none statistically significantly). While some individual athlete data showed strong linear relationships, this was not constant, indicating that for most athletes, maximum force or velocity alone were not dictating stroke power. Using group-level data, it might be assumed that increasing force generating capacity should be the focus for strength coaches and athletes, but by adding the individual level data, it can be seen that for a number of athletes, V0 has a stronger correlation with power and therefore increases in maximal velocity are more likely to lead to improvement in power for these athletes. The results show large differences between individuals, indicating one piece of advice (i.e. 'focus on increasing F0') would not improve power for all athletes.

4.4.1 Limitations and Delimitations

As mentioned in the methods, due to the level of participant and the nature of the competitive season, it was not possible to control data collection timings and activity prior to testing. Efforts were made to minimise the effect of fatigue through scheduling with the coaches and to schedule testing at similar times of season, but these factors may mean some trials are not representative of maximum capacity, rather *maximum effort at the time*.

A further limitation is that the distinctions in group level may not have been linear. The definition of 'elite' and 'sub-elite' may have resulted in groups more comparable in performance level relative to 'club' paddlers, which may have exacerbated differences in post-hoc testing. Classifying athletes according to level is always difficult as performance is not limited to isolated groupings. Having perfectly distributed groups may have resulted in differences between all three groups, or in no differences between groups, but was not realistically achievable in voluntary research. This difficulty further emphasises the value of understanding athletes as individuals.

The paddle length on the ergometer was matched to what athletes would normally use on water based on an assumption of a centre of pressure located 20 cm from the distal end of the blade. On water, the centre of pressure of the blade moves throughout the stroke as the depth and lateral movement of the blade changes (Morgoch et al., 2016). Force measurement systems often assume force is being applied at the centre of the blade (Aitken & Neal, 1992; Gomes et al., 2015). Data of elite kayakers' paddle set-up show an average blade length of 50.4 cm (Ong et al., 2005), and as typical 'wing' shape blades get wider towards the tip (e.g. Sumner et al., 2003) the assumption of a centre of pressure 20 cm from blade tip was considered acceptable.

The calculation of F-V and P-V profiles from this ergometer assumes that each stroke was completed in the same way, with velocity being the only factor to change. Without detailed kinematics of the movement, this cannot be confirmed but the experience level of the kayakers and the use of multiple familiarisation trials increase the likelihood of repeated movements. To record F-V in a sporting-specific movement, the movement needs to be recreated with as few additional constraints as possible which inevitably means a large number of degrees of kinematic freedom and therefore less researcher control.

Calculation of F0 and V0 rely on extrapolation from 12 data points from each stroke. While the relationship between force and velocity was well explained by a linear fit, in agreement with previous research (Bozic & Bobana, 2018; Giroux et al., 2016; Haugen et al., 2019), the small number of data points mean small changes could cause large differences in extrapolated values. The use of extrapolated values enables improved comparison between sports and movements where the same velocities or forces may not occur, but extrapolated values can still be compared, which would be of practical value, in particular for strength and conditioning coaches.

With regards to the power profile, the maximum velocities measured were not always far beyond the velocity at maximum power. This could have resulted in an increase in calculated P0 or SR_{opt} if data on the descending limb were limited. Through pilot work, the resistance on the ergometer was changed according to athlete to try and ensure data occur on the ascending and descending limb of the power-velocity curve, but for some athletes it seems maximum power is achieved at velocities very close to maximum achievable, attempting to increase velocities beyond this level would likely lead to a technical breakdown and violate the assumption of repeated movements.

Normalisation was conducted by dividing power and force values by mass to the power 0.67. Although this has been recommended by Jaric et al. (2005) for measures of force and power, many sports biomechanics studies use ratio normalisation to body mass. There is not unanimous agreement in the value of ratio normalisation, with some finding this method removed almost all explained variance of mass during running (Mullineaux et al., 2006) and others finding a correlation between mass and force to still be visible after normalisation in walking and running (Wannop, Worobets, & Stefanyshyn, 2012). In kayak research, ergometer and on-water measured paddle force and power have often not been normalised (Begon et al., 2009; Fleming et al., 2012; Nilsson & Rosdahl, 2016) although results have been reported separately for gender (Bjerkefors et al., 2018; Gomes et al., 2015), or data have been reported individually (Gomes et al., 2011; Mononen & Vitasalo, 1995; Wainwright et al., 2013). Clearly then, there is no precedent in sprint kayaking for a particular normalisation, but this also means there has not previously been any account taken of size differences between athletes. Allometric scaling to the power 0.67, which is based on the relationship between volume and cross-sectional area, is intended to remove the variability in results that is due to size and therefore allow comparison between athletes regardless of anthropometrics. This is important in group analysis where means and standard deviations of groups are compared and if size were not accounted for, may skew the results.

4.4.2 Application

By comparing data across groups, it was clear that power is an important attribute for sprint kayakers. However, as different measures of power result in different conclusions, the comparisons and conclusions drawn must be within the context of the measurement used. The increase in F0 and in SF-V of elite athletes relative to sub-elite and club paddlers indicates an area for improvement for club or development coaches to work on. It is important to note this study uses a movement-specific force generation so while general strength may improve F0, it is the application of that force through the kayak-like movement pattern that will be of most benefit, so co-ordination and body position should be considered when developing training plans for developing force.

The literature discussed in this chapter highlights the importance of F-V testing in a movement pattern which is similar to that used in the competition environment. Despite this, many S&C tests are conducted with non-specified movements such a bench pull/press or squats. For kayaking, the applicability of these tests to the water-based competition environment is not clear. Ergometer testing as has been conducted in the current study would allow S&C coaches to better assess the transferability of training.

For elite athletes, ergometer testing of the type developed here can provide the coach and support staff with an additional data set to support and optimise an athlete's training; the individual nature of the profiles (e.g. Figure 4.7) demonstrates the variety that exists in athletes' capabilities, regardless of similar levels of attainment. The repeatability and short duration of this test makes it easy to integrate into the training schedule. This would give the S&C and technical coaches a chance to investigate the influence of training blocks on certain performance attributes, as has been done in other sports (Colyer et al., 2017).

The individual nature of F-V profiles may also be important when it comes to crew boat selections: athletes who are selected based purely on the basis of time are likely to have a similar power output, but the data above highlight that this does not mean that they are likely to have a similar F-V profile (Figure 4.7). Matching athletes who have different profiles is likely to mean their peak power does not occur at the same speed. As the athletes would be required to paddle at the same stroke rate, it is therefore likely that the performance of both athletes would be compromised. While coaches often do not have the luxury of many athletes to choose from of a similar standard, these assessments undertaken early on could develop successful crews going forwards. Further research in this area would be beneficial to crew-boat selection for crews of all levels.

Another use for this form of testing would be equipment testing. In the current study, shaft length was matched to the athlete's own paddle. However, adjusting this on the ergometer could allow for assessment of change in a relatively controlled environment that is more sport-specific than would otherwise be available. In a similar manner, Sprigings et al. (2006) used the P-V profile of athletes to predict blade size based on the equation for drag, which shows that drag force is directly proportional to the blade surface area and velocity through the water. Using the force and velocity attained at the instant of peak power, an estimation of blade size for peak power was calculated.

Although their approach did not intervene to look at impact on performance, using P-V and F-V profiles as the basis for intervention could create an efficient and logical testing procedure. This environment would also reduce some of the issues with on-water testing; Ong et al. (2006) changed paddle set-up to reflect the results of a regression analysis of a group of Olympic paddlers but only one trial in each condition, unknown variability and unknown influence of environment make conclusions difficult to support.

Understanding how this information relates to on-water performance is important for the applied impact of this research. It might be logically expected that those who demonstrate stronger correlations between V0 and power would be more likely to make use of high stroke rates on water, which further research will help to elucidate.

4.5 Conclusion

This study demonstrates the importance of maximal power in sprint kayak performance, with elite athletes exhibiting significantly higher power than sub-elite or club paddlers. It highlights that there are bigger differences between force generating capacity than maximal velocity capacity in developing athletes but that there is no universal elite F-V profile for younger or developing athletes to work towards. The data therefore indicate that at group level, the power-velocity relationship can explain differences in performance levels, and that the maximal force aspect of the force-velocity relationship also informs the differences in level.

The study also highlights the importance of individual athlete analysis. Seven athletes exhibited a positive correlation between maximal velocity and power. Although only one of these reached statistical significance, the data show maximal velocity is an important element in producing maximal power for some athletes. This indicates that group level conclusions can disguise individual athlete differences and could limit performance gains if training plans are based solely on group data.

Chapter 5: Individuality of SR and DPS in determining boat velocity

5.1 Introduction

In all cyclical sports, velocity is the product of the distance covered in one cycle and the number of cycles completed in a set time; in kayaking commonly-used coaching variables are the distance per stroke (DPS) measured in metres, and stroke rate (SR), measured in strokes per minute (spm), while velocity is commonly reported in metres per second ($m \cdot s^{-1}$). Distance per stroke has also been referred to in literature as stroke distance (Wainwright et al., 2015), stroke displacement (McDonnell et al., 2013a) or stroke length (Ong et al., 2006). Research into these factors in kayaking, and their relevance to performance, can be informed by their investigation in other cyclical sports, which use similar break downs (although sometimes with different terminology, Table 5.1).

Table 5.1: Commonly used terms for distance per cycle and cycle frequency in sprint sports.

Sport	Distance per cycle	Cycle frequency	Example Literature
Kayak	Distance per stroke (DPS)	Stroke rate (SR)	McDonnell (2013)
Athletics	Step / Stride length (SL)	Step / Stride frequency (SF)	Salo et al. (2011)
Cycling	NA- force output measured	Cadence /pedalling rate	Dorel et al. (2005)
Swimming	Stroke length (SL)	Stroke rate (SR)	Sidney et al. (2011)
Rowing	Distance per stroke (DPS)	Stroke rate (SR)	Hofmijster et al. (2007)

The maximum number of strokes completed in a minute, irrespective of how far the boat moves with each stroke, will be determined by the maximum speed of movement of the athlete, while the maximum DPS will be contingent on the appropriate application of the maximum force possible within one stroke. Muscular force is controlled by a number of factors: the muscle architecture, comprising muscle fibre length, type, pennation angle, cross sectional area, tendon length and tendon elasticity (for review, see Cormie, McCuigan, & Newton, 2011), and the mechanical properties for stimulation-activation, force- length, force-time and force-velocity relationships.

The force-time and force-velocity relationships may underpin the relationship between cycle rate and cycle distance: at high cycle rates, durations may be too short for maximal force to be produced (Neptune & Kautz, 2001). Cyclical movements are thought to increase power output by making use of the stretch-shortening cycle (SSC; Jimenez-Reyes et al., 2014), where pre-stretch occurs in whole muscle tendon unit (MTU), allowing the muscle to activate at a more advantageous length and velocity and giving time to generate full activation, all before shortening commences (Fukashiro, Hay, & Nagano, 2006). While no research could be found that looks at the SSC in kayaking, the cyclical motion of the legs and trunk produce conditions suitable for its use by muscles such as the quadriceps, hamstrings and rectus abdominis. In a modelling study, Nagano, Fukashiro and Komura (2003) found the contribution of the series elastic component increased with increasing motion frequency in cyclic heel raises, further highlighting the importance of stretch-shortening for cyclical sporting movements.

5.1.1 Cyclical Sport Examples

It is important to bear in mind that the application of force in most sports is different to that in kayaking. In athletics sprinting for example, the vertical and horizontal directions of force applied to the ground can be easily measured (Morin et al., 2011), and the resultant direction of force application assessed. In kayaking, force application throughout a stroke is applied to a moving fluid, which has much more complicated properties than solid ground. Even in other water-based sports such as rowing, the use of a pivot in the form of the oarlock, creates an external mechanical structure, which is then both more predictable and easier to measure (Hofmijster, Landman, Smith, and Van Soest, 2007).

For all sprint-based sports, athletes need to create enough force to first overcome drag resistance before they can increase velocity, and resistance increases with the square of speed, as shown by the equation for drag (Equation 1; Section 2.4.1). The influence of drag is especially important for water-based sports such as rowing and kayaking, as the density of water is almost 800 times higher than that of air. For some sports, such as athletics, the overcoming of drag is a small fraction of the overall effort and is therefore largely ignored in research, while for others, such as water-based sports, overcoming drag is a large component of performance (Pendergast, 2005). The influence of the environmental conditions on on-water performance is high as water temperature has a significant effect on water density and, thus, drag (Yi, Han & Zheng, 1998).

5.1.2 Kayak coaching viewpoint

As highlighted in Chapter 2 of this thesis, some coaches set a target SR which they think athletes will need to achieve to win or medal during an international event, while others believe SR to be more of an individual choice, with seven of the 12 coaches interviewed highlighting individual differences. In 200 m racing, a range of SRs have been used successfully, with researchers concluding "individual optimum must exist" (McDonnell et al., 2013b, p. 47). Although not every coach was clear on whether there was an individual optimum SR, or if so, what the determining factors might be, others were clearer in their beliefs. Physiology and anthropometrics were the most commonly considered attributes, but paddle set-up was also considered to influence SR as demonstrated by the quotes in Chapter 3. These views from elite coaching knowledge highlight the differences between athletes and provide examples for their cause. They are largely based on experience rather than empirical data and do not clarify whether individual optimums exist or whether there is a universal optimal SR. While useful for direction, this experiential knowledge cannot be treated as evidence for performance determinants.

Sample race data (Figure 5.1) from a World Cup A-Final highlight the different SRs used to win international medals. The three medallists whose data are documented, finished within half a second despite large differences in peak SR (~166, 173 and 182 spm for the gold, silver and bronze medallists respectively). Despite the clear differences in magnitude, the pattern of SR changes across distance was similar across the medallists. These data were measured by the ICF with radio-controlled GPS units with accelerometers placed on all boats in Olympic class events. From this, 10 m velocity and stroke rate values were available for all competitors, although the calculation algorithms for SR were not made public. Taken in isolation, these data might lead to the idea that a lower stroke rate is an advantage in this event, in opposition to research (Brown et al., 2011) but all other boats in this field (n = 6) were within the range of these profiles (mean ± SD = 174 ± 7.9 spm), indicating the likelihood of individual optimums varying within the group.

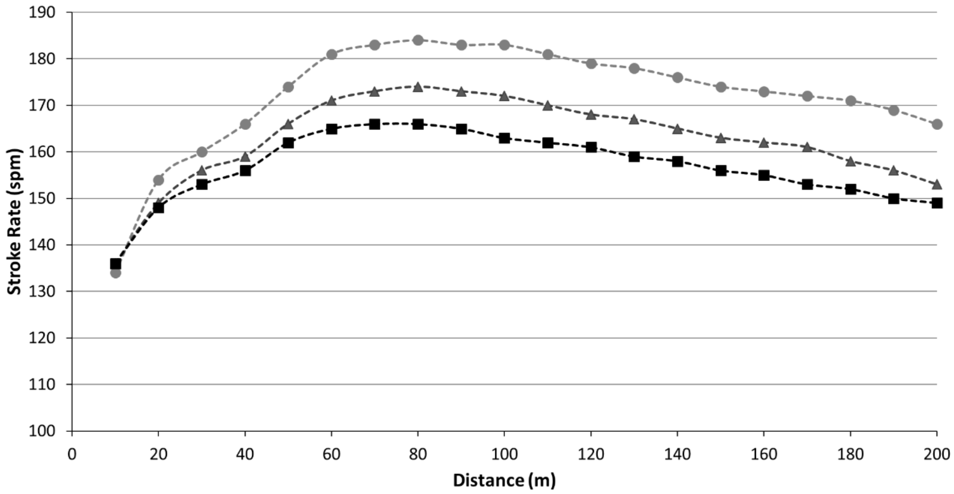


Figure 5.1: International medallists' SR-distance data from World Cup 2016 (ICF, 2016). Shapes representative of position: squares first place, triangles second place and circles third place.

5.1.3 Individuality in cycle rate and distance per cycle

Individual differences are due to the negative interaction between SR and DPS, whereby an increase in one factor results in a decrease in the other, making it possible for different strategies to result in similar velocities. This negative interaction has been found during sprinting in kayaking (McDonnell et al., 2013a), athletics (Hunter, Marshall, & McNair, 2004), cycling (Martin et al., 1997) and swimming (Sidney, Alberty, Leblanc, & Chollet, 2011).

In sprint kayaking, SR has been found to differ between ability levels, with international standard athletes demonstrating significantly higher SR than national and club paddlers (Sanders & Kendal, 1992; Brown et al., 2011). Both studies had limitations, however: Brown et al. used panning footage filmed at 50 Hz, 100 m from the finish line at a height of one meter to record athletes in lanes 4 and 6, which would inevitably have been restricted by other athletes blocking the image, extreme angles creating parallax error, and low accuracy of calibration. Sanders and Kendal (1992) meanwhile used a single stroke and assumed it to be representative of all maximal velocity strokes, reporting SR to vary between 118 and 136 spm for five international standard athletes paddling at maximal velocity. Although taking the minimum and maximum SR corresponds with the lowest (4.63 $m \cdot s^{-1}$) and highest (5.38 $m \cdot s^{-1}$) velocities, a linear trend is not well defined. As only one stroke was filmed at a time and athletes were not blinded to the capture area, it is not clear if the stroke recorded was representative of all strokes but this relatively large difference between elite athletes is nonetheless clear. Additionally, only the average of four individually measured strokes was given, so variability for those athletes is also not clear.

McDonnell et al. (2013b) analysed the K1 200 m event for men and women during the World Championships from televised video data and found an average SR for the race, excluding the first five seconds to remove the effect of initial acceleration, of 158 spm for men (N = 7) and 139 spm for women (N = 5). The video data available for this study were only recorded at 24 Hz and therefore only an average SR per 8-10 strokes was taken, but the high coefficient of variation within races of 2.2-8.9% demonstrates clear intra-individual variability, while an average ranging from 145 to 172 shows high inter-individual variability. The authors highlighted the likelihood of an individual optimum SR existing and speculated it would be based on "strength, anthropometry, physiology, and equipment." This research also highlighted the range of SR and DPS that can be used to achieve the velocities needed to medal at international events, as show in Figure 2.16 in Chapter 2.

To draw from better-researched sports, Craig and Pendergast (1980) analysed the US swimming championships and cited that across almost all events and stroke styles, distance per stroke was the differentiating factors between finalists and those who did not make the final. In summarising information available for coaches, Sidney et al. (2011) highlighted the inter-individual differences found at Olympic level swimming, with different combinations of SR and SL used by individual athletes to achieve similar speeds. In athletics sprinting, there is no universally accepted optimum ratio between SL and SF, with some research demonstrating the higher importance of SF (Mero, Luhtanen, Viitasalo, & Komi, 1981; Morin et al., 2012; Nagahara et al., 2018), and others highlighting the importance of SL (Debaere et al., 2013b; Krzysztof & Mero, 2013; Weyand et al., 2000). Hunter et al. (2004) investigated the interaction effect between SL and SF within 36 athletes and found a wide range of combinations of SL and SF, even for groups with similar maximal velocity. They attributed the differences to leg length, height of take-off (TO) and vertical velocity of TO. Miller, Umberger and Caldwell (2012) examined the influence of physiological factors on the SL and SF during sprinting through modelling and found both were affected by F-V, force-length, excitation-activation and series elastic force-extension relationship, with the force-length relationship found to have a larger effect on stride length. While the movement pattern of track sprinting is very different to kayaking, these physiological factors Miller et al. (2012) found to underpin the relationship would likely be the same for other cyclical movements, such as sprint kayaking. Computer modelling of a sprint kayak performance, however, would involve either a huge number of assumptions, or measurements of factors that are exceedingly difficult to measure accurately on water with the technologies currently available. The above research in swimming and athletics, combined with those discussed in kayaking, show that differences between individuals are clearly present in many cyclical sports.

The differences between individuals have been speculated to be due to anthropometric factors in sprinting (Hunter et al. 2004) and kayaking (McDonnell et al. 2013a). At group level, Hunter et al. (2004) found sprint velocity to be largely explained by step length (r = 0.73), which was in turn explained by flight distance (r = 0.89), but neither of these significantly correlated with leg length, despite their conclusion that leg length likely influenced individual use of step length/step frequency. Long limbs can be an advantage due to larger moments arms but they would also increase moment of inertia so there are theoretical advantages and disadvantages. Sprint kayak athletes have been found to have no significantly different skeletal anthropometrics relative to the general public (Ackland et al., 2003), but no research could be found investigating whether anthropometrics of sprint kayakers are related to their SR choice.

All of the above research looking at SR and DPS, or their equivalents in other sports, have focused on inter-individual (between athlete) variation, very few studies have been found investigating intra-individual (within athlete) variation in cycle rate or cycle distance. The few that have been published are discussed below.

5.1.4 Methodologies to understand individual performance

Other methods used in athletics could more easily be used to understand the relationships in sprint kayaking. Salo et al. (2011) analysed television footage of international 100 m sprinting races to determine whether athletes could be considered as “reliant” on either SL of SF. The authors investigated 11 athletes with data for at least 10 races each and calculated average SL, SF and velocity over the 100 m, discounting the first step and accounting for final step discrepancies, for each race. SL and SF were then each correlated against velocity and the resulting correlation coefficient for SL-velocity was subtracted from the value for SF-velocity, giving a dimensionless ‘r’ value (diamond shape, Figure 5.2) as an indication of which was more strongly correlated to velocity.

Bootstrapping the data allowed the authors to create 90% confidence intervals (CI) around the values for each athlete (black lines, Figure 5.2). Athletes were classed as "reliant" on SL if the lower bound of the 90% CI was above -0.1 (A9, A 10 and A5) or on SF if the upper limit of the 90% CI was below 0.1 (A11).

