# Investigating the determinants of sprint kayaking performance

by

Joshua A. J. Goreham

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

at

Dalhousie University
Halifax, Nova Scotia
December 2023

Dalhousie University is located in Mi'kma'ki, the
ancestral and unceded territory of the Mi'kmaq.
We are all Treaty people.

## Dedication Page

To Rhys,

Your determination to throw every one of your toys on the ground for Mom and Dad to clean up is impressive. I like to think you got a little bit of that determination from me. This degree was not easy, but it shows that with hard work you can accomplish what you set out to do. I also learned a lot of cool things in the process. Keep being determined and curious and you can accomplish whatever you want to.

Love,
Dad

## Table of Contents

## List of Tables

## List of Figures

# Abstract

The over-arching focus of this doctoral research was to investigate the determinants of sprint kayaking performance through a biomechanical lens. Research aims were created using a deterministic model based on the literature. The model influenced the dissertation's original goal of developing an integrated system to measure body, boat, and paddle kinematics, as well as the kinetics acting on the overall athlete-paddle-boat system during on-water paddling. Due to sub-par validation results of two integral pieces of equipment (i.e., an inertial measurement system for measuring body kinematics and a wireless instrumented paddle for measuring force and power output) this goal was not able to be achieved. However, three important, related studies were conducted to fill gaps in the sprint kayaking literature. The first study investigated the pacing strategies used by elite sprint kayakers during international races. The results showed pacing strategies differ due to race distance, and that medallists used different strategies than non-medallists (i.e., bottom three finishers). The second study established the role of stroke parameters (i.e., stroke rate (SR) and stroke length (SL)) as determinants of sprint kayak performance and investigated how SR and SL were correlated with kayak speed at different phases of the race. While the first study showed the importance of an end-spurt in longer distance races, the second study showed how athletes create this end-spurt, which was by increasing SR. The third study established the relationship between boat kinematics in six degrees of freedom and kayak speed during the two phases of the stroke cycle. A stepwise regression analysis indicated pitch, roll, yaw, vertical acceleration, and lateral acceleration impulses were related to kayak speed, with different effects depending on their timing within the stroke cycle. The third study's results were based on existing theories surrounding hydrodynamic drag. Overall, the results of this doctoral research adds to the performance knowledge in the sprint kayak and sports biomechanics literature. As new technology is developed, researchers should continue to investigate the effects of resistive forces on kayak performance, as currently, more knowledge exists on propulsive forces.

## List of Abbreviations and Symbols Used

$A$ – kayak surface area

$\alpha$ - critical alpha value for statistical significance

AccX – acceleration in the x-axis

A-finalists – athletes or boats the qualified for the A-finals

ASI – asymmetry index

$b$ – slope

$\beta$ – regression coefficient

Bottom 3 – three worst rankings in race

B-finalists – athletes or boats the qualified for the B-finals

$C_D$ – drag coefficient

CI – confidence interval

CoM – center of mass

$d$ – Cohen's $d$ effect size

$D_F$ – drag force

D1 – delay between start of force application and kayak acceleration

D2 – delay between kayak deceleration and end of force application

DPA – discrete point analysis

DoF – degrees of freedom

EFE – elbow flexion/extension

ES – Cohen's $d$ effect size

F – female

$F$ – ANOVA's $F$ statistic

$F_{aerodynamic}$ – aerodynamic drag force

$F_{hydrodynamic}$ – hydrodynamic drag force

$F_{mean}$ – mean force

$F_{peak}$ – peak force

$F_r$ – resultant force

$F_{total}$ – total drag force

$F_x$ – force in x-direction

$F_y$ – force in y-direction

g – acceleration due to gravity

GPS – global positioning system

HBP – hand to back pocket

HCS – hand to contralateral shoulder

HTH – hand to head

Hz – Hertz

IMU – inertial measurement unit

J-shaped – pacing strategy “J” shape

K1 – single kayak

K2 – double kayak

K4 – kayak fours

kg – kilogram

$\frac{kg \bullet m^2}{s^2}$ – units of work

$\frac{kg \bullet m}{s^2}$ – units of a proxy to work

L – stroke on left side

M – male

m – meters

m:ss.00 – minutes:seconds.milliseconds

m•s$^{-1}$ – meters per second

m•s$^{-2}$ – meters per second squared

m•stroke$^{-1}$ – meters per stroke

MC1 – men’s canoe singles

MC2 – men’s canoe doubles

MK1 – men’s kayak doubles

MK1 – men’s kayak singles

N – Newtons

n – sample size

*ns* – non-significant

$\eta^2$ – partial eta squared

N•s – Newton seconds

OGL – One Giant Leap power meter

OLS – ordinary least squares

$p$ – probability value

$\rho$ – water density

PC – principal component score

PCA – principal component analysis

$P_D$ – drag power

$r$ – correlation coefficient

$R^2$ – coefficient of determination

R – stroke on right side

RMSE – root mean square error

ROM – range of motion

s – seconds

$s$ – significant

SAA – shoulder abduction/adduction

SE – standard error

SEM – standard error of mean

SFE – shoulder flexion/extension

SIER – shoulder internal/external rotation

SL – stroke length

spm – strokes per minute

SPM – statistical parametric mapping

split-by-$p$ – $p$ is equal to the number of calculated principal components

SR – stroke rate

$t$-tests – Student’s $t$-test

$T_{en}$ – paddle entry

$T_{ex}$ – paddle exit

$T_P$ – propulsive phase

$T_W$ – water phase

Top 3 – three best rankings in race

Tukey’s HSD – Tukey’s honestly significant difference test

U-shaped – pacing strategy “U” shape

USD – United States Dollars

$v$ – kayak velocity

$\bar{v}$ – average velocity

$v_{combined}$ – combined velocity for all boats

VIF – variance inflation factor

W – Watts

WK1 – women’s kayak singles

WK2 – women’s kayak doubles

WK4 – women’s kayak fours

$x^3$ – cubic relationship

X – x-axis

Y – y-axis

Z – z-axis

3D – three-dimensions

˚ – degrees

˚•s$^{-1}$ – degrees per second

°C – degrees Celsius

± – plus or minus

ΔF – difference between left and right force output

$|t|$ – t-statistic

# Acknowledgements

The process of completing a PhD is a long one. A lot of people played a role in my development as a scientist, and I do not want to leave anyone out. That said, I only have a page, so if I do not mention you by name, know that I truly thank you for helping me complete this degree.

First, I'd like to thank my supervisor Michel, for introducing me to research. I can honestly say I had no idea what I was getting myself into when you asked me if I'd like to do research in your lab back in 2012. By introducing me to research you also helped teach me to think critically about problems we face in research and in life. I feel as though I have benefitted from this in many ways. We have collaborated on projects for over a decade. That's hard to believe, but I'm thankful you saw something and took a chance on me.

I have had many professors provide guidance to me over the years. I would especially like to thank Dr. Kozey, Dr. Kimmerly, and Dr. Landry for being a part of my PhD committee. You have all given me great feedback over the years which has helped me develop as a researcher. You also helped make the path of this project clearer when I could not see the forest through the trees. Thank you for giving me the opportunity to learn from you.

I would like to thank all the students that worked alongside me in the BENLab. It is safe to say I learned a lot from each of you. Thank you for being there to talk to and to laugh with throughout this journey. Ryan, Kathleen, and Kayla, thank you for collaborating with me on various projects, and for the walks to get coffee to help make sense of what was going on in our academic lives.

To my colleagues at the Canadian Sport Institute Atlantic, and to the coaches, athletes, and staff at Canoe Kayak Canada. Thank you for allowing me to work alongside you while I completed my PhD studies. I learned a lot from each and every one of you, which made me a much better Sport Scientist. I would also like to say thank you to the organizations that helped fund my research.

To my family. Mom, Dad, and Fal, you have heard me talk about my research for years and years, yet you very rarely asked the dreaded question: "when will you be finished?". Although Poppa asked me every week for the past 3 years, I'm finally there. The support you have shown me goes unmatched, and as I say all the time, I would not have finished this without you.

Finally, I want to thank my co-author in life. Megan, I cannot imagine how many times you've heard me say "I need to work on my thesis tonight" over the years. You have been my biggest supporter since I started this degree. I am not sure you knew exactly what you were getting into, but I'm glad you gave it a shot. As this journey ends a new one will begin. I cannot wait to collaborate with you on many more projects in the future. Thank you.

# CHAPTER 1: Introduction

The sport of sprint kayak has been contested at the Summer Olympic Games since 1936 and is still one of the most popular sports in the world today. There is no doubt it is a long journey for a sprint kayaker to get to the Olympic Games, as it requires an athlete to paddle thousands of kilometres from the time they first sit in a boat to when they line up for the pinnacle race of their career. Questions arise, like how does a kayaker becomes an Olympian? What makes one kayaker more successful than another? What are the physical and technical differences between an elite kayaker and a novice kayaker? Due to the importance of technique on sprint kayaking performance, the over-arching topic of this PhD thesis was to investigate the determinants of sprint kayaking performance through a biomechanical lens.

The goal of sprint kayaking is to race competitors from a start line to a finish line either 200 m, 500 m, or 1000 m away. To do this, each athlete sits alone (or when racing in crew boats, with one or three other teammates), in a long, narrow kayak. The athlete sits in a carbon-fiber seat with their legs outstretched and their feet on a footboard. They use a paddle with two blades to propel themselves through the water at relatively fast velocities (i.e., 4 to 7 $m \cdot s^{-1}$). To begin moving in the forward direction, the athlete must take a “stroke” on one side of the boat by submerging one paddle blade into the water and pulling it in a lateral and posterior direction. This is part of the water phase, which begins with the entry phase, and is followed by the pull and exit phases (Figure 1.1) (McDonnell et al., 2012). The stroke is completed by pulling the paddle shaft with the bottom hand and pushing the shaft with the top hand, all while rotating the torso and maintaining overall balance and exerting force within the legs (Logan and Holt, 1985). During the stroke’s water phase the athlete is applying forces to the water via the paddle blade. The reaction forces are acting back onto the paddle blade and then transferred through the paddle shaft, through the athlete’s arms, trunk and legs, and into the boat via the seat and the footboard (Michael et al., 2009). If the resultant propulsive force is greater than the resistive drag forces acting on the boat, the boat will accelerate in the forward direction (Gomes et al., 2015). As the athlete reaches the end of the stroke and the blade is posterior to the athlete, they remove the blade from the water (i.e., the exit phase) to end the water phase and begin the aerial phase. During the aerial phase the athlete is rotating their body so they can repeat the process on the contralateral side of the boat.

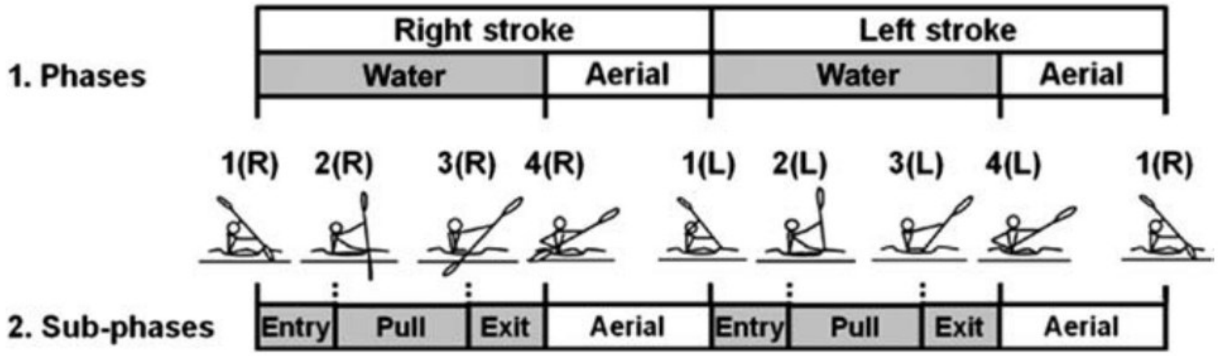


Figure 1.1 Example of sprint kayak stroke analysis split into phases (i.e., water and aerial) and sub phases (i.e., entry, pull, exit, and aerial). R, stroke on right side; L, stroke on left side. Figure reprinted from McDonnell et al., (2012).

Various approaches investigating how to increase kayak velocity (which reduces race time) can be found in the literature. Two review articles developed models and theories, which have gained considerable traction on kayak performance from a kinematic and kinetic perspective within the kayaking community. This dissertation will explain and discuss how we use both kinematic and kinetic approaches to help explain kayak performance. The first approach was developed by McDonnell et al., (2013) where they created a deterministic model to explain the kinematic parameters that are related to kayak velocity. First, the researchers explained kayak velocity by dividing it into its two kinematic parameters (i.e., stroke time and displacement per stroke). The group suggested that the athlete manipulates the parameters as needed to increase their speed; however, the correlations between kayak speed and stroke time were greater than the correlations between speed and displacement per stroke. Therefore, they suggested the better approach to increase kayak speed is to decrease stroke time. It should be noted that a more common term in sprint kayaking is stroke rate (SR), which is the inverse of stroke time. Thus, it is common in sprint kayaking terminology that increases in SR will increase kayak speed. This information provides insight on how to improve speed in short bouts of paddling, as these data were collected from studies that measured variables during very short durations of time (e.g., 10 seconds of paddling). However, since sprint kayak races occur over longer durations and distances, their results are not completely appropriate for increasing kayak speed while racing. Typically, sprint kayak race times are approximately 35, 120 and 220 seconds for the 200 m, 500 m, and 1000 m distances, respectively (Goreham et al., 2021). For example, although there is a strong relationship between speed and SR during short duration of paddling, less is known about the relationship between the same two variables over long durations of racing. The same could occur for other parameters, like displacement per stroke, which is also known as stroke length (SL), where kayak performance may increase when SL is modulated. More investigation is needed to better understand the concept of pacing strategies, and when the athlete(s) should modulate stroke parameters for optimal performance.

The other approach was published by Michael et al., (2009), who used a kinetics lens to investigate kayak performance. The group stated that there are three ways to increase kayak velocity, which include increasing propulsive forces, decreasing resistive forces (i.e., drag), or do both at the same time (Michael et al., 2009). Despite the concept being straightforward, there is still a large gap in the literature to fully explain these effects. As discussed in the literature review section of this dissertation, there are few studies that have investigated paddle forces and resistive forces in sprint kayaking, and those that have include notable limitations to their study designs (Baker, 1998; Harrison et al., 2019; Niu et al., 2019). Therefore, more research on how these forces affect kayak velocity are needed. By combining the kinematic and kinetic parameters of kayaking (i.e., kayak displacement and velocity, paddle force, etc.) it is believed that the kayaking motion would be better discussed in regard to the propulsive and resistive phases of the stroke.

A modified deterministic model was developed to help investigate the determinants of sprint kayaking performance and technique (Figure 1.2). The deterministic model was built based on the studies by McDonnell et al., (2013) and Michael et al., (2009), but included other important work in the field. The deterministic model will be fully discussed in the coming chapters of this dissertation; however, a brief summary has been included to help guide the reader. Of note, the information above the dashed horizontal line in the deterministic model is more product-oriented (i.e., what happened), whereas information below the dashed line is process-oriented (i.e., what caused it to happen). A more detailed purpose of splitting the deterministic model in two parts will be discussed in the *Literature Review* in Chapter 2; however, the basic purpose is to highlight that traditional deterministic models show what variables are important, but not how they are generated from a biomechanical standpoint (Glazier and Robins, 2012). Secondly, it is important to note the words “velocity” and “speed” are often used interchangeably throughout the sprint kayak literature. From a physics standpoint, velocity is a vector quantity (which has a direction and a magnitude), whereas speed is a scalar quantity that only has a magnitude. It will be important for the reader to take note of this important difference while reading this dissertation. It can be argued that speed, in the sprint kayak literature context, also has a direction, which is from the start line to the finish line. Sometimes velocity is discussed in the literature with direction being implied as being towards the finish line as well. It was attempted to stay consistent with these terms throughout the dissertation; however, the literature has dictated some uses of the terms.

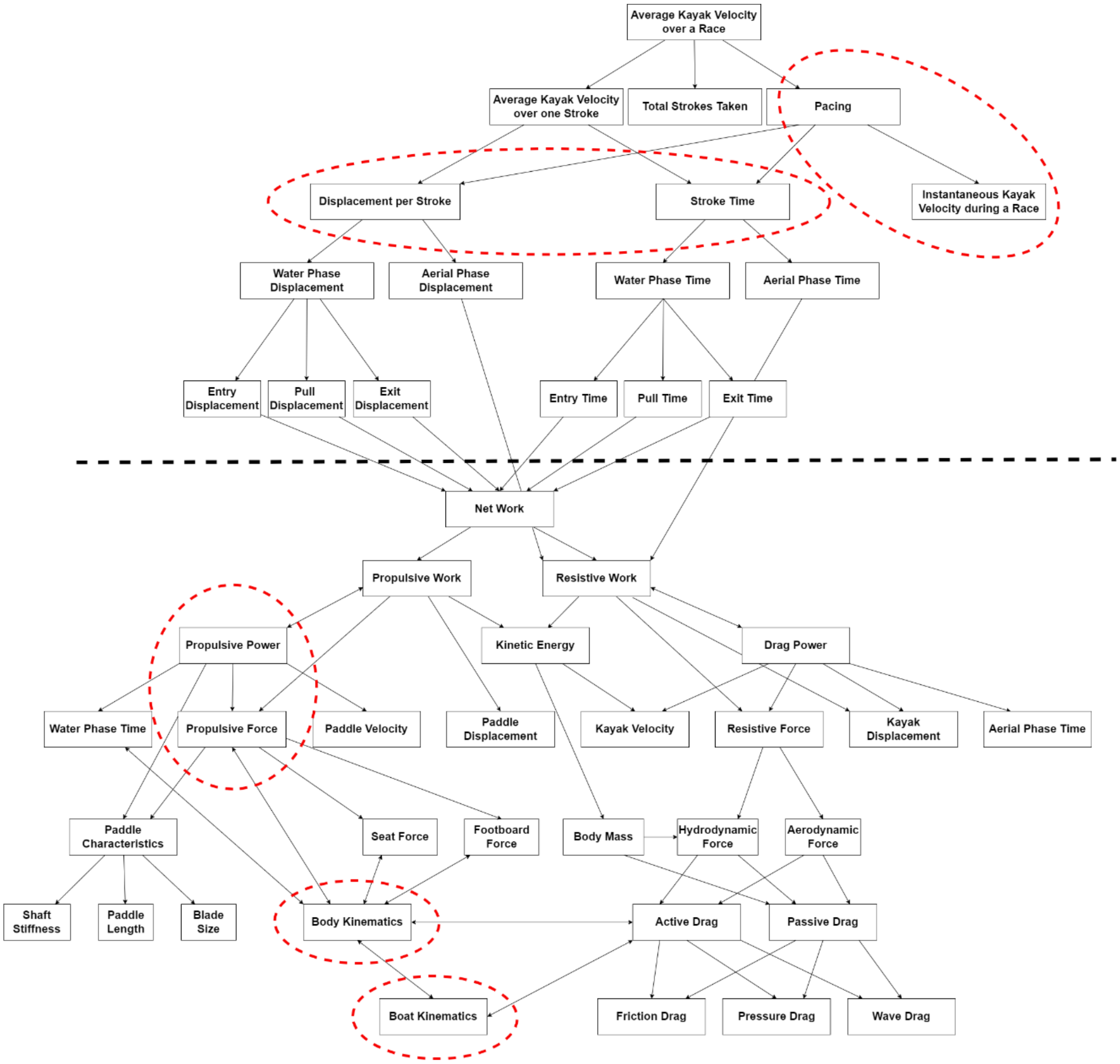


Figure 1.2 Deterministic model adapted from McDonnell et al., (2013) to include the amount of propulsive and resistive work created by the athlete-paddle-kayak system. Dashed circles highlight areas of the deterministic model that were investigated for this thesis.

The deterministic model above highlights factors that influence sprint kayak performance (Figure 1.2); however, until recently there have been few tools to help coaches identify technical flaws. Research investigating sprint kayak technique has been conducted since the 1970's when biomechanical equipment became portable and on-water data collection became more feasible (Plagenhoef, 1979). However, despite published literature on sprint kayak biomechanics, the sport is still instructed using primarily qualitative information via verbal feedback from a coach. Two pieces of equipment that are becoming more common in sprint kayak training, and may bring more quantitative instruction to the sport, are the instrumented paddle and the inertial measurement unit (IMU). The wireless instrumented paddle provides information on the magnitude, shape, and timing of the propulsive forces an athlete applies to the paddle shaft and water per stroke. The quantity of propulsive forces applied to the water directly relates to how much the boat accelerates in the water, and thus is a good measure of kayaking technique and performance (Gomes et al., 2015).

The second device, an IMU includes a triaxial accelerometer, a triaxial gyroscope and a global positioning system (GPS). Currently, an IMU is commonly used to measure two parameters in sprint kayaking: kayak speed and SR. By combining the IMU's GPS and integrating the acceleration signals, the kayak's instantaneous speed can be calculated (Janssen and Sachlikidis, 2010). One use of instantaneous kayak speed is to plan an appropriate pacing strategy for the athlete by studying a graph showing kayak speed over time or distance. To complement this information, it is also possible to determine the athlete's instantaneous SR using an IMU. As previously noted, SR is the inverse of stroke time. Stroke time can be measured by calculating the time it takes between consecutive strokes. A stroke can be identified by detecting each peak in time-series forward acceleration waveforms. Based on the literature, IMUs are being underused in sprint kayaking. For example, kayak acceleration seems to have been glanced over or dismissed by fellow researchers, as there are only a few research articles relating it to kayak performance (Gomes, 2015; G Vadai et al., 2013; G. Vadai et al., 2013). In addition, the existing literature highlights how excessive boat movement (in all planes) increases the amount of resistive forces acting on the kayak, which in turn decreases kayak speed. Interestingly no study to date has measured boat kinematics with a gyroscope (Gomes et al., 2018; Michael et al., 2009). Based on these gaps in the literature, it is believed that quantitative stroke biomechanics analysis is an area of research that can benefit the sport of sprint kayak. Multiple studies have investigated technique through the biomechanical analysis of the limbs during the kayak stroke. Unfortunately, many of these studies have been completed on land using a kayak ergometer, and the results are mixed when determining if ergometers are an appropriate method to simulate on-water sprint kayaking

(Begon et al., 2008; Fleming et al., 2012; Klitgaard et al., 2020). This is typically due to the affect of the water and buoyancy forces on technique, which are not present on an ergometer. One area that has been linked to boat motion is the effect of body kinematics and the center of mass (CoM). It is possible that unnecessary body movements may be causing unwanted boat movements which increases hydrodynamic drag and thus decrease performance. With miniature IMUs being developed, networks of these devices can now be used in unison to quantify limb kinematics, including changes in limb positions and joint angles. These measurements can be used to quantify overall body movement which can then be related to boat kinematics.

The IMU and wireless instrumented paddle mentioned above are only two of the many new pieces of technology being introduced to sprint kayaking research. As shown in the *Literature Review* chapter of this dissertation, there is a greater need to better understand boat movement and its relationship with performance. IMU's are the perfect tool to measure boat movement in three dimensions; however, they do not explain the mechanism behind why the boat is moving a certain way. To do this, researchers are beginning to instrument all parts of the kayak with load cells to measure the forces and moments acting on the boat while paddling. Researchers from our laboratory recently quantified the three-dimensional forces and moments acting on the seat and footboard while paddling on an ergometer (Bugeya Miller, 2021). The overall goal of this dissertation was to eventually quantify both the resultant movement of the boat (i.e., kinematics measured with an IMU) and the cause of the movement (i.e., kinetics measured with load cells). The work by Bugeya Miller (2021) primarily focused on the kinetics during ergometer paddling. Collecting data on an ergometer in this case was the logical first step in a bigger project (due to the more controlled laboratory environment), where the long-term goal is to collect kinetics data during on-water paddling.

## Research Aims and Objectives

Although some technology has promising uses for sport science research and practice, it is important that researchers and sport scientists use valid and reliable equipment to better understand sport biomechanics. As mentioned previously, one of the original goals of this doctoral research was to develop an integrated system to measure full-body, boat, and paddle kinematics, as well as the kinetics acting on the overall athlete-paddle-boat system (i.e., seat, footboard, and paddle). To do this, multiple pieces of technology were required to be validated prior to undertaking such a large-scale project. As you will read in this thesis, instrumentation validation results caused some of the proposed aims to be unable to be completed.

This dissertation was written in two sections. The first section discusses three studies that investigated the kinematics of sprint kayaking, which are important concepts highlighted in the deterministic model above. The research aims in the first section were to investigate the pacing strategies used by elite sprint kayakers, to establish the role of stroke parameters (i.e., stroke rate and stroke length) as determinants of sprint kayak performance, and to establish the role of boat kinematics in generating resistive forces as a determinant of sprint kayak performance. The second section of this dissertation discusses two validation studies that were completed to develop the on-water kinetic measurement system for sprint kayaking. Specifically, the first aim of this section was to validate an IMU system with the goal of measuring on-water athlete body kinematics to better understand sprint kayaking technique. The second aim of this section was to validate an instrumented paddle and power meter to quantify on-water propulsive paddle forces and power output. The over-arching topic of this PhD thesis was to investigate the determinants of sprint kayaking performance through a biomechanical lens, and therefore the deterministic model above (Figure 1.2) was used to guide the research aims. Overall, five research studies were completed in this dissertation. The general areas where the research aims exist in the deterministic model are highlighted as red, dashed circles in Figure 1.2.

### *Section 1 – The Kinematics of Sprint Kayaking*

### *Chapter 3 – Using Principal Component Analysis to Investigate Pacing Strategies in Elite International Canoe Kayak Sprint Races*

Rationale:

Scientific information on pacing strategies was lacking in sprint kayak research, especially compared to other racing sports (i.e., athletics, swimming, etc.). Due to the increase in technology usage in the sport (i.e., GPS), data highlighting elite sprint kayakers' pacing strategies were publicly available. This information was also collected at higher sample rates, which allowed for high-resolution split analysis (i.e., 10 m splits) and provided more insight into pacing strategies compared to traditional split reports from race organizers (e.g., four 250 m splits per 1000 m race). Analyzing high-resolution data points per race required using a new data analysis technique. Principal component analysis (PCA) allowed for an in-depth analysis of successful vs. non-successful sprint kayak pacing strategies at different time points within the race.

Aims and Hypotheses:

1. The first aim was to use high split-resolution time-series data and PCA to analyse boat velocity and investigate the current pacing strategies of elite canoe kayak sprint athletes at major international competitions. It was hypothesized that all-out, positive, and reverse J-shaped pacing strategies would be used in 200 m, 500 m, and 1000 m events, respectively.
2. The second aim was to determine if there were differences in pacing patterns for medallists (i.e., first to third place) versus non-medallists (i.e., bottom three competitors per race). It was hypothesized that there would be differences in pacing patterns between medallists and non-medallists in all events, and that these differences would be detectable during specific time points within the race (i.e., acceleration phase, middle portion, end spurt, etc.).

### *Chapter 4 – Pacing Strategies and Relationships Between Speed and Stroke Parameters for Elite Sprint Kayakers in Single Boats*

Rationale:

It is well known that there is a strong correlation between kayak speed and stroke rate; however, this correlation is only useful when analyzing short bouts of paddling. The rationale for this study was to investigate pacing strategies using high-resolution data for four single-athlete discipline events (men's kayak 200 m and 1000 m, and women's kayak 200 m and 500 m), while also determining the relationships between stroke parameters (SR and SL) and kayak speed throughout the entire race distance. These results will explain the current understanding of when athletes should rely on SR and SL to increase speed at different time points within the race.

Aims and Hypotheses:

1. The first aim was to investigate the pacing strategies during elite sprint kayak single-boat races. It was hypothesized that athletes would follow an all-out, positive, and seahorse shaped pacing strategy for 200 m, 500 m, and 1000 m race distances, respectively.
2. The second aim was to determine the relationships between stroke parameters (i.e., SR and SL) and kayak speed throughout the race.

### *Chapter 5 – The Relationship Between Boat Kinematics and Sprint Kayak Performance*

Rationale:

Kayak speed depends on the combination of propulsive and resistive forces; however, the causes of hydrodynamic drag in sprint kayaking are not well understood. Based on the factors affecting hydrodynamic drag, two variables can be altered by the athlete: the kayak's surface area in contact with the water and the boat's velocity. In other words, the athlete's boat kinematics affect the resistive forces acting on the boat, and thus are related to performance (i.e., kayak speed). No studies to date have investigated the relationship between boat kinematics and kayak speed. Due to the proliferation of IMUs and GPS in the sport, we are now able to measure on-water linear and angular movements of the boat at high sampling rates. Therefore, the aim of this study was to quantify boat movements to better understand the relationship between boat kinematics, resistive forces, and sprint kayak performance. Furthermore, since this technology is relatively new to the sport, normative boat kinematic values are not widespread in the sprint kayak community. Therefore, another rationale of this study was to quantify boat kinematics for a group of elite sprint kayakers.