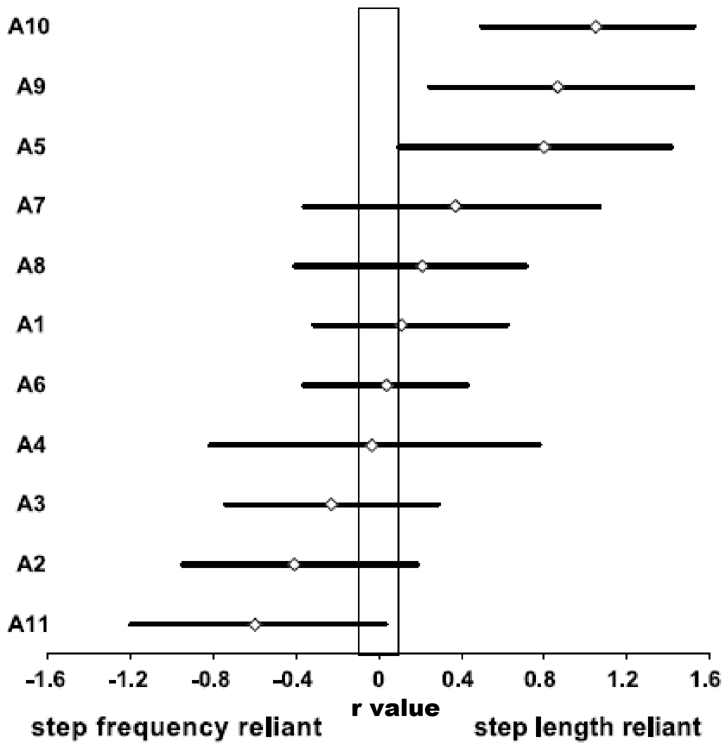


Figure 5.2: Diagram of 'reliance' from Salo et al. (2011). Individual athlete r values (difference between correlation of step length with velocity and step frequency with velocity) with 90% confidence intervals. Those whose confidence interval does not cross the distal threshold line are considered 'reliant'.

The authors' interpretation of this was that if the variable in which the athlete is reliant is reduced, they are not able to achieve as high a maximal velocity, regardless of increases in the less-preferred variable. The reliance differed between athletes in both inclination and size, with some athletes not being classified as reliant on either. International races were analysed so all athletes would have been exerting maximal effort, but this also meant only around ten efforts per athlete were analysed, which is a small number from which to bootstrap and generate confidence intervals. These confidence intervals were used to classify so while highlighting individual differences well, these categorisations should be interpreted with caution. Although this method could, in some respects, be replicated in kayaking, televised data are neither so readily available nor of the same quality. As kayak races are longer, the perspective of the camera is often changing for viewers' entertainment which would prevent SR measurement. Additionally, the dimension 'r' value carries no weight in statistics and does not ease interpretation so would not be recommended.

An alternative method for understanding individual performances would be to use case studies. In a case study of an elite breaststroke swimmer, Fritzdorf, Hibbs and Kleshnev (2009) found higher stroke rate to correlate with lower performances for the race performances of the athlete investigated. While case studies allow for an in-depth examination of the individual's characteristics, they do not allow for any patterns to be discerned among different levels of athlete so are not of much value to coaches besides those for the athlete examined.

Clearly there are merits to understanding an individual's data but there is not yet an accepted methodological approach that allows unambiguous interpretation of how individuals utilise the two components of cyclical movement (e.g. SR and DPS) to maximise speed, or how this reflects group analyses.

5.1.5 Equipment interaction with cycle rate

Cycling, rowing and kayaking all use equipment to apply force to their surrounding environment to create movement. A bike is an efficient mechanical system, and force and torque measurement have been available to cycling practitioners and researchers for many years and therefore torque-cadence and power-cadence relationships have been measured frequently in cycling, with increasing cadences consistently found to reduce force per pedal stroke (Löllgen, Graham, & Sjogaard, 1980; Martin et al., 1997; Palmer, Borghouts, Noakes, & Hawley, 1999). This has allowed coaches and athletes the ability to calculate optimal cadence for sprinting specifically for each athlete from the apex of the power-cadence curve (Dorel et al., 2005; Martin et al., 1997; Williams, Doust, & Hammond, 2006). Pedal rate choice has been linked to crank length, fibre type, body position, joint kinematics and joint kinetics (Faria, Parker, & Faria, 2005; Hansen, Andersen, Nielsen, & Sjøgaard, 2002; Martin, 2007). Crank length has been found to strongly affect the optimum pedalling rate (rate at which peak power is achieved) in both cycling (Martin & Spirduso, 2001) and hand cycling (Krämer, Hilker, & Böhm, 2009). Martin and Spirduso (2001) found optimal pedal rate to decrease with increasing crank length, while optimal pedal speed increased significantly with increasing crank length. In cycling, this relationship has a clear evidence base and calculations are relatively simple. Increasing paddle length is likely to result in much more complicated changes to the paddle path and kinematics of the paddle and paddler. No studies could be found that have investigated this, the valuable insight gained in cycling highlights the value this research can have.

In rowing, Nolte (2009) demonstrated through theoretical modelling that shorter oars would increase efficiency and that by increasing resistance on the blade (by increasing its size or improving its shape), angular velocity of the oar and therefore SR could be maintained. As with any kind of modelling, there were simplifications involved and it is not clear how much of an impact neglected factors such as angular acceleration and moment of inertia of the oar, would have. Barrett and Manning (2004) investigated the relationship between anthropometry, boat set-up and performance in 15 National level rowers and found that bigger (larger height, arm span and mass), stronger athletes tended to be more successful paddlers, with the authors concluding that the seemingly strong correlation between oar length and race time (r = -0.86) was not a representation of the oar set-up being a primary determinant, but as a covariate to athletes' anthropometry, although normalisation was not conducted so the inter-relationships are not clear. While rowing is more like kayaking than cycling, the fixed pivot point and the movement of the centre of mass of the athlete relative to the movement of the centre of mass of the system of rower, boat and oars, create two large differences so that measurement systems used in rowing cannot be transferred. From these examples, we can see that equipment choice is likely to influence stroke characteristics, but the complicated nature of a kayak stroke means results cannot be inferred accurately from other sports.

5.1.6 Technique interaction with cycle rate

The shape of the stroke force-time curve during the kayak paddling stroke has been shown to vary with changing SR (Gomes et al., 2015; Figure 2.5), with increases in SR being associated with an increase in the peak force and a temporal shift of this peak to earlier in the stroke cycle. Despite similarities in impulse between different SRs, the shape of the curve was described as becoming 'more rectangular' with higher SR and was associated with improvements in boat velocity. Although there were some limitations in the measurement system used, for example the assumption of a stable pivot point around the bottom hand, a centre of pressure assumed to act at the centre of the blade and the low accuracy of commercially available GPS for distance definition, the insight into on-water stroke force profiles and acute changes between stroke rates with the same system was novel and interesting. Although no stroke rates above race pace were used, Gomes et al.'s (2015) results would also appear to indicate that athletes' ability to generate force quickly does not limit SR within freely chosen range.

The kinematics of the stroke have also been found to vary with increasing SR, with an increase in SR resulting in a decrease in anterior-posterior displacement (Therrien et al., 2012). As these data were collected on an ergometer with a sliding complex, the comparison to on-water paddling may be limited but the differences in the shape of the stroke between individuals are of interest (see Figure 5.3 showing the repeatable, individual nature of the shape of the stroke despite the constraints of ergometer paddling). The DPS describes the distance moved by the boat within each stroke, as opposed to the distance moved by the paddle so the relationship described by Therrien et al. does not necessarily infer a shorter DPS, although clearly DPS could not be measured on an ergometer.

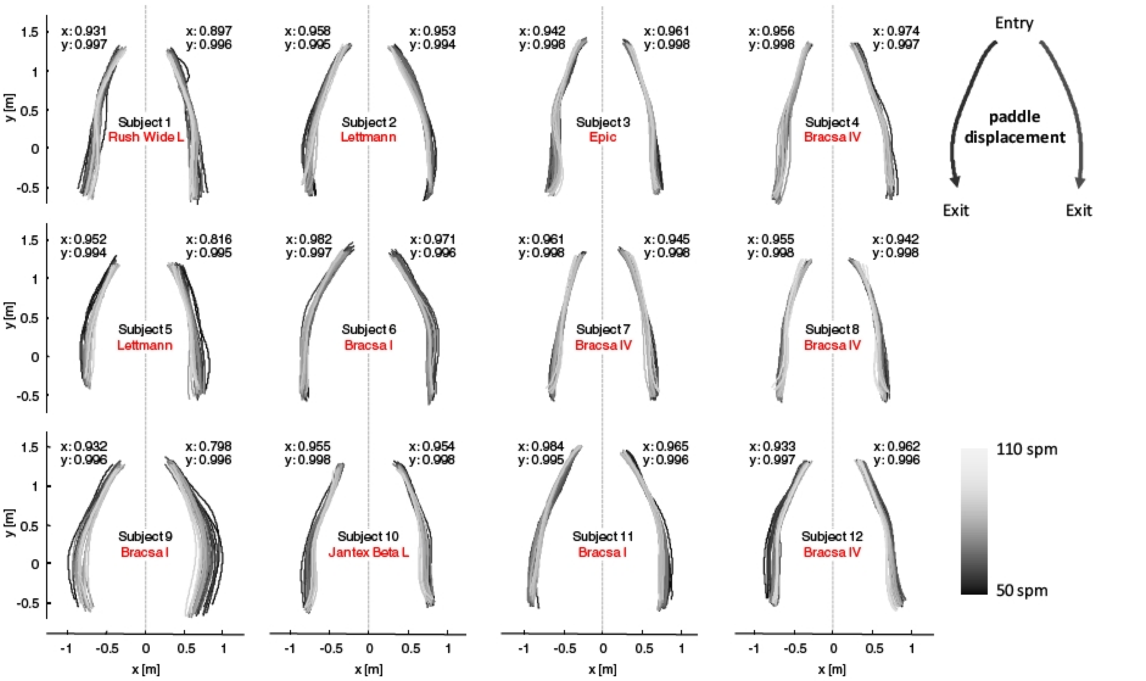


Figure 5.3: Stroke path pattern on a kayak ergometer viewed from above at increasing stroke rates adapted from Therrien et al. (2012). The y axis is anterior-posterior and the x axis is medio-later movement. Red text shows paddle used by each athlete.

Differences in DPS between individuals could be due to technical performance on water; 'slip' is a technical concept of inefficiency whereby the paddle moves in a posterior direction and does not contribute to the forward movement of the boat and therefore reduces DPS. Researchers have quantified slip as the backward movement of the blade relative to an external reference frame (e.g. Sanders & Kendal, 1992; Wainwright, 2013) and it has subsequently been used in the generation of Wainwright's deterministic model (as seen in Chapter 2) and noted as the second strongest determinant of change in boat velocity during a pull, highlighting it as a factor to be minimised for optimal performance (Wainwright et al., 2016). As discussed in Chapter 2, the hydrodynamics of the paddle are not well defined; Kendal and Sanders (1992) related successful paddling to reduced slip alongside greater lateral paddle movement. The authors postulated that this lateral movement was used to obtain lift citing that this would ‘minimise the need for backward movement.’ Recreating paddle path from above, as Kendal and Sanders have (Figure 2.9), shows that the paddle moves in an arc in the global reference frame, and therefore the view of slip as a failure to ‘lock the blade’ and a technical inefficiency may be an over-simplified, inaccurate, sagittal plane view.

While rowing is seemingly the most similar Olympic sport to kayaking, the momentum provided by athletes moving within the overall system of rower, oars and boat, creates a significant difference in boat movement pattern, and the fixed rotation position of the oars creates a much more predictable movement. By testing nine experienced rowers across SR of 20-36 spm, Hofmijster et al. (2007) found that higher stroke rates result in higher mechanical power, boat velocity, efficiency of the blades and net efficiency, despite a decrease in velocity efficiency (defined as the ratio between power produced and power not lost to velocity fluctuations). The higher boat velocity fluctuations increase the time taken to row a competition distance and, therefore, decreasing stroke rate may have an advantage (Hill & Fahrig, 2009) which is not present in kayaking. There are technical changes which occur in synchrony with changing SR, indicating there may be technical causes for differences within and between athletes, giving further justification for research examining these differences.

5.1.7 Trainability of cycle rate/distance per cycle

Adaptations to cycle rate and/or distance per cycle in sprint sports through training have also been found to be individual specific. For example, Bezodis, Kerwin, Cooper and Salo (2018) found four elite sprint athletes responded differently across a five-month period. Generally, increases in velocity during the maximal velocity phase were more strongly linked to changes in SF than SL. Over the five months, step velocity and SF decreased during strength-focused training phases and increased during high intensity sprint-based blocks, supporting the changes in F-V found through training in bob-skeleton athletes (Colyer et al., 2018). Bezodis et al. hypothesised that the force-producing capability and the ability to produce that force quickly - essentially the F-V relationship - was likely to be the underpinning mechanism to the changes found and considered the importance of fixed anthropometric factors in stride length.

In 37 'competition level' swimmers, Girold et al. (2006) found three weeks of overspeed training increased SR but decreased DPS in a 100 m race effort, resulting in no overall change in velocity while over strength training was found to increase SR with no changes in DPS, resulting in an increase in velocity in the cohort of regional and national athletes studied. The group was split and so individual differences at the start, or following intervention were not noted and could have influenced the conclusions. Additionally, the methods employed for 'overspeed' training involved an elastic tube that was manually kept taut and athletes being encouraged to increase SR, but SR was not measured during the training efforts. Overall, it appears focussed training may be able influence SR/DPS but more research would be needed to understand how and why these changes occur.

5.1.8 Summary of literature

The above research highlights the negative interaction of cycle rate and cycle distance, and the importance of individual athlete differences across a range of cyclical based sports, including kayaking. By looking at sports that have been subject to considerably more research than kayaking, methods that have led to insights around these differences can be investigated (e.g. Salo et al., 2011), and the interventions put in place from the understanding gained (e.g. Martin & Spirduso, 2001; Bezodis et al., 2018).

5.1.9 Aim & Research Questions

The aim of this study was to investigate the inter- and intra-athlete variability in SR, DPS and velocity in order to gain insight into whether individual sprint kayakers are using SR and DPS in different ways to maximise velocity.

Research Question 5.1: *Is SR or DPS more important in determining boat velocity in a group of elite sprint kayakers?*

Research Question 5.2: *Do elite athletes use SR and DPS in different ways to achieve boat velocity?*

Research Question 5.3: *Are the relationships between SR and velocity, or DPS and velocity, determined by anthropometrics?*

5.2 Methods

5.2.1 Participants

The participants were 25 kayak athletes (Table 5.2) who were all part of the National Governing Body (NGB) Podium or Podium Potential funded squads, corresponding with the level of 'elite' and 'sub-elite' from the previous chapter. A sub-group of 15 athletes (Table 5.3) took part in the intra-individual variation element. Ethical approval was gained from the University of Lincoln School of Sport and Exercise Science ethics committee.

Table 5.2: Group level participants' characteristics for each gender (mean ± SD)

Gender	N	Mass (kg)	Height (cm)	Arm Span (cm)	Paddle Length (cm)
Male	12	81.3 ± 4.6	182.7 ± 3.8	188.3 ± 4.3	218.0 ± 2.2
Female	13	71.3 ± 6.1	172.9 ± 3.9	176.3 ± 6.0	215.6 ± 0.7

Table 5.3: Individual athlete participant characteristics

Athlete No.	Gender	Mass (kg)	Height (cm)	Arm Span (cm)	Paddle Length (cm)
2	F	61.6	168.8	171.0	215
3	F	84.0	174.5	180.0	216
15	F	62.0	175.0	177.0	215.5
28	F	72.4	174.0	176.8	215
31	F	73.4	172.7	180.5	217
33	F	73.0	172.5	171.7	215
36	F	79.4	175.0	182.2	215.5
1	M	85.8	191.6	198.8	223
4	M	86.6	183.5	188.7	217
5	M	80.1	179.0	184.0	217.5
9	M	79.2	183.3	189.6	216
11	M	78.3	183.0	186.4	218
16	M	76.6	185.4	192.1	217
20	M	84.5	185.2	187.6	218.5
30	M	75.8	177.0	183.3	217

5.2.2 Data collection

Athletes taking part in only the inter-individual aspect of the study completed one testing session, while those who were also involved in the intra-individual variation aspect completed a minimum of three data collections throughout the season. For inter-individual comparison, data were collected as close to the major, targeted competition as was logistically possible- this date varied between athletes as some were focusing on World Junior Championships, some on senior European or World Championships, others on World Cup racing and some on National Regattas. For those who took part in the intra-individual data collections, each was spaced a minimum of four weeks apart between March and September, representing the entirety of the racing season for sprint kayak. This ensured all athletes had finished their winter, strength focused training blocks and were actively competing during this period.

Each session consisted of an athlete-controlled race-style warm up, as they would usually undertake prior to regatta racing. The warm-up may have differed between athletes as they have devised what they feel works best for them, but would have been consistent for each athlete. This was followed by six efforts of 100 m from stationary on the regatta course, with 12 minutes of recovery between efforts. This distance is commonly used in training, is long enough to attain top speed (occurs around 50m; unpublished data from the NGB) and to maintain it without much influence of fatigue or pacing. Recovery was controlled by asking athletes to come off the water and sit in a heated minibus between efforts so that the athletes could keep warm without inducing fatigue. The first three efforts were always completed with a tailwind and the latter three with a headwind, to reduce the effect of fatigue as much as possible. Trials in which wind speed exceeded 4 $m \cdot s^{-1}$ (corresponding to a gentle breeze on the Beaufort scale) were discarded, resulting in an average wind speed of 1.8 $m \cdot s^{-1}$, with a standard deviation of 0.9 $m \cdot s^{-1}$.

Following on-water data collection for inter-athlete analysis, the mass, height and arm span of each athlete were taken to investigate the influence of these potentially confounding variables. For those taking part in the intra-participant investigations, mass was taken after each session.

5.2.3 Equipment

An RTK GPS unit (Igtimi, Dunedin, New Zealand) was attached to each boat immediately behind the cockpit, aligned with the midline of the boat (Figure 5.4). These units contain differential GPS and triaxial IMU (accelerometer, gyroscope and magnetometer) components. Accuracy and reliability testing undertaken by the NGB (unpublished) found units to be comparable to light gates (approximately 800 tests; r^2 = 99.99%) and to have high reliability (59-130 test per unit, average SD = 0.016 s). Linear accelerations were recorded at 100 Hz while differential GPS was recorded at 10 Hz.

Figure 5.4: Igtimi unit attached behind cockpit of participant

For each data collection, a weather buoy (RPR Met, England) was used to record water temperature, wind speed, wind direction, humidity, air pressure, and air temperature. Wave size and start direction were recorded manually. The weather buoy was positioned approximately halfway through the 100 m effort. Weather data were reported for an average of 10 s periods and therefore the number of data points covering the efforts ranged between two and four. Data were synchronised with the on-board GPS unit using GPS timestamping present in both devices' output data.

5.2.4 Data processing

Data were taken directly from the unit after each collection and were processed using MATLAB R2017a (the Mathworks Inc, Natick, MA, USA). Stroke start and end were detected from sign change (negative-to-positive and positive-to-negative respectively) of the boat's forward linear acceleration (Figure 5.5). From this, stroke rate (strokes per minute) was calculated per stroke as 60 divided by the duration of the stroke in seconds, and distance per stroke was calculated from the positional data at the stroke start, to the position at the beginning of the next stroke. Velocity was calculated as the differential of the positional GPS data.

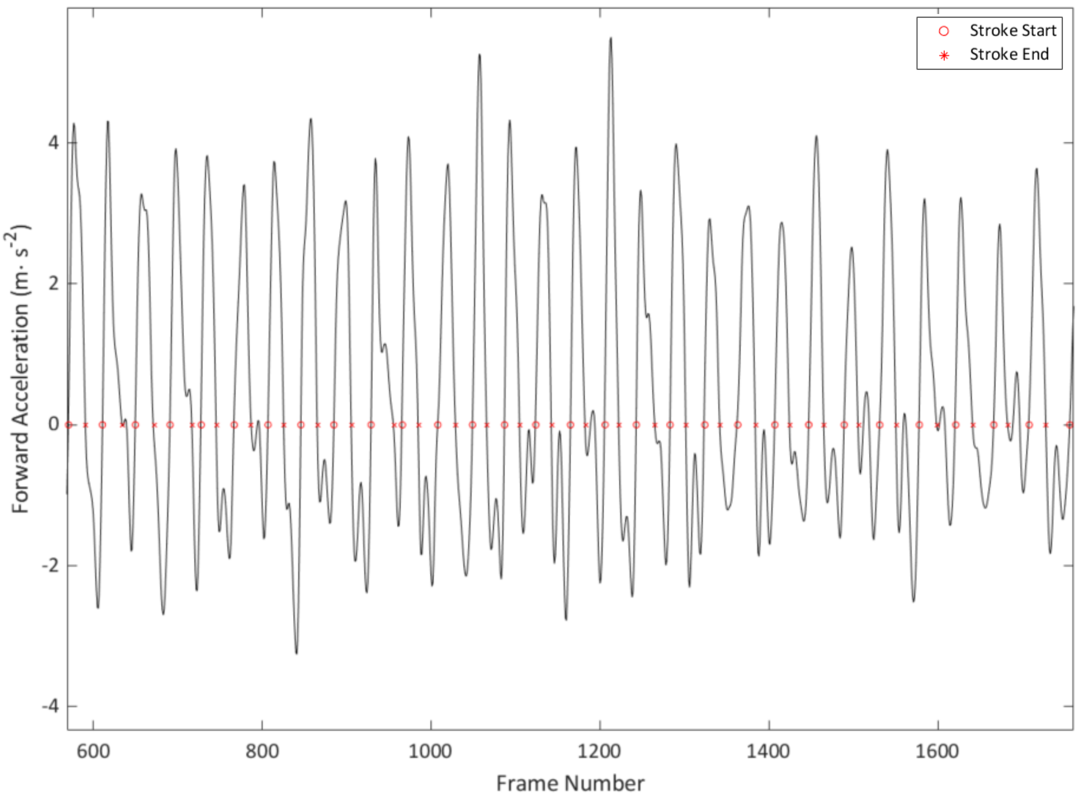


Figure 5.5: Example stroke detection (red circles) from forward linear acceleration trace of the steady state portion of a trial.

For each effort, velocity was first smoothed using a 5-point moving average and then the start of steady state was identified using an automated detection of the breakpoint (Mullineaux, 2017), whereby a curve is fitted to the velocity data, rotated so that the first and last points are equal to zero, and the trough represents the breakpoint. A threshold drop of 10% from the breakpoint was then used to define the end of the steady state period. This means "steady state" is from breakpoint to whichever is earlier: the end of the effort or when velocity has dropped by 10%. It does not therefore refer to a set distance or time (Figure 5.6).

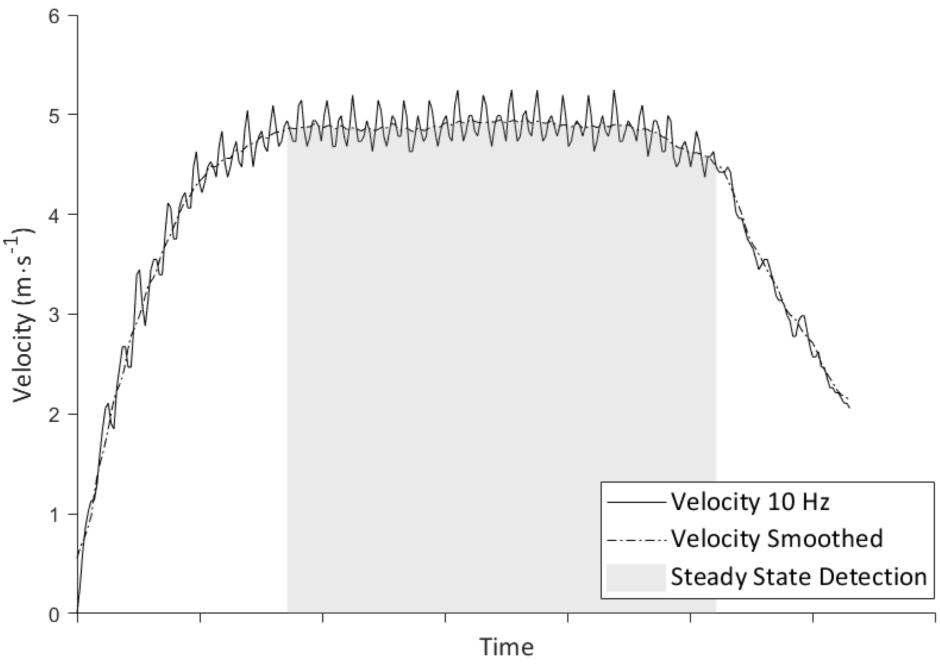


Figure 5.6: Velocity trace for an example trial, with steady state (area between breakpoint and the earlier of end of effort or 10% reduction in velocity) shaded.

The distance and duration of this steady state period was input, along with the athlete's mass for the corresponding date, and the environmental weather conditions, into a weather normalisation model. The weather model (unpublished validation; British Canoeing, 2015) uses the aforementioned environmental factors to calculate air and water density and therefore aero- and hydro-dynamic drag based on Equations 1 and 2, as discussed in Section 2.6.3. The model includes standardised frontal surface area of a sprint kayak for different genders and age groups and, using this and the measured velocity of the boat, data were adjusted to compare to datum conditions and provide a 'normalised time'.

5.2.5 Statistical analysis

Data were analysed using SPSS (IBM SPSS Statistics for Windows, Version 22.0., IBM Corp., Armonk, NY) and Microsoft Excel (2010). Significance was set at $p = 0.05$.

5.2.5.1 Group analysis

To compare across the group, averages of velocity, SR and DPS were taken from the six efforts completed by each athlete. As all data were normally distributed (Shapiro-Wilk test p value > 0.09) and linearity and homoscedacity were visually confirmed, Pearson's correlations were computed across: normalised velocity, SR, DPS, mass and arm span. A Bonferroni adjustment to the alpha value was not made; the correction is often used to reduce the chance of type 1 error, but inevitably increases the risk of type 2 error that real relationships may be missed (Armstrong, 2014; Perneger, 1998).

The group were then separated based on gender and, although these sub-sets all demonstrated normal distribution (Shapiro-Wilk test p value > 0.12), the sample sizes were small and the assumption of linearity was not met through visual inspection. Therefore the non-parametric equivalent correlational tests of Spearman's rho were run (Table 5.6 for female data and Table 5.7 for male data).

5.2.5.2 Individual analysis

To understand how SR, DPS and velocity varied for each individual, SR-velocity and DPS-velocity correlations were taken across all 18 trials completed (three testing sessions of six trials). Due to small sample sizes, some non-parametric distributions, and variable linearity Spearman's correlations were run. Visual assessment of linearity was conducted and subjectively categorised into: clear strong linear pattern ('Strong'), apparent linear trend ('Medium'), potential linear trend ('Low') and no linear trend ('None'), examples of each of these can be seen in Appendix 3.

5.3 Results

At group level, SR was found to have a stronger correlation with boat velocity ($r = 0.87$; $p < 0.01$) than DPS with boat velocity ($r = 0.67$; $p < 0.01$; Table 5.4, Figure 5.7). Athlete mass and arm span correlated positively and significantly with normalised velocity. Statistically significant correlations were found between DPS and arm span ($r = 0.58$; $p < 0.01$; Table 5.4), and between arm span and mass ($r = 0.67$; $p < 0.01$; Table 5.4). The range of SR (119 – 158 spm) was proportionally higher than that of DPS (2.02 - 2.45 m), with both SDs higher in female athletes compared to male (Table 5.5).

Table 5.4: Group normalised boat velocity, SR, DPS, arm span and mass correlations (Pearson's) and p-values, * indicates significance at the level α < 0.05.

		Normalised Velocity	SR	DPS	Arm Span
SR (spm)	r	0.87*	-		
	p-value	<0.001			
DPS (m)	r	0.67*	0.25	-	
	p-value	<0.001	0.228		
Arm Span (m)	r	0.59*	0.36	0.58*	-
	p-value	0.002	0.074	0.002	
Mass (kg)	r	0.62*	0.53	0.48	0.67*
	p-value	0.001	0.006	0.014	<0.001

Table 5.5: Normalised boat velocity, SR and DPS for male and female athletes (mean ± SD).

Gender	N	Normalised velocity ($m \cdot s^{-1}$)	SR (spm)	DPS (m)
Male	12	5.62 ± 0.14	147.25 ± 5.13	2.27 ± 0.08
Female	13	4.74 ± 0.29	131.56 ± 9.58	2.12 ± 0.29

Once analysed according to gender, the only significant correlation for females was between SR and velocity (Table 5.6), while for males the only significant relationship was a negative correlation between SR and DPS (Table 5.7). For gender-specific groups, arm span and mass were not specifically related to boat velocity, SR or DPS.

Table 5.6: Female normalised boat velocity, SR, DPS, arm span and mass correlations (Spearman's non-parametric) and p-values. * indicates significance at the level α < 0.05.

		Normalised Velocity	SR	DPS	Arm Span
SR (spm)	r	0.89*	-		
	p-value	<0.001			
DPS (m)	r	0.11	-0.26	-	
	p-value	0.721	0.384		
Arm Span (m)	r	-0.51	-0.50	-0.01	-
	p-value	0.088	0.082	0.972	
Mass (kg)	r	0.02	0.05	-0.08	0.17
	p-value	0.957	0.873	0.789	0.578

Table 5.7: Male normalised boat velocity, SR, DPS, arm span and mass correlations (Spearman's non-parametric) and p-values for male athletes, * indicates significance at the level α < 0.05.

		Normalised Velocity	SR	DPS	Arm Span
SR (spm)	r	0.29	-		
	p-value	0.354			
DPS (m)	r	0.37	-0.71	-	
	p-value	0.236	0.010*		
Arm Span (m)	r	0.03	-0.22	0.29	-
	p-value	0.923	0.484	0.359	
Mass (kg)	r	0.06	-0.18	0.16	0.35
	p-value	0.846	0.587	0.618	0.259

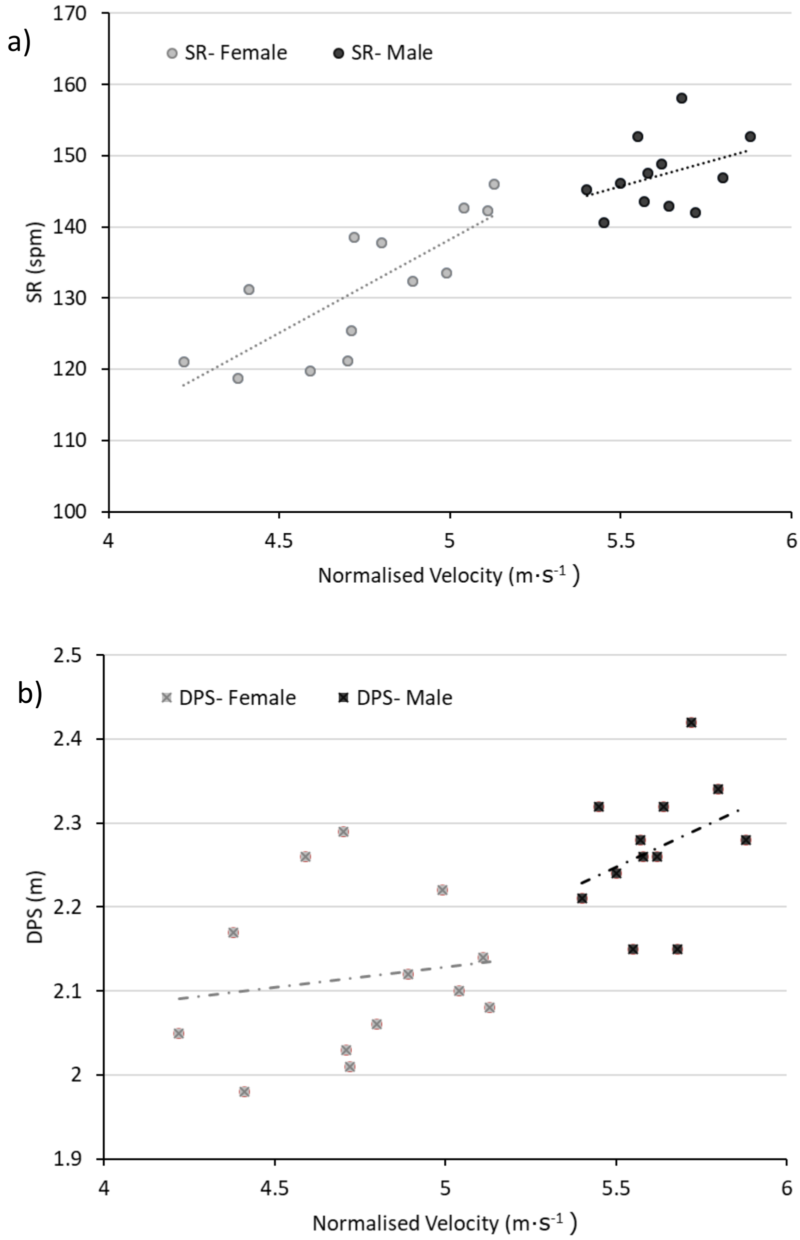


Figure 5.7: a) SR-velocity (circles) and b) DPS-velocity (square) average from each participant with the linear group trend marked. Lighter shaded shapes are female data, darker shaded shapes are male data.

Of the 15 athletes who took part in intra-athlete part of this study, 11 (six females and five males) were found to have a significant correlation between SR and boat velocity (Table 5.8). Six of these (two females and four males) also had a statistically significant correlation between DPS and boat velocity and a further three (zero female) were found to have a correlation between boat velocity and DPS but not SR.

Table 5.8: Individual athlete correlation r and p-values (Spearman's non-parametric). * indicates significance at the level α < 0.05.

Athlete No.	Gender	SR-Vel r	p-value	Linearity	DPS-Vel r	p-value	Linearity
2	F	0.29	0.27	Low	0.35	0.18	Low
3	F	0.91	0.00*	Medium	0.23	0.33	None
15	F	0.79	0.00*	Strong	0.81	0.00*	Medium
28	F	0.89	0.00*	Strong	0.02	0.94	None
31	F	0.84	0.00*	Strong	-0.16	0.53	None
33	F	0.73	0.00*	Strong	-0.02	0.92	None
36	F	0.82	0.00*	Strong	0.48	0.00*	Medium
4	M	0.38	0.08	Low	0.44	0.04*	Low
20	M	0.29	0.16	Low	0.67	0.00*	Medium
9	M	0.77	0.01*	Medium	0.34	0.17	Low
11	M	0.55	0.02*	Medium	0.77	0.00*	Strong
1	M	0.03	0.68	None	0.57	0.00*	Medium
30	M	0.42	0.04*	None	0.52	0.01*	Medium
5	M	0.95	0.00*	Strong	0.55	0.02*	Medium
16	M	0.53	0.02*	Strong	0.67	0.00*	Low

a)

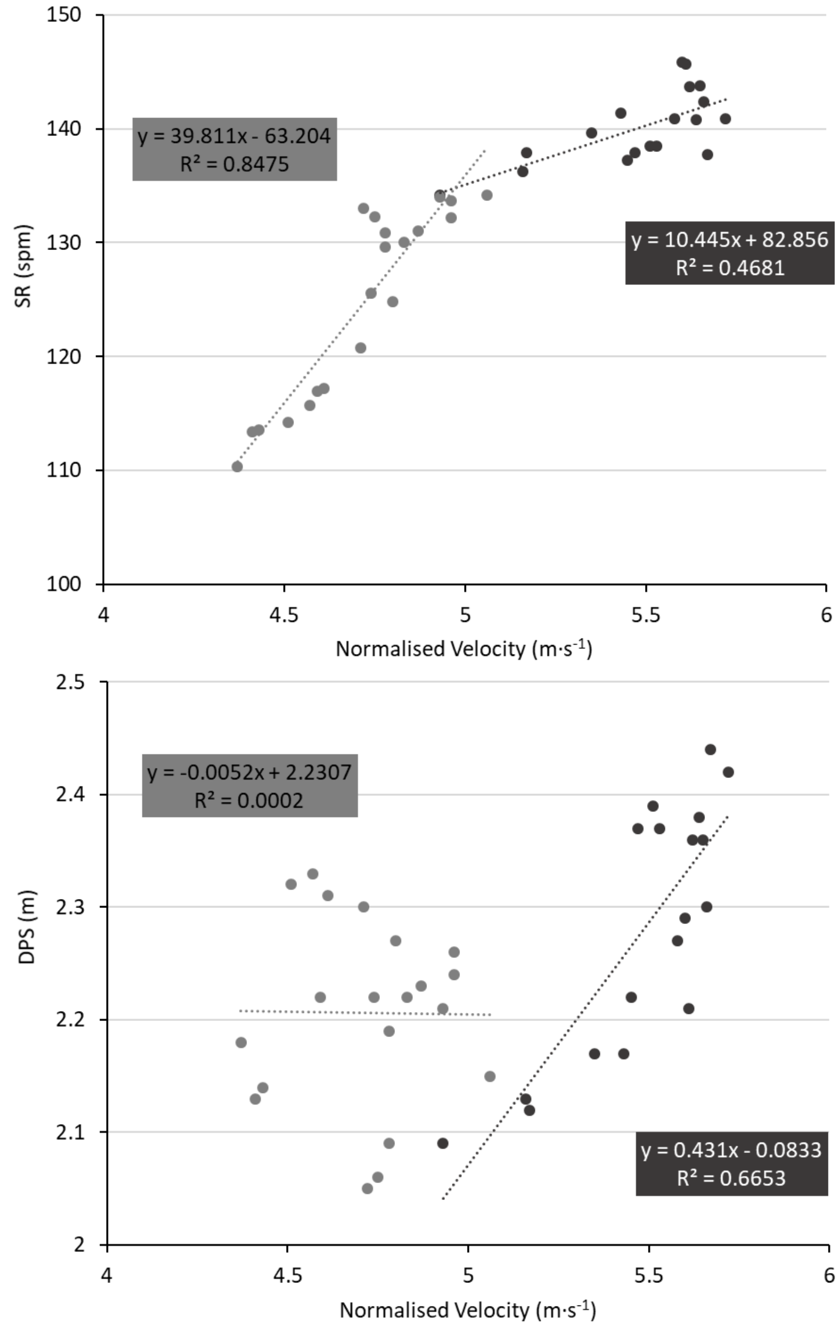


Figure 5.8: a) SR-velocity and b) DPS-velocity scatter plots for two example athletes, with each trial marked as a data point. Light grey shows an athlete with a 'strong' correlation in SR-Vel and no correlation for DPS-Vel; dark grey shows an athlete with 'Medium' correlation with SR-Vel and 'Strong' correlation in DPS-Vel.

5.4 Discussion

As the product of SR and DPS is boat velocity, the significant relationships found between both of these variables and boat velocity at group level were expected, but the apparent difference in conclusions when compared to analysis divided by gender and in the intra-athlete data sets were larger than expected, highlighting the issues associated with apportioning statistical significance at different levels.

At group level, the positive correlation between stroke rate and boat speed agreed with previous kayaking research, which has shown an increase in SR with higher ability levels

(Sanders & Kendal, 1992; Brown et al., 2011). In the current study group-level variability in stroke rate determined 75% of the variation in boat speed, while DPS explained 44% (r^2 values, Table 5.4). SR and DPS are not independent relative to velocity and an increase in one would be expected to incur a decrease in the other, a relationship shown by the negative correlation between SR and DPS in male athletes. An overview of the data split according to gender would indicate that SR is more important for female athletes and neither SR nor DPS appear to significantly correlate with boat velocity for the male athletes studied. The mechanical laws underpinning the SR, DPS and velocity relationship are not different between males and females, although males are both heavier and faster (Tables 5.2 and 5.5), both of which would increase drag. The relationship between velocity and drag is non-linear and therefore may mitigate the correlation across genders; the same increase in velocity for a faster athlete would lead to a larger increase in drag, which may reduce the likelihood of increased SR. Alternatively, the differences exhibited in the strength of the correlation could be due to artefact of the spread of the data, highlighting the difficulty of correlational statistical analysis- mathematically, a larger range of values will lead to an increase in the reported strength of a relationship (Altman, 1991). The SR range for women was much larger than for men (Table 5.5), resulting in a stronger correlation coefficient.

The range of SR measured in this study (119-158 spm) broadly agreed with that reported in previous literature (118-136 spm; Kendal & Sanders, 1992; 158 spm for men and 139 spm for women, McDonnell et al., 2013b). As the current study used a single value of SR as the average for the sustained maximal velocity phase, it might be expected that it would be lower than the single maximal stroke used in Kendal and Sanders but is more likely to be representative of capacity given the small, clearly defined capture area of the other authors. Values in the current study are considerably higher than those found in Brown et al. (68.92 ± 3.37 spm; 2011) for international level paddlers. Brown et al. did not describe their definition of a stroke and as the value is approximately half of those above, it may be that a single stroke was from paddle entry to paddle entry of the same side, rather than to paddle entry on the opposite side, which is commonly used. There are other possibilities for the discrepancy, including the limited view from the single camera causing errors, or the calculation of SR incorporating the whole effort, including the start which is known to have a different stroke pattern, and indeed is often discounted, for example McDonnell et al. (2013b) only measured SR after the first five seconds of initial acceleration.

There were significant group level relationships for mass and arm span with boat velocity, showing heavier athletes and those with longer arms go faster, in partial agreement with Fry and Morton (1993), who found differences in selected and non-selected international level athletes in body mass, skinfolds, height and sitting height. Those with longer arms might logically be expected to have longer strokes due to a longer forward and backward reach but it does not necessarily follow that these longer paddle strokes would lead to increased distance per stroke of the boat and hence the lack of a significant relationship between the latter and arm span. Assuming that the elite and sub-elite athletes involved in the current study are relatively lean, the link between mass and performance would be expected as an increase in mass is likely to be due to an increase in muscle mass (and therefore strength) or an increase in height (and therefore reach), supported by the correlation between arm span and mass (Table 5.4). The athletes used in the current study had similar arm span and mass (mean ± SD; male: mass 81.3 ± 4.6 kg, arm span 188.3 ± 4.3 cm; female: mass 71.3 ± 6.1 kg, arm span 176.3 ± 6.0 cm) to those who competed in the 2000 Olympic Games (male: mass 85.2 ± 6.2 kg, arm span 190.6 ± 7.3 cm; female: mass 67.7 ± 5.1 kg, arm span 172.8 ± 7.5 cm; Ackland et al., 2003). For the current study, once split based on gender, the relationships between anthropometric variables of mass and arm span with boat velocity were no longer significant, once again highlighting the potential issues with group level correlations. Fry and Morton (1993) did not report the gender of athletes used so it is not clear if there were differences between genders for selected and non-selected athletes.

5.4.1 Individual differences

When looking at intra-individual relationships, the amount of variability in an individual's normalised boat velocity across trials that could be explained by variation in SR differs (mean ± SD; 0.61 ± 0.28). The proportion explained by changes in DPS also varied considerably (0.41 ± 0.29; Table 5.8). These differences demonstrate the individuality in strategies that athletes have adopted – either consciously or subconsciously – to maximise velocity. Individuality in these factors in elite sprint kayakers has previously been reported in small sample sizes, only one athlete in a group of ten was reported to have a strong correlation between stroke displacement and velocity (Hay & Yanai, 1996 in McDonnell et al. 2013a). Similar findings have been reported in athletics with Salo and colleagues (2011) reporting individual 'reliance values' of the correlations of SL-velocity and SF-velocity, with values from -0.6 to 1.05, with more athletes showing a reliance on step length than on step frequency. The equivalent values for the current study would vary between -0.54 for Athlete 1, to 0.92 for Athlete 33, with more athletes indicating a stronger correlation with SR than DPS- the opposite of that found in sprinting. 'Reliance' is not a term used in the current study, but the similarity in between-athlete range is clear. The individual differences have large implications for research**: if only group level research had been conducted, it might be concluded that an intervention that increased SR would likely lead to an improvement in performance but using the current data it can be seen that this would not be the case for some athletes.**

There are a number of reasons for differences between athletes, from muscle physiology, through technical performance, to equipment, as outlined in Figure 1.1. While many of these factors are individual, some are outside of the athlete's control (e.g. anthropometrics such as segment lengths), some are trainable (e.g. maximal force production and muscle cross sectional area) and others are arguably trainable (e.g. muscle fibre type, MTU stiffness). Two of the factors linked to SR and DPS respectively (maximal speed and maximal force production) are discussed in detail in Chapter 3. Measurement of all of the factors is clearly outside the scope of this thesis but the schematic provides an indication of where future research could be focused to understand the causes of the individual differences highlighted in this study.

Differences in training focus, or the difference in underlying muscle fibre of these different training groups, could provide some insight into some of the causes of the individual differences. While the muscle biopsies needed to be able to ascertain fibre type distribution were not taken in the current study, muscle fibre type is thought to be related to a muscle's maximum contraction speed, and muscle biopsies have shown sprinters to have considerably higher type II fibres than long distance runners (Gregor, Edgerton, Perrine, Campion, & DeBus, 1979). The athletes within this cohort are all very high-level kayak performers, however, they do not all compete across the same distance. As mentioned in the literature review (Chapter 2), at Olympic level males compete in the 200 m and 1000 m distances, while females compete in the 200 m and 500 m distances. As athlete funding in the UK is achieved based on Olympic events, all the athletes in the study focus on one of these distances. The training regime for an athlete who is focused on 200 m is different from that of an athlete focused on 1000 m. For an athlete who is used to training for the 200 m, asking them to do a 100 m maximal effort sprint is not outside what they will be used to doing in training, while for a 1000 m paddler, such short, maximal work will be less common. Additionally, there may be technical differences due to training background; in track and field athletics, sprinters and middle-distance runners have been compared with both mechanical and technical differences (Bushnell & Hunter, 2007). Race-specific distances would have been highly fatiguing, drastically reducing the total number of data points which could be collected as well as introducing the confounding variable of fatigue during the effort which may directly mitigate the relationship between SR or DPS and velocity. The distance of 100 m was therefore considered best to limit in-effort fatigue and to allow collection of multiple data points within one data collection in order to conduct the correlation.