Aims and Hypotheses:

1. The first aim was to determine which six degree of freedom (DoF) boat kinematics, measured by calculating a proxy to impulse, predict kayak speed during the propulsive and resistive phases of the stroke cycle. It was hypothesized that resistive forces affecting friction (forward and vertical acceleration), and

pressure and wave drag (pitch and yaw angular velocity) will affect mean kayak speed the most.

2. The second aim was to report normative boat kinematics values measured by an IMU (i.e., acceleration and angular velocity) from a group of National to World Class level sprint kayakers.

### *Section 2 – The Development of an On-Water Kinetic Measurement System for Sprint Kayaking*

To re-iterate, the original goal of this doctoral research was to develop an integrated system to measure full-body, boat, and paddle kinematics, as well as the kinetics acting on the overall athlete-paddle-boat system (i.e., seat, footboard, and paddle). Examples of the questions to be answered by the system were: (a) how the upper body and lower body work together to provide efficient kayak performance, and (b) if parameters extracted from a boat mounted IMU's signals are correlated to characteristics of stroke technique. To answer these questions, multiple pieces of technology were required to be validated prior to undertaking such a large-scale project. In Figure 1.3 below, the areas that were intended to be studied are highlighted. Forces and moments (red circles) were to be measured at both hands, the seat, and the footboard. Joint center kinematics (yellow markers) were to be measured at upper- and lower-body joints on the arms, legs, and core. Boat kinematics (black square) were to be measured on the posterior deck of the kayak. Inverse dynamics (blue arrows) were to be measured using force and body positions. Muscle activity (green rectangles) were to be measured using wireless electromyography technology on select muscles in the arms, legs, and core muscles. Finally, all of these measures were intended to be used to investigate which variables contribute to the forward propulsion (black arrow) of the kayak. As shown in Section 2 of this dissertation, two separate validation studies were completed on body kinematics and paddle forces.

Figure 1.3 Example of the originally proposed measurement locations during on-water sprint kayaking.

### *Chapter 6 – The Validation of a Low-Cost Inertial Measurement Unit System to Quantify Simple and Complex Upper-Limb Joint Angles*

Rationale:

On-water body kinematics during sprint kayaking are difficult to measure accurately. Low-cost inertial measurement unit systems are now able to quantify limb movements and joint angles during complex movements. Although this system shows promise to be able to quantify sprint kayak technique, it was important to investigate the system's accuracy before using it to collect on-water data. It was decided that a controlled, laboratory validation study, examining both simple and complex upper-limb movements would be required to quantify the system's validity.

Aim and Hypothesis:

1. The aim of this research was to establish the criterion validity of the Notch® IMUs system, a low-cost system (<$500 USD) with smartphone real-time kinematic tracking capabilities. It was hypothesized that the Notch® IMU system would provide acceptable criterion validity when compared to a gold-standard motion capture system, and the results would depend on the movement, joint, and plane being measured. Specifically, it was hypothesized that the IMU system would be

more likely to be valid when measuring simple single-joint movements occurring in one plane.

### *Chapter 7 – The Validation of a Commercial Wireless Power Meter for Sprint Kayaking*

Rationale:

A significant portion of this thesis depended on the ability to measure on-water force and power output in sprint kayakers. One option to measure these data was by using the One Giant Leap power meter paddle. Previous research had shown that the One Giant Leap power meter provided valid force and power measurements during on-water slalom kayaking (Macdermid and Fink, 2017). Due to the velocity differences between slalom and sprint kayaking, another validation study with sprint kayakers as participants was required to ensure the device was valid for the second population.

Aims and Hypotheses:

1. The first aim was to determine the construct validity of the One Giant Leap power meter for sprint kayaking. A first experiment determined construct validity, where it was hypothesized that the OGL paddle's mean power output would have a strong cubic relationship with mean kayak velocity.
2. If found to have acceptable construct validity, a second aim was to determine the concurrent validity of the paddle's force measurements. It was hypothesized that the OGL paddle's force outputs would not be significantly different from the known weight forces during a concurrent validation process.
3. A final aim was to determine if a wider range of calibration weights would provide better concurrent validity than the suggested range of calibration weights. It was hypothesized a calibration range encompassing all test weights (i.e., a wider range) would provide better validity than a calibration range that did not encompass all test weights (i.e., a narrow range).

# CHAPTER 2: Literature Review

The majority of sprint kayak biomechanics research has investigated how sprint kayak technique relates to key performance indicators (McDonnell et al., 2013; Wainwright et al., 2015). In one example, researchers reviewed the literature to create a deterministic model with the goal of associating kinematic variables with average kayak velocity (Figure 2.1) (McDonnell et al., 2013). As with all biomechanical deterministic models, the goal was to list all factors that explain a mechanical quantity at the model's next highest level; therefore, an athlete's average kayak velocity over a race was explained by the average kayak velocity over one stroke and the number of strokes taken, followed by the stroke time and the displacement per stroke (Chow and Knudson, 2011). The deterministic model went on to break down stroke time and displacement per stroke into their respective factors depending on whether the paddle blade was in the water (i.e., the water phase) or in the air (i.e., the aerial phase). To strengthen the model, the researchers included correlations between levels from previous literature. Strong relationships were found between SR (i.e., the inverse of stroke time) and the average kayak velocity over one stroke ($r$ = -0.86), and between average water phase time and average kayak velocity ($r$ = -0.83). A low correlation was found between average kayak velocity over one stroke and the displacement per stroke ($r$ = 0.19), meaning an athlete should attempt to increase their SR while maintaining their displacement per stroke in order to increase their velocity. Although the model included five levels, no relationships were shown between the last two levels, which suggests there is a lack of information in the literature explaining these relationships. Specifically, although identified as factors that explain water phase displacement (and time), there were no relationships reported between the entry, pull, and exit phases of the water phase and water displacement or time (Figure 2.1).

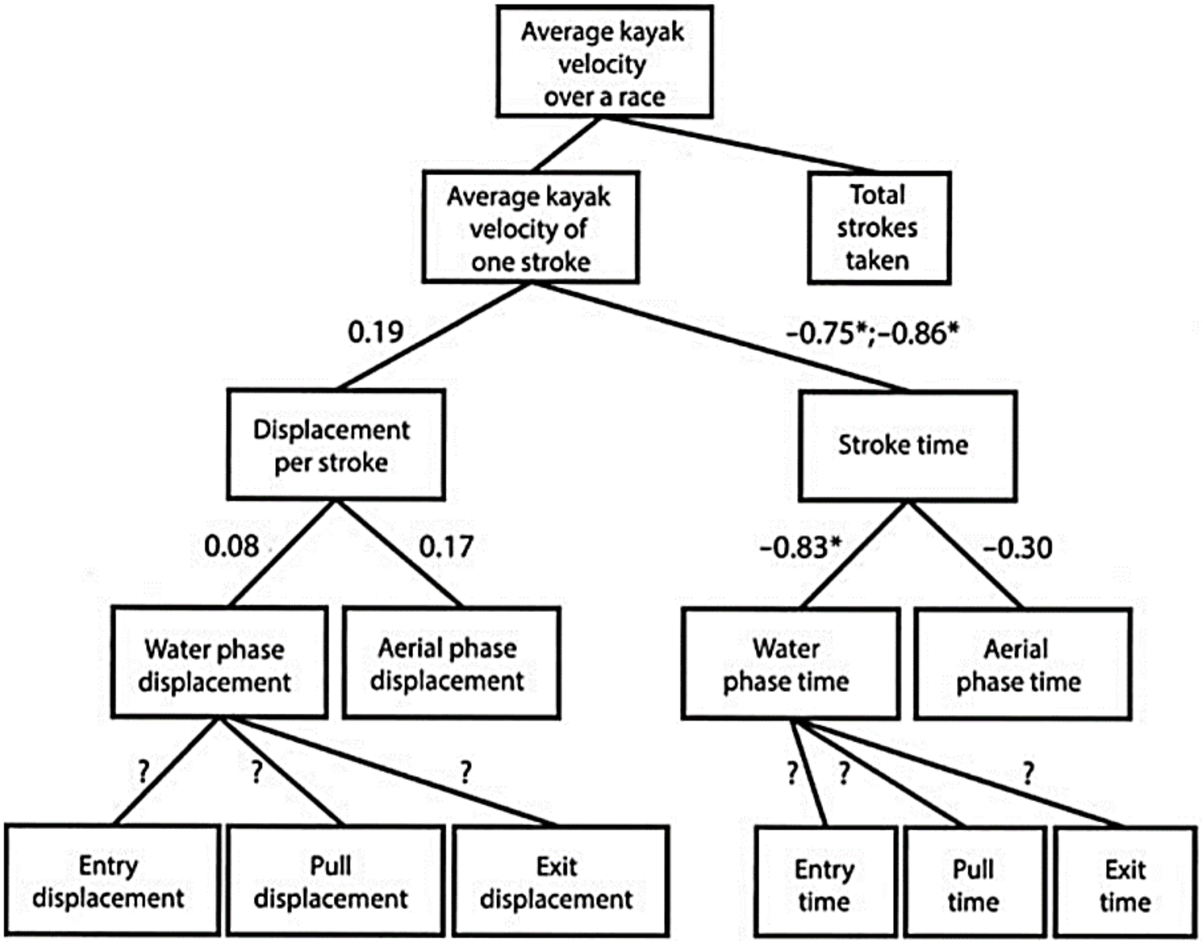


Figure 2.1 A kinematic deterministic model for average boat velocity in kayaking. Figure reprinted from McDonnell et al., (2013). Each numerical value is the correlation (found in previous literature) between average kayak velocity and the quantity in the lower box. Two correlations mean there were two studies investigating the relationships. *, indicates statistical significance ($p < 0.05$); ?, indicates relationship is unknown.

One important concept McDonnell et al., (2013) omitted in their deterministic model was when an athlete should increase or decrease their SR and displacement per stroke to enhance their performance during a race. For example, the article's primary message was for coaches to focus on ways for their athletes to increase SR, which due to the causal relationship in the model, would then increase kayak velocity. However, this message does not consider the importance of pacing during sprint kayak racing (Bishop et al., 2002; Bonetti and Hopkins, 2010; Borges et al., 2013). The concept of pacing will be discussed in future sections and chapters of this PhD dissertation.

The deterministic model by McDonnell et al., (2013) was a strong first attempt at explaining the relationships between average kayak velocity, SR and displacement per stroke. However, the group took a broad kinematic approach and did not go into detail as to which mechanical quantities best explained the relationships between water and aerial phase displacements and stroke time. As mentioned above, one of the rules of deterministic models is that factors listed determine the factors of the higher level (Chow and Knudson, 2011). The factors therefore also need to be causal. However, the authors did not try to explain what causes pull displacement. The causes may include propulsive force generated during the pull phase of the stroke and the magnitude of resistive forces acting against the boat direction of travel (i.e., drag).

In another review paper on sprint kayaking biomechanics, it was stated that kayak performance (i.e., time it takes to complete a race and thus kayak velocity) depends on two primary mechanisms; propulsive effort by the paddler and drag forces acting on the kayak (Michael et al., 2009). Therefore, to increase kayak velocity the paddler must increase their power output (in the forward direction) or decrease drag forces acting on the overall system (i.e., the boat, the athlete, and the paddle) (Michael et al., 2009). The group highlighted that most of the drag acting on the kayak-athlete-paddle system is from hydrodynamic forces, due to water interacting with the kayak itself. Since most racing kayaks are made by the same manufacturers (i.e., Plastex and Nelo), their hull profiles are very similar, and therefore decreasing the overall drag acting on the system is primarily athlete-dependent and can only be changed by how their boat moves through the water (i.e., their boat kinematics).

Michael et al., (2009) took a kinetic approach to explain kayak performance and did not discuss the relationships between displacement per stroke, SR and average kayak velocity. It is believed that both kinematic and kinetic approaches are important in understanding kayak performance, and the relationships between propulsive and drag forces (i.e., kinetics) and performance (i.e., average kayak velocity) specifically, must be explored further. However, it seems that the most appropriate method to do this would be to include both kinetic and kinematic information in the model.

A primary goal of the article by Chow and Knudson (2011) was to emphasize the importance of a theoretical basis for all sport biomechanics research. Many times, researchers arbitrarily choose performance variables to study, without incorporating them into a theoretical framework. Frameworks can then be strengthened by correlating the variables to determine their association, and thus provide stronger evidence that one variable may affect another variable. Although this conceptually makes sense, other researchers have made a strong case that deterministic models do not inform us on technique (i.e., how the movement occurred), but inform us on the performance (i.e., what movement occurred) (Glazier and Robins, 2012).

By combining both the McDonnell (2013) and Michael (2009) models, it makes sense to explore kayak performance from both a top-down (i.e., kinematic) and bottom-up (i.e., kinetic) approach, which would result in investigating the net work acting on the overall system. The net work is to the sum of the propulsive work and the resistive work. This can also be presented as “the what occurred” vs. “the how it occurred”. As shown in Figure 2.2, the deterministic model created by McDonnell et al., (2013) has been adapted (and influenced by Michael et al., (2009)) to better illustrate the influence of how propulsive and resistive work affect performance.

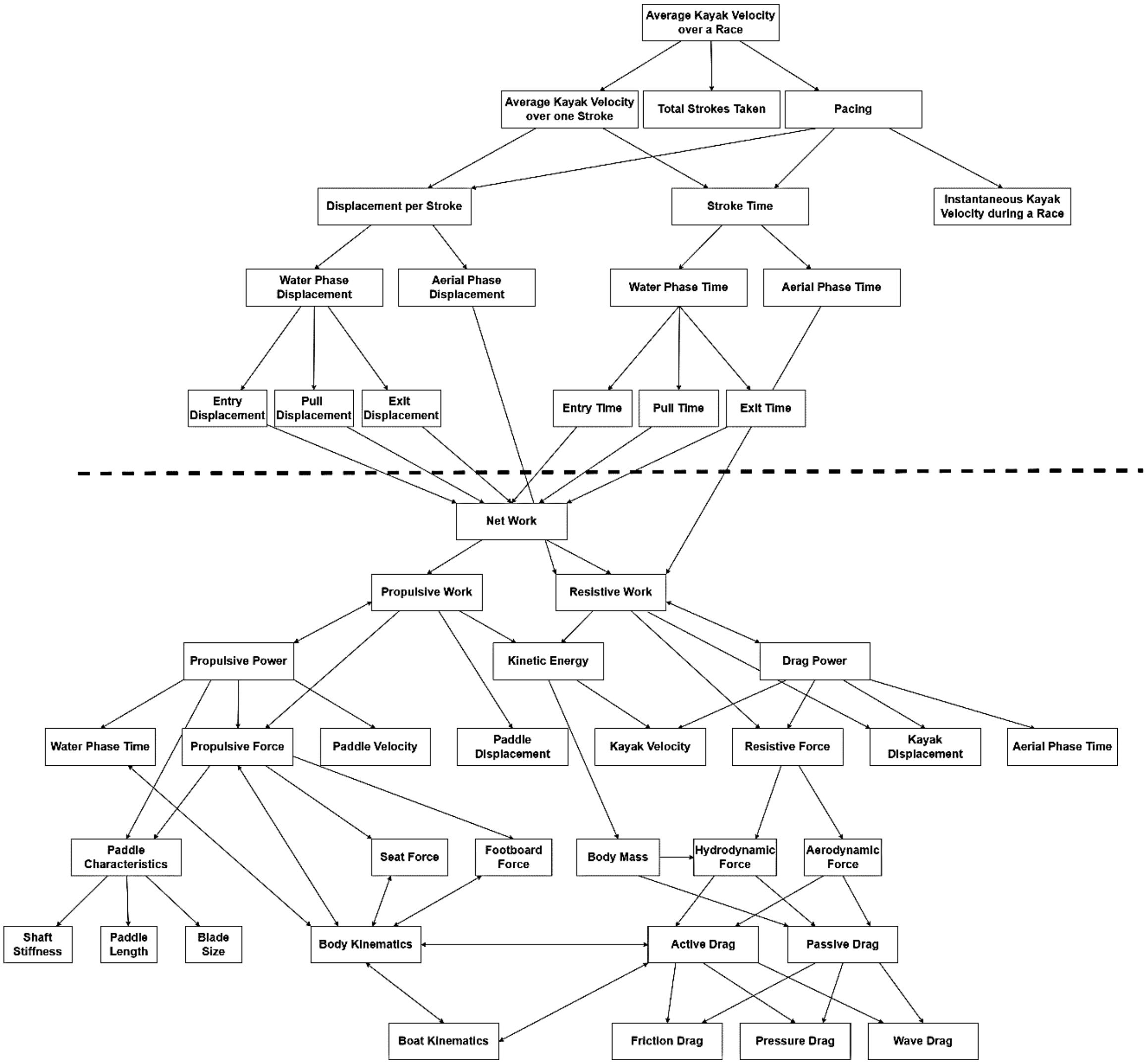


Figure 2.2 Deterministic model adapted from McDonnell et al., (2013) to include the amount of propulsive and resistive work created by the athlete-paddle-kayak system. Above the dashed horizontal line indicates “what occurred”, whereas below the horizontal line indicates “how it occurred”.

Although it makes sense to determine the relationships between on-water technical variables and their mechanistic causes, very little research has been published investigating them. In one case, Shin et al., (2018) found strong relationships between velocity and kinetic variables (collected on an ergometer) like force output (*r* = 0.78) and pull power (*r* = 0.92). Klitgaard et al., (2021) correlated maximum kayak velocity to the average (*r* = 0.61) and maximum (*r* = 0.51) footboard forces. They also reported the relationship between maximum kayak velocity and force impulse over one stroke cycle ($r = 0.63$) and with force impulse over 10 seconds of paddling ($r = 0.83$). These articles begin to help determine which biomechanical features are important for sprint kayak success; however, more research is needed.

Although the kinetic variables listed above are correlated with kayak velocity, they may have a detrimental effect as well. An area of sprint kayak research that is lesser developed is the effect of drag on kayak velocity. For example, a stronger athlete may be able to provide more force to the paddle and water (originating from connection between the athlete and the footboard and seat) which should theoretically increase velocity. However, depending on the direction the force is applied it could affect the boat movement, which may also increase hydrodynamic drag and cause the boat to slow down. This is why efficient technique is such an important factor for success in the sport of sprint kayaking. Boat movement is relatively easy to measure now with the introduction of validated IMU and GPS technology to the sport (Fernandes et al., 2021). Therefore, it is now more feasible to measure velocity fluctuations and the three-dimensional accelerations and angular rotations of the boat during the kayak stroke (Bonaiuto et al., 2020).

The following literature review will highlight published research that explains the mechanical factors that have been shown to affect average kayak velocity using both a kinematic and kinetic theoretical framework. In addition, gaps in the literature will be highlighted to show where scientific investigation is required.

## Pacing in Sprint Kayak Races

A concept that is missing from the deterministic model in McDonnell et al., (2013) is pacing. Pacing has been defined as the “goal-directed regulation of exercise intensity across an exercise bout” (Smits et al., 2014). Many deterministic models relate stroke time (or cycle time in other sports) to velocity. Although this is mechanistically correct for short trials of paddling (e.g., 10 seconds, 50 m, etc.), it does not consider the type of pacing strategy being used to complete the entire race distance. By definition the athlete(s) with the greatest average velocity will win the race. However, it is important to determine the appropriate pacing strategy to ensure the instantaneous velocity does not decrease at specific time points within the race as premature fatigue may occur (Skorski and Abbiss, 2017). For example, a 200 m race has a much different physiological demand than a 1000 m race, as there is more time to "over pace" during the longer race distance. From a physiological standpoint, an athlete should ensure they have energy remaining to complete the race distance fully, and ideally be able to increase or at least maintain their velocity as they near the finish line (Skorski and Abbiss, 2017). One way to modulate velocity throughout the race is to change the stroke rate. As mentioned, much of the literature to date has calculated the correlation between stroke rate and velocity during a very short period of time or distance at a steady state intensity (McDonnell et al., 2013). Since sprint kayak races are completed over much greater durations and distances, it is not always appropriate to infer that when the athlete increases their stroke rate their velocity will also increase for the entire duration of the race.

Compared to other racing sports, there have been very few articles published examining pacing strategies in sprint kayak. One of the first articles investigating pacing in sprint kayak gathered 250 m split data from World Championship events between 2004 and 2011 (Borges et al., 2013). The researchers investigated various factors for men's kayaking events, like number of athletes in the boat (i.e., K1, K2, K4), race distances (i.e., 500 m, 1000 m), race levels (i.e., A final, B final, etc.), and competitive seasons. One of their main results was the difference in pacing strategy found between single boats (K1) and crew boats with four athletes (K4) over the 1000 m race distance. The researchers showed the K1 1000 m athletes followed a reverse J-shaped pacing profile, where the fastest 250 m split was the first split and the second fastest split was the final split (i.e., 4th 250 m). This type of strategy indicates the K1 athletes have a strong "end-spurt", where they increase their velocity to finish the race by using the remaining energy available to them. They noted the K4 boats maintained a velocity similar to their average velocity from the entire race distance in the final split, which indicates they did not complete an end-spurt. They attributed the lack of an end-spurt to the increased drag larger crew boats encounter compared to smaller, K1 boats, which would make increasing their boat speed more difficult that late in the race. They also mentioned that it was not possible to determine if an end-spurt was present in 500 m races, as they only analyzed two, 250 m splits for that race distance. Due to this important limitation in how race organizers reported split time data, the authors called for higher resolution data from GPS units in the future.

Currently, 70% of canoe sprint Olympic events are raced over 500 m; therefore, there is a pressing need to study pacing strategies of 500 m events. The only other study to investigate pacing over the 500 m distance was completed in a laboratory on a kayak ergometer (Bishop et al., 2002). The authors recruited eight male K1 paddlers to complete two, two-minute paddling tests to determine which pacing strategy produced the greatest power output. The two pacing strategies in question were an even pacing strategy, and an all-out pace for ten seconds followed by an even pacing strategy for the remaining duration of the trial. The all-out strategy proved to have greater peak power output, average power output, and average power output in the first minute of the two-minute test. The even pacing strategy only had a greater power output in the second minute of the test. Although the all-out strategy generated a greater amount of power output, and thus was the superior test for a two-minute race, the authors did not test a positive pacing strategy. The positive strategy occurs when there is a quick acceleration to a peak velocity and a gradual reduction in velocity over the remainder of the race. This omission of testing the positive pacing strategy is unfortunate, as this strategy has been adopted in other racing sports for races that are generally 90 to 120 s in duration (Abbiss and Laursen, 2008; Sandford et al., 2018). This highlights a gap in the sprint kayak literature, and more investigation into optimal pacing strategies for 500 m events is required.

Three articles have investigated pacing strategies in shorter, 200 m race distances. The first study used video to measure velocity and stroke rates for seven male and five female K1 200 m medallists during international events between 2006 and 2011 (McDonnell et al., 2013). The researchers measured SRs from race video found on the internet, which had low resolution (i.e., 24 Hz), and overall poor quality. They reported that athletes followed an all-out pacing strategy over the shorter race distance. More importantly, this was the first study to include SR data in their analysis. They reported that SR decreased linearly from after the acceleration phase to the finish line for these athletes. Redwood-Brown et al., (2021) found similar results when they investigated the relationships between SR, stroke length (i.e., SL), and boat velocity. They analyzed pacing strategies from 646 paracanoe 200 m races in both male and female athletes. Their results highlighted that paracanoe athletes followed either all-out or positive pacing strategies, and that SR was the best predictor variable of boat velocity. Their results indicated that between 12.9% and 34.1% of the variation in boat velocity was contributed due to peak SR, and therefore athletes who could increase their SR the greatest would likely be successful in the discipline.

In another study, Pickett et al., (2020) investigated K1 200 m pacing strategies in 19 men's elite and sub-elite athletes, and also reported that all athletes followed either a positive or all-out pacing strategy. The group also investigated relationships between SR, SL, acceleration, fatigue index, and velocity. Perhaps the most important result was the importance of SL as a strong predictor of 200 m race time for elite athletes. This is important because it differs from the findings of Redwood-Brown et al., (2021), and as shown in the deterministic model by McDonnell et al., (2013) (Figure 2.1), SL (i.e., displacement per stroke) had a low correlation with the average kayak velocity of one stroke. The lower correlation indicates the parameter is not as important for performance, which should lead coaches and athletes to spend less training time trying to improve it. However, despite the importance of correlations between performance parameters, they should be interpreted in the context of the race. For example, the group also reported that SR can be used as a measure to predict performance level amongst a group of athletes of varying skill levels, and the importance to maintain SR while fatigued. This may be true of 200 m races, but the same relationship may not hold true for longer distance races and as a consequence, could mislead training programs.

The sprint kayak pacing literature leaves many questions unanswered, primarily due to the low-resolution data that has been published to date. Race dynamics amongst competitors can change tremendously over longer race distances, therefore only reporting four 250 m splits does not provide the resolution needed to appropriately analyze pacing strategies. With the widespread use of GPS units in sports today, a higher-resolution dataset should be the gold standard when investigating pacing strategies (Borges et al., 2013).

Another intriguing concept in the sprint kayak pacing literature was highlighted by Borges et al., (2013) when their data showed athletes in A-finals adopted different pacing strategies than those racing in B-finals. Specifically, the researchers found the middle portion of the race was slower for B-finalists during 1000 m races, and that there was more variability in pacing strategies amongst the B-finalists (compared to A-finalists) in 500 m and 1000 m events. The authors did not account for factors that may have led to their results though, instead hypothesizing aggressiveness, experience, and anaerobic fitness to be potential causes why A-finalists' pace differently than B-finalists.

To conclude this section on pacing strategies, future research should include performance parameters, like SR and SL, to pacing strategy analysis. This information gives more context as to how sprint kayakers can modulate their velocity during a race which will help enhance their chances of success.

## Propulsive Forces

Propulsive forces originate in the kayak stroke when the paddle blade is in the water. The paddle blade-water interaction causes a force which is transmitted through the body to the seat and the footrest, which then accelerates the kayak (Michael et al., 2009). For a kayak to accelerate, the propulsive force being generated by the athlete must be greater than the drag forces acting on the entire athlete-paddle-kayak system (Baker, 2012; Michael et al., 2009). This statement is largely theoretical, due to the difficulty in measuring active hydrodynamic drag forces acting on the kayak and paddle, and the aerodynamic drag forces acting on the athlete (Gomes et al., 2015). However, researchers have been measuring the propulsive forces applied by the athlete to the water since 1986 when Stothart et al., (1986) instrumented a kayak paddle with two strain gauges just above the connection between the blade and the paddle shaft. Their work influenced subsequent studies to use wireless instrumented paddle shafts to measure the propulsive forces an athlete applies to the water during a kayak stroke (Bonaiuto et al., 2020; Gomes et al., 2015; Kong et al., 2020; Macdermid and Fink, 2017; Romagnoli et al., 2022). Some researchers have tested wireless instrumented paddle shafts to determine their validity (Macdermid and Fink, 2017).

### *Optimal Force Profiles*

Like the sport of rowing, much of the research investigating propulsive paddle forces in sprint kayaking have used paddle force profiles to do so (Baker, 1998; Gomes et al., 2015; Warmenhoven et al., 2018a). Three primary characteristics of force profiles have been investigated in the sprint kayaking literature: the shape of the profile, the magnitude of the profile, and the timing of the profile. Harbour, (2019) combined various types of paddle force profiles into one figure to help visually depict ways to improve kayak and race velocity (Figure 2.3).