All of the athletes who took part in this research study have competed at international and/or national level sprint kayak events. While this means they are very skilled sprint kayakers, there are areas for improvement to be identified. Coaches' philosophies vary even within an elite cohort, as shown in Chapter 2; for some, it is more important to develop the application of power within a stroke before increasing the rate, while for others, there is a small range of SR within which athletes are expected to optimally perform. This means the training history of athletes, even at top level, varies. Individual differences in movement patterns, as highlighted by Therrien et al. (2012; Figure 5.3), and their relationship with lift and drag forces generated, may help to explain the individual differences found in the current study.

Athletes' use of equipment may also change how they maximise velocity. Currently within the NGB system, equipment set-up is not measured or monitored and is just chosen according to the athlete's perception of how any changes to equipment feel in the water. Frequently, paddles remain unchanged for years and often they are a result of 'what was available at the time'. There are two dominant paddle manufacturers who equip the majority of international paddlers: Braca (braca-sport.com) and Jantex (www.jantex.sk). Indeed, of the cohort in this study, 12 used Braca and 13 Jantex. Each of these companies has at least 10 different designs which can be bought in up to 10 sizes, with adjustable shaft length and a range of blade sizes and paddle lengths (Table

5.3) were apparent in the current group. From a simplistic mechanical viewpoint, increasing blade size while maintaining all other factors would allow for an increase in drag force used to propel the boat forwards, proportional to the equation for drag (Equation 1, Section 2.4.1). However, it is unrealistic to expect all aspects of a stroke to stay the same, and increasing force relies on the athlete's ability to redirect that higher drag force through the upper limbs, torso, through the legs to the boat, which demands a system stiffness and therefore muscle strength which is hard to achieve.

In other sports, changing equipment has been shown to affect cycle rate. For example, changing crank lengths affects cycle frequency and movement velocity, with optimum cadence for power production found to decrease with increasing crank lengths (Martin & Spirduso, 2001). Using the current study, the influence of changing paddle set-up could be better understood as changes in SR or DPS would provide context for the given individuals.

5.4.2 Limitations & Delimitations

A session consisting of six 100 m maximal efforts with 12 minutes recovery is well within the bounds of a normal training session but may limit performance in that any single effort is unlikely to be a true maximal; in sprint-based sport competitions, athletes are rarely asked to compete more than twice in a single day. The 12 minutes used in the current study was longer than the nine minutes found to be sufficient in maintaining power output (Ainsworth, Serfass, & Leon, 1993). Re-synthesis of adenosine triphosphate (ATP) and phosphocreatine (PCr), the primary substrates in anaerobic exercise, to 76 % and 96% of resting values occurs over 4 minutes of recovery in males (McCartney et al., 1986), indicating ample recovery time was given for physiological recovery. The above recovery research has focused on cycling, but the duration and maximal nature of the efforts make it probable the same would apply for recovery during kayak sprints. In order to control and standardise the recovery, it was necessary to take the athletes off the water and impose a passive recovery in a heated minibus. Passive recovery has been shown to increase, or have no impact on power output in subsequent short sprints in cycling and swimming (Bishop, Ruch & Paun, 2007; Hoianaski et al. 2007; Toubekis et al., 2005), although there is some evidence active recovery may be beneficial in longer recovery durations (Brown & Glaister, 2014). As data collections took place outside between March and September in the UK, the risk of fatigue from trying to keep warm during an active on-water recovery, or the risk of injury from failing to keep warm (Scott, Hamilton, Wallace, Simpson & Muir, 2016), was considered greater than any potential risk to performance from passive recovery.

Wherever possible, all testing was done following a rest day. Where this were not possible, testing was conducted following the lightest day of training to try and minimise the effect of delayed onset muscle soreness (DOMS) or residual fatigue from previous training. Research has shown that DOMS can reduce strength, power and range of motion and force generation (Cheung, Hume, & Maxwell, 2003) as well as being found to reduce stride length in running (Harris, Wilcox, & Smith, 1990). However, most studies into the effect of DOMS deliberately induce very high levels of DOMS through high eccentric loading and repetitions. During the competitive season, these kind of taxing or novel movements would not be part of the training programme and therefore DOMS are unlikely to have influenced result unduly.

The selection of a ‘steady state’ portion of the sprint was based on coaches’ division of race phases (Section 3.3.3) in order to use data that were representative of the effort. Although coaches’ definitions differed (Figure 3.4), almost all included a ‘race pace’, ‘maintenance’ or ‘cruise’ phase which could be considered as a ‘steady state’. By disregarding data prior to this, in the start or acceleration phases – as has been done in previous research (McDonnell et al., 2013b) – results are delimited to maximal ‘steady state’ paddling. The mean is likely more representative of this phase as SR changes less rapidly (Figure 5.1).

Multiple collection dates were used for the intra-athlete analysis. While the maximal nature of the efforts meant this is the only way to collect data on large numbers of trials without fatigue dramatically influencing performance, the training in between collections was not able to be controlled due to the elite training schedule athletes adhered to. In conjunction with this, data collections were a minimum of four weeks apart and therefore the environmental conditions, in particular water temperature, differed between collections. While we can account for the effect of this on boat velocity with modelling, we cannot account for the impact on SR. The normalisation for environment approach used attempts to account for the differences in conditions between dates and has been used in the applied setting of canoeing for the past few years, with similar models used by other nations, including a matrix of adjustments based on wind speed and water temperature used in Germany. As with all models, it is not without its limitations. The model assumes the main effect of wind occurs directly in line with the motion of the boat, with relatively little consideration for the challenging technical influence of a side wind. It does not account for the additional energy expenditure that would occur through the duration of a race, although in a 100 m effort this is unlikely to have a large effect. By reporting ten second averaged data, gusts of wind are not accounted for, nor are fluctuations in the velocity of a stroke. However, the purpose of the model is not to perfectly remove the effect of all conditions which would be hugely computation-heavy, rather to give a better representation of comparing across different time points.

5.4.3 Application

As mentioned by some coaches in the interviews, SR has previously been used to determine training zones:

> *Anything up to 65 is CAP, 75 is threshold, around 75, couple of strokes either side but around 75 is threshold. Getting towards 85-90 is sub race pace, this is for 1000s, sub race pace and 100 plus, 110, is race pace for 1000*

Training zones based on SR have generally fallen out of favour due to physiological evidence of different work rates at the same cycle rate for different athletes (Abbiss, Peiffer, & Laursen, 2009), a point that is highlighted by the data above. While SR-based training thresholds still occur in rowing, the lower SRs make individual differences smaller and therefore differences in work rate would be less dramatic. The current research indicates the importance of individual differences in SR and would therefore undermine the use of a SR to determine a threshold for a group of athletes.

The results of this study indicate that individuals use different combinations of SR and DPS to increase their boat speed. In theory, this would indicate that an athlete who relies on increasing SR to improve boat speed, might work against an athlete who would maintain SR and increase DPS in order to increase boat speed. Identifying these differences could allow coaches to pair or team up athletes based on the stronger correlation, although more evidence would be needed to see if this resulted in a faster crew boat.

In Chapter 2, a number of the coaches commented on not knowing much regarding paddle set-up for their athletes. The increase in understanding about how athletes optimise performance individually, both from this chapter and the previous one, could be used to understand the mechanisms and potentials benefits arising from interventions with paddle set-up.

5.5 Conclusion

At group level, it appears that SR is more important than DPS in enhancing boat velocity, and that anthropometric factors of arm span and mass both correlate positively with performance. The conclusion that would be based on these results – that heavier athletes and those with longer arms are faster – is undermined once data were separated by gender. The spread of data at group level creates artificially strong relationships.

There are further clear individual differences in how athletes utilise SR and DPS to optimise on-water performance, with five athletes showing strong correlations between SR-velocity only, three showing strong correlations with DPS-velocity only and six having positive correlation with both parameters. Group analyses would disguise these individually different relationships, potentially leading to sub-optimal training. Scientists should be aware of individual nature of performance when running interventions: a seemingly positive outcome in increasing SR may not be a positive result for some athletes.

Chapter 6: Can ergometer profiling explain technical performance?

6.1 Introduction

As described in Chapter 2, kayak ergometers are frequently used to assess or monitor athletes for both research and training purposes. While there is evidence demonstrating the similarities in kinematics between ergometer and on-water paddling (Begon et al., 2008), research has shown some differences in muscle activity, with higher anterior deltoid activity on the ergometer and higher triceps and latissimus dorsi activity on the water (Fleming et al., 2012). The data from Chapter 4 demonstrated that ergometer-measured power is a determinant of sprint performance in kayaking, differentiating between performance levels, in agreement with previous research (van Someren & Palmer, 2003). Mechanically, power is the product of force and velocity, and in sporting movements including kayaking (Chapter 4; Schofield, 2015), force has been found to decrease with increasing velocity in a linear relationship (e.g. Martin et al., 1997; Sprague et al., 2007).

In kayaking, as in other cyclical sports, velocity is the product of cycle frequency (stroke rate; SR) and cycle distance (distance per stroke; DPS). The unconstrained duty cycle in kayaking means athletes dictate their own SR and a range of SR have been found to be used in achieving the highest velocities at national and international level in this thesis (Chapter 5) and in previously published research (McDonnell et al., 2013b). Chapter 5 also found that SR was a stronger determinant of boat velocity than DPS at group level, in opposition to some research in athletics sprinting (Hunter et al., 2004; Ito, Ishikawa, Isolehto, & Komi, 2006). The strength of the correlation between SR-velocity and DPS-velocity differs between individuals (Chapter 5), in agreement with data from Salo et al. (2011) in sprinting.

Previous research in other sports has alluded to a link between physical capacity and technical performance. For example, Hunter et al. (2004) postulated that increasing step length in sprinting would require development of strength and power, while the importance of creating high forces quickly could be linked to higher step frequencies. Recently, researchers have attempted to link power and F-V profiles to 100 m sprint performance (Slawinski et al., 2017). Using televised data, they found performance to be linked to both ‘power’ and velocity, but not maximal force capacity. Calculations of force and power from video data would necessarily make a number of assumptions in calculating kinetics from kinematics, reducing the value of this data. No studies could be found that have compared directly measured power and FV to any sporting performance.

6.1.1 Aim & Research Questions

The aim of this study was to investigate the relationship between power and FV ergometry profiling and sprint performance in kayaking. It was hypothesised that power would be positively correlated with sprint performance, and that FV gradient would be negatively correlated with SR, indicating that those who are more force-dominant on the ergometer utilise a higher DPS technique on water, while velocity-dominant athletes would use a higher SR.

Research Question 6.1: *do force- and power- velocity profiles determine on water performance in a group of elite and sub-elite kayakers?*
Research Question 6.2: *does the gradient of these athletes’ force-velocity profile relate to their use of SR and DPS?*

6.2 Methods

Twenty-six kayakers (14 male, 12 female) took part in the study, all of whom competed nationally or internationally. Data from ergometer profiling (Chapter 4) and on-water profiling (Chapter 5) were combined in this study and no additional data were collected. Testing therefore consisted of two sessions, one on water and one on the ergometer, both completed on the same day. Recovery between the sessions was not controlled other than being longer than 90 minutes and without additional training in between. As these athletes are all part of the NGB programme, they will previously have been advised about optimising recovery strategies including hydration and nutrition. Details on the data collections can be found in Sections 4.2.3 and 5.2.2.

In brief, the on-water session consisted of a full race-day warm up, followed by six maximal effort 100 m sprints from standing with 12 minutes of off-water recovery in between. An on-boat differential GPS (10 Hz) and inertial measurement unit (IMU; 100 Hz; YachtBot, Igtimi, New Zealand) was attached, and data relating to the environmental conditions were collected throughout. Following a minimum of 90 minutes recovery, the ergometer testing was completed. This consisted of a warm-up and then five trials of 14 maximal strokes on a custom built iso-inertial kayak ergometer (Schofield, 2015), with three minutes recovery between trials.

From the on-boat data, average boat velocity (V_{ss}), maximum velocity (V_{max}), 10 m time, SR and DPS were calculated for the steady state period across six trials using MATLAB R2017a (the Mathworks Inc, Natick, MA, USA). Maximum velocity and 10 m time were calculated in addition to the steady state velocity as described in Chapter 5 in order to compare how ergometer testing relates to the start and maximum velocity elements of sprint kayaking. From the iso-inertial ergometer, in addition to the three pull-averaged measure of power used to document capacity in Chapter 4 ($Power_{pull,ave}$, $Power_{pull,max}$, $P0_{pull}$), stroke-averaged trial average ($Power_{str,ave}$), trial maximum ($Power_{str,max}$), and hypothetical maximum ($P0_{stroke}$) were calculated. Stroke average powers were considered pertinent to compare to on-water performance as the inclusion of a recovery phase may more accurately represent the on-water conditions. F0, V0 and $S_{F\text{-}V}$ were calculated from the F-V profiles which were in turn constructed from the 12 pull-phase means as in Chapter 4. Optimum stroke rate (SR_{opt}) was calculated from the stroke power-SR profile only. Force and power values were normalised by dividing by body mass$^{0.67}$ (Jaric et al., 2005), as in Chapter 4 and discussed in Section 2.8.1.

Statistical analysis was run in SPSS (IBM SPSS Statistics for Windows, Version 22.0., IBM Corp., Armonk, NY). Shapiro-Wilk tests for normality and visual assessment for linearity and homoscedacity were conducted for each variable to assess whether parametric or non-parametric correlations should be conducted. As a number of variables violated one of more of the assumptions, non-parametric Spearman's correlations were calculated at group level between each of 14 variables: V_{ss}, V_{max}, 10 m time, SR, DPS, $Power_{pull,ave}$, $Power_{pull,max}$, $P0_{pull}$, $Power_{str,ave}$, $Power_{str,max}$, $P0_{stroke}$, S_{FV}, F0, V0 and $SR_{opt,str}$.

6.3 Results

Correlations showed that all six measures of power as recorded during a maximal test were all strongly correlated to each other and to V_{ss}, V_{max} and 10 m time during maximal on-water sprinting, with stroke averages resulting in slightly higher correlations with on-water velocities than pull-phase averages (Table 6.1). All of these measures of boat velocity were also strongly correlated with each other and with both SR and DPS on-water.

Table 6.1: Spearman's correlation matrix results for comparison of all on-water and on-ergometer data. * indicates statistical significance ($p < 0.05$).

		Vel_{SS}	Vel_{max}	10 m Time	SR	DPS	Power $_{pull,ave}$	Power $_{pull,max}$	$P0_{pull}$	Power $_{str,ave}$	Power $_{str,max}$	$P0_{stroke}$	F0	V0	S_{FV}
Vel_{max}	r	0.95*													
($m \cdot s^{-1}$)	P	<0.001													
10 m Time	r	-0.92*	-0.84*												
(s)	P	<0.001	<0.001												
SR	r	0.86*	0.86*	-0.78*											
(spm)	P	<0.001	<0.001	<0.001											
DPS	r	0.63*	0.62*	-0.61*	0.29										
(m)	P	0.001	0.001	0.001	0.166										
$Power_{pull,ave}$	r	0.90*	0.90*	-0.78*	0.83*	0.56*									
($W \cdot kg^{-0.67}$)	P	<0.001	<0.001	<0.001	<0.001	0.004									
$Power_{pull,max}$	r	0.90*	0.92*	-0.77*	0.84*	0.55*	0.98*								
($W \cdot kg^{-0.67}$)	P	<0.001	<0.001	<0.001	<0.001	0.004	<0.001								
$P0_{pull}$	r	0.88*	0.88*	-0.76*	0.83*	0.54*	0.97*	0.97*							
($W \cdot kg^{-0.67}$)	P	<0.001	<0.001	<0.001	<0.001	0.005	<0.001	<0.001							
$Power_{str,ave}$	r	0.95*	0.96*	-0.85*	0.86*	0.61*	0.94*	0.94*	0.92*						
($W \cdot kg^{-0.67}$)	P	<0.001	<0.001	<0.001	<0.001	0.001	<0.001	<0.001	<0.001						
$Power_{str,max}$	r	0.95*	0.96*	-0.84*	0.85*	0.61*	0.91*	0.94*	0.89*	0.98*					
($W \cdot kg^{-0.67}$)	P	<0.001	<0.001	<0.001	<0.001	0.001	<0.001	<0.001	<0.001	<0.001					
$P0_{stroke}$	r	0.94*	0.94*	-0.86*	0.84*	0.63*	0.92*	0.91*	0.88*	0.97*	0.94*				
($W \cdot kg^{-0.67}$)	P	<0.001	<0.001	<0.001	<0.001	0.001	<0.001	<0.001	<0.001	<0.001	<0.001				
F0	r	0.90*	0.89*	-0.81*	0.85*	0.52*	0.88*	0.87*	0.83*	0.90*	0.89*	0.89*			
($N \cdot kg^{-0.67}$)	P	<0.001	<0.001	<0.001	<0.001	0.007	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001			
V0	r	0.43*	0.41*	-0.32	0.37	0.34	0.63*	0.62*	0.68*	0.48*	0.44*	0.45*	0.25		
($m \cdot s^{-1}$)	P	0.032	0.041	0.11	0.071	0.098	0.001	0.001	<0.001	0.015	0.024	0.022	0.225		
S_{FV}	r	-0.63*	-0.63*	0.57*	-0.59*	-0.32	-0.49*	-0.50*	-0.40*	-0.60*	-0.65*	-0.60*	-0.78*	0.22	
	P	0.001	0.001	0.003	0.002	0.12	0.014	0.012	0.049	0.002	<0.001	0.002	<0.001	0.303	
$SR_{opt,str}$	r	0.77*	0.75*	-0.72*	0.79*	0.34	0.67*	0.72*	0.71*	0.81*	0.80*	0.75*	0.62*	0.39	-0.39
(spm)	P	<0.001	<0.001	<0.001	<0.001	0.103	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.001	0.057	0.057

6.4 Discussion

All power parameters correlated very strongly with all of the on-water performance variable (Table 6.1). meaning athletes who demonstrated higher power values also achieved a higher boat velocity and indicating power as measured on the ergometer can clearly be described as a determinant of sprint kayak performance. Of the six power variables, $Power_{str,ave}$ correlated most strongly with all of the on-water performance measures (V_{ss}, r = 0.95; V_{max}, r = 0.96; 10 m time, r = -0.85), although $Power_{str,max}$ and $P0_{stroke}$ exhibited almost identical r values.

On-water performance variables displayed extremely high correlations between V_{ss} and V_{max}, and therefore each of these parameters has very similar correlations with all other measured variables, but time to 10 m demonstrates slight differences. This emphasises the different requirements needed in start performance relative to movement at speed, in agreement with many of the coaches interviewed in Chapter 3. The strong relationship between 10 m time and F0 also supports coaches belief that the start of an on-water effort is more of a 'raw pull', and is supported by research which has found kayak sprint start performance to correlate with maximal strength in gym-based strength exercises (Uali et al., 2012).

Ergometer measured V0 has a significant correlation with boat velocity (Vel_{max} and Vel_{SS}) but this relationship would be classed as 'medium' according to Cohen's measures of effect size (Cohen, 1988) and is not as strong as that between F0 and boat velocity which shows a 'strong' effect size. This suggests that maximal force capacity is more important than maximal velocity to kayaking performance, directly opposing findings from athletics sprinting (Slawinski et al., 2017). Slawinski and colleagues were looking at the whole effort including acceleration, rather than just the steady state portion, which would affect the outcome. Maximal velocity was not statistically significantly linked to any of the other key variables, unlike in athletics where Morin et al. (2012) looked at the mechanical determinants of sprint running performance and concluded, in opposition to the current study, that a more velocity-oriented FV profile produced best performance. Maximising speed of movement may be less important in the on-water environment relative to sprinting as increasing paddle speed through the water may result in more 'slip' rather than a proportional increase in boat speed, which has been shown to correlate negatively with performance (Wainwright et al., 2015).

The findings of this study partially support the hypothesis that those athletes who are highly force-dominant would use longer, more powerful strokes (higher DPS) and that those who are velocity-dominant would use a higher stroke rate. F0 correlates significantly with DPS with a medium effect size, but V0 does not correlate with SR. In kayaking, increasing movement speed will not necessarily result in increasing boat speed if technical efficiency does not support the increase and DPS is reduced to a greater extent than SR is increased. The correlation between SR and F0 appears to indicate that those who are able to produce more force also use higher SR. There is no apparent theoretical reasoning for this, and the positive correlation may be the result of multicollinearity or an extended range of SR as seen in Chapter 4. The strong correlation between $SR_{opt,str}$ as measured on the ergometer and SR on-water provides further support that the ergometer well replicates on-water sprinting demands.

Three differences between the ergometer and on-water task are that of balance, connection to the water and equipment. The current study appears to indicate that some athletes are not utilising their physiological capacity on-water, particularly their maximal velocity capacity, potentially due to an offset in one of the three above factors. For example, a forceful athlete may not have the balance to be able to use a high percentage of their force; they may have technical inefficiencies with the blade moving though the water without increasing boat speed; or they may have a sub-optimal paddle set-up which causes them to artificially raise or decrease their SR through changes in blade surface area or moment arm. Future research focusing on force and power measurement on-water will allow better understanding of these relationships.

This study used multiple correlations and did not use the Bonferroni adjustment to the alpha value. While this might increase the risk of type I errors (false positives), the interpretation of one test is not dependant on the number of tests run (Perneger, 1998) and the Bonferroni adjustment is considered a very conservative measure, recommended to be used when it is highly important to reduce type I error, or when many correlations without theoretical basis are conducted (Armstrong, 2014), neither of which is the case in this study.

The strength of the correlation between the ergometer and on-water performance allow coaches to understand where performance gains could be made. For athletes who are strong in the gym but cannot transfer that strength to water, the ergometer could help direct training aims. If they are able to produce high power on the ergometer, they could focus on technical application of force in the boat, while if they are not able to produce high power, force generation at speed through multi-joint coordinated movements may improve performance.

Previous research has concluded that an optimal SR must exist for each individual athlete (Plagenhoef, 1979; McDonnell et al., 2013b) as – contrary to the current study, and other group level analyses, showing strong correlations between SR and velocity – world medallists do not always have the highest SR. McDonnell and colleagues attributed differences in optimal SR to strength, anthropometry, physiology and equipment, the significance of the correlation of F0 and power measures with SR goes some way to supporting some of these ideas. More research is needed to investigate the within athlete relationships of these factors.

6.5 Conclusion

The high correlation found here between the normalised power measured on an ergometer and on-water performance demonstrates the value of the ergometer as an applied tool to optimise and individualise training. At group level, it seems that many factors relating to power, as well as maximal force generation, underpin multiple aspects of on-water performance. As well as being a valuable training tool, this also means any interventions on this ergometer can be directly linked to on-water performance, including paddle set-up parameters.

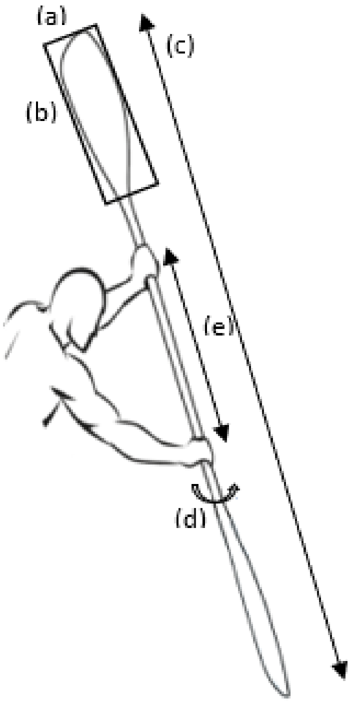
The gradient of an athlete's F-V profile has a 'medium' sized effect on on-water technical performance, with a significant correlation between F0 and DPS but none between V0 and SR. The correlations that cannot be supported by theory must be interpreted with caution and future on-water research at individual level would be of considerable value in understanding the interaction between capacity and technique.

Chapter 7: The Effect of Paddle Length on Power and Force Velocity Profiles

7.1 Introduction

There is a paucity of research into the effect of paddle set-up on performance in sprint kayaking, despite coaches' beliefs that research could have large benefits (Chapter 3, Section 3.3.4). Robinson et al. (2002) conducted a review of technology in sprint kayak, first highlighting the importance of force production to kayak performance and subsequently stating "technology absolutely dictates this relationship" (p. 68). Their review proceeded to discuss boat and paddle technology developments including the possible merits of the wing blade relative to a flat blade but did not discuss paddle set-up parameters other than blade shape design, potentially due to the sparsity of research in the area to review at that time.

There are currently no International Canoe Federation (ICF) regulations on paddle design or set-up. Many elite level paddlers use paddles made by manufacturers Jantex or Braca; of the 25 athletes in the elite and sub-elite categories in Chapter 5, 12 used Braca and 13 Jantex. Each of these companies has different designs (primarily focusing on different shape of the blade), which then come in different blade sizes (changing the surface area of the blade while maintaining relative shape), and with different shaft lengths (Brača, 2019; Jantex, 2019). Athletes then freely choose where their hands are placed on the paddle shaft and the angle of the blades relative to one another (feather angle). This results in five main factors of paddle design and set-up to be chosen by the athlete and coach prior to or after buying a new set of paddles (Figure 7.1).



Measurement		Definition
(a)	Blade size	Surface area of the blade. Available as small, medium and large etc.
(b)	Blade shape	3D shape of the blade. International paddlers use 'wing' paddles which are concave in two planes. Multiple variants available
(c)	Paddle length	Length of the paddle from the tip of one blade to the tip of the other.
(d)	Feather angle	The angle between the face of one blade and the face of the other.
(e)	Grip width	Distance between the hands on the paddle. Measured from the middle finger on the left to middle finger on the right.

Figure 7.1: Diagrammatic representation of paddle set-up with labels and design measurement definitions.

The large number of variables associated with paddle setup is evident with some commercial companies (Epic Kayaks, 2019) using 15 independent variables within their algorithms for consumer paddle selection (Table 7.1). No justification or evidence is provided to support the outcome and no additional details could be found on the algorithm used by the website.

Table 7.1: Information required by Epic Kayak's (2019) 'Paddle Wizard' to recommend a paddle set-up.

Blade Shape	Paddle Length
- paddler type	- paddler type
- boat style	- boat style
- stroke width	- stroke width
- stroke length	- stroke length
- average 500 m time	- seat height
- distance focus	- height
- weight	
- strength	
- height	

Very few studies could be found that have quantified the influence of changing any of these paddle set-up parameters on performance (Table 7.2) and in those that have, methods used vary considerably. Each of the published research papers will be discussed below.

The effect of changing **blade shape** has been investigated in a wind tunnel (Sumner et al., 2003) and a towing tank (Jackson et al., 1992). Both methods are a simplification of the complex dynamic flow around the blade during a paddle stroke, and of the paddle path, but give insight into the forces acting on a wing blade (e.g. Figure 2.11) compared to a traditional 'drag' or flat blade of similar surface area. Sumner et al. (2003, p. 12) state that "the relative lateral motion between the water and the blade is kept to a minimum" during paddling. This contradicts the suggestion by Kendal and Sanders (1992) and Jackson et al. (1992) that lateral movement of the wing blade is important for generating lift forces and contributes to forward propulsion. Sumner et al. (2003) concluded that through yaw angles of ±20° and pitch angles of 0-30°, drag forces are slightly higher using a wing blade but found lift forces measured from a wing blade across all ranges to be indistinguishable from those of a flat plate. However, the 20 second measurement using steady-state flow conditions in a wind tunnel is not applicable to the short duration, dynamic movement of a sprint kayak stroke. In direct contrast, Jackson et al. (1992) used movement through water from stationary and found the wing paddle to have large increases in lift forces relative to the flat (or drag) blade, and to be considerably more efficient. Jackson measured 'angles of attack' from 0-90°, equivalent to the positive 'yaw' angles in Sumner et al. (2003), with a much broader range. Sanders and Baker (1998) outline six theoretical advantages of the wing blade: less energy is lost to moving the water; larger vortices increase paddle efficiency; the curved motion of stroke increases physiological economy; an increase in effective pull time; a longer duration at (sagittal plane) paddle vertical and a more effective use of athlete's mechanical system. Although not all these theories have an empirical evidence base, Sanders and Baker (1998) cited their own applied (unpublished) research in support and discuss the high level of individuality in paddle path and in particular, the range of lateral movement, potentially indicating that athletes could benefit from different designs dependant on technique. No research could be found that has investigated differences between commercially-available blade designs, meaning manufacturer's claim that design changes that make the blade ‘shorter, wider and more twisted’ create one that is “extremely aggressive [and] more stable with excellent exit” (Jantex, 2019) cannot be substantiated.

Sprigings et al. (2006) used instantaneous force and velocity measurements from an ergometer to recommend an ‘optimal’ **blade size** for elite kayakers based on maximising power, having first outlined their expectation that “excessive energy will be lost during the main body of the race if the drag force created on the paddle blade is not matched with the individual muscle force-velocity characteristics of the individual.” Sprigings et al. looked at the cable velocity and force at which maximum power occurred and input these values, along with values for water density and blade drag force coefficient from previous literature, into the equation for drag to calculate recommended frontal surface area. Despite the authors’ comparison to F-V and P-V profiles, the graphs and descriptions used in the study indicate a power-time curve was used to understand where ‘peak’ power occurs, and it is not clear which stroke was used. Two of the limitations to this study were acknowledged by the authors: the use of an ergometer and the attempt of the athletes to recreate ‘500 m race pace.’ However, one of the largest limitations is the assumption that drag force is the only contributor to forward boat movement, with lateral movement of the paddle attributed to a constraint placed on the athlete by the width of the boat, rather than for any potential positive purpose such as utilising lift forces. Although the result revealed that the calculated blade sizes matched those already used by the elite athletes for five of the 12 elite athletes tested, and the remaining seven were recommended a 5-10% increase, this finding should be viewed with caution given the methodological limitations. Further, frontal area of the blade was determined using 2D digital images, therefore discounting any curvature and likely underestimating measured blade size. As no performance testing of different blade sizes was conducted, this study’s conclusions are based on the above assumptions and cannot directly inform the influence of changing blade size on any performance metric.

Lee (2013a) compared two paddle set-ups on water but not with sprint kayaks or typical sprint kayak paddles so the author’s conclusions that a **feathered blade** (90° difference in blade face position) reduced stroke rate (SR) and increased distance per stroke (DPS) compared to a flat blade (same blade face angle) cannot be assumed to also apply in sprint kayaking. An abstract by the same author concluded that greater **grip width** resulted in higher trunk rotation and a decrease in boat stability, as measured by greater roll of the boat (Lee, 2013b). This finding is interesting but again, without additional information on the boat, paddles and methodology used, it cannot be assumed to be true for sprint kayakers also.

Regression modelling was used by Diafas et al. (2012) to compare the anthropometric and paddle data from 55 male and 26 female kayakers. Measurements included: height, mass, torso length, arm span, arm and leg lengths, paddle length, blade length and blade width. The conclusions of the authors that "**paddle length** is selected based on body length and morphology" (p.24) is not surprising, especially when taken in conjunction with the coaching ideas presented in Chapter 3 of this thesis of how to best set up the paddle. However, the lack of performance data means this method does not increase our understanding of how to optimise paddle set-up for individuals but does give an overview of the sizes typically used by sub-elite level athletes. Conversely, Ong et al. (2005) found anthropometrics only explained 20% of paddle length differences between athletes. Seat height relative to the cockpit top was found to be significantly different when the anthropometrics and equipment set-up of sprint athlete in the top 10 at the Olympic Games were compared to those who finished lower down and a trend for increased grip width in the top 10 athletes was reported but no other differences. These factors were not normalised to sitting height or arm span and differences are slight (best = 1.2 cm lower seat and 2.3 cm wider grip). This paper combined those in crew boats and across different race distances, so discrepancies due to these factors are disguised. There is therefore very little research from which to advise paddlers as to how to choose their paddle length and research in this area will directly benefit athletes and coaches.

Further investigating the relationship between grip width and anthropometrics, Ong et al. (2006) used group data to create a regression equations and subsequently used the equation to change grip width (grip width = 3.557 + [0.376 x height]) and seat-foot rest distance (-15.975 + [0.603 x height]) in three elite athletes. Athletes were tested once over a 100 m sprint in each of three conditions of grip width: preferred, regression predicted, and regression predicted plus one standard deviation (of group grip width). Predicted grip width was smaller than preferred for all athletes and predicted plus one SD was larger, although the magnitude of this difference varied (2.9, 4.2 and 5.6% for each athlete). Changing away from what the athlete usually used to the predicted set-up was found to result in decreases in boat speed (average 3.9%) for the two athletes with the largest magnitude of change in grip width, but an increase in boat speed for the other athlete (2.6%). Decreasing grip width relative to preferred distance increased stroke length and reduced SR for all three athletes, while increasing grip width decreased SR with a variable effect on stroke length (two increased, one decreased). It is not clear how grip width was controlled while the athletes paddled and the use of only one trial and no additional measure of variability make these conclusions limited. Increasing grip width would decrease the distance between the lower hand and the centre of pressure but increase the distance from the top hand to the centre of pressure. Too little is known about the path and orientation of the blade in the water to understand what impact this would have and assumptions that could be made of a sagittal plane 'pivot' movement are likely an oversimplification. This highlights the difficulty in drawing conclusions from on-water testing where there are many confounding variables and only a few repetitions are possible, allowing the value of ergometer testing to be emphasised.

It is not clear if athletes were told how much or in which direction set-up was changed in Ong et al.'s (2006) study. An athlete's belief that they are able to achieve a certain goal has been described as their self-efficacy (Bandura, 1977) and this has been found to influence performance, with a meta-analysis concluding that self-efficacy beliefs positively influence performance (Moritz, Feltz, Fahrback, & Mack, 2000). Therefore, an athlete's perception of whether a certain change in equipment is likely to lead to improvements or detriments to performance may become self-fulfilling and blinding participants to change is worthwhile. No studies could be found that have blinded participants to interventions in equipment set-up to investigate performance changes, perhaps due to a perceived increase in injury risk or other ethical considerations. Physiologically, athletes have been found to be able to improve time trial performance when deceived about power output. By using a pacer set at 2% and 5% higher output than a baseline test but having been told the pace matched that at baseline, athletes were able to reduce completion time, reaching statistical significance in the 2% condition (Stone et al., 2017). While not influencing a mechanical aspect, this percentage change may therefore provide some guidance as to an intervention change which may not be detected but still creates meaningful change.

Caplan (2009) found an offset between blade and shaft (Figure 7.2) to increase boat velocity in outrigger canoeing. Using modelling of paddle movement and forces, focusing on the sagittal plane, an offset angle of -20^{o} between the blade face and the shaft increased mean boat velocity by synchronising the moment the blade face was vertical with the maximal paddle velocity. These findings are only directly relevant for the specific athlete investigated as technique varies between athletes (Sanders & Baker, 1998). This example is also highly oversimplified as it was 2D and uses steady flow, and there are large differences between the strokes of single-blade outrigger canoeing and sprint kayaking. Despite this, the methodology of simulation modelling could provide a way of assessing paddle set-up changes without the confounding variables of the environment-provided the 3D kinematics and kinetics of the paddler and assumptions of the interaction with the water could be measured and validated.

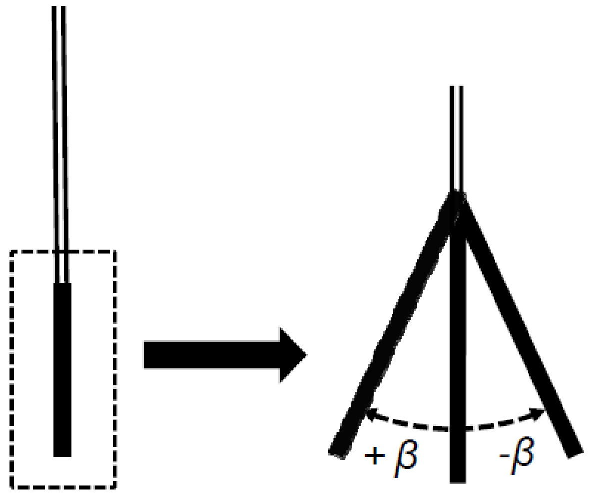


Figure 7.2: Diagram of blade offset angle (β) described in Caplan (2009)

No studies to date have manipulated sprint kayak paddle set-up parameters and measured the effect in on water performance in 3D. This is unsurprising as motion capture or force measurement systems that could be used for on-water measurement are still uncommon and the environment causes issues for technology, as highlighted in chapter 2. While force has been measured in 2D in canoe paddling (Tullis et al. 2018), sprint kayaking on-water force measurement is limited to 1D and/or makes limiting assumptions such as a fixed centre of pressure on the blade (Gomes et al., 2015; Nilsson & Rosdahl, 2016). Despite the importance of force and power to sprint kayak performance (van Someren & Palmer, 2003), the effect of changing paddle set-up on these metrics has not been assessed. The level of accuracy needed to measure differences between subtle set-up changes is very high and even if currently possible, the confounding factor of weather conditions would further reduce any practical implications. As such, ergometer studies investigating changing paddle set-up would be of particular value.

The importance of individual level analysis, particularly at elite level, has recently been emphasised (Bartlett et al., 2007; Glazier & Lamb, 2018; Glazier & Mehdizadeh, 2019). Variation between athletes has also been considered from a statistical standpoint, with Mullineaux et al. (2001) advocating the use of simple analyses to avoid problems combining individual and group level data. Despite these recommendations, there is no precedent within sport science research for individual-based analysis.

Table 7.2: Summary of research papers investigating paddle set-up parameters in kayaking.

Authors	Paddle set-up factor	Study Design	Brief Conclusions & Observations
Jackson (1992)	Blade shape	Description from first principles & tow tank testing of blades	Wing paddle is more efficient compared to flat blade design. Authors speculate that increasing size of vortex rings and SR will lead to improvements in performance.
Sumner et al. (2003)	Blade shape	Wind tunnel testing of different blades	A Norwegian-style wing blade resulted in higher force generation than a conventional or flat blade face.
Sprigings (2006)	Blade size	Ergometer force application	Individual blade size recommendations can be made using the force and power profiles of individuals. Most elite athletes were using blade size within 5% of predicted optimal. Calculations based solely on drag forces.
Ong et al. (2006)	Grip position	On-water intervention	Based on anthropometric correlations of Olympic kayakers, grip width was matched to a regression equation. Changing from what the athletes were used to resulted in decreased boat velocity.

Table 7.2 continued

Authors	Paddle set-up factor	Study Design	Brief Conclusions & Observations
Caplan (2009)	Blade offset angle	Simulation modelling	Mathematical modelling of paddle path demonstrated an offset angle of the blade face relative to the shaft results in better performance in outrigger canoe.
Diafas et al. (2012)	Paddle length	Modelled anthropometrics against paddle set-up of elite	Correlational analysis showed relationships between some anthropometric factors and paddle set-up. As no performance measure were used, the assumption is high level paddlers are using optimal set-up.
Lee (2013a)	Feather angle	On-water intervention	Sea kayak blades found to increase DPS and decrease SR with 90° offset between blade face compared with no offset.

Based on the limitations of on-water collection, it was decided that investigation into changes in paddle set-up should be conducted in such a way that the effect of the intervention could be clearly measured. Combining the data from Chapters 4 and 5, has shown the relevance of force-velocity and power-velocity profiling on the ergometer to on-water spring kayak performance, thereby providing a measurement system both relevant to performance and in a controlled environment. The same studies have also highlighted the need for individual analysis as differences between individuals can be hidden if only group analysis is conducted.

7.1.1 Aim & Research Question

The aim of this study was to explore the differences in force-velocity and power-velocity profile resulting from changes in paddle length in experienced kayak athletes, with analysis at both group and individual level.

Research question 7.1: *does changing paddle length result in changes in force-velocity and power-velocity profiles?*

7.2 Methods

7.2.1 Participants

Ten elite (n = 3) and sub-elite (n = 7) kayak athletes took part in this intervention study (Table 7.3), categorised in the same way as in Chapter 4 (Table 4.2). Most participants had previously taken part in the ergometer study outlined in Chapter 4 and all athletes involved took part in this form of F-V testing approximately every 4-6 weeks. All participants had completed ergometer testing at least four times in the year prior to testing so no additional familiarisation was conducted. The methods used in this study are the same as those used in Chapter 4 so only the key details of the procedures will be repeated here. Ethical approval was gained from the University of Lincoln School of Sport and Exercise Science ethics committee.

Table 7.3: Group level participants' characteristics for each gender (group mean ± SD)

Gender	N	Age (years)	Mass (kg)	Height (cm)	Arm Span (cm)	Paddle Length (cm)
Male	7	21.3 ± 2.7	82.5 ± 4.5	180.7 ± 4.5	187.2 ± 4.2	217.1 ± 1.2
Female	3	25.3 ± 6.6	72.1 ± 3.0	171.4 ± 1.6	177.4 ± 6.8	215.0 ± 1.0

7.2.2 Data collection

Following a standardised warm up designed by the athletes' physiotherapists and strength and conditioning (S&C) coaches (Appendix 2), each participant completed six trials on the ergometer: a total of two trials at each of three different paddle lengths. Trials were completed in randomised order without grouping for condition. The paddle lengths chosen were: matching that used when paddling their K1 (PL_{NORM}); 1% of the total length longer (around 2 cm; PL_{LONG}); and 1% shorter (PL_{SHORT}) than PL_{NORM}. The paddle length on the ergometer assumes a force application at a fixed centre of pressure of the blades 20 cm from the blade tip and the PL_{NORM} is therefore 40 cm shorter than the paddle length would be on-water (see Chapter 4, section 4.2.2 and Figure 4.2a for detail). The 1% change in length represented a typical change that might be made by a coach or athlete in the high-performance system. Single changes larger than this are highly unlikely to be made at one time and therefore results would be less likely to have impact. Grip position relative to the midpoint of the shaft and grip width were matched to on water set-up through use of 3D-printed grip markers (Figure 7.3).

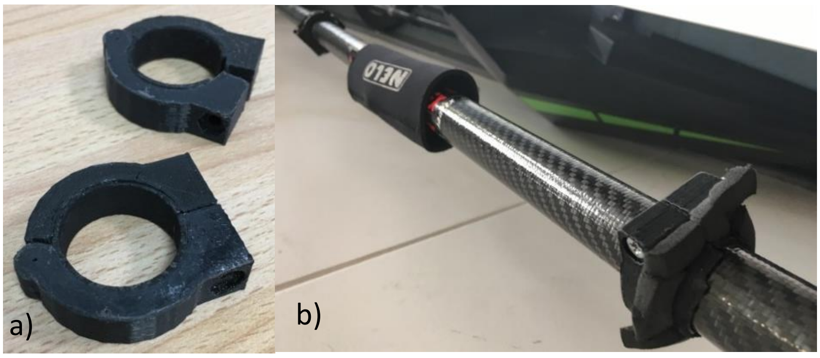


Figure 7.3: 3D printed grip markers to control hand position on the ergometer shown a) separately and b) on the paddle shaft. Collar shown on the paddle shaft used to disguise condition of trial.

Athletes were not informed about the direction of the change and the central connection between the paddle was covered to reduce visible effect of changing length, as can be seen in Figure 7.3b. There were three minutes of passive recovery between trials (Hoianaski et al. 2007; Toubekis et al., 2005).

Each trial was conducted in the same manner as in Chapter 4 (Section 4.2.3), with 14 maximal standing strokes from a stationary start position. Additionally, calculations and processing were also replicated from Chapter 4 and a full description can be found in Section 4.2.4. Chapter 6 demonstrated that the strongest relationships between power and on-water performance were the stroke average values (Table 6.1). However, pull power averages are reflective of a maximal capacity without reference to duty cycle so are also of interest for strength and conditioning coaches. Power measures for analysis were therefore: $Power_{str,ave}$, $Power_{str,max}$ and $Power_{pull,ave}$.

7.2.3 Statistical analysis

Data were analysed using SPSS (IBM SPSS Statistics for Windows, Version 22.0., IBM Corp., Armonk, NY) and Microsoft Excel (2016). Statistical significance for group analysis was set at $p < 0.05$.