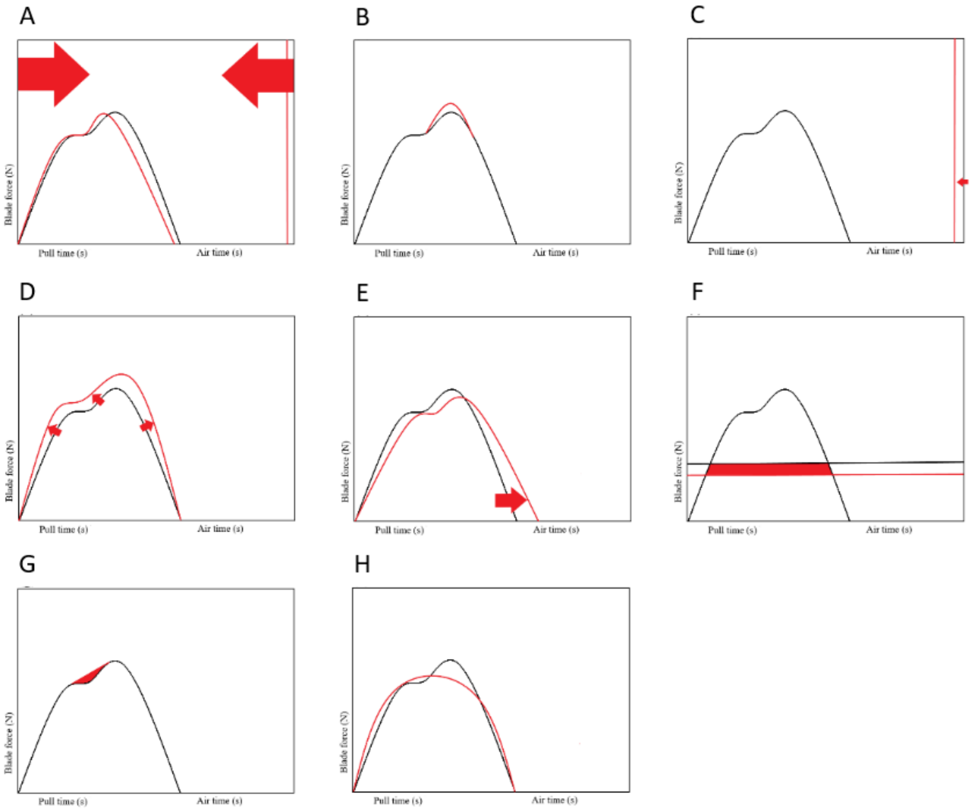


Figure 2.3 Potential strategies to improve kayak and race velocity using different force profiles. Panel A. reduce stroke time, B. increase peak force, C. reduce duration of aerial phase, D. increase stroke impulse, E. increase the percentage of time in the pulling phase of the stroke, F. reduce the passive drag force acting on the boat (due to body mass), G. increase stroke smoothness to reduce bimodal waveform characteristic, and H. improve squareness (i.e., make a more rectangular shaped force waveform). Red lines, shaded areas, and arrows indicate proposed change to force profile for increased performance. Figure adapted from Harbour, (2019).

Force profiles have been used much more frequently in rowing research compared to kayaking research. This is likely due to the ease of measuring force in one plane, which is similar to the rowing stroke; however, benefits of using force profiles have been seen in both sports (Gomes et al., 2015; Warmenhoven et al., 2018a). Examples of these benefits include stroke phase detection, magnitude and impulse of the force, timing of key events within the stroke cycle, and qualitative analysis when synchronized with video or other biophysical data (Sperlich and Baker, 2002; Warmenhoven et al., 2018a). Another benefit of using these data is to track an athlete's progression over a training block or season (Sperlich and Baker, 2002). The following sections will discuss the three primary characteristics of paddle force profiles in more detail.

### *Shape of the Force Profile*

It was proposed that the shape of kayak stroke force profiles, when combined with boat velocity and acceleration data, was a plausible method to detect errors in kayaking technique (Sperlich and Baker, 2002). However, over 20 years later only two researchers have attempted to relate the shape of force profiles to boat kinematics and technique (Bonaiuto et al., 2020; Gomes, 2015). Potential reasons for this could be because wireless instrumented paddles are difficult to use, expensive and often have different characteristics than an athlete's preferred paddle (i.e., stiffness, length, blade size, etc.). Further, accelerometers and gyroscopes, which measure boat kinematics, only became popular in the sport within the past 10-15 years (Janssen and Sachlikidis, 2010). With recent technological advances it is believed that more research can now be undertaken to understand the relationship between the shape of a force profile and other performance parameters. One example is boat kinematics. Fortunately, there is a small basis for this potential research to build on, as although only two studies have combined force profile shapes and boat kinematics, there are a few additional studies that have investigated the shape of force profiles on their own.

Some force profile characteristics may benefit performance more than others. For example, Michael et al., (2009) suggested that the most effective force profile would theoretically have a peak force that occurs quickly following the catch of the blade and is prolonged as long as possible before the blade is rapidly removed from the water. The goal of reaching peak force quickly and preserving the force is to generate the greatest stroke impulse possible, which would ultimately cause the force profile to be rectangular in shape (Gomes et al., 2015). The impulse from a paddle stroke originates from the momentum and kinetic energy that is applied to the water from the paddle's blade (Jackson et al., 1992). This impulse is shown by a U-shaped vortex that follows the paddle blade as it travels through the water and can be directly quantified by measuring the vortex radius (Jackson et al., 1992). The more energy that is created from the stroke (i.e., the greater propulsive work done by the net force of the paddle stroke) will cause greater vorticity (i.e., impulse) and thus a more effective stroke (Harrison et al., 2019). Stroke impulse can be measured indirectly by calculating the area under a force-time profile, and thus, is highly dependent on the shape of the waveform. For this reason, the shape of the force-time waveform is deemed important in sprint kayak research.

Gomes, (2015) studied the relationships between paddle force profile shapes and kayak performance during her PhD research. In one of her PhD studies she compared force profiles at varying SR's and found that the shape of the force profile changed as the SR increased (Gomes et al., 2015). Specifically, as the SR increased to race pace levels (i.e., >120 strokes per minute; spm) the force profiles adopted a rectangular shape with two-peaks (i.e., bimodal), whereas when paddling at lower intensity SR's (i.e., <120 spm) the force profiles maintained a triangular shape with only one-peak (i.e., unimodal; Figure 2.4). The group hypothesized that the two peaks were due to an aggressive catch when travelling at greater boat velocities, which caused the boat to accelerate slightly before the paddle "grabbed" the water (Gomes et al., 2015). They also hypothesized that the bimodal shape of the force profile could be altered by using a stiffer paddle shaft; however, this was not tested. Interestingly, Baker, (1998) also discussed reported unimodal and bimodal force profiles; however, they did not relate the force profile shapes to differing SR's. According to Baker, (1998), the reason for the first peak in a bimodal force profile is due to slight elbow flexion following the catch position of a stroke. Unfortunately, no data supporting this claim was reported, and therefore more research should be completed to understand the relationship between body kinematics and force application.

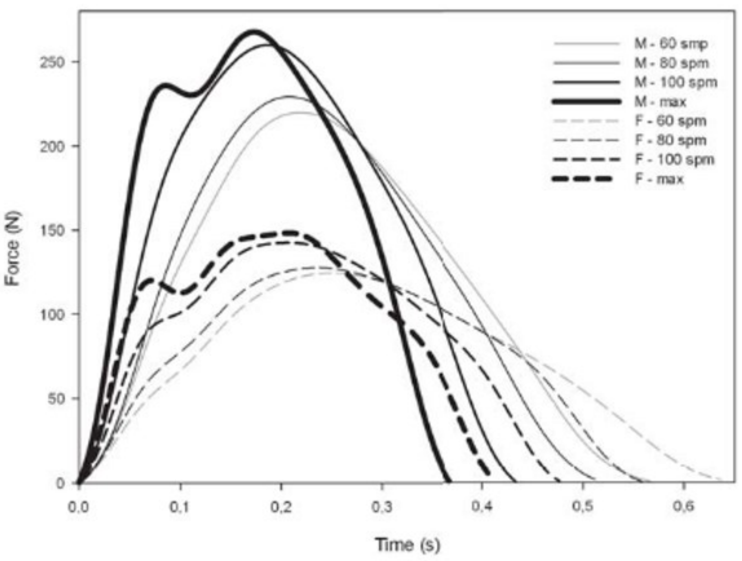


Figure 2.4 Mean normalized force-time curves for male (M) and female (F) kayakers at four different stroke rates (60, 80, 100, maximum spm). Solid lines, male; dashed lines, female; spm, strokes per minute. Figure reprinted from Gomes et al., (2015).

Another interesting result from Gomes et al., (2015) is the difference in force profile shapes between male and female kayakers. As shown in Figure 2.4, the force profile at the maximum SR condition for both sexes is bimodal; however, for the next highest SR condition (i.e., 100 spm) the female force profile is bimodal, whereas the male force profile is unimodal. It is currently unclear why the force profile shapes are different during the same SR condition between sexes, but it could be related to the absolute maximum SR an athlete is capable of. The researchers reported the maximum SR for males to be 124 ± 7 spm, whereas for females it was 112 ± 3 spm, a difference of 12 spm.

Although there are many statistical methods to compare the shape of waveforms, researchers and sport scientists have used a discrete percentage metric to determine the shape of a force profile in the literature (Gomes et al., 2015; Kleshnev, 1998). The percentage metric of a singular stroke, which is believed to be a good measure of stroke efficiency, can be calculated by dividing the paddle's mean force ($F_{mean}$) by the peak force ($F_{peak}$) and multiplying it by 100 (Equation 1) (Kleshnev, 1998).

Equation 1. $$\text{stroke efficiency} = \frac{Fmean}{Fpeak} \times 100$$

Gomes et al., (2015) reported that a greater percentage (i.e., 100%) indicates a more rectangular profile, whereas a lower percentage (i.e., 50%) represents a triangular shape. The researchers found the metric increased significantly from 53.3 ± 3.3% to 64.8 ± 3.7% when twenty athletes paddled at a low SR (i.e., 60 spm) compared to a race pace SR (i.e., >120 spm). The method of using a percentage metric to quantify a force profile's shape may be suitable to those wanting to use discrete metrics; however, this method does not indicate whether there are fluctuations in the waveform shape, and thus may miss some important information about technique. Future analyses of stroke profiles could use time-series waveform analyses like principal component analysis (PCA) or statistical parametric mapping, among others, or simply continue investigating total impulse (Warmenhoven et al., 2018b).

No published literature has shown whether a unimodal or bimodal force profile is preferred among coaches or scientists; however, one researcher hypothesized that fewer fluctuations in the force profile provides a more efficient stroke due to less energy being required to create the same amount of velocity (Baker, 1998). This reasoning indicates that a unimodal profile is preferred and highlights an important knowledge gap in the kayaking literature. No data has been presented showing the effect of force profile fluctuations on boat movement. It is believed that by measuring boat kinematics (i.e., acceleration and rotation) simultaneously with paddle force output, a better understanding of kayak performance and technique can be gained (Sperlich and Baker, 2002). Current data suggests that greater stroke force impulse is related to greater boat velocities and has been shown to be a significant difference between competitive and recreational kayakers (Gomes et al., 2015; Niu et al., 2019). However, it is possible that there is a limit to the amount of impulse that can be applied to the water. This issue can potentially be magnified if force output is applied in a way that the boat does not accelerate smoothly and causes a less efficient stroke due to increased resistive forces. Another issue could arise if a larger impulse is applied to the left side of the boat compared to the right side of the boat, or vice versa, as this situation could cause boat movement asymmetries, and excessive pitch, yaw, and/or roll of the kayak (Day et al., 2011). Unfortunately, it is currently not understood if fluctuations in the shape of the force profile translate directly to the shape of the kayak's acceleration or angular velocity profiles. Smoothness of force profiles have been investigated in rowing, and their findings showed that elite rowers have smoother force profiles than non-elite rowers (Hill, 2002; Soper and Hume, 2004; Warmenhoven et al., 2018a).

One noteworthy observation in the literature is that although the shape of the force profile changes as SR increases, the impulse per stroke does not change. Gomes et al., (2020) found no significant difference in impulse as SR increased, meaning the impulse from a stroke at 60 spm was similar to the impulse generated at greater than 120 spm. This is an important result as one could expect impulse to decrease due to the decreased stroke cycle time at a higher SR. This result is likely one of the primary reasons boat velocity increases as SR increases (Gomes et al., 2020). For example, if the impulse of one stroke at 60 spm is 64 N•s the total impulse for all strokes in one minute is equal to 3840 N•s. If one stroke at 120 spm has the same impulse as a stroke at 60 spm (i.e., 64 N•s) the total impulse for one stroke in one minute at the higher SR would be double that (i.e., 7680 N•s). In one exception, which is based on an unpublished case study, it was shown that the impulse for one elite male kayaker increased as SR increased (Gomes, 2015). The group believes this is only true for the most elite paddlers (i.e., Olympic medallists) as they are more proficient at higher SR's (Gomes, 2015). This hypothesis should be tested further; however, due to the few athletes who medal in an Olympic race it would be difficult to recruit for such a study.

Only one study has compared force profile impulse between paddling skill levels. Niu et al., (2019) compared force profile output between competitive and recreational paddlers and found that the faster, competitive paddlers had significantly greater blade force and impulse compared to the less experienced cohort. Their finding was expected as greater boat velocities are due to the sum of the net propulsive forces acting on the boat through the paddle stroke (Niu et al., 2019). Unfortunately, there were many limitations to their study, which affirms more research is needed on this topic. One of the primary limitations was the group of paddlers tested. Competitive paddlers had more than five years of paddling experience, whereas the recreational paddlers had no experience at all.

Future studies should test novice athletes that have some paddling experience instead of recreational participants. It is expected the differences found between elite and novice athletes would be much more meaningful, as novice athletes would be able to conduct some of the basic skills for sprint kayaking. For example, they likely have better balance than their non-experienced counterparts. Another limitation was the group used an instrumented paddle that was not wireless, which could severely affect paddling technique. Also, all data were collected in a 50 m pool, where only 4-6 strokes could be measured and therefore is only relevant to the start of a kayak race. Finally, the group did not control for SR, which as discussed multiple times above, plays a large role in kayak velocity and paddle force profiles.

Due to the importance of SR and impulse on kayak velocity, a new metric was created to calculate the work done by an athlete in a race, which was also believed to explain stroke efficiency (Baker, 1998). Baker, (1998) reported the equivalent of work could be calculated by multiplying the impulse of a stroke by the SR (Equation 2). However, it is important to note that the SI units of the created metric equal $\frac{kg \bullet m}{s^2}$ and not the SI units of work, which are $\frac{kg \bullet m^2}{s^2}$.

Equation 2. $$work = impulse \times stroke\ rate$$

Gomes et al., (2020) later stated the equation was “an estimate of work”, and it was shown to be linearly correlated to velocity ($R^2 = 0.798$; Figure 2.5) which made the group suggest paddlers should aim for short and powerful strokes compared to longer strokes.

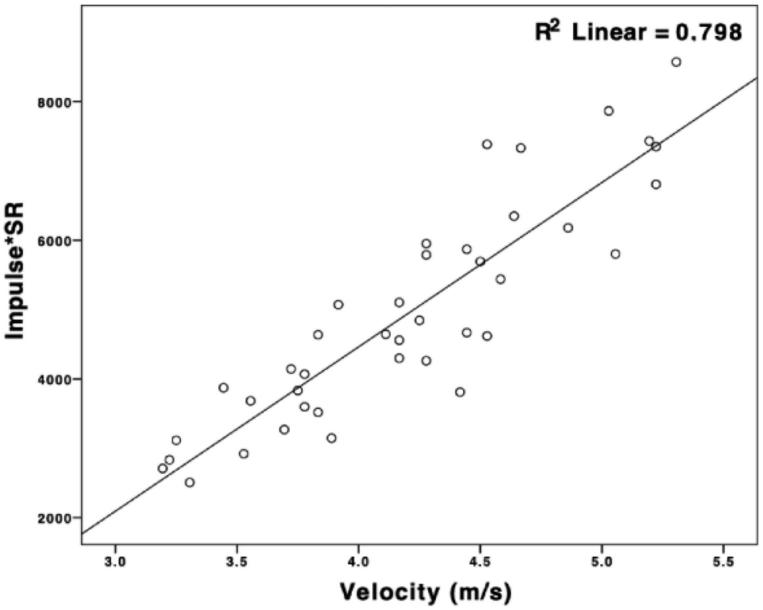


Figure 2.5 Relationship between impulse × SR and kayak velocity. Solid line, tendency line; $R^2$, coefficient of determination. Figure reprinted from Gomes et al. (2020).

One limitation to research investigating the shape of force profiles in kayaking is that no one has studied whether individual kayak athletes have their own force "signature" or not. Force signature is a term that was coined in rowing, and essentially means each athlete could have their own individual force profile that is noticeably different from their peers (Warmenhoven et al., 2018a). Previous research has shown that some rowing athletes have their own force signatures which are stable over time (Figure 2.6) (Ishiko, 1971), while others have shown that an athlete's force signature can change due to coaching and technical instruction (Warmenhoven et al., 2018a; Wing and Woodburn, 1995). These results have caused rowing researchers to question if there is an optimal force signature or not (Warmenhoven et al., 2018a). Despite more research being published on force profiles in rowing than in kayaking, there is still no clear relationship between force signatures and rowing performance (Warmenhoven et al., 2017). This is believed to be an important gap in the knowledge of sprint kayaking as well; therefore, future studies should investigate force profiles more thoroughly and determine whether force signatures exist in the sport, as well as determine whether force signatures are stable over time, both within a race and over a training block. This type of investigation would also help determine whether there are differences in force profiles between novice and elite kayakers.

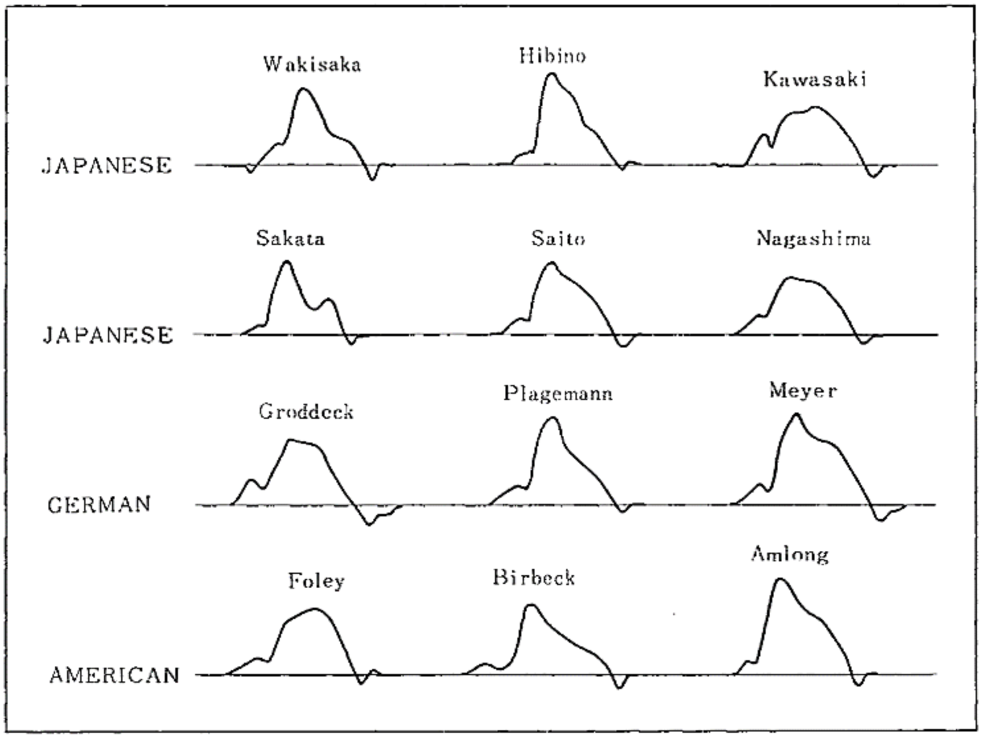


Figure 2.6 Examples of oar pin force-time profiles from elite rowers from different nationalities and coaching philosophies. Figure reprinted from Ishiko (1971).

### *Magnitude of the Force Profile*

When investigating kayak paddle force sport science researchers have mostly reported variables like peak force. This method of investigating performance is known in the literature as discrete point analysis (DPA) and/or critical features analysis, where maxima, minima or other key performance indicators are chosen from a time-series waveform (Lees, 2002; Warmenhoven et al., 2018a; Warmenhoven et al., 2017). The original interest in paddle force variables came from two studies published a decade apart, which both suggested that coaches could build databases of their athlete's paddle kinetics in hopes to optimize their kayak stroke over time (Aitken and Neal, 1992; Sperlich and Baker, 2002). It was also suggested that the variables could be related to overall kayak performance between elite and sub-elite athletes and the normative values collected could be used to train novice kayakers (Aitken and Neal, 1992). Although this seemed like a good approach to measure kayak performance, only one study to date has compared peak paddle force and kayaking skill level. Kong et al., (2020) found National-level sprint kayakers generated approximately 340 N of peak force output during maximal effort sprint kayaking in crew boats, whereas recreational- and school-level athletes produced ~240 N and ~220 N of peak force, respectively.

A primary theme that arose when reviewing the sprint kayak literature is few studies have reported paddle forces, and those that have are not always in agreeance with one another. For example, one study reported that elite male single kayak (K1) athletes apply an average peak paddle force of 375 N at 90 spm over a 1000 m race, whereas elite female K1 athletes apply 290 N at 99 spm over 500 m races (Baker, 1998). Unfortunately, these data were reported in a coaching seminar presentation and not from a peer-reviewed scientific study and should be viewed as anecdotal evidence (Baker, 1998). However, due to the lack of information on paddle forces in the literature, their results have been cited in many published articles discussing this topic (Bonaiuto et al., 2020; Gomes et al., 2015; Michael et al., 2009). In another study, Gomes et al., (2015) reported much lower peak forces for both elite males (274 ± 35 N at 124 ± 7 spm) and females (153 ± 11 N at 112 ± 3 spm), but still found a significant inter-trial correlation between peak forces and mean kayak velocity ($r = 0.663$, $p < 0.001$). Surprisingly, these data were collected over a shorter race distance (200 m) where large power output is needed, and therefore, force output should theoretically be greater than when collected over longer distances.

Three other published studies reported on-water peak paddle forces from elite kayakers (Bonaiuto et al., 2020; Harbour, 2019; Ong et al., 2006). In one study, three athletes (one male, two females) paddled 50 meters at their maximum velocity prior to entering a six-metre calibrated capture volume, where the researchers measured their peak paddle force over one left and one right stroke (Ong et al., 2006). The male athlete produced an average peak force of 349 N, whereas the female athletes both produced an average of 243 N. Unfortunately, no specific SR information was provided other than measured strokes were between 61 spm to 71 spm. As mentioned above, it is important for SR to be controlled for when comparing peak force output between studies. Another pilot study reported one elite female athlete produced an average peak force of approximately 140 N at 82 spm, whereas the elite male athlete produced an average peak force of approximately 305 N at 90 spm (Bonaiuto et al., 2020). The final study collected on-water force data from four elite male athletes, and reported their average peak force to be 233.9 ± 21.1 N over 113 strokes while paddling at 68.2 ± 3.9 spm (Harbour, 2019). As shown, there are very few consistencies between studies for an elite paddling cohort, which calls for more standardized approaches to measuring propulsive force data during on-water paddling.

The three articles mentioned in the paragraph directly above measured peak paddle force outputs in elite kayakers; however, only two studies have reported paddle force outputs from sub-elite kayakers. One study found that their lone participant produced an average peak force of 200.6 ± 7.9 N in their left hand and 213.5 ± 9.6 N in their right hand over 500 m (Aitken and Neal, 1992). Unfortunately, they did not provide descriptive information about their participant (i.e., age, sex, average kayak velocity, stroke rate, etc.), and therefore it was difficult to compare their results to an elite population. Despite missing this information, the results were most similar to Gomes et al., (2015) results, even though they tested the most elite population, as inclusion criteria for their study was that the athlete must have qualified for the 2012 Olympic Games. In another study of ten male sub-elite paddlers, they produced similar peak forces of 237.3 ± 42.0 N while paddling at 82 ± 6.8 spm (Romagnoli et al., 2022).

As discussed, there is no clear understanding as to what peak paddle force magnitudes an elite kayaker produces during a race, and this is most likely due to three main issues visible in the literature. First, data presented does not always highlight exactly when the force output was collected during a race or time trial, or how long the collection lasted for. For example, it should be expected that accelerating a kayak from a static position (i.e., the start of the race) requires greater propulsive force than what is required during the race when the boat has overcome inertia and is travelling at a near constant velocity. However, results in the literature are conflicting, as Baker (1998) reported that common peak paddle forces at the start of races are much greater than the overall race average (i.e., 525 N vs. 375 N for males), whereas Gomes et al., (2011) found that a female World Championship medallist's first stroke peak paddle force was less than the average of her remaining strokes (i.e., 286 N and 295 N, respectively).

Highlighting the issues with differences in study designs in kayak research, Gomes et al., (2011) collected peak paddle forces in a 25 m swimming pool, and thus their findings are not practical as they could only capture 2-4 strokes before the participant had to stop paddling. This is an important limitation, as most sprint kayakers do not reach their peak velocity until they are 60 m into the race, and therefore research conducted in small capture volumes limits the potential application of the results (Goreham et al., 2018). However, there are some benefits of collecting biomechanical data in an indoor pool environment. These include controlling for environmental constraints, like wind, water temperature and depth; all variables that can affect kayak speed and performance (Harrison et al., 2019; Warmenhoven et al., 2018a). Indoor pools are also good locations to develop and test new technologies, and to collect pilot data.

The second issue with propulsive force measurements in kayak research is the possibility of introducing constraints that may confound the force profile measurements. Warmenhoven et al., (2018a) recently highlighted the concerns with not accounting for constraints in rowing research and how it can affect the practical applications of a researcher's study results. The group created a framework to guide future research in the area (Figure 2.7), which are based on understanding Newell's Model of Constraints (Newell, 1986). Newell's Model of Constraints includes three types of constraints, which are the task, organismic and environmental constraints. A task constraint is related to the task at hand, like competing in a 200 m race versus a 1000 m race. An organismic constraint is related to the performer, which could be the pressure an athlete feels when training versus when they are about to race for an Olympic medal. And finally, an environmental constraint is an environmental factor that may affect the athlete's movement or performance. An example of this type of constraint was highlighted in the paragraph above regarding testing indoors in a swimming pool where there is no wind, and the depth of the pool remains constant.

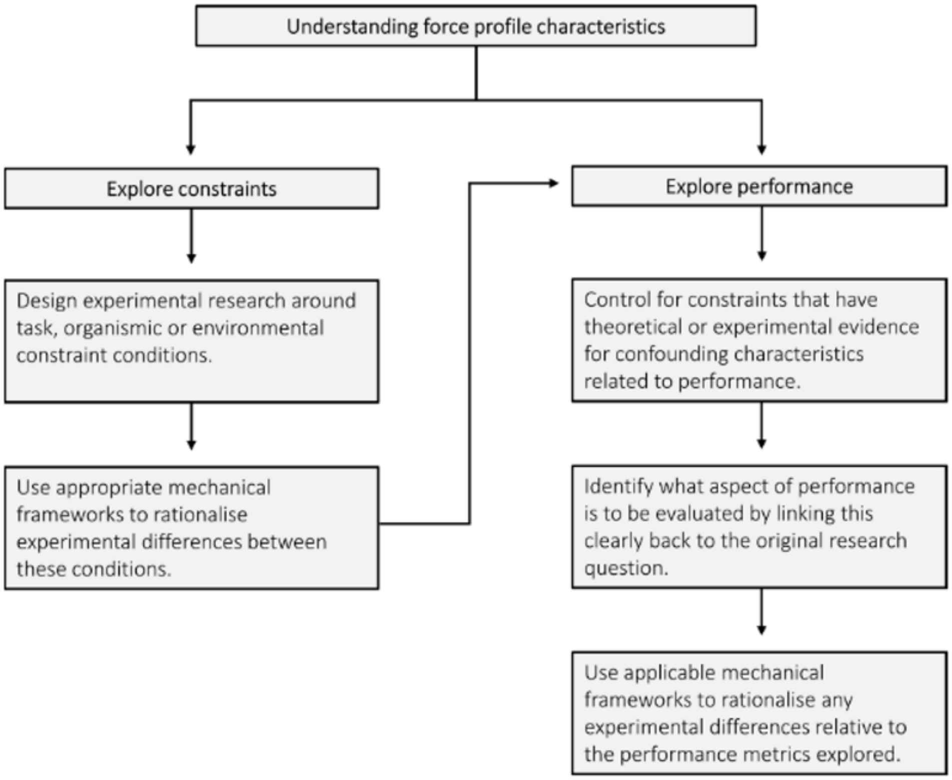


Figure 2.7 A research framework to aid in the investigation of force profile characteristics. Figure reprinted from Warmenhoven et al., (2018a).

Task constraints are often introduced in kayaking research, as a common method of measuring kayaking technique is by paddling on a kayak ergometer in a laboratory environment (Bjerkefors et al., 2017; Bonito et al., 2022; Fleming et al., 2012). To date, there is no strong evidence showing that the biomechanics of on-water kayak strokes are similar to strokes taken on a kayak ergometer, and therefore paddling on a kayak ergometer is often viewed as a violation of a task constraint. In fact, one recent study showed stroke kinematics and some parameters (i.e., SR) were significantly different between on-water and ergometer paddling (Klitgaard et al., 2020). That said, some literature may be beneficial when trying to understand pacing-related variables, like force output. For example, Michael et al., (2012) recruited ten elite kayakers to paddle on an ergometer to simulate a 500 m race and found that peak paddle force decreased significantly ($p$ = 0.025) from the start of the race (i.e., approximately 330 N) to the middle and end of the race (i.e., approximately 300 N and 295 N, respectively). Unfortunately, as mentioned it is unknown whether these results are transferrable to on-water paddling, which calls for more research in this area. Therefore, it is currently up to knowledge users whether or not they incorporate this research into their practice.

Another issue when determining why the magnitude of peak paddle forces differ between groups of athletes and research articles is due to the equipment being used to collect data. One researcher stated that paddle force depends on the paddle length, the position of the hands on the shaft and the shape and size of the blade (Gomes, 2015). The researcher noted that a wider handgrip width increases the paddle force whereas a smaller handgrip width decreases paddle force (i.e., due to a change in the moment acting at the handle positions) (Gomes, 2015). This change in force output is due to the locations of the strain gauges in the paddle shaft, and since some researchers create their own instrumented paddles, it is unlikely that the instrumented paddles used in all research studies function similarly. For example, Gomes et al., (2015) developed the FPaddle, where two strain gauges were placed inside the paddle shaft 0.8 m from the tip of the paddle blades; whereas Aitken and Neal, (1992) attached four strain gauges on the paddle shaft 0.01 m and 0.05 m from where the blades connect to the shaft. The bending of the paddle shaft allowed for the reaction force to be measured in both cases; however, the reaction forces would be proportional to the distance the hands were to the blade tip (i.e., where the force is applied to the water), and this was not reported in neither study. Baker, (1998) did not report the number, type or locations of the strain gauges used to collect the paddle force measurements in their research. Furthermore, it has been shown that altering a paddler’s preferred equipment setup (e.g., changing their hand grip width, foot-bar distance from seat, etc.) causes greater differences in kinetic measures, like paddle force and impulse, than in kinematic differences, like upper-body and paddle positions (i.e., elbow joint angle, paddle angle at entry, etc.) (Ong et al., 2006). Therefore, equipment set-up is another important factor to consider when comparing study results.

Differing strain gauge locations within a paddle shaft have been reported to be an issue before; however, it was the best method next to measuring the actual blade forces at the time (Michael et al., 2012). To date there have been a few studies that have measured blade forces during on-water kayaking; however, due to multiple study design flaws it is difficult for practitioners and researchers to translate the results to compare with past or future research (Helmer et al., 2011; Löppönen et al., 2022; Niu et al., 2019). The results from one of these studies provides preliminary information as to where the peak forces occur on the blade during a stroke (Figure 2.8). This information can potentially help researchers conducting simulation studies apply better force estimates in their computational models (Harrison et al., 2019; Nakashima et al., 2017; Niu et al., 2019). Due to the difficulty in designing and constructing a blade that measures forces it is expected that paddle forces will be measured using paddle shaft deflection methods for the foreseeable future.

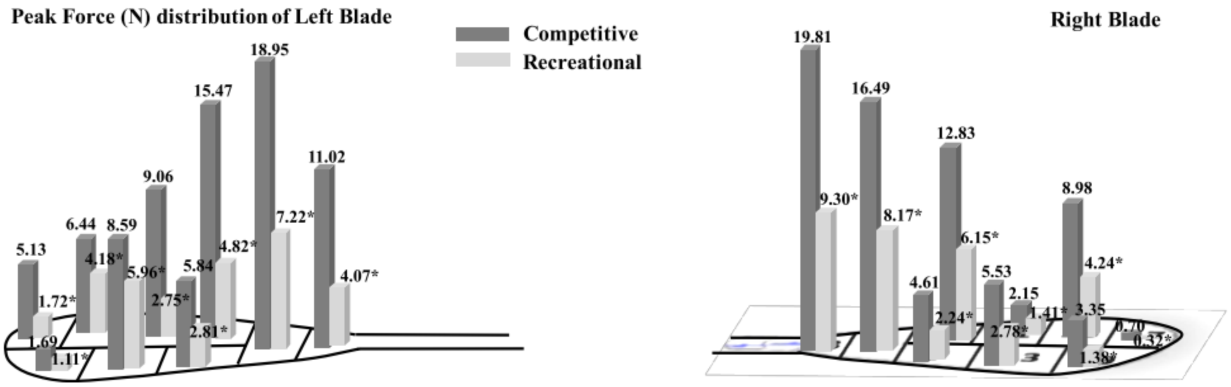


Figure 2.8 Peak force distribution on blade of kayak paddle for competitive (n=15) and recreational (n=15) paddlers during on-water kayaking. Reprinted from Niu et al., (2019).

One of the biggest gaps with current research investigating peak force or other variables (i.e., mean force, impulse, work, etc.) is that the research designs are not conducted in a way that the results can be transferred to affect kayak performance. Future studies should be conducted in a manner that replicates on-water paddling in competitive environments as often as possible (Plagenhoef, 1979). It is understood this is not always possible, due to technological costs, access to athletes that are also willing to participate in research studies, and environmental constraints; however, more effort is needed to ensure the study designs have ecological validity. For example, none of the studies mentioned above occurred in a competitive situation (i.e., an actual race or time trial scenario). One research group stated there are both “explosive” (i.e., fast-twitch muscle fiber dominant) and “fluid” (i.e., slow-twitch muscle fiber dominant) paddlers, with the more explosive paddlers more likely to race shorter distances (i.e., 200 m) and the more fluid paddlers racing longer distances (i.e., 1000 m) (Mann and Kearney, 1980). Research investigating peak paddle force should report the distances the participants paddled for, whether it was a time trial and if competitors were present, and which part of the trial the peak forces correspond to, so comparisons between participants and studies can be made.

Despite a call for more standardization and control of kayaking studies looking to better understand performance, the benefits of obtaining an athlete’s peak force is still not completely understood. For example, rowing literature has highlighted the advantages and disadvantages of using metric-based approaches (i.e., DPA) to measure performance in the past (Warmenhoven et al., 2018; Warmenhoven et al., 2018b; Warmenhoven et al., 2017). Hill (2002) introduced an important view when discussing the use of peak force metrics to differentiate between athletes’ techniques. The researcher stated that although two athletes may have similar peak forces, the shapes of their force-time profiles can be quite different, meaning they rely on different techniques to produce similar peak forces; however, one of the athletes would likely have a greater stroke impulse (Hill, 2002; Warmenhoven et al., 2018a). Further to this point, with differing instrumented paddle equipment designs the peak force is often difficult to compare and therefore the shape of the force profile is likely the more important factor in better understanding kayak technique.

To conclude, measuring paddle forces to compare kayak performance seems to have an important role in attempting to better understand kayaking technique. As reviewed above, and in agreeance with Gomes (2015b), there is a scarcity of studies investigating force output in kayaking. Although there is no clear understanding of which metrics or variables provide meaningful information on kayak technique, there seems to be an obsession with peak force amongst researchers. To move the boat in a forward direction at high velocities requires propulsive forces which travel from the water through the paddle and the athlete’s body to the seat and footboard of the kayak (Michael et al., 2009; Ong et al., 2006). Theoretically, greater paddle forces will cause more force to travel through the body and eventually reach the boat; however, this has not been studied often to date. Stroke efficiency would play a large role in this movement, and therefore, more information is needed showing how the boat moves in combination with paddle force. One researcher has mentioned that force output is the primary variable needed to quantify performance, but the boat's velocity and acceleration was also crucial to understanding kayak technique (Sperlich and Baker, 2002). Unfortunately, combining these data (i.e., paddle force and boat kinematics) for research purposes is not widespread yet. In fact, there is little information on kayak acceleration in isolation of force data. It is possible that this task will become easier as appropriate technology continues to be developed.

### ***Timing of the Force Profile***

One method to systematically analyze sport technique is by investigating the movement's phases and the timing at which they occur. Phase analysis is a portion of an observational model, which is used to qualitatively analyze a sport movement (Lees, 2002). An observational model for kayak sprint technique was developed in attempt to standardize the way researchers report their results in the literature and for sport science practitioners to report to coaches and athletes (McDonnell et al., 2012). The researchers reviewed the literature relating to sprint kayak technique phases and found that nine phase-related positions within the paddling stroke had been reported. The group eventually combined the phases into a two-phase model for basic analyses (i.e., water and aerial) and a four-sub-phase model for more detailed analyses (i.e., entry, pull, exit and aerial). The phases were defined by paddle orientations throughout the stroke, and thus allows researchers to relate the timing of the paddle's force profile to where the paddle is in three-dimensional space. An example of a sub-phase position is when the tip of the blade makes initial contact with the water; which is also known as the "catch position" and initiates the entry phase (McDonnell et al., 2012). The article concludes by recommending the new phase analysis models should be used by coaches and researchers so studies and athletes of various kayak sprint skill-levels can be compared more accurately (McDonnell et al., 2012).

To date there has been little published literature that has measured paddle force and related it to the phases of the kayak stroke directly, despite suggestions that aligning phases and paddle kinematics to paddle forces may be the most optimal way to compare kayaking techniques for coaches and researchers (Gomes et al., 2020; McDonnell et al., 2012). A possible reason for the lack of research in this area may be due to the availability of technology and the feasibility of collecting kinematic data of the stroke cycle on-water. Video cameras have been used to visualize stroke cycle phases for many years; however, there are many issues with this method of measurement (Plagenhoef, 1979). As mentioned above, the catch position is often reported in the literature, yet when waves are present it may be difficult to see when the tip of the blade touches the water (McDonnell et al., 2012). Other downfalls to conducting phase analysis using video includes small capture volumes where the kayaker paddles through which only allows for one or two strokes to be analyzed per trial, and that the athlete must paddle perpendicular to the camera to ensure proper detection of key paddle positions (McDonnell et al., 2012; Shapiro and Kearney, 1986). Furthermore, if only one camera is used from a sagittal viewpoint the boat and paddler will occlude paddle positions on the far-side of the body. These issues are all in addition to difficulties time synchronizing video to paddle force data (Romagnoli et al., 2022).

One novel method to combat camera measurement issues is the use of an IMU attached to the paddle shaft. The IMU is able to provide three-dimensional orientation as well as detection of key paddle positions within the stroke (Gomes, 2015). For example, an IMU measuring paddle acceleration at high sample rates (e.g., ≥ 100 Hz) is able to provide the exact timing of when the tip of the paddle blade touches the water (i.e., by detecting a large peak in acceleration). By time-synchronizing the IMU to a force transducer within the paddle shaft (using GPS and coordinated universal time) the exact orientation and stroke cycle phase can be known at all times throughout a force-time profile. Some commercial options with this technology are available (e.g., Kayak Meter Pro by One Giant Leap). In addition to time synchronization, the kayak's acceleration profile can also be compared to the increase in paddle forces. This example is similar to what was analyzed in a study by Vadai et al., (2013), where they compared paddle orientation to kayak acceleration and angular velocity over one stroke cycle. Unfortunately, the group did not give any information on the population studied.

Although paddle orientation is believed to be important, only three trends regarding paddle orientation and performance emerged from the kayaking literature. The first was that the peak kayak velocity occurs when the paddle shaft is vertical during the water phase (i.e., 90° to the horizontal water surface). An article published four decades ago reported the boat velocity increased the greatest shortly after the paddle shaft was perpendicular to the water (Mann and Kearney, 1980). They found that a vertical blade allowed the boat to increase its velocity for longer durations and in turn allowed for faster race times. Understandably, the researchers believed paddlers should adapt a technique that allows the paddle shaft to be vertical for greater periods of time (Mann and Kearney, 1980). Other authors have suggested that this could be due to the peak paddle force occurring at the same time; however, this had not been measured until recently (Aitken and Neal, 1992; Fernandez-Nieves and De Las Nieves, 1998; Kendal and Sanders, 1992; Romagnoli et al., 2022). Theoretically, this is the part of the stroke when the greatest increase in contact surface area between the paddle blade and the water occurs (Aitken and Neal, 1992; Michael et al., 2009). As shown in Figure 2.9, the resultant paddle force is acting in the opposite direction as the direction the kayak is travelling, unlike at the catch and exit positions, and thus the resultant force is at its greatest (Michael et al., 2009). Since the resultant force is directly related to kayak propulsion, it can be assumed the most efficient stroke orientation should be at this position as well (Fernandez-Nieves and De Las Nieves, 1998).

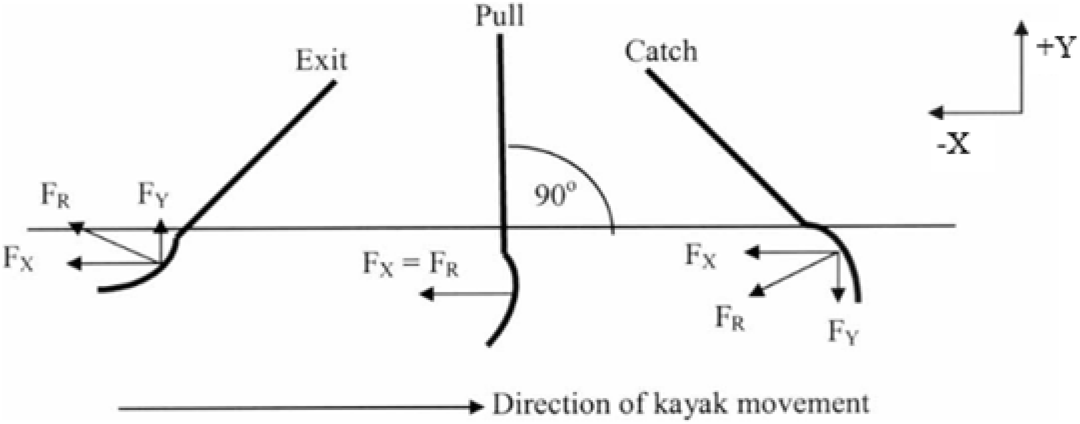


Figure 2.9 Kinetics of the paddle during the water-phase of the stroke cycle. $F_x$ = force in x-direction; $F_y$ = force in y-direction; $F_r$ = resultant force. Figure adapted from Michael et al., (2009).

The second trend was that the boat decelerates early (i.e., just after blade entry) and late (i.e., prior to when the paddle exits the water) in the water phase. Gomes et al., (2020) reported delays between force production and kayak acceleration. The cause of these delays was likely due to the propulsive forces being less than the resistive forces acting on the kayak system. This is arguably a more important result, as it shows although part of the water phase, the paddle can still be inefficient. This result also promotes athletes to strive for a faster paddle exit from the water or else their kayak will decelerate and likely plays a large role as to why SR has a stronger relationship with velocity than SL does (Gomes, 2015; Sanders and Kendal, 1992). Both of the first two trends were recently discussed in a study that looked to determine which phases of the stroke contribute to propulsion (Romagnoli et al., 2022). The study used the e-kayak system and video analysis to detect force output during three different phases of the stroke (i.e., entry, propulsion, and exit). The authors stated that non-propulsive phases of the stroke's water phase occur when the paddle has vertical displacement and is travelling at the same speed as the kayak (i.e., between phases A and B and phases C and D; Figure 2.10). Propulsive phases occur when the blade is fully immersed in the water to when it begins being extracted from the water (i.e., between phases B and C; Figure 2.10). Stroke characteristics during the propulsive phase include the paddle blade moving horizontally in the opposite direction of the kayak, as well as faster than the kayak (Romagnoli et al., 2022). During this time the propulsive forces are greater than the drag forces acting on the kayak, and thus kayak speed increases.

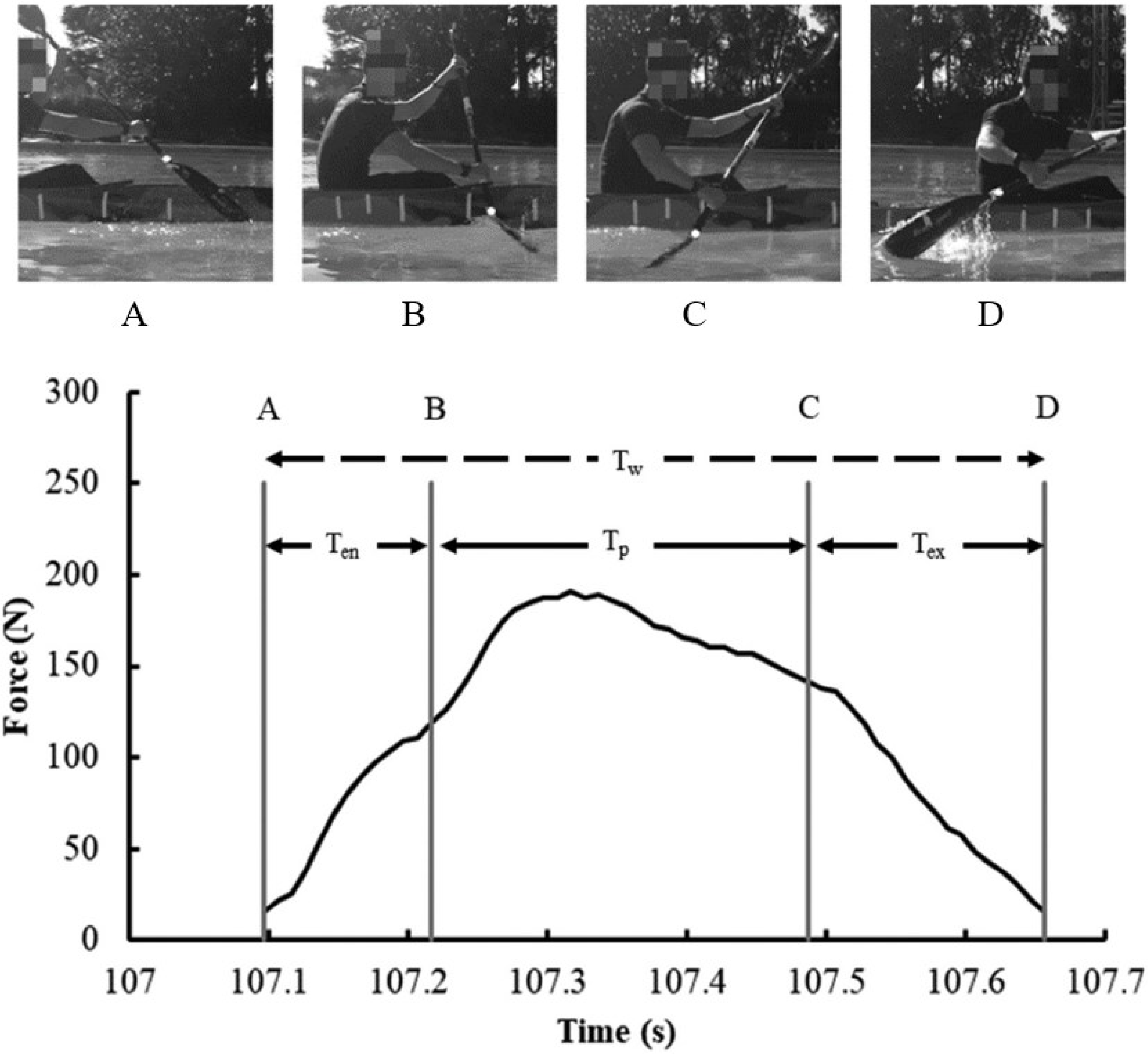


Figure 2.10 Paddle positions during the water phase of the kayak stroke. A. first contact between blade and water, B. blade fully immersed, C. start of blade extraction, D. last contact between blade and water, and the corresponding force output during each phase. $T_W$, water phase; $T_{en}$, entry; $T_p$, propulsive; $T_{ex}$, exit; N, newtons; s, seconds. Figure adapted from Romagnoli et al., (2022).

The third trend in the literature related to paddle orientation is based around stroke cycle asymmetry. Like the other two trends, very little research has been completed around stroke asymmetry in kayaking, despite success in the sport being extremely reliant on balance (Harrison et al., 2019). It is common knowledge that it is difficult for novice athletes to stay upright in their boat if they are unable to balance in it. Plagenhoef, (1979) was the first to state that the paddle must apply force on both sides of the boat equally to ensure equal work; however, since then only a handful of researchers have investigated the concept. Using a computational model, Harrison et al., (2019) reported asymmetry between left and right strokes can decrease the boat's velocity by 0.7-0.9% per stroke. The decrease in boat velocity could be due to excessive yaw of the boat in the water, potentially causing a greater drag force acting on the kayak system. Despite the lack of knowledge in this area of sprint kayaking, it is still not understood whether symmetrical strokes are ideal for all paddlers; however, two studies suggest elite kayakers are more symmetrical than novices (Plagenhoef, 1979). Limonta et al., (2010) showed that elite athletes had smaller saddle rotations and more symmetrical elbow, knee, and pelvic angle range of motions in the frontal plane compared to novice athletes. In the sagittal plane, elite paddlers showed a significant right-left difference in their minimum elbow flexion angle (i.e., 12% asymmetry), whereas novice athletes showed significant asymmetries in all kinematic parameters that were measured (i.e., minimum, maximum and full range of motion for knee and elbow flexion joint angles). It is important to note that this study looked at body kinematics (i.e., not paddle orientation) and was completed on an ergometer in a laboratory environment, thus on-water asymmetries between skill levels are still unknown. The second study measured boat acceleration using an accelerometer for three athletes of varying skill levels (one elite, one intermediate, and one novice) and a found stroke impulse and stroke time became increasingly more asymmetric as skill level decreased (Vadai et al., 2013). Unfortunately, this study did not provide any measures of kayak performance (e.g., velocity).

Force output asymmetries between the left and right strokes have recently been presented in the literature. Although asymmetry was not a primary research question, Kong et al, (2020) collected force output data from paddlers in double crew boats and showed a figure that depicted symmetric and asymmetric strokes from one participant (Figure 2.11). Asymmetries in shape, magnitude, and timing were visible, which may cause the reader to have questions about the participant and the trial the data was collected from (i.e., skill level, age, sex, years training, time of race strokes were chosen, etc.). These questions would help understand when to expect asymmetries to occur, and potentially the causes of the asymmetries.

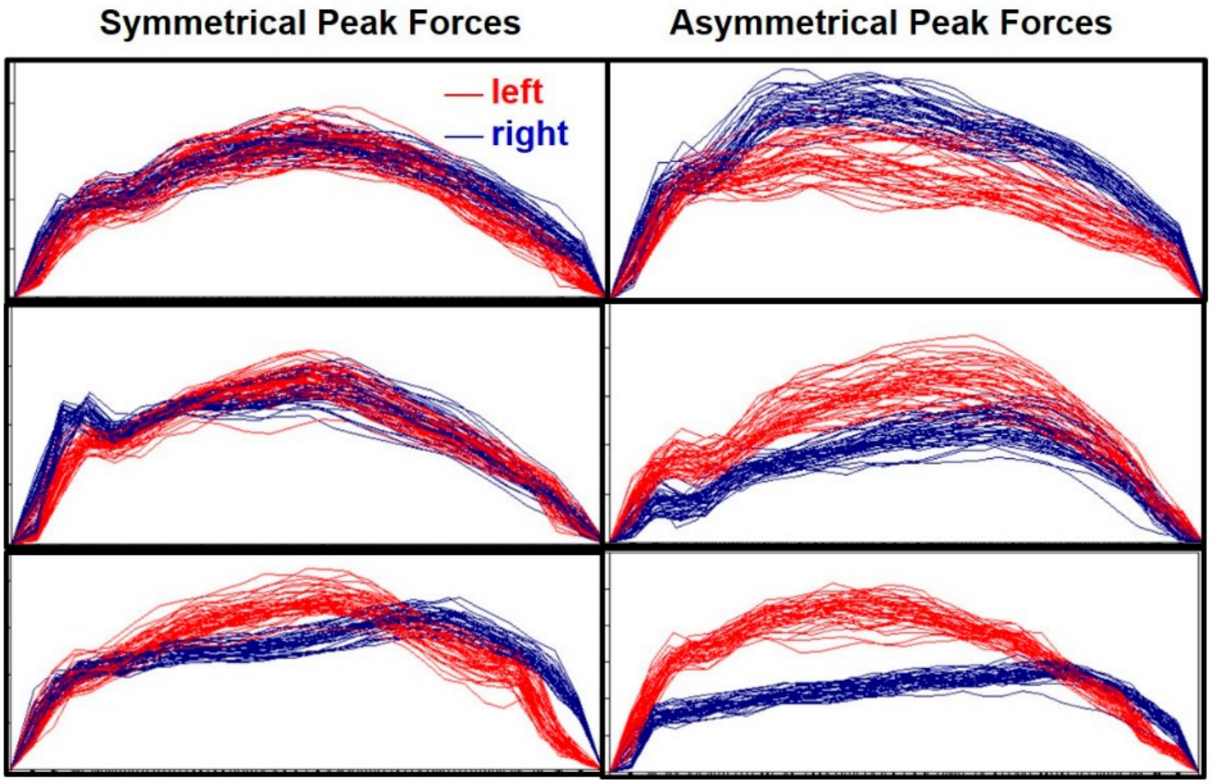


Figure 2.11 Example of time normalized stroke force profiles from one participant during maximal intensity paddling. Red waveforms indicate a left stroke, and blue waveforms indicate a right stroke. Figure reprinted from Kong et al., (2020).

Based on the existing literature, there is a clear need for more information on how the boat reacts to the magnitude, shape, and timing of the force application from the paddle. Currently, there are more data published on body segment kinematics in the kayaking literature, both on-water and on an ergometer, than there is on paddle forces and boat movements (Baker et al., 1998; Bjerkefors et al., 2017; Limonta et al., 2010; Mann and Kearney, 1980). Likely the biggest flaw in kayaking literature to date is that boat kinematics (i.e., the effect of technique) and its relationships with body kinematics and stroke kinetics has not been investigated sufficiently.

## Propulsive Power Output

In addition to propulsive paddle forces, an area that is being researched more often in sprint kayaking is propulsive power output. Like other aspects of applied biomechanics work, the measurement of propulsive power output during on-water paddling is becoming easier due to improvements in strain gauge technology (Macdermid and Fink, 2017). The total power of aquatic motion is equal to the sum of the external power and the internal power (Pendergast et al., 2003). The external power includes two components. Drag power, which is the power dissipated against drag forces (i.e., the power to overcome drag forces), and kinetic power, which is the power lost to the water. Kinetic power is what causes the water to accelerate away from the boat during aquatic motion (Pendergast et al., 2003; Toussaint et al., 2006). Drag and kinetic power can be considered the combination of both passive and active drag. The combination of these variables are the equivalent to mechanical power, and in some literature, is also called drag power (Di Prampero et al., 1974; Romagnoli et al., 2022). Drag power is equal to the hydrodynamic drag force multiplied by the kayak velocity (Di Prampero et al., 1974; Michael et al., 2009; Romagnoli et al., 2022). The internal power is the power the athlete needs to generate to accelerate the limbs relative to the body's CoM (Pendergast et al., 2003). This is also equivalent to the propulsive power, which is equal to the force applied to the water through the paddle, and the paddle's velocity moving through the fluid (Romagnoli et al., 2022; Sprigings et al., 2006; Sumner et al., 2003). A dynamic balance occurs when the drag power is equal to the propulsive power (Romagnoli et al., 2022). When there is a dynamic balance, the propulsive and drag powers offset each other, thus the kayak travels at a constant velocity. To increase kayak velocity, the athlete must ensure the propulsive power generated is greater than the drag power acting against the boat. Therefore, athletes are always looking for the optimal balance between force output and velocity of the paddle during the stroke (Sprigings et al., 2006).

An efficient stroke is a stroke where the majority of the energy generated is directed to forward propulsion (Sumner et al., 2003). Another way to quantify this is propulsive efficiency. Propulsive efficiency is equivalent to the power to overcome drag forces divided by the total power output (Barbosa et al., 2010; Sumner et al., 2003). Therefore, propulsive efficiency increases by reducing the number of forces acting in directions other than the forward direction. An example is asymmetries in power output, where greater output on one side of the boat can cause a yawing of the boat which decreases efficiency (Day et al., 2011; Gomes et al., 2018; Redwood-Brown et al., 2021). This is an example of power loss, which can be due to boat drag, blade inefficiency (i.e., slip), and poor technique (Seiler, 2015). All of these variables can cause fluctuations in velocity, which have been shown to effect power loss by approximately 5-10% (Cuijpers et al., 2017; Sanderson and Martindale, 1986). As will be discuss later in the Literature Review, this concept acts as a feedback loop, where unwanted kayak movements increases the amount of drag forces acting on the boat, which causes a fluctuation in velocity, and thus more power output is required to recoup the lost velocity.

There is no doubt that obtaining propulsive power output measurements would be highly beneficial to sprint kayak performance evaluation. Although power output is often measured in other cyclical sports, it is not common during on-water sprint kayaking. This is likely due to two primary reasons. First, kayaking is a complex movement which includes motion in multiple planes. It is much easier to quantify power in sports where the majority of movement occurs in two planes instead of three (i.e., rowing and cycling) (Kleshnev, 2006). The second reason is due to the lack of technology available with an acceptable level of validity (McDonnell et al., 2013). It is well known that it is important to validate of a piece of technology prior to using it in an applied setting. This is also difficult in sprint kayak, as there is no gold-standard measure of power output, especially in an on-water environment. That said, one group used a creative method to measure the construct validity of a power meter during on-water paddling by comparing its measurements to the cubic relationship between power output and velocity in aquatic locomotion (Barbosa et al., 2010; Di Prampero et al., 1974; Michael et al., 2009; Toussaint et al., 2006). For example, to increase kayak velocity, one must overcome the hydrodynamic drag forces resisting the overall system. Therefore, increasing the overall power output. Since drag power is equal to drag force multiplied by kayak velocity, we can use the following equation (Equation 3).