7.2.3.1 Group analysis

Power ($Power_{str,ave}$, $Power_{str,max}$ and $Power_{pull,ave}$) and theoretical maximal force (F0) were normalised to $bodyweight^{0.67}$ (Jaric et al., 2005) as in Chapter 4 and discussed in Section 2.8.1. Theoretical maximal velocity (V0) was not normalised. Group level one-way ANOVAs were conducted to compare the three measures of power, F0, V0 and $SR_{opt,str}$ when using the three different paddle lengths. The assumption of homogeneity of variance was met in all cases ($p > 0.90$), but F0 was non-normally distributed for all groups and although ANOVAs are reportedly robust to violations in the assumption of normality (Schmider et al., 2010), non-parametric Kruskal-Wallis tests were run additionally.

To investigate if anthropometrics influenced an athlete's responses, as might be expected based on coaches' opinions (Section 3.3.4) and previous literature (Diafas et al., 2012; Ong et al., 2006), normalised stroke power was correlated against paddle length as a proportion of arm span (PL_{AS}). As PL_{AS} was found to be non-normally distributed, with a visually assessed 'medium' linearity (see Appendix 3 for examples), a Spearman's rank order correlation was run.

7.2.3.2 Individual analysis

Typical intra-day variability for each individual was quantified using mean, standard deviation (SD) and coefficient of variation (CV; $CV = \frac{SD}{Mean} * 100$) of the $Power_{str,max}$, $Power_{str,ave}$, $Power_{pull,ave}$, F0, V0 and $SR_{opt,str}$ across five trials with normal paddle length in the testing session prior to the intervention. The SD was then used to calculate and upper and lower bound around the mean for PL_{NORM} in the subsequent intervention testing. If the resulting values for PL_{LONG} or PL_{SHORT} were outside of the upper or lower bounds for the athlete, a change was considered to have taken place. Change was noted if values were outside 68% or 95% confidence intervals (mean + 1 SD and +2 SD respectively). As each athlete's values were only being compared to themselves, no normalisation was conducted. In addition, Cohen's *d* for effect size was calculated for each athlete to compare PL_{SHORT} and PL_{LONG} against PL_{NORM}.

7.3 Results

For F0, the Kruskal-Wallis test revealed no significant difference ($p = 0.98$), in agreement with the ANOVA ($p = 0.97$). At group level, none of the performance variables were found to differ significantly between paddle lengths (Table 7.4) from the ANOVA ($p > 0.05$) and were in fact notably similar.

Table 7.4: Group level stroke power, F0 and V0 for the three paddle length conditions (mean ± SD). P values are from ANOVA for stroke power and V0, and from Kruskal-Wallis test for F0.

	PL_{SHORT}	PL_{NORM}	PL_{LONG}	p-value
$Power_{str,ave}$ ($W \cdot kg^{0.67}$)	30.57 ± 5.67	30.58 ± 4.98	30.88 ± 5.42	0.98
$Power_{str,max}$ ($W \cdot kg^{-0.67}$)	36.71 ± 5.27	36.75 ± 5.38	37.09 ± 5.34	0.97
$Power_{pull,ave}$ ($W \cdot kg^{0.67}$)	46.41 ± 8.81	46.09 ± 7.26	46.49 ± 8.81	0.99
F0 ($N \cdot kg^{-0.67}$)	16.18 ± 1.72	15.97 ± 1.61	15.86 ± 1.63	0.83
V0 ($m \cdot s^{-1}$)	11.39 ± 1.95	11.73 ± 1.71	11.75 ± 1.93	0.79
SR_{opt} (spm)	173.42 ± 25.98	170.16 ± 17.93	167.28 ± 13.63	0.62

Paddle length as a proportion of arm length was found to correlate significantly and inversely with normalised stroke power ($r = -0.397$; $p = 0.03$; Figure 7.3).

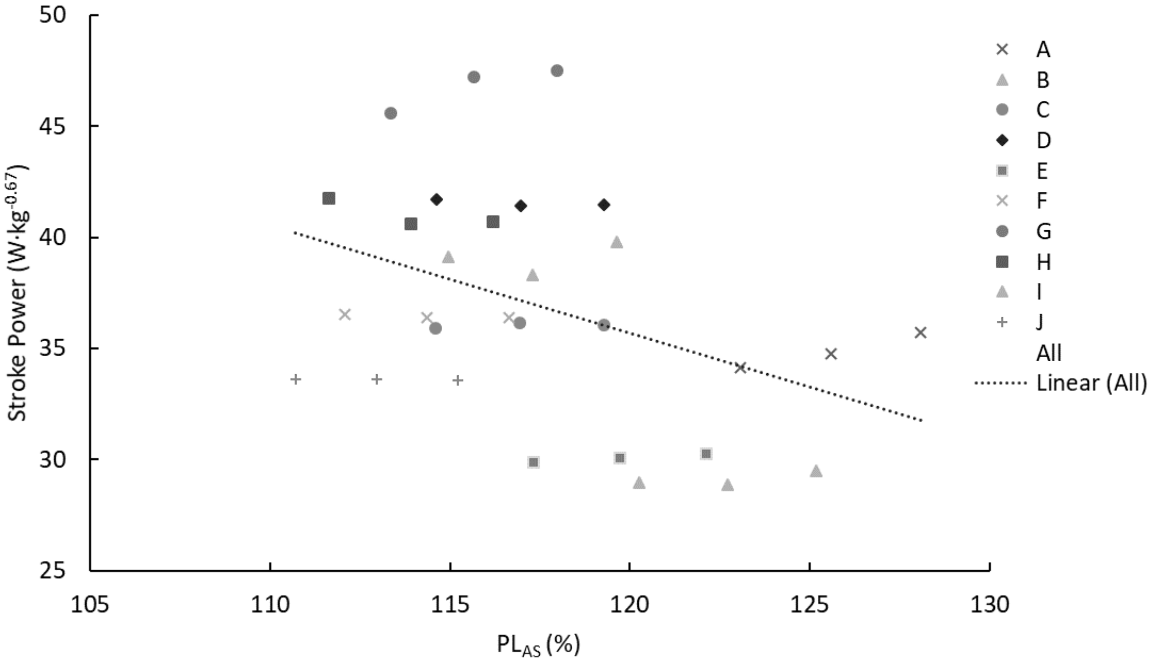


Figure 7.4: Data showing the relationship between normalised stroke power and paddle length as a proportion of arm span. Shapes represent individual athletes; the trend line is calculated from grouped data.

The intra-day coefficient of variation for athletes was 2.2 ± 1.5% (mean ± SD) for stroke power, 3.7 ± 2.4% for F0 and 4.3 ± 2.9% for V0.

At an individual level, there was meaningful change in stroke power output for three athletes, with Athlete 39 achieving significantly higher power with a longer paddle and Athletes 10 and 7 significantly lower power when using a shorter paddle (Table 7.5). Four athletes (10, 11, 39, 49) opposed the group trend for F-V, with higher F0 with a longer paddle. Six athletes exhibited meaningful difference in F0, V0 or both (Table 7.5).

Table 7.5: Mean of stroke power, F0 and V0 for each athlete in each paddle set-up position. Light grey shading indicates value more than 1 SD away from normal paddle length values. Darker grey shading represents values over 2 SD of normal paddle length value.

			$Power_{str,ave}$			$Power_{str,max}$			$Power_{pull,ave}$			**F0**			**V0**			**SR_{opt}**		
Athlete	**Mass**	**Gender**	**PL_{LONG}**	**PL_{NORM}**	**PL_{SHORT}**	**PL_{LONG}**	**PL_{NORM}**	**PL_{SHORT}**	**PL_{LONG}**	**PL_{NORM}**	**PL_{SHORT}**	**PL_{LONG}**	**PL_{NORM}**	**PL_{SHORT}**	**PL_{LONG}**	**PL_{NORM}**	**PL_{SHORT}**	**PL_{LONG}**	**PL_{NORM}**	**PL_{SHORT}**
10	75.3	F	511	515	501	646	629	618	726	728	729	267	265	265	11.9	12.1	12.1	176	177	179
59	71.5	F	390	393	376	515	504	506	571	613	571	248	249	258	10.1	10.7	9.8	160	158	155
7	78.5	F	435	435	421	519	515	512	676	682	660	243	244	246	12.3	12.3	11.8	149	150	152
11	80.0	M	531	522	520	692	694	689	753	746	748	342	338	345	9.8	9.8	9.6	154	157	155
66	82.4	M	713	706	705	812	812	818	1066	1062	1050	335	345	339	14.2	13.6	13.9	186	186	237
9	84.9	M	611	615	620	709	709	711	910	924	937	261	267	265	17.2	16.9	17.5	169	173	172
39	69.4	M	797	759	795	950	945	912	1160	1088	1154	362	354	371	14.1	13.6	13.6	192	199	189
16	84.1	M	674	675	689	770	767	789	1033	1016	1055	296	308	310	16.0	14.8	15.4	164	170	170
53	87.5	M	646	626	621	749	722	737	1076	1009	1060	317	327	337	15.5	13.7	14.1	166	160	169
49	80.4	M	514	520	519	624	625	625	792	820	786	308	307	305	11.3	11.8	11.3	156	159	156

Table 7.6: Effect size of performance parameters in PL_{LONG} and PL_{SHORT} compared to PL_{NORM}. Light grey shading indicates an effect size larger than 0.8.

		$Power_{str,ave}$		$Power_{str,max}$		$Power_{pull,ave}$		**F0**		**V0**		**SR_{opt}**	
Athlete	**Gender**	**PL_{LONG}**	**PL_{SHORT}**	**PL_{LONG}**	**PL_{SHORT}**	**PL_{LONG}**	**PL_{SHORT}**	**PL_{LONG}**	**PL_{SHORT}**	**PL_{LONG}**	**PL_{SHORT}**	**PL_{LONG}**	**PL_{SHORT}**
10	F	0.38	1.23	1.38	0.87	0.15	0.11	0.53	0.08	0.46	0.00	0.48	1.05
59	F	0.22	1.33	0.65	0.10	2.16	2.18	0.14	1.40	2.34	3.55	0.66	1.06
7	F	0.02	1.16	0.25	0.22	0.42	1.40	0.26	0.40	0.51	3.97	0.24	0.25
11	M	0.30	0.10	0.10	0.23	0.15	0.04	0.76	1.40	0.04	0.37	2.59	1.54
66	M	0.58	0.10	0.09	0.86	0.08	0.27	1.40	0.95	1.41	0.60	0.05	2.76
9	M	0.47	0.58	0.01	0.09	1.28	1.10	1.24	0.35	0.87	1.73	0.72	0.25
39	M	5.96	5.66	0.71	4.44	4.51	4.09	0.72	1.53	0.70	0.01	0.85	1.20
16	M	0.16	2.99	0.24	2.20	1.42	3.21	2.57	0.35	2.17	1.15	1.06	0.07
53	M	2.23	0.52	3.30	1.83	6.57	5.02	0.76	0.74	1.92	0.45	1.30	2.00
49	M	0.54	0.06	0.08	0.01	1.30	1.55	0.15	0.20	0.63	0.70	0.61	0.77
Group	-	0.06	0.00	0.06	0.01	0.05	0.04	0.07	0.12	0.01	0.12	0.18	0.17

7.4 Discussion

This study has measured the acute effects of changing paddle length on power and force production in elite and sub-elite kayakers for the first time. There was not a consistent response across the group, with athlete responses found to be highly individual. Pull and stroke powers resulted in different outcomes, with six athletes showing meaningful differences in $Power_{pull,ave}$ but only three athletes exhibited a notable change in $Power_{str,ave}$ due to paddle length. In addition, notable changes in F-V profile (F0, V0 or both) were seen for six of the participants and two athletes exhibited a change in optimal SR due to paddle length change.

At the group level, a 2 cm change in paddle length did not change power production, the maximum velocity with which the paddle can be moved (V0) or the maximal force that can be produced (F0) on an ergometer. This is supported by previous group level research: Martin and Spirduso (2001) used the iso-inertial load method in cycling and investigated the effect of five different crank lengths on power output and found only a 4% variation across lengths that varied by 83%, which was only statistically significant at the extreme lengths.

Individual effect sizes were calculated using the mean and standard deviation (SD) of the two trials per condition. The effect sizes reported in Table 7.6 result in a number of 'large' effects which are not apparent based on the 'typical variability' measure. It would be expected that the SD of five trials would be higher than that of two and therefore the measure of typical variability for 'notable change' is more conservative.

For six of the ten athletes, F0 was higher with a shorter paddle compared to the matched paddle length, with notable increases for four athletes. If the paddle is considered in the sagittal plane as a simple 2D lever with a single pivot point (e.g. at the lower hand), a reduction in length outside the fulcrum (e.g. from the lower hand to the blade tip) would enhance the force output at the ergometer paddle tip for the same force applied to the paddle at the hands, as has been discussed to affect rowing oar set-up (Nolte, 2009). While this would be a clear benefit, the movement involved in paddling is not as simple as a 2D lever with a fixed pivot, and technical differences in paddling, such as lateral paddle movement, amount of trunk/hip rotation and arm kinematics may explain why enhancements in force with shorter paddles are not found universally, further supporting individual analysis.

Optimal SR changes were not consistent, with seven of the athletes reducing SR_{opt} with a longer paddle (one notably), but five lowering SR_{opt} with a shorter paddle. In cycling, increasing crank length was found to result in a decrease in optimal pedal rate (rate at which peak power is achieved) and an increase in optimal pedal speed, with the trade-off of these two parameters resulting in the small change in overall power (Martin & Spirduso, 2001). Maximum force and velocity are not reported by Martin and Spirduso (2001), the decrease in optimal speed with shorter pedals is *likely* to reflect a more force-orientated profile, in similarity with many of the athletes tested here. As individual results were not reported in the cycling paper, it is not known if all athletes exhibited the same response.

Longer paddles were found to result in a higher V0 for half of the athletes tested (notable for three; Table 7.5). A longer paddle may be expected to travel further for the same range of motion of the athlete so for the same stroke duration, an increase in velocity would be achieved. However, increasing length of paddle would also increase the rotational inertia which would then decrease velocity for a given force applied to the paddle. A trade off in the individual's management of these factors may explain the differences found.

The values for power found in this study are considerably higher than those found in other kayak ergometer research studies. Bjerkefors et al. (2018) reported values of 610 W for male and 359 W for female using strain gauges attached to the paddle, while van Someren and Palmer (2003) reported 'peak power' of international 200 m athletes from the direct output of a commercial ergometer of 615 W. Many commercial ergometers use a stroke average, with 'peak' being the highest average stroke rather than the highest measured within one stroke. This may explain differences between the current study and the commercial ergometer data from van Someren and Palmer (2003), but Bjerkefors et al. (2018) did not use this commercial output. Differences between the published research and the current study may be due to athlete level, distance focus of athletes or the time relative to the season testing was conducted.

Schofield (2015) reported stroke power, F0 and V0 for male 200 m and 1000 m focused paddlers measured on an isoinertial ergometer (Table 7.7). While some of the athletes reported in the current study are within the range of Schofield (2015) and overall stroke power is similar, the average F0 was lower and the average V0 was higher within the current study. Schofield only reported means and standard deviations but the relatively high SD in that study indicates large inter-individual variation, with comparable SD in the current study for F0, although it is higher in stroke power and V0 (Table 7.5). The 200 m athlete group in Schofield's study included three Olympic medallists so it might be expected that higher power outputs would be attained than both the 1000 m group in the same study, and the athletes in the current study. Schofield's isoinertial ergometer did not account for bungee tension and only calculated power based on derivatives of flywheel velocity and therefore is likely to underestimate power output. Gore et al. (2013) attributed 20% of the underestimation (of 13-21% total) in a Dansprint ergometer to the lack of account of bungee tension. Increasing the mean measured in Schofield (2015) by 20% would result in an average of 824 W for 200 m paddlers, higher than the male average found in the current study, as would be expected for athletes of that level.

Table 7.7: Selected power, force and velocity values from Schofield (2015) isoiertial ergometer testing of elite kayak paddlers.

Variable	200 m (mean ± SD)	1000 m (mean ± SD)
Stroke Power (W)	687 ± 62.6	613 ± 72.2
Stroke Power (W/kg)	8.29 ± 0.65	7.32 ± 0.4
F0 (N)	617 ± 91.9	592 ± 145.3
V0 ($m \cdot s^{-1}$)	11.68 ± 1.42	10.64 ± 1.96

7.4.1 Individual differences

The relationship between force and velocity was found here to be **individually responsive** to change as well as **individually different,** as shown in chapter 4. The underlying mechanics of F-V profiles have been covered in detail in Sections 2.8.2 and 4.1.1. Individual differences have been noted in F-V profiles by other researchers in jumping, sprinting, rowing and kayaking (e.g. Samozino et al., 2012; Samozino et al., 2016; Schofield, 2015; Sprague et al., 2007). An 'optimal' profile was described by Samozino et al. (2012) for vertical jumping and is detailed in Chapter 4 (Section 4.1.5), based on power, limb extension range and inclination of the jump; no research could be found that describes an 'optimal F-V profile' for cyclical movement and F-V profiles from sprinting do not correlate with F-V profiles from jumping (Jimenez-Reyes et al. 2018). In complex cyclical movements, 'optimal' for an athlete may be underpinned by intrinsic muscle and tendon mechanics and their interaction with the technique employed. This incorporates factors such as: the individual muscle F-V and force-length relationships, muscle cross sectional area, muscle and tendon length, elastic properties of the muscle and tendon, antagonistic activation, primary muscles and joints used in the movement, cycle distance, cycle speed and range of motion. Clearly modelling an 'optimal profile' based on so many factors would be difficult but would be a valuable area for future research.

It might be considered that anthropometrics could be causing differences between athletes as paddle lengths were relative to lengths already being used rather than a length proportional to an anthropometric length. Ong et al. (2006) found only 25% of variability (n = 42) in paddle length to be described by anthropometric measures of height, bi-acromial breadth, chest girth, arm length and arm span, indicating these measures are only a small factor in paddle length choice, despite height and arm reach (maximum height arm can reach vertically) being the only variables mentioned to guide choices for coaches (ICF, 2019). If there were a universal optimal PL_{AS}, a clear relationship between PL_{AS} and stroke power would be expected, which data at individual level would replicate. A larger range would be needed to understand how paddle length as a proportion of arm span affects power but individual and group level trends can be seen to diverge (

Figure 7.4). Taking key examples, Athlete 10 had the highest paddle length percentage and yet increased power with an increase in paddle length while Athlete 16 had the second shortest paddle and exhibited a (small) increase in power relative to matched length when using the shorter paddle. The results of this study combined with previous research (Ong et al., 2006; Diafas et al., 2012) indicate that anthropometrics do not provide a complete picture for optimising paddle set-up for individual athletes, although future research in the area, such as a paddle set-up intervention based on anthropometrics, would be valuable.

Paddles are designed so that all of the blade and none of the shaft enters the water to allow for most efficient paddling. While viewed from the sagittal plane, it could be postulated that there is therefore an optimum length based on sitting height and arm length but this would be disregarding the reported lateral movement of the paddle (Sanders & Kendal, 1992), which has been found to vary between athletes (Therrien et al., 2012), as well as the complex 3D movement involved in kayak paddling. It is not known if any differences in paddle path between individuals are linked to anthropometrics; future research in this area would greatly improve understanding of how paddles can be individualised.

No previous research could be found that has used an athlete's own variability to signify intervention change within sport science research. This method allows individualised measures of notable change to be calculated, which is extremely important in applied sport science as winning margins can be as small as hundredths of a second and the existence of individual differences in technical performance between athletes are known by coaches (e.g. Chapter 3).

The individual coefficients of variation (% CV) found in this study are similar to those found in cycling: 3.3 ± 0.6% for power, 2.7 ± 0.9% for maximum velocity and 4.4 ± 1.0% for maximum torque (mean ± SD; Martin et al., 1997). Although used for validation and reliability check of equipment rather than to monitor change, Martin et al. (1997) used the same iso-inertial method in cycling and quantified % CV for participants over four trials, the same number used in the current study. The participants in Martin et al. were 'active males' rather than high level performers and therefore % CV might be expected to be higher, but cycling is a more constrained movement than kayaking, which would likely reduce the variability, these two differences resulting in a similar level between high level kayakers and active males cycling.

7.4.2 Limitations & Delimitations

The main limitation of this study was the use of an ergometer; to apply these findings to on-water performance would involve assumptions and disregard for the technique of sprint kayaking on-water. As highlighted in the literature review of this thesis (Chapter 2), the forces applied by the paddle to the water are complex, three dimensional and require direct, accurate measurement of the paddle path and, as a result, are little understood. Combined with the relatively unknown effect of environmental conditions on performance, this makes biomechanical measurement of the effect small changes in paddle length on-water extremely difficult as it is not known whether any changes are due to the paddle length intervention or to these other confounding variables. By using a towing tank, or other controlled indoor body of water, developing technologies may allow measurement of paddle path and forces in a controlled manner in the near future.

In addition to paddle path differences, the paddle length on the ergometer is related to the paddle length used on water via an assumption of the centre of pressure acting a fixed distance (20 cm) from the blade tip. As discussed in Section 4.4.1, a fixed centre of pressure may not be realistic as data on a canoe blade shows changes throughout a stroke (Morgoch et al., 2016). As a canoe blade is flat, more movement of the centre of pressure may be expected than in the spoon shape of a kayak wing blade. A fixed centre of pressure has regularly been assumed for force measurement on-water as well as on ergometers (Aitken & Neal, 1992; Gomes et al., 2015). The effect of paddle length changes on the centre of pressure path are not known and warrant further research when the technology is available.

The percentage changed used in this study was very small (1%) but reflected what would be used by coaches in the elite environment. By using a larger magnitude of change, it might be expected that bigger effects would have been found- both positive and negative. However, measurement making large changes could also risk missing a 'peak' as groups of elite athletes are unlikely to be using paddle set-ups with large detrimental effects. As the overall aim of this thesis was to better inform coaching of elite sprint kayak performance, conclusions based on a realistic change were deemed pertinent. Larger changes with development level athletes would be valuable future research.

Sprint kayaking features 200, 500 and 1000 m events and the focus distance of athletes used in this study was not controlled. Athletes focused on different events train differently; for the 1000 m event, efficiency is of high importance, while 200 m athletes focus more on explosive power (van Someren et al., 2000; van Someren et al., 2008). As well as measured differences in P-V and F-V reported for different distance focus (Schofield, 2015), these differences may lead to changes in paddle path, stroke length and stroke rate which would mitigate how changing paddle length would influence on-water performance.