Equation 3. $P_D = D_F \bullet v$

where, $P_D$ is equal to drag power, $D_F$ is equal to drag force, and $v$ is equal to kayak velocity. This is a simplified equation, but by substituting in the equations for drag force and kayak velocity, we obtain the expanded equation for drag power in Equation 4.

Equation 4. $P_D = {}^1/_2\, C_D \rho A v^2 v$

where $\rho$ is equal to water density, $A$ is kayak surface area, $C_D$ is drag coefficient and $v$ is velocity. By combining like terms, we see drag power is proportional to velocity cubed (Equation 5).

Equation 5. $P_D = {}^1/_2\, C_D \rho A v^3$

The specific power meter validated by Macdermid and Fink, (2017) was the One Giant Leap (OGL) (Kayak Meter Pro, Nelson, NZ). It is, to our knowledge, the first paddle to measure instantaneous power output on-water. There have been multiple studies published recently which used OGL paddles to report on topics such physiological testing, training load and programming, and stroke kinetics (Hogan et al., 2021, 2020a, 2020b; Kong et al., 2020; Macdermid et al., 2019; Winchcombe et al., 2019). The benefit of measuring power output on-water basically comes down to obtaining a direct measure of exercise intensity (Hogan et al., 2020a). Currently in sprint kayaking training, variables like heart rate, speed, cadence, and distance paddled are used to inform training programs. These variables may be effective for measuring intensity for indoor sports, but they are not ideal for sports which are affected by the environment. For example, it is not uncommon to see a direct head wind add 10-20 seconds to total race time per 1000 m paddled, thus speed is not an ideal measure of exercise intensity. In fact, one study measured this exact phenomenon during on-water graded exercise tests and found stroke rate and speed measures misrepresented training zones when compared to power output (Hogan et al., 2020b). One training zone was actually quantified by a SR change of two strokes per minute, which is not realistic and too small of a SR range for an athlete to aim for during training. Furthermore, power output data has also been used to describe performance and skill level. The study, already detailed in the *Magnitude of the force profile section* above, used peak and mean propulsive power output measures as well as the work done to distinguish skill level in 74 sprint kayakers (Kong et al., 2020). They found National-level sprint kayakers generated more peak power, average power, and work done compared to recreational- and school-level paddlers, therefore propulsive power output may be an ideal way to distinguish between athletes' ability to apply their power to the water.

Overall, the ability to measure propulsive power output during on-water sprint kayaking would allow researchers and applied practitioners to better understand the sport. It would also allow other performance professionals (e.g., strength and conditioning coaches) to understand the amount of power output needed in training and how to best transfer the power developed to enhance on-water performance (Petrovic et al., 2020). There is a clear need for more development in this area.

## Resistive Forces

There are three methods to increase kayak velocity. The athlete can increase propulsive paddle forces, decrease the resistive forces (i.e., drag) acting on the kayak system, or do both (Baker, 2012; Baudouin and Hawkins, 2002; Harbour, 2019; Michael et al., 2009). To reduce drag forces acting on the kayak, the athlete must alter the mechanical interaction between the kayak and the water. Currently, specific methods to decrease resistive forces on a sprint kayak are largely unknown; however, theories do exist.

The total drag force ($F_{total}$) acting on the kayak system can be broken down into hydrodynamic ($F_{hydrodynamic}$) and aerodynamic drag forces ($F_{aerodynamic}$; Equation 6) (Michael et al., 2009). During kayaking, the majority of drag forces are present from hydrodynamic forces, as aerodynamic drag forces account for only 7-8% of the total drag (Jackson, 1995).

Equation 6. $F_{total} = F_{hydrodynamic} + F_{aerodynamic}$

Hydrodynamic drag forces can be quantified using Equation 7 and consist of friction drag (i.e., surface drag), pressure drag (i.e., form drag) and wave drag (Hay, 1993). Friction drag accounts for most of the hydrodynamic drag (66-73%) and is due to the friction between the kayak's hull and the water (Baker, 2012; Gomes et al., 2018; Jackson, 1995; Michael et al., 2009). Friction drag is known to be affected by the athlete's body mass, the roughness of the exterior surface of the hull and the velocity of the kayak (Gomes et al., 2018; Harrison et al., 2019; Mantha et al., 2013). The literature states that the primary ways to reduce friction drag is to reduce the wetted surface area of the boat or by changing the friction coefficient (Jackson, 1995; Mantha et al., 2013; Michael et al., 2009). Only one of these methods of reducing friction drag is possible to obtain better kayaking performance, as the International Canoe Federation have rules in place ensuring athletes and coaches do not add substances to the exterior surface of the hull to change the friction coefficient (Gomes et al., 2018).

Equation 7. $$F_D = ½\, C_D \rho A v^2$$

where, $F_D$ is the drag force, $C_D$ is the coefficient of drag, $\rho$ is the density of the fluid, $A$ is the surface area of the object interacting with the fluid, and $v$ is the object's velocity.

Since the amount of friction drag changes due to the amount of wetted surface area, it is important to note that vertical boat motion causes the boat to be submerged at varying depths throughout the stroke (Tullis et al., 2018). To explain further, lift and drag forces from the paddle cause the kayak to propel in a forward direction (Jackson, 1995). It is likely that the vertical component of the paddle forces being applied cause the boat to accelerate in the vertical direction, which in turn causes the kayak's wetted surface area to change during the stroke and increases the creation of waves (Gomes et al., 2018; Jackson, 1995; Tullis et al., 2018). As the propulsive phase of the stroke ends the kayak begins to decelerate, which may be due to an increase in wetted surface area, and thus more friction drag as the boat sinks deeper into the water. This is primarily theoretical, as no one has investigated this theory in kayaking; however, more acceleration in the vertical directions would likely be the cause of slower kayaking velocities (Michael et al., 2009). One way to measure this motion would be to use a tri-axial accelerometer. An athlete with greater vertical acceleration oscillations could potentially have slower race times due to an increase in friction drag (Figure 2.12) (Michael et al., 2009). The magnitude of friction drag is important for performance, as a 2% decrease in friction drag would equate to a 0.5% increase in K1 speed (Jackson, 1995).

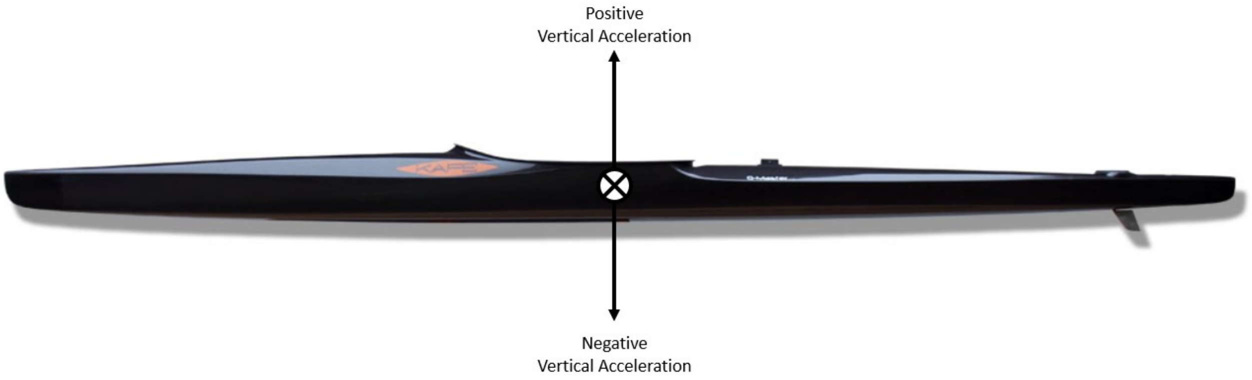


Figure 2.12 Vertical accelerations at the kayak's center of mass.

Pressure drag is due to the separation of water to allow the hull of the kayak to pass through it, and accounts for 21-24% of passive hydrodynamic drag (Gomes et al., 2015; Gomes et al., 2018; Michael et al., 2009). Pressure drag is affected by the shape of the kayak's hull, the pressure difference between the bow and stern, and is proportional to the kayak velocity squared and the frontal surface area (Gomes et al., 2018; Mantha et al., 2013). It has been suggested that one way to decrease the frontal surface area would be to make the hull narrower; however, this would likely decrease the kayak's stability (Gomes et al., 2018). To date no one has investigated how a kayak's frontal surface area changes during on-water paddling. The primary reason for this is that there is no feasible equipment to do so in an on-water environment. Theoretically, the kayak's frontal surface area would be at its lowest when the yaw angle is at 0˚ relative to the direction of travel (Figure 2.13A). On the other hand, the kayak's maximum frontal surface area, and the greatest amount of pressure drag, would occur when the kayak is pointed perpendicularly to the direction of travel (Figure 2.13B). Therefore, an indirect way to measure pressure drag would be to measure the yaw angle during the kayak stroke. Like measuring vertical accelerations, the IMU's gyroscope could provide an angular velocity measurement of the rotations occurring around the vertical axis of the boat. By integrating the angular velocity waveform, the direction the bow is pointing can be determined (i.e., the yaw angle). An athlete with a greater yaw angle would theoretically be slower than an athlete with a lesser yaw angle due to an increase in pressure drag acting on the kayak. Due to this concept, it could be stated that an operational definition of pressure drag is when the kayak's absolute yaw angle increases (in either a positive or negative direction from 0˚).

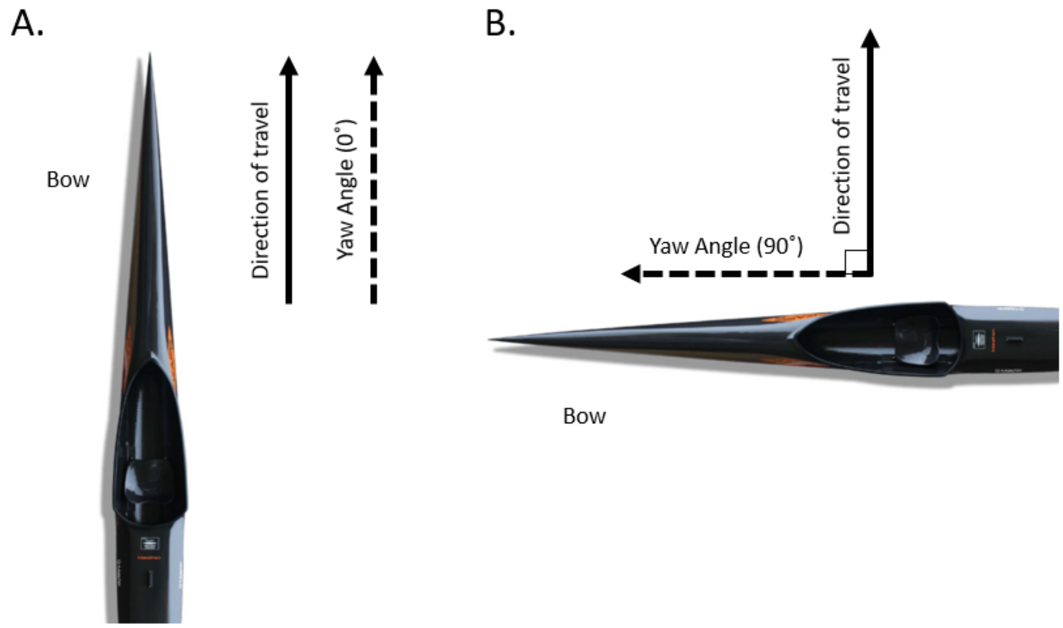


Figure 2.13 Example of kayak yaw angle. A. Bow of kayak pointing parallel to the direction of travel (i.e., yaw angle = 0˚). B. Bow of kayak pointing perpendicular to the direction of travel (i.e., yaw angle = 90˚).

The final type of hydrodynamic drag, wave drag, results from the water accelerating away from the kayak (i.e., the resistive force due to the production of waves by the kayak) and/or from wave-breaking (i.e., the resistive force due the boat travelling through the waves) (Gomes et al., 2018; Michael et al., 2009; Pendergast et al., 2005, Sanders and Kendal 1992). Wave drag depends on the shape of the kayak's hull, the motion of the kayak, the kayak's travelling velocity, and the body mass of the kayaker (Gomes et al., 2018; Mantha et al., 2013; Prétot et al., 2022). Like friction drag, wave drag is related to the kayaker's mass, where heavier athletes experience greater wave drag than lighter paddlers. Gomes et al., (2018) measured a kayak's passive drag by towing the kayak with one male paddler simulating three different body masses (i.e., 65 kg, 75 kg and 85 kg). The researchers towed the kayak over 300 m using an in-field towing system at velocities of 2.78 m•s$^{-1}$ to 5.56 m•s$^{-1}$. The group used a load cell to measure the passive drag force on the kayak system over three different trials for each body mass condition and found that overall drag increased exponentially as velocity increased, and that the heaviest body mass condition produced the greatest friction, pressure and wave drag

(Figure 2.14). Wave drag specifically increased as a function of velocity to the power of four and accounted for between 9% and 20% of passive drag at the maximum towing velocity. One limitation to this study was that the frontal area of the kayak was assumed to not have changed throughout the trials. This assumption must be highlighted as the frontal surface area plays a large role on the kayak's wetted surface area, and the yaw angle is not constant during a kayak stroke (Mantha et al., 2013; Michael et al., 2009).

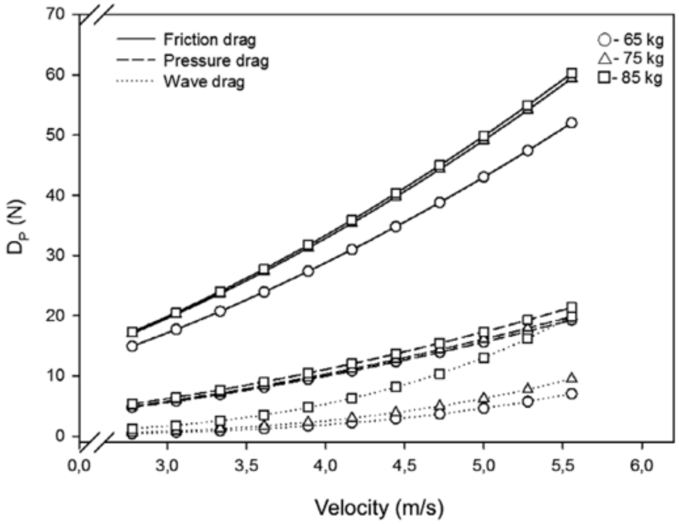


Figure 2.14 Types of passive drag (i.e., friction, pressure, and wave) shown as a function of kayak velocity for three simulated weight conditions (i.e., 65, 75 and 85 kg). Figure reprinted from Gomes et al., (2018).

The results from Gomes et al., (2018) are theoretically sound, as the interaction between the bow of the kayak and the water generates a greater force as kayak velocity increases. It can also be expected that this force becomes greater if the body mass in the kayak is heavier. The larger force between the boat and water creates longer waves, which equates to more wave drag (Mantha et al., 2013). Unlike at slower velocities, the longer waves dissipate more energy from the kayak system and thus the athlete must generate a greater power output to maintain a constant kayak velocity (Mantha et al., 2013). In other words, due to the cubic relationship between power and velocity, more power output is needed to increase velocity by a certain amount at higher speeds than is needed to increase velocity by the same amount at lower speeds. Due to these relationships, wave drag can be expected to be greater in wavy conditions, and therefore, it has been hypothesized that an increase in unnecessary kayak movements cause an increase in wave drag (Gomes et al., 2018; Mantha et al., 2013; McDonnell et al., 2013; Michael et al., 2009; Prétot et al., 2022). Fortunately, an IMU can be used to infer the amount of wave drag present on the kayak, since wave drag cannot be measured directly (Figure 2.15) (Higgens et al., 2016; Wainwright et al., 2014).

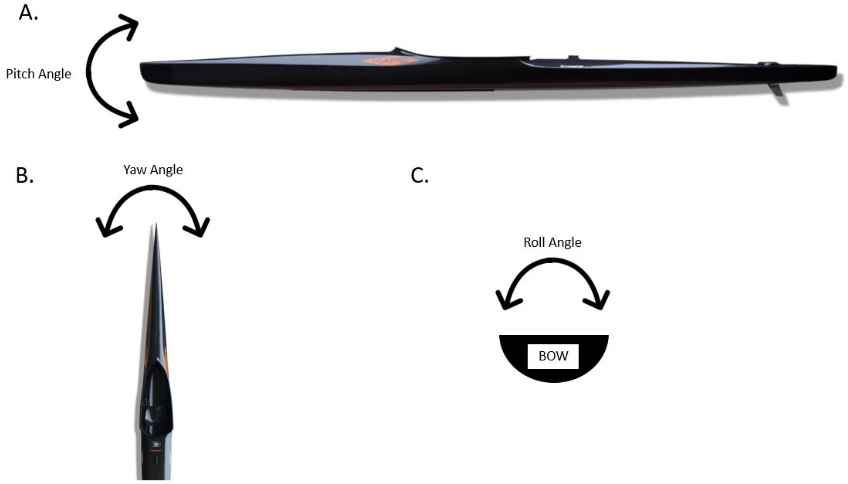


Figure 2.15 Example of kayak rotations. A. Pitch angle shown with sagittal view of kayak. B. Yaw angle shown with transverse view of kayak. C. Roll angle shown with frontal view of kayak.

The majority of studies investigating hydrodynamic drag during sprint kayaking has investigated it during passive motion (i.e., being towed at constant velocity); however, a large portion of drag during active paddling is from active drag (Gomes et al., 2015; Harbour, 2019; Pendergast et al., 2005, 2003). Active drag includes the forces associated with boat movement and changes in inertia while paddling (Harbour, 2019; Zatsiorsky, 2008). Although difficult to measure directly, active drag is affected by many factors (i.e., skill level, environmental conditions, anthropometry, kayak design, boat kinematics, etc.) (Gomes et al., 2015; Gray et al., 1995; Ong et al., 2006; Pendergast et al., 2003; Van Someren and Howatson, 2008). Using metabolic measurements and a towing apparatus, Pendergast et al., (2005) found active drag to be greater than passive drag during kayaking. These methods are cumbersome though, especially in outdoor environments; therefore, more feasible methods are needed to measure this important variable. As some solutions to indirectly measuring active drag have been discussed above, there is a common belief that angular velocity boat movement variables like pitch, yaw, and roll should be used as surrogates to quantify active drag (Harbour, 2019; Prétot et al., 2022; Wainwright et al., 2014). Despite researchers mentioning the importance of maintaining low levels of pitch, yaw, and roll to reduce drag forces, there is very little published information investigating it (Brown et al., 2011; Gomes et al., 2018; Michael et al., 2009). Based on the potential relationships between boat movement and drag forces highlighted above, and in agreeance with Michael et al. (2009), future research should investigate the effect of excess and unnecessary boat movement on kayaking performance.

### Boat Kinematics

One of the primary goals of this thesis was to determine whether an IMU can provide meaningful information regarding boat movement, kayaking technique, and performance. From an efficiency standpoint, the lesser the kayak moves in directions other than the forward direction, the more efficient it will be (Michael et al., 2009; Soper and Hume, 2004). Therefore, it is important to try to measure these motions. There are two types of boat kinematics in kayaking that are of interest: linear acceleration and angular velocity. Currently, there is more information on boat movement in rowing than in kayaking (Warmenhoven et al., 2018a; Worsey et al., 2019). Both acceleration and angular velocity can be measured in three-dimensions (i.e., in the x-, y-, z-planes) using a triaxial accelerometer and gyroscope, respectively. Wagner et al., (1993) were the first to discuss boat movement (i.e., spatial motion) in a boat sport. Acceleration was simplified into “translational velocity” in their article, with each axis having its own descriptive name. The forward axis was defined as the travelling axis, as the boat travels along this axis in a forward direction. The other two axes, lateral and vertical, were termed the side-slipping and dipping axes, respectively. They followed conventional kayaking terms to identify angular velocity axes, with the rolling motion being rotation around the travelling axis, yawing around the vertical axis, and pitching around the lateral axis. In kayaking the travelling axis is better known as the longitudinal axis (Brown et al., 2011) or the forward horizontal axis (Bonaiuto et al., 2020; Harbour, 2019), whereas the side-slipping and dipping axes are called the lateral and vertical axes, respectively. Accelerations along these axes have also been called surge, sway, and heave (Harbour, 2019). Coordinate system conventions depend on many factors (i.e., type of technology, rigid body being measured, etc.), and vary within the kayak literature (Bonito et al., 2022; Michael et al., 2009). An example of the coordinate system for an accelerometer and gyroscope sensor module can be seen in Figure 2.16. The forward direction is along the y-axis, the lateral direction is along the x-axis, and the vertical direction is along the z-axis. Positive angular rotations follow the right-hand rule, meaning positive roll is the boat rolling to the right, positive yaw is the bow of the boat yawing to the left, and positive pitch is the bow of the boat pitching in the upward direction. The following two sections will discuss acceleration and angular velocity variables in more depth.

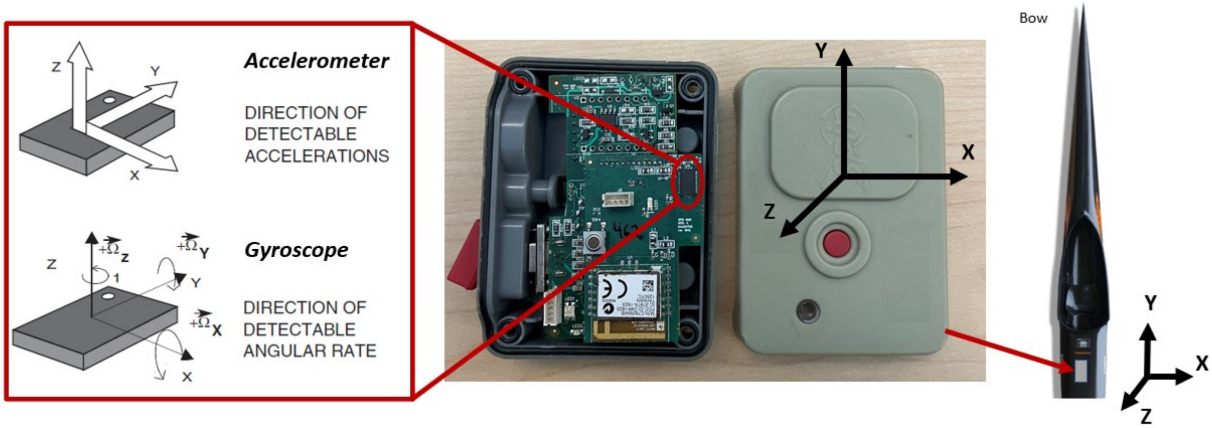


Figure 2.16 Example of the coordinate system for the LSM330DL linear sensor module 3D accelerometer and 3D gyroscope (STMicroelectronics©, Indiana, USA). The sensor is located in the IMU and GPS casing, which is then placed on the kayak.

### *Acceleration*

There have been only a few published articles that have investigated boat acceleration in kayaking, despite evidence indicating potentially strong relationships to performance (Gomes, 2015; Gomes et al., 2020; G. Vadai et al., 2013). For example, both positive and negative boat acceleration is directly related to propulsive and drag forces acting on the athlete-boat system (Baker, 2012; Gomes, 2015; Michael et al., 2009). This relationship is shown clearly in Figure 2.17, where despite paddle force being applied to the water, the boat decelerates for a substantial period of the stroke (Gomes, 2015). Interestingly, the authors found positive forward acceleration does not occur until approximately 0.05 s after propulsive force application, and negative acceleration begins approximately 0.23 s before the propulsive force application ends. This is due to drag forces being greater than propulsive forces at the time of deceleration. It is expected that studying intra-cyclical stroke acceleration profiles could allow athletes and coaches to pinpoint exactly when athletes are decelerating during the stroke, and thus work to improve it.

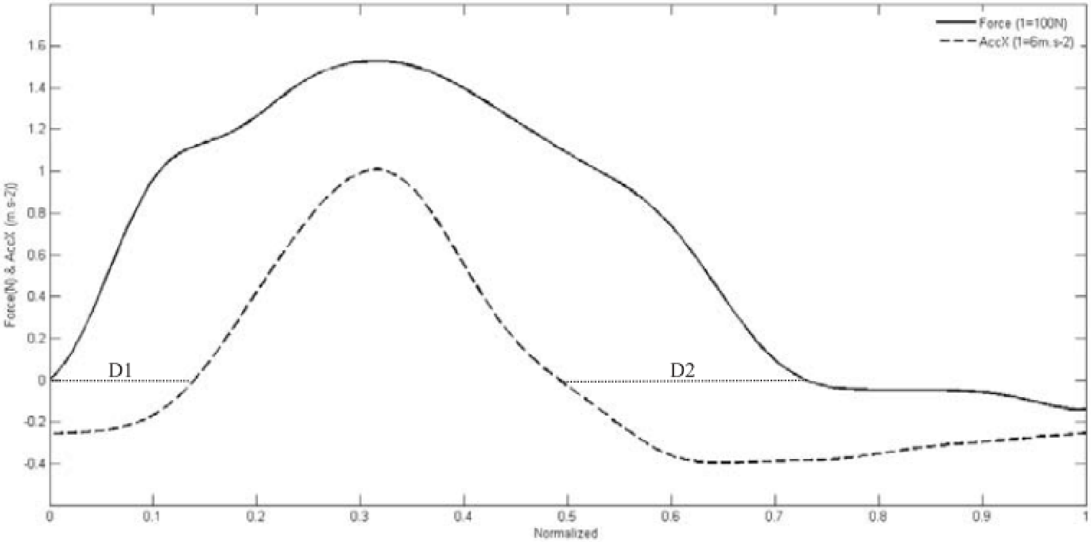


Figure 2.17 Mean stroke force and mean kayak forward acceleration from a normalized single stroke phase. D1 - Delay between start of force application and kayak acceleration. D2 - Delay between kayak deceleration and end of force application. Figure reprinted from (Gomes, 2015). AccX, acceleration in the x-axis; N, Newtons; m•s$^{-2}$, meters per second squared.

Research has not shown how accelerations in other directions affect performance, as the study mentioned above only studied the acceleration in the forward direction of the kayak. A call for investigating acceleration in all three directions was suggested in an influential review article by Michael et al., (2009). Since triaxial accelerometers are much more commonplace in research and practice now, it is agreed that more data should be collected to determine how the other kayak axes react during the stroke.  In an ideal scenario, accelerometers can be used to illustrate the resultant boat movement from the forces being applied to the overall system. For a kayak to travel forward, the athlete must apply a force to the water using a paddle shaft and blade, which then causes a reaction force to travel back through the paddle and body and transfer to the kayak through the seat and footboards. Due to the many movements athletes make during the stroke (i.e., their technique) there are a lot of instances where the body can affect the resultant movement of the boat and the generated energy be lost to the environment (Michael et al., 2009). However, it is difficult to quantify all forces and moments acting on the system during training and competition, but fortunately some researchers are studying the topic (Bonaiuto et al., 2020; Bugeya Miller, 2021; Klitgaard, 2021). For example, Bugeya Miller, (2021) instrumented a kayak ergometer with three, six DoF load cells in the seat and both left and right footboards. By including the propulsive force (via an instrumented paddle), information on how athletes apply force to the system can be measured through their experiment. By eventually moving this instrumented set-up to on-water paddling, the resultant movement and its causes can be measured. Currently, the exact mechanisms causing boat kinematics to change may not be known, but an accelerometer is a feasible way to obtain meaningful data to detect flaws in the athlete's technique.

An example of detecting technical flaws using an accelerometer is by measuring imbalances between the left and right strokes without input from a force-measuring device (Bonaiuto et al., 2020). This could be done by comparing either discrete variables from the acceleration waveforms (i.e., maximum forward acceleration), or from comparing the waveforms from the left and right strokes themselves. As discussed in the *Propulsive Forces* sections above, similar approaches can be completed to investigate the magnitude, shape, and timing of the acceleration profile.

Understanding how the boat accelerates during the water and aerial phases of the stroke can unlock important information about the stroke mechanics. To conduct temporal phase analysis of the acceleration profiles resources could be used to study the time spent accelerating or decelerating during a stroke (Lees, 2002). Some of this work has already been completed, as it has been shown that the percentage of the time spent positively accelerating during the stroke increases as stroke rate increases (Gomes et al., 2020). This leads to future questions about how the kayak is moving in other directions during both phases of the stroke too. For example, the more unnecessary boat movement occurring during the aerial phase could be investigated further to learn ways to decrease it, and thus reduce the amount of active drag and kinetic energy being lost to the water (Holt et al., 2021). Also, no published literature indicates normative acceleration values. Therefore, it is currently difficult to compare acceleration profiles between athletes.

### *Angular Velocity*

Interestingly, the topic of boat movement has been discussed in kayaking since the early 1980's and in rowing since the late 1970's (Ishiko, 1971; Mann and Kearney, 1980). Unfortunately, like acceleration, there is very little information published regarding boat angular velocity in kayaking (Michael et al., 2009; Tullis 2018). One researcher used a notational analysis approach to investigate technical themes between 135 club, national, and international paddlers who competed in 200 m and 500 m races (Brown et al., 2011). The researchers analyzed trunk movement of the paddler and the "rocking" (i.e., roll) and "bouncing" (i.e., pitch) of the boat. The group found that the international-level athletes' boats rolled and pitched less than the club-level athletes. They also reported that the international-level athletes paddled with less trunk movement (i.e., trunk rotation and forward lean) than their lesser-skilled counterparts. Their results suggest that less trunk movement and thus, less boat movement, is related to performance in kayaking. However, since the study used a notational analysis study design, no gyroscopes were used to collect these data, and therefore, the validity of their findings are not known. Now that the technology is more common, future studies should take a more objective approach to measure a boat's angular velocity by using triaxial gyroscopes.

Despite not being measured in previous research studies, the primary theory regarding less boat movement being a good indicator of performance is due to the thought that the body movements not in the same direction as the boat movement (i.e., the forward direction) will negatively affect the hydrodynamic drag acting on the boat (Michael et al., 2009). In other words, unnecessary body movements are wasted energy, and therefore, more efficient technique reduces active drag acting on the boat and allows for a greater kayak velocity (Michael et al., 2009; Pendergast et al., 2003). As mentioned in the *Resistive Forces* section of this literature review, friction drag is the primary force acting against the propulsion of the boat. With excess boat movement more water will interact with the surface of the boat (by increasing the wetted surface area), which would theoretically decrease boat velocity. Due to this reasoning, Gomes et al., (2018) hypothesized that excess boat movement is the biggest contributor to active drag.

An important question is what causes excess boat movement in kayaking. It has been suggested that it is due to large changes in body CoM velocity during the kayak stroke (Mann and Kearney, 1980). Since there are many mechanical interactions between the athlete, paddle, boat and water during the kayak stroke, maintaining a constant CoM velocity requires the athlete to provide balance and stabilization to the system (Nakashima et al., 2017). On top of these interactions, an extremely light kayak and almost frictionless surface adds more difficulty to the movement, and thus could explain potential differences between elite and novice kayaking technique and performance (Mann and Kearney, 1980; Michael et al., 2009).

Like other areas of sprint kayak research, rowing has slightly more information on boat stability. Wagner et al., (1993) were the first to instrument a rowing shell with gyroscopes. The group used gyroscopes to compare boat kinematics between an elite rower and a non-elite rower and found that there were more deviations in yawing and rolling for the less-skilled athlete (Figure 2.18). Unfortunately, they did not measure how yawing and rolling of the scull were related to the rower's body movements in the boat. That said, more variability in these waveforms suggest the non-elite athlete produced more unnecessary movements and inefficient strokes.

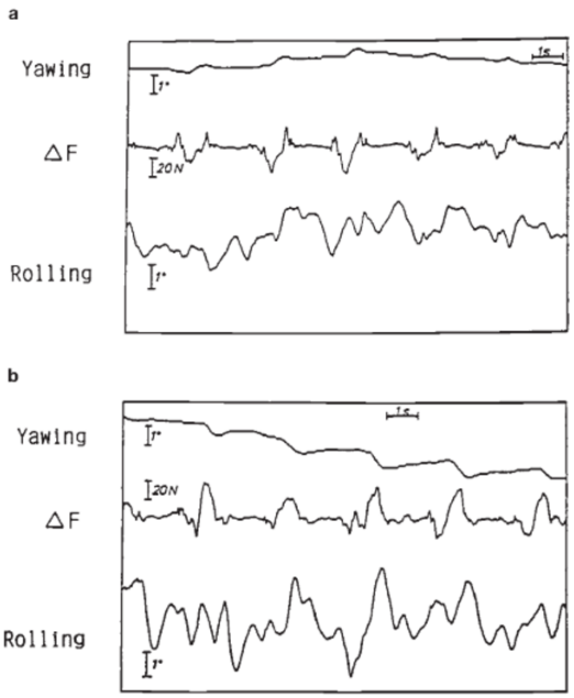


Figure 2.18 Angular deviations and oar force difference between the right and left oar (ΔF) from A. an elite rower's scull and B. a non-elite rower's scull. Rolling and yawing depicted in degrees and ΔF depicted in Newtons. Figure reprinted from Wagner et al., (1993).

In a more recent study, Sinclair et al., (2009) measured pitch, yaw and roll in eleven experienced scullers but also aimed to learn what caused changes in boat orientation during the stroke. To do this the group measured oar pin and foot stretcher forces over 250 m of rowing at a SR of 32 spm. The researchers also related the athlete's CoM location to the changes in pitch, yaw and roll of the boat, and that the largest amount of boat pitch occurred when the athlete was in the "finish" position. In rowing, the finish position is when the athletes' legs are in full extension and thus their CoM is near the bow of the boat. While in this position a large amount of "bow down" pitch occurred due to the added weight near the front of the boat. These results agree with Loschner et al., (2000) who found heavier rowers experience more pitch than lighter rowers. Sinclair et al., (2009) suggested measuring vertical force application in the seat, which would help researchers investigate how boat orientation is affected due to changes in CoM location in the rowing scull. Following the trend mentioned above, the researchers mentioned the reduction in boat orientation fluctuations (i.e., smoother boat movements) will decrease energy loss through hydrodynamic drag.

The primary objective of Loschner et al., (2000) was to investigate the importance of boat movement in rowers. The group used three uniaxial gyroscopes to measure the pitch, yaw and roll in thirteen rowers as they rowed for 20 strokes at four different SR's. Interestingly, they found that although the timing and amplitude of arm and leg drive was similar between athletes (i.e., limb kinematics and kinetics), the boat orientation was not. They reported that athletes had similar time-series patterns for boat pitch, but yaw and roll time-series patterns had large variations and were not similar between athletes. One concern the group addressed was that the relationship between boat orientation and boat velocity was still not well understood. For example, they highlighted the need for some yawing of the boat to allow for propulsion; however, there was no evidence as to what the optimal amount of yaw was. The group concluded their study by stating some athletes were better than others at keeping the boat stable, but they did not relate this to skill level or ability. The concept of optimal boat rotation was recently raised in sprint kayak literature as well when Bonaiuto et al., (2020) mentioned there is likely a trade-off between high force outputs, which require high body rotations, and the resulting boat rotations.

As shown, very few researchers have investigated boat rotation in kayaking, and as such even more questions begin to arise. Unfortunately, little knowledge exists around the effect of boat movement on performance, which based on the evidence, deserves a lot more attention in future studies. As such, multiple researchers have suggested more studies should investigate pitch, yaw, and roll movements to better understand sprint kayaking technique (Bonaiuto et al., 2020; Gomes, 2015; Michael et al., 2009). Furthermore, this literature review indicates body movement likely has a significant effect on boat movement. One way to understand this relationship better would be to measure the athlete's CoM movements simultaneously with their boat's kinematics. As IMU technology continues to develop, it is now possible to obtain both body and boat kinematics during on-water kayaking.

**Velocity Fluctuations**

A common theme in the aquatic sport literature is "velocity fluctuations". Velocity fluctuations have been discussed in both pacing and technical (i.e., intra-stroke) terms, and it has been established that they both have a negative effect on performance (Baudouin and Hawkins, 2002; Cuijpers et al., 2017; Gomes, 2015; Hill and Fahrig, 2009; Hofmijster et al., 2007; Klitgaard et al., 2020; Sanderson and Martindale, 1986; Seiler, 2015). As mentioned previously, velocity is dependent on both propulsive and drag forces. Therefore, the goal should be to increase propulsive forces and decrease drag forces (Soper and Hume, 2004). To be more specific, hydrodynamic drag is proportional to velocity squared, thus drag increases fourfold when velocity doubles (Hill and Fahrig, 2009). The power to overcome drag is also related to velocity cubed (Hofmijster et al., 2007; Mantha et al., 2013; Michael et al., 2009; Zatsiorsky and Yakunin, 1991). Therefore, it is in the paddler's best interest to maintain a constant velocity to not have an unnecessary increase in energy expenditure (Seiler, 2015). Research has shown that there is an estimated 5% efficiency loss due to velocity fluctuations, and approximately 5 seconds lost over 2000 m of rowing (Hill and Fahrig, 2009; Sanderson and Martindale, 1986).

Velocity fluctuations depend on multiple factors including technique, power output, and the environment (Hill and Fahrig, 2009). Two of these factors can be controlled, and one is dependent on the other. For example, if technique is efficient, modifying power output (and thus velocity) is not as detrimental to performance. Swimming and rowing researchers believe technique can be quantified by measuring the body or boat's change in velocity (Barbosa et al., 2010; Seiler, 2015). The same belief is true in kayaking. During the kayak stroke and depending on the phase of the stroke they are in, the boat either accelerates or decelerates. During these movements energy is dissipated from the boat and is absorbed by the water (Sanderson and Martindale, 1986). This effect is heightened when large fluctuations in velocity occur, as it modifies both the interaction between the boat and water (i.e., wave drag) and the boundary layer characteristics (i.e., pressure drag) (Day et al., 2011). It can therefore be hypothesized that erratic kayak movement (i.e., bad technique) would cause an increase in energy dissipation and thus a decrease in performance (i.e., boat velocity).

Technique has been defined many different ways, but generally it is known in the literature as a specific sequence of movements, which can be simplified broadly to kinematics (Lees, 2002). It is therefore important to understand the effect of kinematics on performance. Multiple authors blame the boat's fluctuating acceleration on the athlete's dynamic movements and application of varying force outputs (Gomes et al., 2020; Sanderson and Martindale, 1986). Depending on the severity, this causes large fluctuations in velocity. A common approach to minimizing velocity fluctuation in water sports is to refrain from modifying stroke rate too much (Cuijpers et al., 2017; Hill and Fahrig, 2009). One theory for this approach is that acceleration increases when stroke rate increases, and to increase acceleration the athlete must increase their body movements. If uncontrolled, it becomes a negative feedback loop as more accelerations cause more drag, more fluctuations in velocity, and slower kayak speeds. One group of rowing researchers believe the way to combat this is to reduce stroke rate when possible and maintain power output by increasing the amount of force applied to the water (Hill and Fahrig, 2009). For this approach to work more understanding of the relationships between stroke rate, stroke length (i.e., distance per stroke), and velocity are required.

Now that the importance of velocity fluctuations for kayak performance is established, a method to quantify these fluctuations is required. Multiple researchers believe technology should be used to measure boat movement and changes in velocity (Bonaiuto et al., 2020; Seiler, 2015; Sinclair et al., 2009). Inertial measurement units and GPS have high sample rates and can measure these data many times per second; therefore, more research is needed to quantify them. Interestingly, this technology may be able to provide even more insight into sprint kayaking technique than currently thought. It is important to note that no one has measured changes in velocity in planes other than the forward direction. The goal of sprint kayak is to reach the finish line before your competitors, and to do that you must travel forward. Hence, movements in all other directions are not required. With the ability of measuring kayak accelerations and rotations in three dimensions, there is currently a need to determine the impact of changes in velocity in all directions acting on the kayak system.

## Summary

As more robust technology is developed researchers are beginning to investigate sprint kayak performance in innovative ways. Based on the literature, an important focus of this dissertation will be on conducting research in practical situations to ensure ecological validity, where results can be directly transferred to on-water performance. This has been omitted in some work due to technology abilities, populations studied, and the overall difficulty of collecting biomechanical data in an aquatic environment. That said, this literature review has identified multiple gaps in previous research and the field as a whole. Three of the four primary gaps include the measurement of on-water propulsive paddle forces, body kinematics, and boat kinematics. Measuring paddle forces and boat kinematics will help develop our understanding of the propulsive and resistive aspects of sprint kayaking and are therefore deemed to be the most important next steps to better understand sprint kayak performance. Quantifying body kinematics is also important as this information will be a method to understand why the boat moves in certain patterns, which likely affects drag acting on the overall system. The fourth gap in the literature is the lack of studies on pacing strategies, and how stroke parameters relate to kayak speed at different time periods within a race. The relationship between kayak speed and SR during short periods of paddling is well understood as it has been highlighted in the literature many times. However, this relationship likely changes as pacing strategies are created and the effect of fatigue is present. More research on this topic is expected to have a big impact on overall performance. The completion of the following studies hope to help bridge some of these gaps within the existing literature, as well as promote more research in this field.

## Section 1: The Kinematics of Sprint Kayaking

The first section of this dissertation includes three original research studies that were completed to address three primary gaps in the sprint kayaking literature. The first study (*Chapter 3*) was completed to investigate the pacing strategies used by elite sprint kayakers during international races. Notably, the study was the first to use the novel statistical technique (i.e., Principal Component Analysis) to determine differences in pacing strategies between top 3 and bottom 3 finishers. The second study (*Chapter 4*) was completed to establish the role of stroke parameters (i.e., stroke rate and stroke length) as determinants of sprint kayak performance. The relationship between stroke rate and velocity is well known in sprint kayaking; however, less is known about how these parameters are related during actual races. Therefore, the primary reason for conducting this study was to investigate how stroke parameters are modulated throughout three different distances during sprint kayak racing. The third study in this section (*Chapter 5*) was completed to establish the role of boat kinematics in generating resistive forces as a determinant of sprint kayak performance. The basis of this study was to investigate the theoretical relationship between boat kinematics and drag forces, and how excessive boat movement affects kayak velocity.

# CHAPTER 3: Using Principal Component Analysis to Investigate Pacing Strategies in Elite International Canoe Kayak Sprint Races

Joshua A. Goreham, Scott C. Landry, John W. Kozey, Bruce Smith, Michel Ladouceur

This chapter is published in *Sports Biomechanics.* The author has the appropriate rights to include this article in their dissertation (Appendix A).

Citation:

Goreham JA, Landry SC, Kozey JW, Smith B, Ladouceur M. Using principal component analysis to investigate pacing strategies in elite international canoe kayak sprint races. Sports Biomechanics. 2020 Aug 28:1-6

## Abstract

The aim of this research was to use principal component analysis (PCA) to investigate the current pacing strategies of elite canoe kayak sprint athletes and to determine if there are differences in pacing patterns between medallists and non-medallists at major international competitions. Velocity data collected using global positioning systems (GPS) from all A-finals of major international competitions in 2016-2017 (including canoe and kayak, single and crew boat, and male and female) were downloaded from the International Canoe Federation's website. Data were normalised by the average velocity within each race and organised by race distance. In total 10, 14 and 16 races were analysed, and they followed all-out, positive, and 'seahorse-shaped' pacing strategies for the 200 m, 500 m, and 1000 m events, respectively. Normalised velocity PC1 ($p = 0.039$, ES = -0.44) and PC2 scores ($p < 0.001$, ES = -0.73) for 1000 m races were significantly different between medallists and non-medallists; however, significant differences between PCs were not found between groups in shorter race distances (i.e., 200 m and 500 m). Data collected using GPS provide information that can be used to better prepare athletes for canoe kayak sprint races lasting between 30 s and 240 s in duration.

Keywords
global positioning systems, performance analysis, inertial measurement unit, race tactics, functional data analysis

## Introduction

Pacing strategies are commonly used to enhance an athlete's performance in head-to-head competitions, where the goal is to cover a given distance faster than all opponents (Skorski and Abbiss, 2017; St Clair Gibson et al., 2001). Pacing strategies have been defined as the goal-directed regulation of intensity across exercise bouts as well as the self-selected tactics adopted by an athlete to complete a race (Roelands et al., 2013; Smits et al., 2014). These pacing strategies are believed to be used to delay fatigue by distributing energy expenditure appropriately (Abbiss & Laursen, 2008; Skorski & Abbiss, 2017; St Clair Gibson et al., 2018). There are multiple types of pacing strategies, which depend on the length and duration of the race (Abbiss & Laursen, 2008). The all-out pacing strategy (i.e., quick acceleration followed by trying to maintain high-power output for as long as possible) is seen in short duration races (i.e., less than 90 s in duration) (Abbiss & Laursen, 2008; Roelands et al., 2013). The positive pacing strategy (i.e., quick acceleration with a slow and steady reduction in velocity) is seen in medium duration races (i.e., approximately 90 s to 120 s in duration) (Sandford et al., 2018). In some sports, there is also an end spurt to finish medium duration races, which has been called a 'seahorse' shaped pacing strategy (Hanley et al., 2019; Roelands et al., 2013). Finally, athletes who compete in events that last greater than two-minutes have used even or varied pacing strategies, which can be dictated by fatigue, the weather, technique or their competitor's race dynamics (Abbiss & Laursen, 2008; Hureau et al., 2018; Skorski & Abbiss, 2017; Smits et al., 2014; St Clair Gibson et al., 2018; Stoter et al., 2016). Some of the varied pacing strategies are a U-shaped or a 'reverse J-shaped' curve, where the athlete's first and last splits are faster than the middle splits (i.e., a fast start and an end spurt) (Borges et al., 2013; Mytton et al., 2015; Roelands et al., 2013). A strong end spurt has been shown to be important for success in many sports including track running, open water and pool swimming, and short track speed skating (Hanley et al., 2019; Konings et al., 2016; Mytton et al., 2015; Thiel et al., 2012; Veiga et al., 2019).

Much of the pacing strategy literature has investigated athlete performance based on splits timing (Corbett, 2009; de Koning et al., 1999; Garland, 2005; Hettinga et al., 2011). Although splits may show information on specific time points within a race, it can be argued that performance and race dynamics can change significantly over large time frames and distances (Thiel et al., 2012). Foster et al. (1994) suggested that pacing strategies be investigated with higher split-resolution (i.e., splits every 5-10% of the race distance); however, many analyses are still conducted using traditional splits (i.e., every 25% of race distance) (Casado and Renfree, 2018). The increased use of inertial measurement units, which often contain a global positioning system (GPS), allows positional data to be collected many times per second. This provides the ability to obtain higher split-resolution time-series data compared to split times measured using automatic timing systems which are commonly used by race organisers. These time-series data, combined with new data analysis methods, have the potential to aid performance analysts to compare pacing strategies from multiple athletes within- or between-races. For example, differences in pacing strategies between medallists and non-medallists have been reported before (Hanley et al., 2019; Konings et al., 2016; Mytton et al., 2015; Thiel et al., 2012; Veiga et al., 2019); however, it is expected that these new analysis methods may provide additional details into the analysis of pacing strategies between the two groups. One statistical method that has yet to be used in the pacing literature is principal component analysis (PCA). PCA is a multivariate statistical decomposition method that uses orthogonal transformations to create new uncorrelated variables (i.e., principal components) from an original data set. More precisely, each calculated principal component (PC) describes one-dimension of variability within the original data set (Landry et al., 2007). Reducing a data set into individual PCs can highlight waveform characteristics and patterns, unmask variations in data, as well as re-present data in ways to aid further statistical analyses (Jolliffe, 2002). Furthermore, PCA has been suggested to be an appropriate method to investigate pacing strategies (Jolliffe, 2002).

A handful of studies have examined pacing strategies in elite canoe kayak sprint athletes during on-water competitions using low split-resolution boat velocity data. The results of these studies show that 200 m, 500 m, and 1000 m athletes follow, respectively, an all-out, positive, and 'reverse J-shaped' pacing strategy (Borges et al., 2013; McDonnell et al., 2013b). Recently (i.e., 2016-2017), the International Canoe Federation equipped every boat, at major international competitions, with a GPS to measure boat positions throughout the race. The collected data were then used to calculate boat velocity in 10 m intervals, and values were made publicly available.

The aim of the current study was to use high split-resolution time-series data and PCA to analyse boat velocity and investigate the current pacing strategies of elite canoe kayak sprint athletes at major international competitions. It was hypothesised that all-out, positive, and reverse J-shaped pacing strategies were used in 200 m, 500 m, and 1000 m events, respectively. A secondary aim of the study was to determine if there were differences in pacing patterns for medallists (i.e., first to third place) versus non-medallists (i.e., bottom three competitors per race). It was hypothesised that there would be differences in pacing patterns between medallists and non-medallists in all events, and that these differences would be detectable during specific time points within the race (i.e., acceleration phase, middle portion, end spurt, etc.).

## Methods

### *Participants and Data Collection*

Inertial measurement units containing a 10 Hz GPS (ST Innovation, Geneva, Switzerland) were used to collect individual boat velocity measurements at 10 m splits for each sprint canoe and kayak race. The inertial measurement unit was placed on the deck of the stern end of each individual boat. The position and velocity accuracy of these data were not provided by the competition host organisations. The ST Innovation Inertial measurement system is based on the PAM-7Q GPS Antenna module (u-blox, Thalwil, Switzerland). Remote GPS antennas were placed in various locations along the racecourse to augment the satellite-based system to increase the measurement accuracy. Based on this information, it can be assumed that the horizonal position accuracy of the satellite-based augmentation system to be 2.0 m and the velocity accuracy to be 0.1 $m•s^{-1}$ (u-blox AG, 2015). Distance, boat velocity, and results (i.e., final placing) data from all sprint canoe and kayak events at the 2016 Olympic Games, 2016 World Cups 1, 2, and 3, and 2017 World Championships were publicly available and were downloaded from the International Canoe Federation's website (www.canoeicf.com) for analysis in MATLAB® (R2020a, MathWorks®, Natick, MA, USA). From this dataset, all A-final data (i.e., 8-9 competitors per race) for sprint canoe and kayak events that are a part of the current Olympic program were saved for analysis, whereas all other data were removed. B-finalists have been shown to be two-times more variable in race-to-race performances, therefore the authors decided to only focus on A-Finalists for this research (Bonetti and Hopkins, 2010). Velocity data were plotted versus distance to detect missing or anomalous data (e.g., due to equipment malfunction or athlete(s) not completing the entire race distance). All data from two boats were removed from the 200 m and 1000 m analyses due to doping violations (i.e., men's kayak singles 200 m 2017 World Championships and men's canoe singles 1000 m 2016 Olympics). Due to the lack of available data for women's canoe (i.e., singles 200 m and doubles 500 m) and men's kayak (i.e., fours 500 m) races, data from these disciplines were not included in the analyses. Single athlete and crew boat information from each event were organised by race distance (200 m, 500 m, and 1000 m). In total, 86 (ten 200 m races), 121 (fourteen 500 m races), and 132 (sixteen 1000 m races) boat pacing strategies (n = 339) were analysed (Table 3.1).

Table 3.1 Table of races analysed. Races in italics denotes data were removed from analysis due to equipment malfunction, missing data, or doping violations. Number in parentheses denote the lane number(s) removed from the analysis.

| Event | Race Distance (m) | | |
|---|---|---|---|
| | 200 | 500 | 1000 |
| 2016 World Cup 1 | MK1, WK1 | WK1, WK2, WK4 | *MC1(4)*, MK1, *MC2(9)*, MK2 |
| 2016 World Cup 2 | MK1, *WK1(3)* | WK1, WK2, WK4 | MC1, MC2, *MK2(7,8)* |
| 2016 World Cup 3 | MK1, WK1 | *WK1(7)*, WK2, WK4 | MC1, MK2 |
| 2016 Olympics | MK1, WK1 | WK1, WK2 | *MC1(6)*, MK1, *MC2(3,6)*, MK2 |
| 2017 World Championships | *MK1(4)*, WK1 | WK1, WK2, WK4 | MC1, MK1, MC2 |

MK1, men’s kayak singles; WK1, women’s kayak singles; WK2, women’s kayak doubles; WK4, women’s kayak fours; MC1, men’s canoe singles; MK1, men’s kayak doubles; MC2, men’s canoe doubles.

### ***Data Preparation***

The boat velocity dataset for each race was organised into a split-by-lane matrix (Figure 3.1, Step 1). To reduce the variability in pacing strategies between the differences in individual races (i.e., distances, boat type, participant sexes, weather conditions, etc.) all boat velocity data were normalised. This decision was based on the following factors. Primarily, boats with one athlete (i.e., singles) are typically slower than multi-athlete boats (i.e., crew boats). Further, boats with male athletes are faster than boats with female athletes (i.e., on the international stage). However, it should be noted that the 200 m analysis was the only analysis that combined both sexes. Secondly, it has been shown that canoe kayak sprint races have an inflated variance because of weather and heat (i.e., temperate (18°C) versus hot (30°C) conditions) which may be dependent on the time of the final being contested (Bonetti and Hopkins, 2010; Roelands et al., 2013).

Data normalisation consisted of dividing each individual boat velocity value (recorded for each 10-meter split) by the average velocity of the entire race (Figure 3.1, Steps 2 and 3) (Garland, 2005; Mytton et al., 2015). The normalised boat velocity dataset were then re-organised into a split-by-place matrix, with data corresponding to the first-place boat in column one of the matrix, second place in column two, and so on (Figure 3.1, Step 4). Each of the steps listed above were repeated for all races. The split-by-place matrix for each race were then combined into one of three larger split-by-place matrices depending on the race distance (i.e., 200 m, 500 m and 1000 m) (Figure 3.1, Step 5). The size of the larger split-by-place matrices differed between distances due to the number of splits and number of boats per race. For example, the 200 m matrix had 20 rows and 86 columns (i.e., 86 boats in ten races with 20 splits) whereas the 500 m matrix had 50 rows and 121 columns, and the 1000 m matrix had 100 rows and 132 columns.

To determine the type of pacing strategies used by the athletes, average normalised velocities were calculated from the GPS data for common split distances (i.e., 50 m for 200 m races, 250 m for 500 m races, and 250 m for 1000 m races). The average normalised velocities were calculated by averaging all 10 m normalised velocities for a given split (e.g., the first five 10 m normalised velocity values were averaged for the first split of the 200 m race distance).

### *Statistical Analysis*

For the secondary aim, PCA was used to describe the variability in the pacing waveforms between the Top 3 and Bottom 3 athletes. The primary goals of using PCA were to reduce the dimensionality of the normalised velocity waveforms by transforming the waveforms into PCs, and to thereby explain the maximum amount of variance in the normalised velocity waveforms using a small number of functions (Jolliffe, 2002). This approach was taken because the differences in waveform variability may not necessarily be detected using common discrete descriptive statistical measures (i.e., maximum values, means, ranges, etc.) (Jolliffe, 2002).

As mentioned above and completed prior to the PCA, the individual race datasets were organised into a larger split-by-place matrix which held all normalised velocity data for a specific race distance (i.e., separate analyses for 200 m, 500 m, and 1000 m race distances) (Figure 3.1, Step 5). These matrices included data for all boats (i.e., not just Top 3 and Bottom 3 boats). The matrices were analysed using the MATLAB® PCA function (Figure 3.1, Step 6). By default, the PCA function centers each column by dividing each cell by the column mean and uses the 'Singular Value Decomposition' algorithm. By centering each column, the PCA results are based on the individual boat's pacing pattern. The PCA function calculated PC coefficients (i.e., loadings) for each normalised boat velocity (i.e., for each 10 m split) (Figure 3.1, Step 7). The percent of the variance explained for each PC was also returned by the PCA function in MATLAB® (Figure 3.1, Step 8). The percent of the variance explained was calculated by dividing the PC coefficient values by the sum of all the coefficient values. Only PCs that cumulatively explained a minimum of 90% of the variance were retained for statistical analysis (Figure 3.1, Step 9) (Brandon et al., 2013).

Unpaired independent *t*-tests were conducted on the retained PC coefficients to detect statistical significance between the Top 3 and Bottom 3 athletes (Figure 3.1, Step 10). For example, if four PCs were required to explain more than 90% of the variance, then four separate unpaired *t*-tests would be conducted (i.e., one for PC1, one for PC2, etc.). A critical $\alpha$ value of 0.05 was used to indicate statistical significance. Cohen's *d* effect sizes were calculated to determine the magnitude of differences between Top 3 and Bottom 3 athletes. The PCA function also calculated the PC score for each PC. To interpret the PC waveforms, single component reconstruction was applied to all PCs that underwent statistical analysis (Brandon et al., 2013). Single component reconstruction was completed by multiplying the mean PC coefficients for one group (i.e., the average PC coefficients for all Top 3 boats) by the PC score (returned in a split-by-$p$ data matrix). For example, for the 1000 m PC2, the average of the Top 3 PC2 coefficients was multiplied by the PC2 score (split-by-1) matrix. This step was repeated with the Bottom 3 PC2 coefficients and then the results were plotted in a normalised velocity (PC2) by distance graph to compare Top 3 and Bottom 3 waveforms. A more detailed description of steps involved for PCA can be found elsewhere (Hatfield et al., 2011; Jolliffe, 2002).