7.4.3 Application

A 2 cm change in total paddle length is likely to be used by coaches in a trial-and-error attempt to better match an athlete to their paddle. This is most likely to happen at development level as elite athletes are generally considered to have 'reached their own natural optimal set-up' (Chapter 3, Section 3.3.9). Decision making for this kind of change would typically involve feedback from the athlete, and the coach's perception of whether technique looked to improve relative to normal set up. This study shows that in experienced kayakers there is unlikely to be a meaningful physiological power enhancement from this magnitude of change of paddle length. However, this finding was not unanimous and there was a notable improvement in power for one athlete (Table 7.5) and there may be larger improvements found for athletes with less experience. This testing could be used as a first step in paddle length change with an improvement in power indicating a strong rationale for trying a particular length change on-water. As a cultural change to evidence-based decision making, this testing could be particularly valuable at development level, but that does not negate the opportunity for potential performance improvements in already successful performers, as with some of the athletes in this study.

In addition, changes in the F-V profile due to paddle length change can also be used to inform training. By understanding how an athlete responds to changes in length, the paddle itself could be used as a training constraint to enhance specific targets, in a similar way to swimmers using fins or paddles (Cardoso, Carvalho & de Souza 2013). For example, if decreasing kayak paddle length decreases an athlete's maximal velocity output and that is an area the coach is trying to improve, the paddle could be shortened for certain sessions, although an awareness of the possible impact on technique would be needed.

The differences between individuals and their different responses to paddle length changes may also present an opportunity for crew boat selection; by matching paddlers according to their F-V profile, or by using a change in paddle length to create more similarities in the athletes' profiles, improvement in crew boat performance may be found, although more research will be needed in this area.

7.4.4 Future research

This study has highlighted a number of areas for future research. The current study investigated the acute effects of changing paddle length by 1%. Larger magnitude of change or an acclimatisation period prior to testing using the new paddle length may result in different results. Similarly, using the same testing protocol in the current study but with developing athletes, potentially in collaboration with larger magnitudes or acclimatisation, would also be valuable future research.

The potential causes for individual variation in performance are numerous and to truly understand the causes of individual differences, invasive, time consuming and expensive experimentation would be needed. Understanding variables individually would add to knowledge about factors affecting performance but an understanding of all of these factors within one cohort is currently prohibitively difficult.

As well as understanding the causes of individual differences, future research could focus on the on-water effect of changes in paddle set-up. While the technology and/or research environment is not readily available, using motion capture with indoor towing tanks or IMU-based systems on regatta courses during calm environmental conditions could allow first, a better understanding of paddling mechanics and second, an understanding of the influence of paddle set-up on these mechanics. Investigating these at an individual level would be most valuable for elite athletes, but group level conclusions may have value for younger or developing athletes.

As mentioned in the application section above, this research could have large implications for selecting athletes for crew boats. Current crew boat selection is described by coaches as 'an art' with little science to guide decision making (Chapter 3 section 3.3.10). There is very little published research on crew boats and none which could be found that has looked at biomechanical measures underpinning conversion of individual to crew boat performance.

7.5 Conclusions

Changing paddle length can affect power production and created changes in the F-V profile of individuals within a group of experienced sprint kayak athletes. Notable changes in $Power_{str,ave}$ were present for three athletes. Small changes can be meaningful at elite level and with a larger or less well-trained group, additional and bigger changes might be expected and future research in this area would be beneficial. The changes in F-V could be used by coaches to create training constraints based on individual aims. A new analytical approach defining notable change based on individual variation has been presented and has considerable value for the applied practitioner as it provides a way of marking individual specific meaningful change for any intervention or training block. The highly individual nature of changes in the F-V and P-V profiles caused by changes in paddle length in this group demonstrates that there is not one optimal paddle length, even when normalised to arm span, and emphasises the importance of this form of individual analysis for both research and applied practice.

Chapter 8: General Discussion

8.1 Thesis structure

The research in this thesis was conducted in collaboration with a kayak National Governing Body and it was therefore vital that research was of value to the staff and athletes who it was being conducted to support. By putting those who would most use the research (coaches) at the centre of it, through interviews to establish variables of highest importance, the subsequent aims were based on performance questions valid to the elite environment.

To develop and achieve these aims, the research can be considered in three parts, as shown in Figure 1.2: the first identified key factors to performance through literature and expert coaching knowledge; the second measured key ergometer (force and power) and on-water (velocity, SR and DPS) variables at a group and individual level and the third investigated how force and power variables change due to an intervention on paddle length on an individual basis.

Section one contained both a review of literature and a qualitative interview-based study with elite sprint kayak coaches. While the key determinants of performance for kayaking had previously been summarised from research (McDonnell et al., 2013a; Figure 2.1) and calculated from a small group of athletes (Wainwright et al., 2016; Figure 2.2), it was not clear if these research conclusions reflected the beliefs of coaches. Directly comparing coaches' opinions to research conclusions inevitably involves some interpretation as the language used is not the same, but drawing from these fields allowed identification of areas that lack empirical evidence and where quantitative data would add value to coaching practice.

An area lacking in empirical evidence, but of high importance to coaches, was that of individualisation in performance, which led to the shaping of Section 2 of this thesis. Sports biomechanics research has traditionally reported only means and standard deviations of groups of athletes, apparently stemming from the outdated biomechanics view that there is a single optimal performance strategy and that the nearer an athlete is to that movement strategy, the better they will perform. In elite sports this is not the perception; research conducted with elite kayakers shows high inter-individual variability in technical performance (e.g. Sanders & Baker, 1998), matching conclusions from the coaching interviews (Chapter 3). Chapters 4 and 5 therefore assessed the individual differences in factors considered to be fundamental to sprint kayak performance at elite level: the relationship between force and power generating capacity in Chapter 4 and that between stroke rate (SR), distance per stroke (DPS) and boat velocity in Chapter 5.

Following on from having established the importance of individual analysis using the information gained in Chapters 4 and 5, the relevance of force-velocity (F-V) and power-velocity (P-V) profiling in Chapter 6, and the limited knowledge expressed by coaches in the field, section three (Chapter 7) investigated how these individual measures can be used to assess the highly under-researched area of paddle set-up, specifically paddle length.

The aims, research questions and context for each study will be outlined below and subsequently the methodologies employed will be critically reviewed. Following this, a review of the contribution of new knowledge of this thesis will be conducted and recommendations for coaches provided. Finally, suggestions for future research will be proposed.

8.2 Addressing the research questions

8.2.1 Chapter 3: Coach interviews

Aim: to explore expert coaches' technical knowledge of sprint kayaking across four topic areas (technique, paddle set-up, crew boats and feedback) and subsequently compare their experiential knowledge to existing empirical evidence and inform research.

Research Question 3.1: *what are the key determinants of performance according to expert sprint kayak coaches?*

To document coaches' beliefs and ground the research with applied purpose, 12 experienced sprint kayak coaches were interviewed. By posing open questions, the variables the coaches raised could be considered the factors they believed to be most important. Although the language used varied between coaches, making comparisons more difficult to draw, six primary mechanics-related areas were identified: water interaction, boat connection, kinematics, force/power, SR/DPS and influence of weather.

The key parameters described by coaches reflected the models in biomechanics literature to different extents. McDonnell et al. (2013a) used previous research to create a descriptive model and included SR/DPS and 'water phase displacement' which might be considered to reflect coaches' mention of water interaction but they did not mention any of the other areas highlighted by coaches as important. Gomes' (2015) theoretical model includes factors that could be considered to reflect all coach highlighted areas Wainwright et al.'s (2014) theoretical model was tested statistically and the resultant model includes the same factors as Gomes', with the exception of boat connection.

The lack of both coach 'buy-in' and relevance of research questions have been found as barriers to the application of sport science research (Fullagar et al., 2019; Tate, Elmarie, Zarko, & Vermeulen, 2017). By putting coaches' beliefs at the foundation of the research questions and having considered the emergent themes against the deterministic models for mechanical validity, these barriers were removed, resulting in more impactful research.

Research Question 3.2: *how does expert coaching knowledge compare to existing biomechanical research in sprint kayaking?*

Each of the mechanical constructs identified by coaches was discussed relative to theory, in line with Lees (1999) statement that "[when measurement variables are chosen by a coach] …the biomechanist has a duty to try and relate specified variable to an appropriate theoretical basis" (page 301). Identified mechanical areas were then compared with the literature available in the area; all six had been the subject of research at some level.

Research varied from investigating factors while removed from human performance, for example Jackson et al. (1992) using a towing tank to investigate the interaction between an isolated paddle blade and water, to highly applied methods such as McDonnell et al. (2013b) using televised footage of international racing to investigate typically used SR. These methodologies clearly had different aims: while McDonnell's research confirmed coaching opinion that SR varies between individuals, Jackson's research was likely not intended for coaches. The discussion of drag and lift forces, however, can still be related to coaches' descriptions of pulling and downward forces, pressure on the blade and mechanical efficiency. Areas such as boat connection and water interaction require complex technology to address in detail; ideally measurement would involve 3D kinematics and force on-water without changing the constraints of paddling (i.e. the mass of the paddle or the boat). Although features of this have been measured in isolation (e.g. foot and seat forces, Nilsson & Rosdahl, 2014), coaches frequently referred to the system (athlete-kayak-paddle) as a whole, indicating isolated research would be less likely to add immediate value to their work.

The kinematics of sprint kayaking have been investigated both on an ergometer (Limonta et al., 2010) and on-water (Begon et al., 2008), but this factor showed some disagreement between coaches. While some believed specific movements are needed to perform optimally, others did not place importance on specific kinematics to overall boat speed. Interestingly, this reflects research that has traditionally felt the need to find an optimal movement pattern but has more recently highlighted the value of variability in movement (Glazier & Mehdizadeh, 2019).

Force, power, SR and DPS were mentioned numerous times by coaches, have been subject to research within the literature and have clear theoretical links to performance. However, research has frequently been limited by methodologies employed such as poor-quality footage for SR detection in McDonnell et al. (2013b) or isometric only force measurement and commercial power output in van Someren and Palmer (2003). In addition, these authors both strove to detect differences *between groups*, with little regard for individual differences, which many coaches emphasised as important, highlighting these areas as valuable prospects for individualised, applied research.

8.2.2 Chapter 4: Ergometer profiling

Aim: to investigate and compare the F-V and P-V profiles of elite, sub-elite and club level sprint kayakers to increase understanding of performance in kayaking and the extent of the individuality of profiles.

Research Question 4.1: *do power and force-velocity relationships explain differences in performance level?*

Pull power was measured in three ways ($Power_{pull,ave}$, $Power_{pull,max}$ and $P0_{pull}$) and all three, along with F0, were found to differentiate between performance levels, with elite athletes exhibiting the highest power with a significant difference relative to sub-elite and club paddlers (Table 4.4). This implied that force was a strong determinant of power between groups. Along with the differences in $S_{F\text{-}V}$, this would indicate athletes at sub-elite and club level should focus on force development to improve power. The standard deviation was high for F0, theoretical maximal velocity (V0) and $S_{F\text{-}V}$ (gradient of the resultant force-velocity profile), alluding to the high individual variation even within the group level conclusions. Splitting the data according to gender resulted in similar trends but different statistical significance. Effect sizes were large, highlighting more differences between groups and indicating meaningful differences exist which did not reach statistical significance.

In agreement with the current study, power has been found to distinguish between international and national level athletes when quantified using a modified Wingate test of 30 second duration, although the force and velocity components were not reported (van Someren & Palmer, 2008). Measurement of force during on-water paddling has been found to be higher in higher level athletes (Fisher et al., 2013) but no measurements of power could be found on-water, likely due to the difficulty of measuring the paddle velocity required to calculate power from force data. Power and force differentiating between performance levels agrees with the conclusions of Dorel et al. (2005) in sprint cycling but contradicts conclusions in athletics sprinting where power and V0 correlate to performance but F0 does not (Morin et al., 2012).

The isoinertial ergometer developed for this research, based on designs used in cycling (Martin et al., 1997) and rowing (Sprague et al., 2007), also accounted for bungee tension, avoiding the underestimation of power found in previous research (Gore et al., 2013). Individual F-V and P-V profiles were created within 12 strokes in a kayak relevant movement, meaning that testing was efficient, and results are relevant to kayak performance; the importance of sport-specific measurement has been established as differences in profiles between counter movement jumping (vertical) and sprinting (horizontal; Jimenez-Reyes et al., 2018).

Research Question 4.2: *how well do group level average profiles represent the individuals in the group?*

Looking at individual athlete's data, Chapter 4 showed different force-velocity profiles for individuals, even with similar values for power output (Figure 4.7), in agreement with Samozino et al. (2012). By correlating F0 and V0 of at least 12 trials against stroke power per individual, differences in how athletes generate power could be seen. For eight athletes, F0 was found to positively and significantly correlate with stroke power, in agreement with the group conclusions. However, this relationship was not significant for the remaining 10, six of whom exhibited negative (non-significant) correlations between stroke power and F0. A positive correlation between V0 and stroke power was found for 14 athletes and was statistically significant for five.

These results highlight how group level conclusions can disguise individual differences. Identification of the contrasting conclusions that can be drawn from group and individual analysis is not new; Yeadon and Challis (1994) found that a group of high jumpers demonstrated a linear relationship with approach velocity and maximum jump height, while plotting an individual's velocity against jump height results in an inverted U relationship between the two variables.

Despite recommendations advocating research based on individual athletes (e.g. Bartlett et al., 2007; Glazier & Mehdizadeh, 2019), little research could be found that has investigated differences between individuals in any performance variable. Force and power velocity profiles, however, have been investigated at group and individual level. Differences were detected in different sports (Giroux et al., 2016), with further research indicating trends for different sports but large individual differences (Haugen et al., 2019). In agreement with this, Morin and colleagues found large differences between athletes when profiled through jumping or sprinting (e.g. Morin & Samozino, 2016; Morin et al., 2012; Samonzino et al., 2012).

8.2.3 Chapter 5: On-water profiling

Aim: to investigate the inter- and intra-athlete variability in SR and DPS, in order to gain insight into whether individuals are using these two parameters in different ways to maximise velocity.

Research Question 5.1: *is SR or DPS more important in determining boat velocity in a group of elite sprint kayakers?*

Across the 25 athletes who took part in the study, SR and DPS both significantly correlated with boat velocity, although SR exhibited the stronger relationship ($r = 0.87$ vs $r = 0.67$). This would imply that SR was the more important factor to enhance to improve performance in sprint kayaking, assuming changes are equally attainable. However, dividing data according to gender showed the relationship to subsequently only be significant for female athletes.

Stroke rate and distance per stroke have previously been found to dictate boat velocity in sprint kayaking (e.g. McDonnell et al., 2013b) and SR has been found to differentiate between performance levels (Brown et al., 2011), in agreement with the current study. Drawing on a sport that has been subject to considerably more research in this area, athletics sprinting has the same cyclical relationship between step length and step frequency and many research studies have aimed to discover which of these parameters is more important, although with inconsistent results (e.g. Morin et al., 2012; Nagahara et al., 2018; Debaere et al., 2013; Weyand et al., 2000), potentially indicating there could also be more complicated answers in sprint kayaking. With this inconsistency in mind, it would be reasonable to suggest that the interplay between stroke length and rate in kayaking may be more complex compared to equivalent land-based events, and therefore requires much more kayak-specific research attention to understand how these factors influence performance.

Research Question 5.2: *do individual elite athletes use SR and DPS in different ways to achieve boat velocity?*

Taking a minimum of 18 efforts each from a sub-group of 15 athletes, boat velocity was correlated against SR and DPS for each individual athlete. Eleven athletes exhibited significant correlations between SR and boat velocity, six of whom had significant correlations with both SR and DPS. An additional three showed significant correlations between boat velocity and DPS only. Investigating the data at this level showed that an increase in SR, as would be recommended based on group level conclusions, would not necessarily be beneficial for three athletes.

In a similar study in athletics, sprinters have been individually classified as step length or step frequency 'reliant' based on the strength of correlations of those parameters with velocity of 10 races per athlete (Salo et al., 2011). Their finding of large differences between individuals agrees with the conclusions of the current study, and goes some way to explaining the discrepancy in research conclusions on the importance of step length and frequency in sprinting.

By understanding how individual athletes develop boat velocity, coaches can modify training to be more efficient. In addition, this information could be used when grouping athletes for crew boats; it is likely if an athlete who has a significant correlation with SR is paired with an athlete who has a significant correlation with DPS, they are likely to be compromised when paddling together, although further research in this area would be needed to clarify this.

Research Question 5.3: *is the relationship between SR and DPS with velocity determined by anthropometrics?*

Initial correlations between boat velocity, SR, DPS, arm span and body mass revealed significant relationships of arm span with boat velocity, body mass and DPS. However, once data were divided into male and female, these correlations did not reach significance, indicating the apparent relationship may be an artefact of the combination of two sub-populations spanning a greater range of values.

Various anthropometric factors have previously been linked to kayak performance by comparing elite with less experienced athletes or the average population (Table 2.7), but these comparisons have not looked at the intervening factor of SR. It might seem logical that someone with longer arms might use longer strokes, but lack of significant correlation once divided by gender indicates this is not the case. In a similar way, in distance running, leg length has not been found to correlate with step length (Cavanagh & Kram, 1989), although the focus during distance running is on efficiency, rather than speed.

8.2.4 Chapter 6: Ergometer vs. on-water performance

Aim: to investigate the relationship between power and FV ergometry profiling and sprint performance in kayaking.

Research Question 6.1: *do force- and power- velocity profiles determine on water performance in a group of elite kayakers?*

Six measures of power during ergometer paddling were all found to be strong determinants of on-water performance, with strong positive correlations between all power measures and all on-water measures (steady state boat velocity, time to 10 m and maximum boat velocity), although stroke-averaged power consistently had the strongest relationships (Table 6.1). In addition, strong correlations between F0 and on-water performance were also present, indicating force generating capacity is also a determinant of performance. This agrees with Chapter 4, where power and F0 were shown to differentiate between performance levels.

The strong relationship between power and sprint kayak performance is supported by previous research (van Someren & Palmer, 2008). Although the correlation between F0 and on-water performance has not previously been investigated, it is not supported by previous research in kayaking which has found no correlation between bench press or pull up strength and on-water performance, lending value to the importance of force application in movement pattern relevant to performance. These strong relationships provide value in particular to strength and conditioning coaches who can investigate the transfer of force and power development in the gym to the likelihood of on-water performance gains.

Research Question 6.2: *does the gradient of an athlete's force-velocity profile relate to their use of SR and DPS?*

Group level correlations indicated that the gradient of the force-velocity relationship was linked to boat velocity, with a more force-orientated profile (steeper F-V gradient) positively linked to 10 m time, Vel_{ss} and Vel_{max} as well as to SR and DPS. V0 measured on the ergometer did correlate significantly with Vel_{ss} and Vel_{max}, but with a smaller effect. F0 had significant relationships with all on-water variables, as well as with stroke power on the ergometer. This agrees with the group level conclusions from Chapter 4 and 5 as SR was found to correlate with boat velocity and F0 correlated with stroke power, so the similar correlations might be expected. The individual differences exhibited in Chapters 4 and 5 warrant the use of caution in interpreting this group-level only analysis.

The S_{F-V} comparisons partially supported the logical hypothesis that those who are more force-orientated would be likely to utilise longer strokes and higher DPS and vice versa, with S_{F-V} (higher value is more force-orientated) negatively correlated with SR, and a correlation between F0 and DPS, although not between SR and V0. The only previous research found that directly investigated the relationship between F-V profiles and technical performance in any sport was in athletics 100 m sprinting (Morin et al., 2012). The researchers concluded that a velocity-orientated profile was a determinant of performance as was step frequency, but step length was not, showing a link between F-V profile and technical performance. Although further research would be needed, this may indicate additional avenues for technical change within kayaking are available as increasing strength may lead to increased distance per stroke.

8.2.5 Chapter 7: Paddle length intervention

Aim: to explore the differences in force-velocity and power-velocity profile created due to changes in paddle length in experienced kayak athletes, at both group and individual level.

Research question 7.1: *does changing paddle length result in changes in force-velocity and power-velocity profiles?*

A change in paddle length as small as 1% was found to elicit changes in power and force-velocity profiles when using individualised measures of change. As with previous studies on Chapter 4 and Chapter 5, group level power, force or velocity data were not significant but individual athletes showed different responses. Three athletes showed notable differences in $Power_{str,ave}$ while six had changes in maximal force or velocity.

All previous investigations of paddle set-up have been severely limited in methodology (e.g. Lok et al., 2013) or assumptions made (e.g. Sprigings et al., 2006) and none had previously investigated the effect of changes in paddle length on performance in any way (Table 7.2). Ong et al. (2006) found changes in paddle and boat set-up to measures determined from regression equations of anthropometric and equipment set-up of Olympic kayakers to result in different changes in the three athletes investigated, in agreement with the current study. Values from the regression resulted in increases in grip width for all, effectively reducing the distance between the hand and the point of force application, as would be done by reducing the paddle length in the current study. Ong's findings of an increase in boat speed for one athlete and decreases for the other two reflects the differences in power change in the current study but without the ability to define whether these changes were notable as Ong investigated only one trial in each condition. Similarly, changes in the relationship between SR and DPS were different between athletes, as F0 and V0 were in the current study. The importance of understanding equipment set-up on an individual, rather than group, basis for elite athletes is clear.

8.3 Critical appraisal of research design

The research studies described above were designed to capture all relevant information in an ecologically-valid way, while not negatively impacting on elite athletes' training schedules. The differences in methodological approach between the studies mean the limitations and delimitations are discussed below as individual studies.

8.3.1 Chapter 3: Coach interviews

8.3.1.1 Subjective analysis

To document coaches' knowledge, interviews were conducted. This qualitative methodology is innately influenced in both the collection and analysis stages by the principle researcher. Production of a question guide (Appendix 1), member checking process and a relatively large participant group, using the entire senior and development coaching teams, reduced the impact of these factors as much as was possible (Creswell & Miller, 2000; Smith & Sparkes, 2016).

Semi-structured interviews follow a guide but also allow probing questions and development of ideas, allowing coaches interviewed to expand on points they think relevant. However, interviews are inevitably influenced by the researcher who has their own epistemologies and ontologies with regards to the research, and the relationship between the interviewer and interviewee, which may also affect the quality of the data collected. These are not necessarily considered flaws in qualitative research (Smith & Sparkes, 2013) but should be acknowledged.