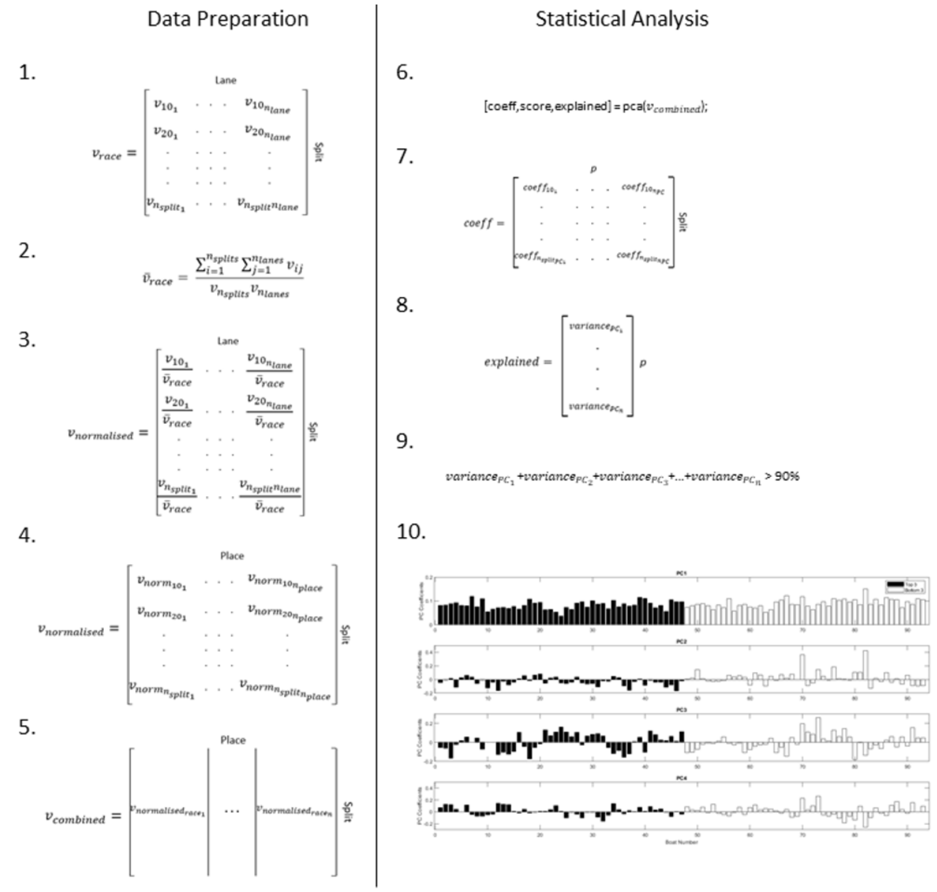


Figure 3.1 Steps for data preparation and statistical analysis. (1) create a split-by-lane matrix for a race; (2) calculate the average race velocity; (3) divide individual velocity measurements by the average race velocity to normalise the matrix; (4) organise the normalised split-by-lane matrix into a split-by-place matrix; (5) repeat previous four steps for each race of a specific distance, then combine the normalised split-by-place matrices into a larger matrix that includes all races; (6) execute MATLAB® PCA function on the split-by-place (i.e., $v_{combined}$) matrix; (7) PCA returns PC coefficients (*coeff*) for the $v_{combined}$ matrix in a split-by-$p$ matrix; where $p$ is equal to the number of calculated PCs

and columns are in descending order of component variance; (8) step 6 also returns the percent of the variation explained ($explained$) for the $v_{combined}$ matrix. $explained$ is returned in a $p$-by-1 matrix, where the rows are in descending order of variance explained; (9) determine how many PCs are needed to obtain a variance explained of >90%; (10) conduct unpaired $t$-tests between the Top 3 and Bottom 3 PC coefficients on the PCs that explain >90% of the variance. $v$, velocity; $\bar{v}$, average velocity, $n$, number of splits, lanes or places.

## Results

The average race times for the 200 m, 500 m and 1000 m races that were included in this research were 37.96 ± 0.54 s, 1:44.84 ± 1.94 s and 3:37.56 ± 3.77 s, respectively. Figure 3.2 presents the normalised velocity waveforms for the three race distances. In all race distances, there was an increase in normalised velocity to a maximum value followed by a race distance specific decline. In 200 m events, the velocity profiles followed an all-out pacing strategy (Figure 3.2, Table 3.2), with an initial increase in velocity followed by a continuous decline. There was no difference between the Top 3 and Bottom 3 athletes in relation to the location within the race where they reached their maximum velocity (Top 3: 54.5±9.1 m and Bottom 3: 54.1±9.8 m). As race distance events increased, the athletes adopted either a positive (500 m) or a seahorse-shaped (1000 m) pacing strategy. In 500 m events, both Top 3 and Bottom 3 athletes reached a maximum velocity at the same location in the race (Top 3: 51.4±10.7 m and Bottom 3: 51.7±12.9 m; Figure 3.2), and normalised velocity decreased for both groups in the second 250 m split (Table 3.2). In comparison, normalised velocity fluctuated multiple times during 1000 m events (Figure 3.2, Table 3.2). The Top 3 athletes in the 1000 m event increased their velocity at approximately 500 m, and again at 750-800 m, whereas the average Bottom 3 athletes could not produce the increase in velocity later in the race. As seen in other distances, Top 3 and Bottom 3 1000 m athletes also reached their maximum velocity at the same location (Top 3: 46.4±9.2 m and Bottom 3: 46.1±10.2 m).

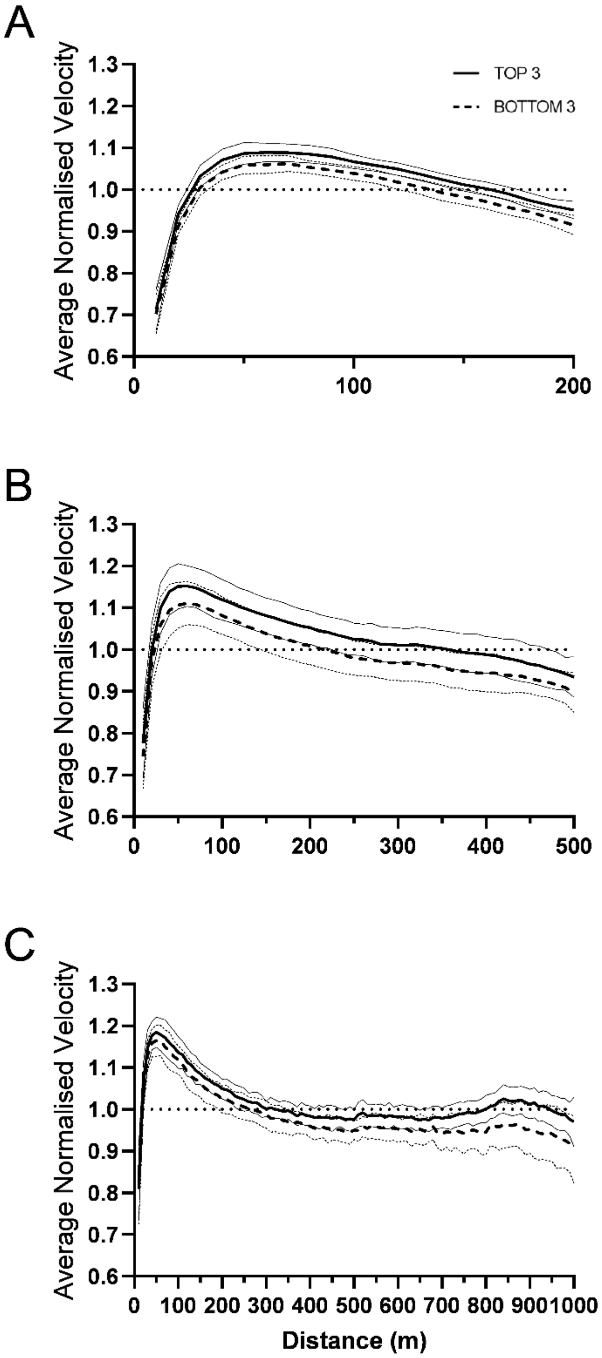


Figure 3.2 Average normalised velocity for the Top 3 (wide solid line) and Bottom 3 (wide dashed line) athletes for 200 m (Panel A), 500 m (Panel B), and 1000 m (Panel C) races. Dotted line, race average. ± one standard deviation shown in thin solid line (Top 3) and thin dashed line (Bottom 3).

Table 3.2 Average (± standard deviation) normalised velocity (% of mean of total race velocity) during traditional splits for all athletes.

| Distance (m) | Split Number | | | |
|---|---|---|---|---|
| | 1 | 2 | 3 | 4 |
| 200 | 0.955 ± 0.152 | 1.067 ± 0.010 | 1.020 ± 0.019 | 0.957 ± 0.022 |
| 500 | 1.051 ± 0.074 | 0.966 ± 0.023 | - | - |
| 1000 | 1.075 ± 0.076 | 0.980 ± 0.014 | 0.968 ± 0.004 | 0.978 ± 0.013 |

Split distances: 200 m race = 50 m split; 500 m race = 250 m split; 1000 m race = 250 m split; -, no value.

The number of PCs required to explain 90% of the variance varied between 1 and 4 depending on the race distance (Table 3.3). PC1 represented the overall magnitude of differences (i.e., the offset in velocity) between the average velocities of the two groups (Top 3 and Bottom 3; Figure 3.3A). PC2 represented the range of differences mid-race and during the end spurt (i.e., changes in plus or minus velocity) within the remaining variability between the patterns reconstructed from the PC1 waveforms and the individual split velocities (Figure 3.3B); PC3 represents the phase shift (i.e., time difference) within the remaining variability between the patterns reconstructed from the PC1 added to the PC2 waveforms and the individual split velocities; PC4's representation of the data set was unable to be specified due to its low explained percentage of variation (i.e., 1.5 %). The normalised velocity variance explained by PC1 was greatest for the 200 m race distance and decreased as race distance increased (Table 3.3) from 97.4% for the 200 m to 77.4% for the 1000 m race. Only PC1 was necessary to explain 90% of the variance for the 200 m and 500 m races (Table 3.3). Four PCs were needed to explain 90% of the variance for the 1000 m race distance. Both PC1 ($p = 0.039$, ES = -0.44) and PC2 ($p < 0.001$, ES = -0.73) were significantly different between the Top 3 and the Bottom 3 athletes for the 1000 m races (Figure 3.3, Table 3.3). The normalised velocity PC1 and PC2 had medium and medium-large effect sizes between Top 3 and Bottom 3 1000 m athletes (Table 3.3).

Table 3.3 Statistical and feature description information for PCs explaining variance and normalised boat velocity waveforms.

| Race Distance (m) | Number of Races | PC | Percent Variation Explained | Difference Top 3 vs. Bottom 3 | PC Feature Description |
|---|---|---|---|---|---|
| 200 | 10 | 1 | 97.4 | *p* = 0.419, *ns*<br>ES = 0.22 | Magnitude |
| 500 | 14 | 1 | 91.3 | *p* = 0.641, *ns*<br>ES = 0.10 | Magnitude |
| 1000 | 16 | 1 | 77.3 | *p* = 0.039, *s*<br>ES = -0.44 | Magnitude |
| 1000 | 16 | 2 | 8.0 | *p* < 0.001, *s*<br>ES = -0.73 | Range |
| 1000 | 16 | 3 | 2.5 | *p* = 0.990, *ns*<br>ES = 0.003 | Phase Shift |
| 1000 | 16 | 4 | 1.5 | *p* = 0.826, *ns*<br>ES = 0.04 | Unspecified |

PC, principal component; *ns*, non-significant; *s*, significant; *p*, *p*-value; ES, Cohen's *d* effect size.

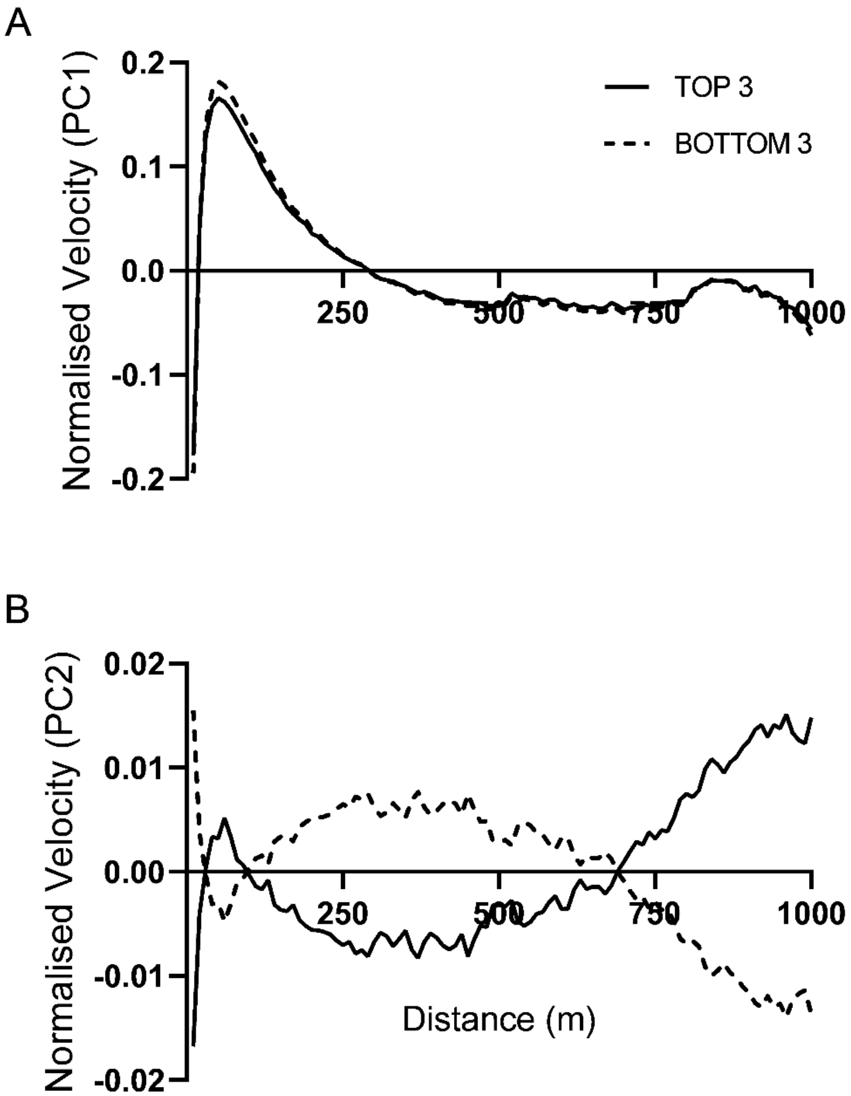


Figure 3.3 Top 3 (solid line) and Bottom 3 (dashed line) average normalised velocity PC1 (magnitude) and PC2 (range feature) values for 1000 m races.

### Discussion and Implications

The results of the study show that the pacing strategy type used in canoe kayak sprint depends on the race distance. All-out, positive, and seahorse-shaped pacing strategies were used for 200 m, 500 m, and 1000 m events, respectively (Figure 3.2).

***Pacing Strategies of Elite Kayakers and Canoeists***

Our finding that 200 m kayakers follow an all-out pacing strategy agree with previous findings (McDonnell et al., 2013). Abbiss et al. (2008) found that short duration events typically follow an all-out pacing strategy. We found that 200 m kayak sprint athletes spend approximately 25-35% of the race in the acceleration phase followed by a gradual decrease in velocity. The amount of time spent in the acceleration phase could be due to the time it takes to overcome inertia and drag forces to reach maximum velocity, and has a similar timing (~10 s) to the depletion of anaerobically-created energy (Abbiss & Laursen, 2008; Gastin, 2001; Michael et al., 2009). The 500 m event followed a positive pacing strategy with a decrease in velocity throughout the race (Table 3.2). The positive pacing strategy is likely related to oxygen consumption kinetics benefits compared to other pacing strategies (i.e., even splits) (Bishop et al., 2002). Athletes were found to follow a positive pacing strategy during 500 m kayak sprint races previously, and is common in other sports that last approximately two minutes as well (i.e., 800 m track running) (Borges et al., 2013; Hanley et al., 2019).

Time-series data from 1000 m athletes in this study showed that long-duration canoe kayak athletes opt for a seahorse-shaped pacing strategy. These athletes begin their race with a submaximal but relatively fast start which leads to a slower second 250 m split (Table 3.2). The third 250 m split is the slowest split in the race, with the final split increasing its velocity due to an end spurt and then a slight decay in velocity to finish the race (Figure 3.2C). This pattern has different characteristics than the pattern found in Borges et al. (2013). As shown in Table 3.2, the average normalised velocity in the final split (0.978 ± 0.013) is less than the average normalised velocity in the second split (0.980 ± 0.014). This finding is more comparable to the 800 m seahorse-shaped pacing strategy found in middle distance runners, despite the duration of 1000 m events in canoe kayak sprint being twice as long as 800 m running (Hanley et al., 2019). If a traditional splits analysis was the only method used, the seahorse-shaped pattern would not have been found which is in contrast to Borges et al. (2013). This gives further evidence to using high split-resolution time-series pacing data as the detail found in our results allows performance analysts to visually and quantitatively identify where end spurts and other variations in velocities occur, whereas traditional splits analysis does not. It should be noted that there are some differences in study designs between the current study and Borges et al. (2013). For example, Borges et al. (2013) did not include canoe or female athletes in their analyses but they did include data from both A- and B-finals. The group found a significant difference between the performances of A- and B-finals, thus further supporting our decision to only investigate A-finals data. Further, Borges et al., (2013) acknowledged that their methods were unable to determine if an end spurt occurred in 500 m races. As shown in the current study, end spurts are not a common characteristic in 500 m races in elite kayak sprint A-finalists.

### ***Differences in Pacing Patterns of Medallists vs. Non-Medallists***

PCA showed that differences in pacing patterns between Top 3 and Bottom 3 athletes varies according to race distance. Differences in normalised velocity PC1 scores for Top 3 and Bottom 3 athletes competing in the shorter duration events (i.e., 200 m and 500 m) were not significantly different (Table 3.3). However, PCA showed a difference in pacing patterns between Top 3 and Bottom 3 athletes, with a significant difference in normalised velocity PC1 and PC2 scores for 1000 m events (Figure 3.3, Table 3.3). These data show that the Top 3 athletes tend to have a similar pacing pattern as the Bottom 3 athletes (Figure 3.2C) with the addition of an end spurt phase starting at approximatively 700 m into the race (Figure 3.3B). Interestingly, as the Bottom 3 athletes reach 700 m their velocity decreased rapidly, and no end spurt was present. This is important as it shows canoe kayak sprint athletes must have enough energy remaining to increase boat velocity late in the race for a strong end spurt phase (Burnley and Jones, 2018; Mytton et al., 2015). Interestingly, it has been shown that there are no end spurt differences between higher and lower ranked rowing competitors (Garland, 2005).

One method to ensure the athlete maintains an appropriate amount of energy for the end spurt phase is to limit excessive energy depletion during the start and middle portions of the race. For example, PC1 was found to be significantly different between medallists and non-medallists (*p* = 0.039; ES = -0.44; Table 3.3), as Bottom 3 1000 m athletes increased their velocity more in the acceleration phase (i.e., first 100 m) than Top 3 athletes did in proportion to the remainder of their race (Figure 3.3A). This tactic likely depletes anaerobic energy stores more than a submaximal start would, which based on the current study's results, are crucial during the final 300 m of the race. For further clarification on these results, it is important to remember that centering individual boat velocities during the PCA process requires the analyst to compare the pattern results in relation to the individual's pacing pattern and not the group as a whole. If PCA is conducted using an uncentered approach, PC1 will account for >99% of the variance explained, which simply means the Top 3 athletes have a greater overall velocity magnitude than the Bottom 3 athletes. This finding is obvious; therefore, since the centered approach uncovers more detail in the pacing patterns, it is the recommended approach for future analyses.

Further differences in pacing patterns between race durations can likely be attributed to more variance explained in PC1 velocity waveforms for 200 m (97.4%) and 500 m (91.3%) events when compared to 1000 m (77.3%) events. These findings show that pacing does not play a prominent role in shorter race distances because of a shorter race duration and primarily using the anaerobic energy system. Athletes do not pace in short distance events, as all elite competitors use an all-out pacing strategy, where the race winner is often the athlete who can reach the greatest velocity and maintain, or only slightly decline their velocity and power output for the race duration (Abbiss & Laursen, 2008). In longer duration races (i.e., 1000 m), athletes must rely more heavily on both the anaerobic and aerobic energy systems (Zouhal et al., 2012). They may also use pacing strategies that complement their strengths and weaknesses as athletes (i.e., their anaerobic vs. aerobic qualities); however, further research is needed to investigate this possibility.

### *Limitations*

The primary limitation to the study is the required amount of data to conduct PCA for all individual disciplines. A common 'rule of thumb' in PCA states that ten waveforms per principal component (per dataset) is required for an appropriate statistical power. To fulfill this requirement, single and crew boat datasets for canoe and kayak athletes were combined for the 1000 m race distance, and male and female data were combined for the 200 m analysis. Ideally this approach would not be taken, as a factor that may affect pacing strategies are the resistive forces (i.e., drag) acting on the boat. Resistive forces are likely different between canoe and kayak boats due to the differences in the wetted surface area between the two vessels (Gomes et al., 2018). In addition to resistive forces, other factors that may affect pacing strategies are the differences between individual and crew boats, as well as sex differences (i.e., male vs. female). However, since race times for canoe and kayak races for the 1000 m race distances are relatively similar physiologically (i.e., for the disciplines analysed in this study), combining datasets is not expected to have a large effect, and thus should not affect the results of the study to a large degree (Gastin, 2001). Furthermore, there were less data available for disciplines that were recently added to the 2020 Olympic program (i.e., WC1 200 m, WC2 500 m, MK4 500 m), and therefore, data from these disciplines were not included in the study's analyses. As more international events occur, enough data will be collected to conduct an analysis for each individual discipline. It is likely that individual national teams who have been using GPS technology to collect boat velocity data for multiple years may have enough data to investigate pacing strategies and patterns for their own athletes.

Another limitation of the study was that for the comparison between medallists and non-medallists, it was chosen to compare the Top 3 and Bottom 3 competitors in races with 8-9 boats. Boats finishing in places four to six were excluded from these groups because canoe kayak races can be won by very small margins of time (i.e., 0.01 s) (Bishop et al., 2002). Therefore, the two groups were chosen to reduce overlap between competitors. It is very difficult to qualify for an A-final at an international event, therefore this should be kept in mind when interpreting the results of this study.

### *Practical Applications*

This research study is a proof of concept for using a new approach to measure and analyze pacing strategies in all head-to-head sports, not just canoe kayak sprint. Coaches and performance analysts can use GPS to measure high split-resolution velocity information, which provides a richer insight into pacing strategies compared to traditional splits analysis (i.e., 250 m for a 1000 m race). In addition, using PCA to investigate pacing strategies allows the coach or performance analyst to determine exactly where an athlete may need to adjust their pacing strategy to increase performance. For example, it was determined that non-medallists exert too much energy at the start and the mid-portions of a 1000 m canoe kayak sprint race, which left them unable to finish the race with a strong end spurt. A traditional splits analysis may not have provided the same conclusion because of a lack of split-resolution (i.e., only four data points for a 1000 m race). The use of PCA to analyze pacing strategies can also be used to determine how an athlete's pacing strategy changes over time or as a result of an intervention (i.e., a different type of training stimulus). The analysis of more than 130 pacing strategies of international long-distance A-finalists provides current canoe kayak sprint coaches and performance analysts with quantitative data highlighting how the most successful athletes pace themselves during their races. The findings from this study can be used as a 'template' for athletes developing new pacing strategies and could aid coaches in planning training sessions and identifying future athletes.

### *Conclusions*

This is the first study to use time-series data to analyse canoe kayak sprint pacing strategies and the findings from this research provide insight on pacing strategies at recent major international events. By using PCA, differences in pacing strategy patterns were identified between medallists (Top 3) and non-medallists (Bottom 3) and between race distances. In accordance with the results from previous literature and our hypotheses, we found pacing strategies in short- and medium-duration events follow an all-out and a positive-pacing approach. The main finding from this research is that 1000 m athletes follow a seahorse-shaped pacing approach and as found in other sports, winning is highly dependent on a strong end spurt phase. This information can now be used by coaches and performance analysts to better prepare for canoe kayak sprint races that last between 30 s and 240 s in duration and shows that PCA is an appropriate and highly effective method to investigate pacing strategies in racing sports.

### Acknowledgements

The authors would like to thank Mitacs and Own the Podium through the Mitacs-Accelerate internship program, Intel® and the Nova Scotia Graduate Scholarship for their financial support. The results of the current study do not constitute endorsement of the product by the authors or the journal.

## Disclosure of Interest

The authors report no conflicts of interest.

## Funding

This work was supported by Mitacs and Own the Podium through the Mitacs-Accelerate internship program, Intel® and the Nova Scotia Graduate Scholarship.

## Link Between Chapter 3 and Chapter 4: Expanding Pacing Strategy Knowledge by Investigating Stroke Parameters During Sprint Kayak Races

Chapter 3 results showed that depending on which distance sprint kayakers were racing they followed either an all-out, positive, or sea-horse shaped pacing strategy. There were many novel results in this study. It was the first study to find kayakers followed a sea-horse shaped pacing strategies during 1000 m races. This would not have been possible without the use of GPS technology attached to the boat. As mentioned, high resolution split data has been requested in racing sports since at least the 1990's, and for good reasons (Foster et al., 1994). One of the motivations for the study was to better understand what athletes do from a pacing strategy perspective throughout the entire race distance. As shown in other research investigating sprint kayaking pacing strategies, this was difficult to do with traditional 250 m splits (Borges et al., 2013).

Although this study provided detailed insight on the pacing strategies elite, international-level sprint kayakers used during their races, it did not provide information on how they executed their race plans. As discussed in both the *Introduction* and *Literature Review* chapters of this dissertation, one instrumental study in the sprint kayaking literature showed the very strong relationship between kayak velocity and stroke time (i.e., $r = -0.86$) (McDonnell et al., 2013). A limitation to this result was that data used to calculate the correlation between these parameters were collected during short durations of paddling, where athletes were paddling at a constant velocity. Therefore, one of the current researcher's concerns was that it may be possible that knowledge users misunderstand the results and believe velocity always increases as SR increases (i.e., a causal relationship). This is likely not indicative of what happens in an actual race where athletes do not follow constant velocities throughout. Therefore, a study was designed to investigate how elite, international-level sprint kayakers modulated both SR and SL during full race distances of 200 m, 500 m, and 1000 m. With the increase in inertial measurement technology usage, it was believed now was the appropriate time to study if athletes rely on SR and SL differently within a race.

# CHAPTER 4: Pacing Strategies and Relationships Between Speed and Stroke Parameters for Elite Sprint Kayakers in Single Boats

Joshua A. Goreham, Kayla Bugeya Miller, Ryan J. Frayne, Michel Ladouceur

This chapter is published in the *Journal of Sports Sciences*. The author has the appropriate rights to include this article in their dissertation (Appendix B).

Citation:

Goreham JA, Miller KB, Frayne RJ, Ladouceur M. Pacing strategies and relationships between speed and stroke parameters for elite sprint kayakers in single boats. Journal of Sports Sciences. 2021 Oct 2;39(19):2211-8.

## Abstract

The study aimed to determine the pacing strategies of elite single-boat sprint kayakers, as well as the relationships between stroke parameters (stroke rate (SR) and stroke length (SL)) and kayak speed throughout the race. High-resolution split speed and stroke parameter data from men's (MK1) and women's (WK1) single-boat A- and B-finals in 2016-2017 international sprint kayak competitions were analyzed. Correlation coefficients were calculated between SR-speed and SL-speed during each split for each race group. Athletes followed all-out, positive, and seahorse-shaped pacing strategies for the 200 m, 500 m, and 1000 m races, respectively. SL-speed had greater correlations during the first half of the MK1 200 m race, whereas SR-speed had greater correlations during the second half. SR-speed correlations were greater than SL-speed correlations throughout the final 150 m of WK1 200 m races. There were large and very-large correlations between SR-speed at the end of both the WK1 500 m and MK1 1000 m race distances, respectively, despite following different pacing strategies. Single boat pacing strategies change due to race distance during major international sprint kayak competitions, whereas the relationships between stroke parameters and speed change depending on athlete sex and the race distance.

Keywords

performance analysis, global positioning systems, inertial measurement unit, race tactics, aquatic sports

## Introduction

It is widely understood that a well-planned pacing strategy contributes to enhanced athletic performance (de Koning et al., 1999). Pacing strategy has been defined as the goal-directed regulation of intensity across an exercise bout, as well as the self-selected tactics adopted by an athlete when completing a race (Roelands et al., 2013; Smits et al., 2014). Pacing strategies are commonly used in sports where athletes, or a team of athletes, are required to race from a start position to a finish position (i.e., a closed-loop race) faster than their opponent(s) (St Clair Gibson et al., 2001). Most pacing literature in aquatic-based sports have been conducted in swimming (Craig et al., 1985; McGibbon et al., 2018; Menting et al., 2019; Simbaña-Escobar et al., 2018; Veiga et al., 2019) and rowing (Brown et al., 2010; Garland, 2005; Gee et al., 2013; Renfree et al., 2012).