Qualitative researchers have recommended the number of participants should be large enough to reach 'theoretical saturation' (O Reilly & Parker, 2013) where any additional interviewees are highly unlikely to add additional themes to the analysis. Theoretical saturation was not reached in this study, despite interviewing twelve coaches, all working for the same organisation and all coaching high-level athletes, representing the entire population meeting the criteria. The range of opinions, emphasis and vocabulary were important factors of note in reviewing interviews. Although this means factors considered 'key' to performance were not unanimous, a range of important constructs were identified. Future studies could focus on reaching a consensus between coaches in order that a new model based on coaching beliefs could be created.

8.3.2 Chapter 4: Ergometer profiling

8.3.2.1 Cross sectional design

The primary research question in Chapter 4 was how the power and force-velocity profiles of athletes of different experience levels varies. This form of cross-sectional design is commonly used in biomechanics research to determine the factors that differentiate between levels. This form of analysis is relatively simple to process but is affected by the variation in each population, which is often overlooked or considered noise (Schmidt & Lee, 2005).

At group level, few significant differences were found. The graphical representation of the group F-V profiles could lead to inference of differences between groups despite non-significant difference and no consistent pattern. The lack of significance was due to high levels of individual variation, which is important information that can be used to individualise training. This level of information would be entirely missed if cross sectional design alone was used and F-V might be considered unimportant to performance, highlighting the value which should be placed on including individual analysis alongside group conclusions in future research.

8.3.2.2 Ergometer replicating on-water kinematics

The ergometer base was a standard Dansprint ergometer, whose use has been found to result in some kinematic and muscle-activity differences from on-water paddling (Fleming et al. 2012). Although an ergometer does not replicate on-water conditions, as the aim of the study was not to replicate or measure kinematics or muscle activity patterns, this is not considered a prohibitive limitation. The widespread use of this base ergometer in elite sport and the subsequent correlation with on-water performance justify use of this ergometer. In addition, the inclusion of force measurement of the bungee improved the accuracy of measurement, without which errors of around 20% have been found (Gore et al., 2013). How an ergometer relates to on-water must always be considered to provide context for conclusions in any future ergometer research.

8.3.3 Chapter 5: On-water profiling

8.3.3.1 Environmental effects

Environmental effects are known to influence performance during on-water kayaking, with water temperature and wind speed having clear mechanical relationships with drag force, as described in Chapter 5. To reduce the effects of weather conditions on results, a combination of a wind threshold and a weather model were used. As this form of theoretical model is very difficult to validate, the combination of two methods was considered best. A cut-off level of 4 $m \cdot s^{-1}$ is higher than what has been used previously (3 $m \cdot s^{-1}$, Gomes et al., 2015; 2 $m \cdot s^{-1}$, Wainwright et al., 2013) and reflects the description of 'light winds' in the Beaufort scale.

The steady state period of all trials was then run through the normalisation model (Appendix 4). This model used weather data collected for each trial, is based on hydrodynamic principles and incorporates the frontal area of a K1 sprint kayak, mass of the system, boat velocity, air and water temperature, wind speed and wind direction to create a 'normalised' boat velocity based on datum conditions. As the training environment was the only one available to collect this data, the limitation of using an imperfect but theoretically sound model was considered acceptable. Further applied testing of this model or other measurement of the impact of environmental conditions on kayak performance would enhance any future on-water research.

8.3.3.2 Six trials maximum per session

No more than six trials could be completed within a single session due to fatigue, meaning to collect enough trials to use correlations for individual athletes, multiple data collection days were needed. Training between these days could have created changes in performance and technical aspects of performance. As all data collection days were within the competitive season (March-September) this effect was minimised. Using a multi-disciplinary approach in future to include any potential physiological markers of fatigue would be valuable.

8.3.4 Chapter 7: Paddle length intervention

As this study used the same ergometer as chapter three, these issues still stand, along with the additional factors below.

8.3.4.1 Paddle length change relative to 'normal'

The paddle length was matched to what is used on water, with intervention differences of 1% relative to this. This means there was no direct relationship between the changes made and athlete height or arm span. Research has shown a significant correlation between anthropometrics and paddle length (Diafas et al., 2012) and the description of paddle length selection given by coaches during interviews is also related to height and arm length (Chapter 3). Using a controlled proportion of height or arm span would have been possible and could be investigated in future research, but would have removed the direct application as seen by athletes and coaches. A larger-scale study investigating F-V profiles of athletes across performance levels with changes to paddle length would improve understanding of how these factors interact.

8.3.4.2 Small change

The use of 1% is a very small intervention, the choice of this difference was to enhance the use directly to coaches. A 1% change was roughly 2 cm, which is the magnitude of change a coach is likely to suggest on-water. However, this does mean that significant differences, which may be present at group level if larger changes were used, were not found. As the focus was on individual's reactions and a number of differences were found, it is clear this small difference is enough to evoke change in some athletes.

8.3.4.3 Only six trials

Six trials were considered the maximum achievable without a large influence of fatigue or an excessive duration of testing, which elite coaches would not have agreed to. However, it means only two trials per condition were recorded. Mullineaux et al. (2001) recommend a minimum of three as a compromise to create 'representative and valid' data, but this is based on the idea of unquantified variability when fewer trial numbers are used. In this study five previous repetitions are used to quantify typical individual variability and this variability subsequently used to mark notable change between conditions per athlete, making the comparison acceptable despite few trials. Future studies could investigate multiple trials across additional testing dates over a short period of time to reduce training affect.

8.4 Contribution of new knowledge

8.4.1 Methodology/approach

8.4.1.1 Documentation of elite coaching knowledge and comparison to literature

The first study in this thesis (Chapter 3) documented elite coaching knowledge in sprint kayaking. This level of coaching knowledge in sprint kayaking has never been documented in this way or compared to biomechanical literature. Differences in coaching philosophies and terminology were apparent and areas of kayaking that coaches feel biomechanics could support were identified.

8.4.1.2 Development of isoinertial ergo with account of bungee tension

The isoinertial ergometer was developed to account for bungee tension as this has previously been reported to create as much as 20% error in power readings (Gore et al., 2013). This design allows power and force-velocity profiles to be created from a single effort without influence from fatigue. Although these profiles have been measured before (Schofield, 2015), bungee tension was not accounted for and only elite level athletes were tested.

8.4.1.3 Validation of ergo for sprint performance

By correlating data from athletes who took part in both studies three and four, a strong linear correlation was found between stroke power and on-water sprint performance. This relationship was strongest with the 'steady state' period of a 100 m sprint, but strong correlations were also found with maximum velocity and with time to 10 m.

8.4.1.4 Profiling of elite and developing sprint kayak athletes

Elite athletes are often inaccessible to researchers and this cohort of elite, development and club athletes represents a rare insight into performance (on and off-water) across all levels.

8.4.1.5 Implementation of regular F-V profiling

The regular testing established during the profiling studies in Chapters 4 and 5 has continued in the elite environment, allowing further insight to be gained across training and Olympic cycles.

8.4.1.6 Paddle length intervention on ergometer

Ergometers have been used to understand the demands of sprint kayaking, but changes to equipment have never been tested in this way. While caution must be used for application of findings to water, insight into the mechanical effect of any paddle change is novel and valuable.

8.4.1.7 Use of statistics for individual analysis

To understand individual performance, group level statistics were not appropriate. While new statistical tests were not devised, data were used in novel ways to understand differences at the highest levels. To the researcher's knowledge, using an athlete's own variability to understand when change in meaningful has not previously been done.

8.4.2 Results and Conclusions

8.4.2.1 Six mechanical sub-themes important to coaches

There were six key areas of importance to elite-level sprint kayak coaches within the mechanics theme: water interaction, boat connection, kinematics, force/power, SR/DPS and influence of weather. As emerging mechanical themes, biomechanical research in these areas can have a greater impact on applied practice.

8.4.2.2 No clear consensus in race phases or terminology from elite coaches

At the highest levels of performance, there is not a clear coach-driven consensus for how to break down a race into phases or in the terminology used.

8.4.2.3 Elite athletes are more powerful and have more force-orientated profiles

Differences in power output were found between club, sub-elite and elite athletes, with power increasing through those levels as might be expected. Elite athletes were found to exhibit higher maximum force and steeper gradient of the F-V relationship, indicating lower level paddlers should aim to improve this aspect of performance.

8.4.2.4 Individuality of F-V profiles

Large inter-individual differences were apparent, with 11 athletes showing stronger correlations between V0 and power and seven showing stronger correlations between F0 and power, regardless of performance level. Individual differences have also been reported in other sports (e.g. Haugen et al., 2019) but it has been considered that there is an individual optimal for jumping (Samozino et al., 2012). The individual differences found in this thesis have subsequently allowed the multi-disciplinary support team to tailor training to optimally support individual elite athletes and to track changes to assess the impact of training blocks.

8.4.2.5 Higher SR does not mean higher velocity for all athletes

Despite correlations showing higher SR with higher levels of performance (e.g. Brown et al, 2010), individual preference for stroke rate had been mentioned by coaches interviewed during the first study and was supported by the findings of study three (Chapter 4). This study found that athletes are individually more reliant on either stroke rate or distance per stroke to maximise velocity, in a similar way to that documented in athletics (Salo et al., 2011).

8.4.2.6 Power correlates with boat velocity and F0 correlates with DPS.

The correlations found with power and performance measures were partially supported by correlations between F-V gradient and SR. It was expected that those who had more force-orientated F-V profiles would rely more on DPS to improve boat speed and F0 was correlated significantly with F0 but SR was not correlated with V0. This indicates the high importance of force generation in a kayak specific movement.

8.4.2.7 Individuals respond differently to paddle length change

No previous research has looked at the influence of paddle length on anaerobic capacity. Changes of approximately 2 cm in paddle length did not create consistent changes across the group in maximal power, force or velocity. Relative to their own individually calculated level of intra-trial variability, three athletes had a significant change in power (one increase, two decreases), while six had significant changes in maximal force or velocity.

8.5 Recommendations for coaching

For coaches and the multi-disciplinary support team (MDT) to use this research, the following recommendations are made:

8.5.1 Clarification of coaching terminology

In some cases, many different words are used for a certain phenomenon, and in others a single word can have different meanings. The word 'catch' can be used in both of these examples: at times being synonymous with 'grip', 'grab' or 'blade entry', at others being found to refer to both a specific time point and a whole phase of movement. Reaching a consensus across performance levels will improve communication between coaches for coach education and between coaches and athletes for more efficient technique improvements.

8.5.2 Clarification of phase classification

While many of the same words were used for phases (start, acceleration, race pace, maintenance), the coaches' definition of these phases differed. For some, the start was only considered as the first few strokes, while for others it could incorporate up to 100 m of paddling. A coaches' consensus of the distances and definitions of each phase will improve training focus and athlete understanding, in particular for athletes on the pathway who are likely to be coached by multiple practitioners.

8.5.3 Athletes are all different

Even for athletes of similar performance levels, large individual differences were found in both on-water and ergometer profiling. The results indicate that athletes produce power (through force and velocity use) and boat speed (through SR and DPS use) in different ways, and it is important to understand these differences to get the most out of training and racing.

8.5.4 FV as a steppingstone between water and gym

The ergometer testing allows a force-velocity profile to be created for an individual athlete in a matter of seconds. While there are without doubt differences in the movement patterns on an ergometer compared to water, ergometer data do still provide insight. These profiles represent factors that are currently very difficult to measure on-water and are essentially an anaerobic capacity test in a 'kayaking-like' movement. The testing structure designed as part of this thesis has been adopted and continued by elite and developing athletes and the staff supporting them. As has been done within the NGB, data from profiles can be used by different members of the MDT in different ways:

Technical coach: understanding deficits: if an athlete is strong in the gym but unable to use that strength on-water, high scores on the ergometer indicate technical application of force during paddling is limiting performance. If an athlete is strong in the gym but with low scores on the ergometer, co-ordination pattern and developing strength during multi-limb complex movements may have a higher benefit. In general, lower level athletes' sprint performance is likely to benefit from working on their kayak-specific maximum force output rather than maximum speed of movement, but there are large differences between individuals.

S&C Coach: using the F-V profile: maximum force output (in a kayak specific movement) both correlated with better sprint performance and differentiated between performance levels, indicating as a general rule that this may be a priority area for development relative to maximal velocity work, although there were large individual differences. Gym-based training according to an individual's profile has been found to lead to greater improvements in power (Jimenez-Reyes et al., 2019). An 'optimal profile' for kayaking does not exist in the way it has been calculated in Samozino et al. (2012) for vertical jumping but assessment of the individual athlete's kayak-specific F-V profile between training blocks will allow assessment of whether the main focus of the block has been achieved (i.e. maximal strength or strength at high velocities) and to understand how individual athletes adapt to certain training block stimuli. The use of a kayak-specific ergometer also allows for better understanding of force and power generating capacity from core gym movements and acts as an appropriate training stimulus. F-V profiles need to be appropriate to the sporting movement as they are not otherwise applicable, as highlighted in difference between horizontal and vertical profiling (Jimenez-Reyes et al., 2018).

Physiotherapist: rehabilitation or injury risk: if an athlete sustains an injury on one side of the body, rehabilitation to regain strength on the affected side is common but is typically limited to maximal strength, not considering velocity of movement. Once an athlete is considered to be fit to return to training, the ergometer can be used to investigate differences in force generation at different velocities, which may still be restricted at higher speeds. Similarly, if an athlete is particularly force or velocity orientated, it may be easy to overload the other variable and put the athlete at a higher injury risk. By measuring and understanding these risks, they can be mitigated.

8.5.5 Influence of paddle length is individual specific

Applying the same magnitude of change across a group of athletes would result in different responses across the group. Although taller athletes do tend to have longer paddles, height does not fully determine the relationship.

At group level, a change in paddle length did not affect power output for most athletes. However, for three of the ten athletes tested, a significant change in power was seen. Even when no change in power output is seen on the ergometer, changing paddle length still affects performance as there are differences in the way the power was created for six athletes (different combinations of force and velocity). There are also likely to be small differences in technique on-water which may change the application of power and therefore may change efficiency, although this was not tested here. Changing an athlete's F-V characteristics may also have benefits for athletes working together in a crew boat.

8.6 Future research

The current studies have added important understanding regarding the individual nature of sprint kayak performance and how that information can be used to benefit elite athletes. However, there are many additional areas of research that would benefit performance understanding.

8.6.1 Monitoring and paddle set-up in developing athletes

Use of F-V profiling to understand how individuals react to training would potentially allow younger athletes to accelerate adaptation to training and achieve better performances. In addition, changes in paddle set-up were found to have a positive impact on performance in elite athletes, who have already reached very high levels of performance. The scope for improvement is larger with developing athletes and therefore there may be more significant gains to be made.

8.6.2 3D kinematics on water

Understanding of kinematics on-water has not moved forward from video data collected in 1992 (e.g. Kendal & Saunders, 1992), almost 30 years ago. Technology is constantly developing, and measurements of 3D kinematics on-water would now be possible with wearable IMU-based systems, although there is still some question over the accuracy, as validations have primarily been conducted in movements that are mostly in the sagittal plane, with weaker correlations found for other plane movements (Blair et al., 2018). Measurement of 3D kinematics would allow both validation of coaches' technical models and quantification of individual variation. These would allow more focused training to work on areas of technique where gains are more likely to occur, for example identifying technical breakdown due to fatigue for a specific athlete.

8.6.3 Paddle path & 3D force measurement through water

In-line with technology developing for human movement, the same technology could be used for monitoring paddle movement. Despite researcher efforts with video (Kendal & Sanders, 1992) or IMU based systems (Morgoch & Tullis, 2011) in the past, paddle movement in 3D has yet to be successfully reported. This means calculations of 'lift' and 'drag' are actually often measures of parallel and perpendicular force to the blade (Gomes et al., 2011). Combining 3D force via strain gauges and 3D movement via IMUs, researchers would be able to quantify the contribution of lift and drag and would be able to better understand the hydrodynamics of kayaking and how it relates to paddle design. This could lead to developments in paddle design that have not previously been considered.

8.6.4 Interventions of paddle set-up on-water

If measurements of kinematics and kinetics on-water were readily available, interventions on-water would also be more feasible. While the outdoor environment will always be a factor in any measurement taken on a regatta course, collecting data within constrained conditions (e.g. maximum and minimum values for wind speed, and water temperature during testing) through having the flexibility to change data collection window, or using indoor water such as a towing tank, would allow acute changes to be quantified. Researchers are seemingly trying to catch up with paddle manufacturers with the latter bringing out new blade designs with little to no scientific research support but only endorsements from high level athletes. Even with factors such as paddle length, blade size and blade angle, which can all be chosen directly by the athlete, there is little science behind what might be advantageous for a given athlete. Interventions using larger differences than used in study 5, in particular using extremes such as 6-10 cm, would also be beneficial.

8.6.5 Crew boats

Much of the kayak research has focused on individual boats. This is understandable as the complexity inevitably increases with increasing boat members. However, five of the nine medals available in sprint kayaking at the Rio Olympics were for crew boats and different boat speed, SR and the timing and synchronicity of athletes are all likely to cause changes in performance relative to a K1. Although some research has been conducted using crew boats with different crews, criteria for successful crews has not been methodically tested, potentially due to the complex nature of factors that may affect crew performance and therefore difficulty in isolating causation.

8.7 Conclusions

Water interaction, boat connection, kinematics, force/power, SR/DPS and influence of weather were identified as key mechanical performance factors in sprint kayaking through interviewing elite coaches and comparing their beliefs to available literature.

Two of these factors were subsequently analysed at both group and individual level: SR/DPS and force/power. At group level, SR and F0 appeared to be of highest importance, but individual analysis showed variable results between athletes, regardless of experience level. Such findings emphasise the importance of assessing individual athlete performance. Ergometer power strongly correlated with on-water performance and the ergometer was therefore used to investigate paddle length changes.

Due to the large differences between individuals, athlete-specific measures of notable change were calculated from variability during previous testing sessions. For changes in paddle length of 1% (approximately 2 cm), power was only notably increased by one athlete, while six showed differences in maximal force or velocity. As in the profiling section, responses to change were highly individual.

This thesis has provided research that can be, and has been, of direct use to the whole multi-disciplinary team in sprint kayaking by focusing on areas that coaches value and in which research has been lacking. Additional research would benefit sprint kayaking performance, particularly in understanding paddle path and direction of force application, and in equipment set-up. Taking an individual approach to analysis and training is clearly important, both in the development of meaningful research and to maximise performance gains.

Chapter 9: References

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Chapter 10: Appendices

10.1 Appendix 1: Question guide for coach interviews

Interview Questions for Coaches

My research is looking at optimising performance in sprint canoeing. I am interested in the technical aspects you, as a coach, look for when trying to help improve technique.

Squad:

Race distance:

Section 1: Introduction

1. How did you get into coaching?
    a. Probe: did you coach other sports beforehand?
    b. Probe: were you a performer?
    c. Probe: how long have you been coaching?

2. Where have you gained your sprint canoeing knowledge? (e.g. courses, peers, trial and error)
    a. Probe: What sources might you use to increase your knowledge now? Are these different to those you might have used earlier in your career?

Section 2: Technical factors

3. Imagining a paddler during a race, what technical aspects would you be looking for to determine "good" technique?
    a. Probe: Can you give me an example?
    b. Probe: why do you think these characteristics are important?
    c. Probe: Do you think they impact directly on performance?

4. How would you rank these factors in order of importance?
    a. Probe: why?

5. Do you consider the race to be made up of separate phases? If so, what are they (specifics needed e.g. first to 10th stroke)?
    a. Probe: why?

6. Should effort be distributed differently across phases?
    a. Probe: is one phase of higher importance?

7. Do you think there are key characteristics “good” technique is made up of in each phase?

8. Does this differ between phases?
    a. Probe: why?

9. Do you think there are certain strength/physiological characteristics which are particularly important?
    a. Probe: power profile of importance? What is your understanding of the P-V relationship?

10. Does this differ between phases?
    a. Probe: why?

11. Do you consider there to be an optimal stroke rate (for each phase)?

Section 2b: Feedback

12. How important do you think it is that athletes receive feedback on these technical factors?

13. What form should this feedback take?
    a. Probe: Does this differ dependant on which technical factor?

14. When do you think this feedback should be given, relative to the effort?

15. Does this differ to how you, as a coach, would like feedback?

Section 2c: Paddle set-up

16. How should an athlete choose their paddle set-up? Which factors are important in this choice?
    a. Probe: based on anthropometry? Power? Trial and error? “feel”?

17. Should an athlete check if their paddle set-up is correct? If so, how?

Section 2d: Crew boats

18. What do you think are the most important factors in technique when in a crew boat?
    a. Probe: are these different to in a K1?

    b. Probe: are these different between seats?

19. How important is synchronicity to crew boat performance?
    a. Probe: why?

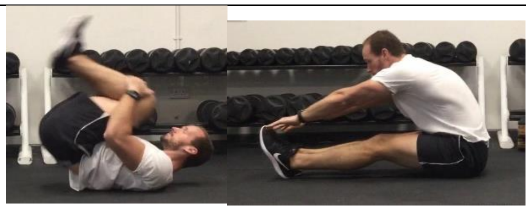
Finally…

20. Are there any particular areas you think would benefit from research?

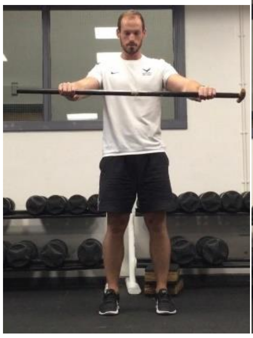
21. Is there anything else you would like to add?

10.2 Appendix 2: Ergometer warm-up

The ergometer warm-up was designed by the strength and conditioning coach and the physiotherapist who were working with the elite athlete group at the commencement of the ergometer testing. The bulk of the warm was designed for all gym sessions and was instructed via an educational video, with a few additions for ergometer testing.

Exercise	Quantity	Example
Back extensions	10	
Calf pumps	10	
Modified straight leg raise	10	
Active straight leg raise	10	
Leg crossover	10	
Tuck and reach	10	

Dead bug	10	
Sitting rotation	10	
Rotation with reach	5	
Cat/Camel	10	
Thread the needle	10	
Bird-Dog	5	
Spiderman	10	

Overhead paddle - Forward lunge - Side lunge - Squat	3 3 3	  
Single leg swings	10	
Rotator cuff band - Band held at waist - Band held behind	10	 
Iso-hold - In front - Overhead	2-3 seconds x 3	 

10.3 Appendix 3: Visual assessment of linearity

Examples of visually assessed linearity in data, taken from the scatterplots of individual athletes of normalised velocity relative to SR. Graph a) shows a ‘strong’ linear relationship, graph b) shows a ‘medium’ strength linear relationship and graph c) shows a ‘low’ linear relationship.