In the sport of Canoe Sprint, the athletes compete in either canoes or kayaks, which are distinct crafts. For this particular study, only kayaks were investigated. In one of the few studies published on sprint kayak pacing strategies, Borges et al., (2013) investigated men's single boat (MK1) 500 m and 1000 m races at World Championships between 2004 and 2011. They identified kayakers in 1000 m races followed a reverse J-shaped pacing strategy (i.e., the first 250 m was the fastest of the four splits and the final 250 m was second fastest). This was the first study to mention an "end spurt" in the sprint kayak pacing literature in over 30 years (Plagenhoef, 1979). The researchers also identified that athletes in 500 m races follow a positive pacing strategy (i.e., a significantly faster first 250 m split) (Borges et al., 2013). However, due to the common occurrence of using a low split-resolution (i.e., 250 m splits), an end spurt could not be identified in this race distance. Goreham et al., (2020) recently investigated pacing strategies for both sprint kayak and canoe athletes using global positioning systems from international races in 2016 and 2017. These pacing strategies were reported by combining single and crew boats and both male and female data. The high-resolution split data (i.e., speed values were collected every 10 m) showed that 200 m and 500 m kayakers follow all-out and positive pacing strategies, whereas male canoe and kayak athletes followed 'seahorse-shaped' pacing strategies in the 1000 m events. The seahorse-shaped pacing strategy, which has been seen in middle-distance running, has a slower 'tail' than the reverse J-shaped strategy as athletes slow down just prior to the finish line (Hanley et al., 2019). Unfortunately, these pacing strategy papers have combined boat types; therefore, it is required that the single boat kayak races of 200 m, 500 m, and 1000 m be parsed out to investigate if all-out, positive, and seahorse-shaped strategies continue to hold true for single boats at these race distances.

Pacing information is important as it shows an athlete's performance outcome; however, it does not provide information on how the athlete reached their specific speeds. Boat speed is the product of two stroke parameters: stroke rate (SR), and the kayak's displacement per stroke (i.e., stroke length, SL) (McDonnell et al., 2013). Athletes can change these parameters during a race to attain their desired speed. For example, it has been shown in the 200 m race distance that elite sprint kayakers increase their SR to their maximum value and then decrease their SR linearly to the finish line (Paquette et al., 2020). A review article reported a very large correlation between average SR and kayak speed in 200 m races (r = 0.89), where both parameters were measured simultaneously (McDonnell et al., 2013). A recent study also showed a large relationship between SR and average kayak speed in Olympic-level kayakers (r = 0.90) (Gomes et al., 2020). Unfortunately, data included in the two studies were not collected or reported in a systematic manner. For example, in McDonnell et al., (2013), the group's review included studies where different SR collection methodologies were used (i.e., different SR measurement technologies and calculation methods). Furthermore, the relationship between SR and speed were established by using either average or maximum values which lacks the temporal resolution to determine the true relationship between SR and boat speed throughout the race. Likewise in Gomes et al., (2020), the researchers used a instrumented paddle to determine SR, which is likely a highly accurate method of measuring this information; however, they too provided a correlation that was calculated from the average SR during the trials, which does not provide insight as to how the relationship between SR and speed changes throughout the race distance. Lastly, no data has been published showing the relationships between SR and speed (SR-speed) in 500 m and 1000 m races, or SL and speed (SL-speed) for any race distance. Therefore, there is a need to identify how elite sprint kayak athletes change their stroke parameters throughout a race.

The study's first aim was to investigate the pacing strategies during elite sprint kayak single-boat races. We hypothesized that athletes would follow an all-out, positive, and seahorse-shaped pacing strategy for 200 m, 500 m, and 1000 m race distances, respectively. The second aim was to determine the relationships between stroke parameters (i.e., SR and SL) and kayak speed throughout the race.

## Methods

Publicly available sprint kayak race data from the 2016 Olympic Games, 2016 World Cups 1, 2, and 3, and the 2017 World Championships were downloaded from the International Canoe Federation's website (www.canoeicf.com) for analysis. Race data included one average speed and one average SR value for each competitor at 10 m intervals. These data were collected using an inertial measurement unit (IMU; Swiss Timing, Geneva, Switzerland) and a global positioning system (GPS; PAM-7Q, u-blox, Thawil, Switzerland) which were placed on the deck of the kayak's stern (Goreham et al., 2020). All A- and B-finals data from the MK1 200 m, women's kayak single (WK1) 200 m, WK1 500 m and MK1 1000 m (from now on termed "groups") were analyzed for this study. All participant data were de-identified prior to analysis. Since all data were publicly available, institutional review board approval was not required.

### *Data Analysis*

Data were imported into a custom MATLAB® program (R2020a, MathWorks®, Natick, MA, USA). Missing data caused by equipment malfunction, athlete(s) not completing a race, and athletes suspended for doping were removed from the analysis. The pacing strategies of 276 boats competing in 35 races were analyzed in this study (Table 4.1). To account for environmental factors, boat speeds ($m \cdot s^{-1}$) were normalized by dividing each individual 10 m split by the grouped average boat speed in the corresponding race (Goreham et al., 2020). The same normalization calculations were completed for SR (strokes per minute; spm). Normalized SL values were calculated by dividing normalized speed by normalized SR. After normalization, all race data for each specific group were combined.

Table 4.1 Table of races analyzed in this study, with letter denoting the final type. Number in parentheses indicates number of boats analyzed per race.

| Event | Race Distance (m) | | | |
|---|---|---|---|---|
| | MK1 200 | WK1 200 | WK1 500 | MK1 1000 |
| 2016 World Cup 1 | A (8), B (8) | A (8), B (8) | A (8), B (7) | A (9), B (9) |
| 2016 World Cup 2 | A (9), B (7) | A (6), B (9) | A (8), B (7) | - |
| 2016 World Cup 3 | A (6) | A (9), B (9) | A (5), B (8) | B (8) |
| 2016 Olympic Games | A (8), B (8) | A (8), B (8) | A (8), B (8) | A (8), B (7) |
| 2017 World Championships | A (7), B (7) | A (9) | A (8), B (9) | A (9), B (8) |

A, A-Final; B, B-Final; MK1, men’s kayak single; WK1, women’s kayak single; -, no race analyzed at event.

Average split values for normalized speed, SR, and SL were calculated for each group. Split distances were dependent upon race distance, where 200 m races were divided into four 50 m splits, 500 m races were divided into five 100 m splits and 1000 m races were divided into ten 100 m splits. All 10 m data for a given split were averaged to obtain an average split value. For example, in the 200 m race distances the first five 10 m data points were averaged, and the resulting value was deemed the average split value for the first 50 m split. This process was completed for all remaining splits in the race.

To analyze relationships between SR-speed and SL-speed, correlation coefficients were calculated using two different methods. For the first method, an overall correlation coefficient was determined using 10 m split speed and stroke parameter data for each race distance. This approach was different than previous research which calculated correlation coefficients using only one average parameter value per race (Gomes et al., 2020). For the second method, correlation coefficients were calculated using 10 m data within each split and were then plotted to display how the relationships between speed and the stroke parameters changed between splits throughout each race distance.

### ***Statistical Analysis***

To analyze the change in parameters between splits, one-way repeated-measures analysis of variance (ANOVA) tests were performed for each group to determine main effects in speed, SR, and SL. When appropriate, Tukey's *post hoc* tests were completed to determine significant differences between splits for each parameter. The alpha value for statistical significance was set at $\alpha = 0.05$. ANOVA effect sizes were calculated using partial eta squared ($\eta^2$). Multiple comparisons effect sizes were calculated using Cohen's *d*. Geisser-Greenhouse epsilon corrections were used if Mauchly's Test for Sphericity were significant. The Shapiro-Wilks test was used to test for normality. Nine of 69 total datasets were non-normal (two each in MK1 200 m, WK1 200 m and WK1 500 m, and three in MK1 1000 m). However, it was decided all data would be analyzed using parametric tests for two reasons. First, each group had a sample size of greater than 50, which satisfies the central limit theorem (Kwak and Kim, 2017), and second, ANOVA statistical tests have been shown to be robust enough to address non-normal data (Blanca et al., 2017). Repeated-measure ANOVAs were conducted in GraphPad Prism 8 (v.8.4.2, GraphPad Software, San Diego, CA, USA) and correlation coefficients were calculated in MATLAB®. Thresholds were set at <0.3, >0.3, >0.5, >0.7, and >0.9 and were considered small, moderate, large, very large, and extremely large, respectively (Hopkins et al., 2009).

## Results

### *Pacing Strategies*

Descriptive information for each kayak group are shown in Table 4.2. Repeated-measures ANOVAs with Geisser-Greenhouse epsilon corrections showed that average speed differed significantly between the four splits for both 200 m groups (MK1 200: $F(2.1, 139.8) = 915.9$, $P<0.0001$, $\eta^2 = 0.93$; WK1 200: $F(1.6, 115.9) = 431.5$, $P<0.0001$, $\eta^2 = 0.86$), the five splits for the WK1 500 m group ($F(1.6, 120.9) = 541.6$, $P<0.0001$, $\eta^2 = 0.88$), and the ten splits for the MK1 1000 m group ($F(3.3, 187.3) = 304.5$, $P<0.0001$, $\eta^2 = 0.84$). Results of *post hoc* analyses for speed can be found in Figure 4.1, Figure 4.2, and Figure 4.3, and in the Supplemental Material Table 4.4, Table 4.7, Table 4.10, and Table 4.13. The average normalized speed profiles show that athletes in MK1 200 m and WK1 200 m groups followed an all-out pacing strategy, whereas boats in WK1 500 m and MK1 1000 m groups followed positive and seahorse-shaped pacing strategies, respectively.

Table 4.2 Descriptive information for the races and boats analyzed per discipline. Average data reported as mean ± standard deviation.

| Discipline | Races (*n*) | Boats Analyzed (*n*) | Race Time (m:ss.00 ± s.00) | Speed (m•s$^{-1}$) | SR (spm) | SL (m•stroke$^{-1}$) |
|---|---|---|---|---|---|---|
| MK1 200 | 9 | 68 | 0:35.63 ± 0.45 | 5.81 ± 0.54 | 153.2 ± 10.9 | 2.27 ± 0.15 |
| WK1 200 | 9 | 74 | 0:41.49 ± 0.57 | 4.95 ± 0.46 | 141.6 ± 11.4 | 2.10 ± 0.15 |
| WK1 500 | 10 | 76 | 1:54.39 ± 1.80 | 4.40 ± 0.35 | 116.8 ± 9.6 | 2.27 ± 0.14 |
| MK1 1000 | 7 | 58 | 3:34.47 ± 2.80 | 4.67 ± 0.33 | 111.9 ± 9.9 | 2.51 ± 0.15 |

MK1, men’s kayak single; WK1, women’s kayak single; n, number of samples; spm, strokes per minute.

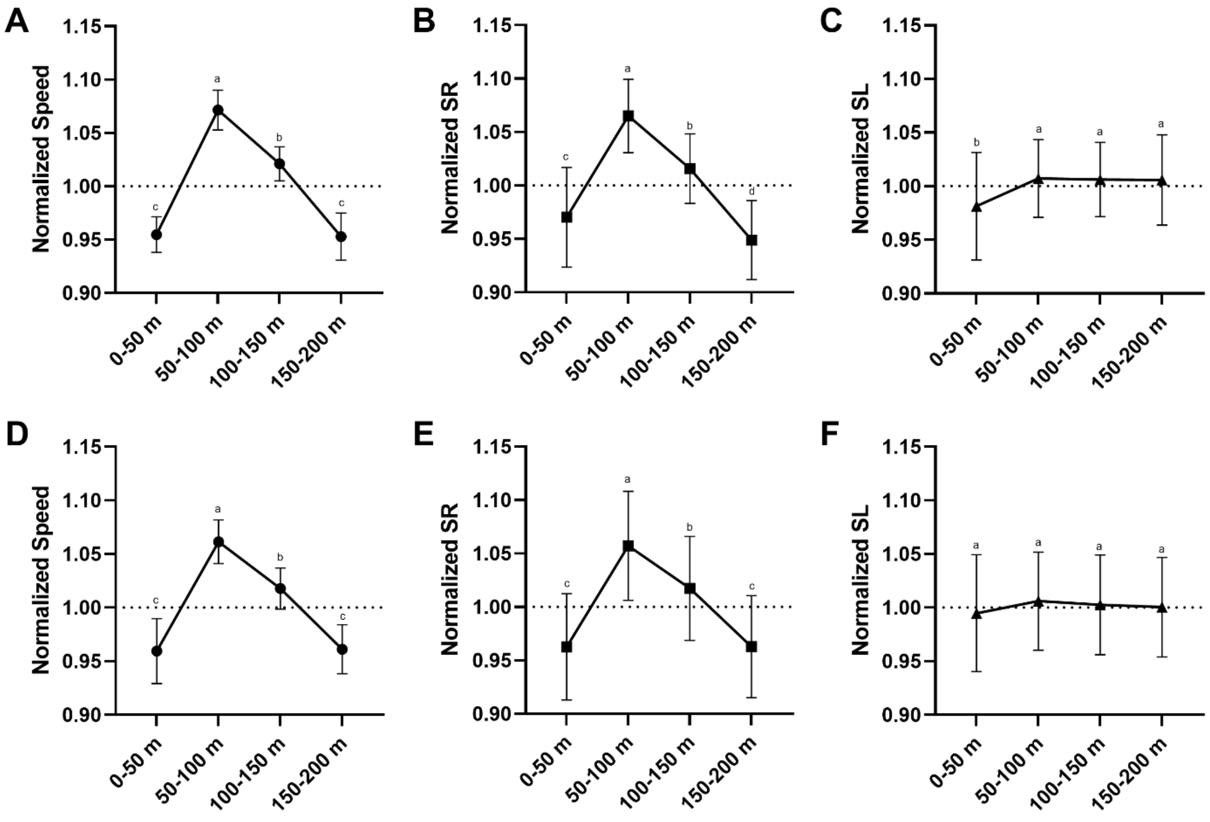


Figure 4.1 Normalized speed, SR, and SL graphs for MK1 200 m (Panels A-C) and WK1 200 m (Panels D-F). Dotted horizontal line indicates the respective average metric value. Error bars indicate one standard deviation from the mean. Means not sharing the same letter are significantly different (Tukey HSD, $p \leq 0.05$).

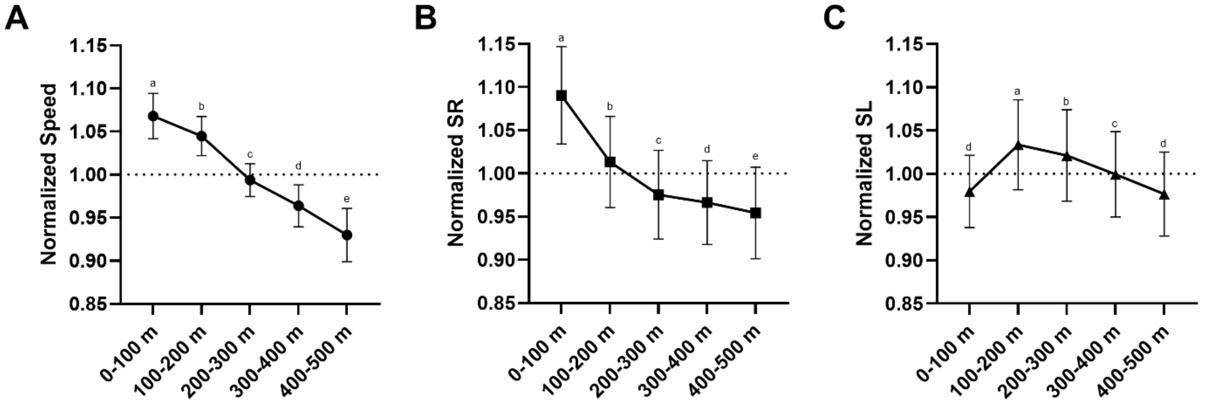


Figure 4.2 Normalized speed, SR, and SL graphs for WK1 500 m (Panels A-C). Dotted horizontal line indicates the respective average metric value. Error bars indicate one standard deviation from the mean. Means not sharing the same letter are significantly different (Tukey HSD, $p \leq 0.05$).

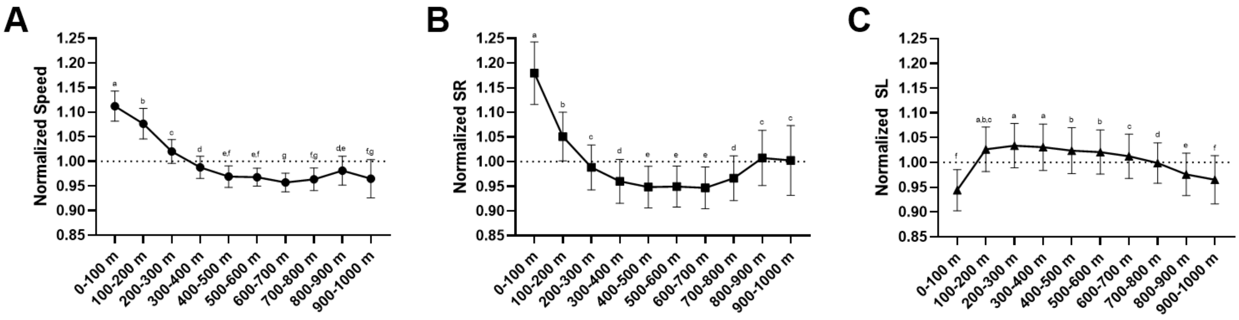


Figure 4.3 Normalized speed, SR, and SL graphs for MK1 1000 m (Panels A-C). Dotted horizontal line indicates the respective average metric value. Error bars indicate one standard deviation from the mean. Means not sharing the same letter are significantly different (Tukey HSD, $p \leq 0.05$).

***Stroke Parameters***

Repeated-measures ANOVAs with Geisser-Greenhouse epsilon corrections showed that average SR differed significantly between the four splits for both 200 m groups (MK1 200: *F*(1.8, 118.3) = 291.6, *P*<0.0001, $\eta^2 = 0.81$; WK1 200: *F*(1.7, 124.2) = 223.9, *P*<0.0001, $\eta^2 = 0.75$), the five splits for the WK1 500 m group (*F*(2.2, 167.8) = 220.7, *P*<0.0001, $\eta^2 = 0.75$), and the ten splits for the MK1 1000 m group (*F*(2.9, 168.1) = 227.4, *P*<0.0001, $\eta^2 = 0.80$). Results of *post hoc* analyses for SR can be found in Figure 4.1, Figure 4.2, and Figure 4.3, and in the Supplemental Material Table 4.5, Table 4.8, Table 4.11, and Table 4.14.

Repeated-measures ANOVAs with Geisser-Greenhouse epsilon corrections showed that average SL differed significantly between the four splits for the MK1 200 m group (*F*(1.9, 127.4) = 14.4, *P*<0.0001, $\eta^2 = 0.18$), the five splits for the WK1 500 m group (*F*(2.4, 184.0) = 72.2, *P*<0.0001, $\eta^2 = 0.49$), and the ten splits for the MK1 1000 m group (*F*(3.0, 173.3) = 86.1, *P*<0.0001, $\eta^2 = 0.60$). The results showed that average SL were not significantly different between splits for the WK1 200 m group (*F*(1.6, 118.3) = 2.4, *P*=0.103, $\eta^2 = 0.03$). Results of *post hoc* analyses for SL can be found in Figure 4.1, Figure 4.2, and Figure 4.3, and in the Supplemental Material Table 4.6, Table 4.9, Table 4.12, and Table 4.15.

***Correlations Between Stroke Rate-Speed and Stroke Length-Speed***

Overall correlations (i.e., one correlation for entire race) between SR-speed were large or very large for each of the four groups; whereas, overall correlations between SL-speed were large for both 200 m groups, moderate for WK1 500 m and small for MK1 1000 m (Table 4.3).

Table 4.3 Correlations between SR speed and SL speed for each race discipline using all race data.

| | SR vs. Speed | | SL vs. Speed | |
|---|---|---|---|---|
| Discipline | *r* | 95% CI | *r* | 95% CI |
| MK1 200 | 0.74 | 0.712-0.760 | 0.66 | 0.630-0.690 |
| WK1 200 | 0.72 | 0.694-0.743 | 0.54 | 0.500-0.573 |
| WK1 500 | 0.68 | 0.662-0.696 | 0.36 | 0.336-0.392 |
| MK1 1000 | 0.72 | 0.706-0.731 | 0.09 | 0.068-0.119 |

*r*, Pearson Product-Moment Correlation. 95% CI, 95% confidence intervals. SR, stroke rate; SL, stroke length. MK1, men's kayak single; WK1, women's kayak single. All *p*-values <0.0001.

Split-based correlations varied throughout the race for each group (Figure 4.4). For the 200 m groups, the strongest relationships between SR-speed and SL-speed occurred during the first 50 m split for both sexes, and then decreased for the remaining 150 m of the race (Figure 4.4A and Figure 4.4B). Furthermore, the trajectory of these relationships also differed between MK1 and WK1 200 m athletes. The largest correlations between SR-speed and SL-speed also occurred during the first 100 m split for the WK1 500 m group (Figure 4.4C). Unlike the other groups, the correlation between SR-speed was the greatest during the last 100 m split for the MK1 1000 m group. The correlation between SL-speed was the largest during the first split for this group and became a negative relationship in the final two 100 m splits (Figure 4.4D).

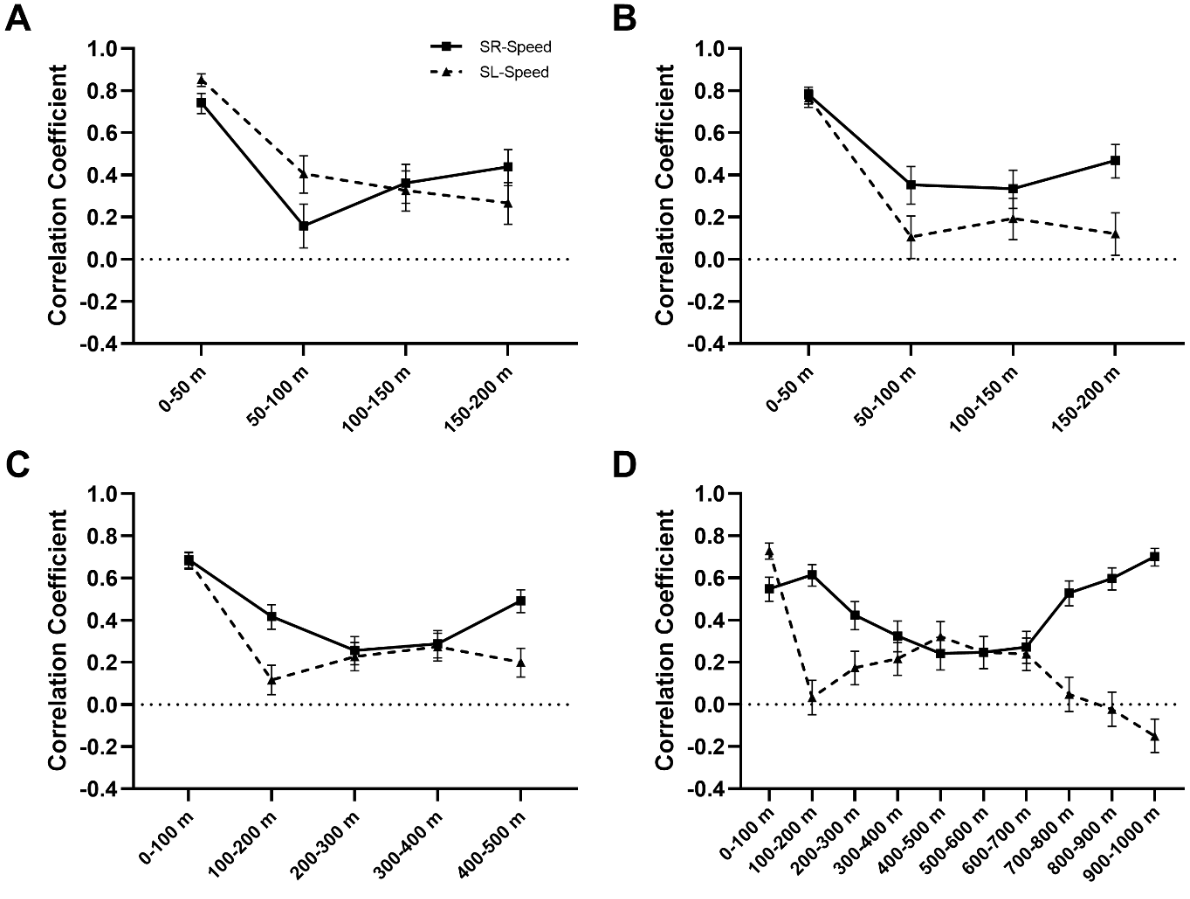


Figure 4.4 Between-parameter correlation coefficients at split intervals for A. MK1 200 m, B. WK1 200 m, C. WK1 500 m and D. MK1 1000 m. Error bars indicate 95% confidence intervals. Dotted lines indicate correlation of zero.

## Discussion

### *Pacing Strategies*

The study's first aim was to investigate the pacing strategies used during elite sprint kayak single-boat races. As hypothesized, our results suggest that single-boat sprint kayakers use pacing strategies which are race distance-dependent, as athletes competing in 200 m, 500 m and 1000 m events present all-out, positive, and seahorse-shaped pacing strategies, respectively. These results were confirmed by using ANOVAs to determine average speed differences between splits. In both 200 m groups, the second split was significantly greater than the final two splits which indicated an all-out pacing strategy. Following the first split in the WK1 500 m group, the average speed for each remaining split was significantly less than its predecessor. This result agrees with previous research that showed single boats follow a positive pacing strategy and do not increase their speed late in 500 m races (i.e., no end spurt) (Borges et al., 2013). Finally, the average speed in the first split of the MK1 1000 m group was significantly greater than all other splits, but most importantly the seahorse-shaped ‘tail’ was highlighted by the 9th split being significantly greater than both the 8th and 10th splits. These results match what was concluded in a recent study that combined both single and crew boats and male and female athletes for all race distances (Goreham et al., 2020).

### *Stroke Parameters and Relationships with Kayak Speed*

The second aim was to determine the relationships between kayak speed and stroke parameters (i.e., SR and SL) throughout elite, single-boat kayak race distances. Our results agree with previous research, showing large and very large overall correlations between SR-speed and SL-speed, for both the MK1 200 m and WK1 200 m race groups (Table 4.3) (Gomes et al., 2020; McDonnell et al., 2013). However, we are the first to show that this relationship is not consistent throughout the entire 200 m race distance. The strongest relationships between SR-speed and SL-speed occur during the first 50 m split for both sexes (Figure 4.4A and Figure 4.4B), suggesting increasing both SR and SL is required to quickly accelerate the boat from a static position at the beginning of the race (i.e., to overcome inertia and hydrodynamic drag). It is interesting that the relationships between stroke parameters and speed are different between sexes in the 200 m groups. Our data suggests that female athletes rely on SR to maintain speed from the 50 m mark to the end of the race (Figure 4.4B), whereas male athletes rely more on SL to increase and maintain speed until the 100 m mark and then SR to maintain speed for the final 100 m (Figure 4.4A). The differences in SR and SL relationships to speed between sexes might be the result of multiple factors. The differences could be due to factors associated with the propulsion forces like relative contribution of muscles used, muscle power, and differences in training programs; however, no published literature has shown differences in technique, kinematics, or muscle activity between male and female sprint kayakers. Even though direct comparisons between sexes have not been shown in the literature, more general factors, like athlete anthropometry (Van Someren and Palmer, 2003), physiology (Bishop, 2000), and equipment choice (Michael et al., 2009), have been shown to affect performance. As such, one potential factor could be differences in resistive forces experienced due to hydrodynamic drag which depends on factors like body mass as well as the different sources of drag (i.e., friction, pressure and wave drag) (Gomes et al., 2018; Mantha et al., 2013).

Likely the most important finding from this research were the relationships between SR-speed and SL-speed for both the WK1 500 m and MK1 1000 m groups. As shown in Figure 4.4C and Figure 4.4D, the relationships were similar between the two groups, despite the athletes following two different distance-dependent pacing strategies (Figure 4.2A and Figure 4.3A). The SR-speed correlations are highest at the beginning of each race followed by correlation increases at the fourth split and seventh split for WK1 500 m and MK1 1000 m races, respectively. This finding is important because it shows SR plays an important role at the start and end of both 500 m and 1000 m races. Also, the increasing strength of SR-speed relationship coincides with decreases in the SL-speed relationship. These results indicate that elite athletes rely on increasing their SR late in the race to minimize the reduction of speed (WK1 500 m) or increase their speed (MK1 1000 m) for the final stages of the race. It is still unknown as to why athletes choose to increase SR instead of SL to complete their races; however, it is likely due to fatigue, as it has been suggested that the decrease in SL late in swimming races is due to physiological strain, and declining power output and propulsion (Laffite et al., 2004; Thompson et al., 2004).

To date, there has only been one other study that has investigated kayak speed and both stroke parameters during a 1000 m race. Paquette et al., (2020) identified that following the initial acceleration phase (i.e., first 250 m split), speed and both stroke parameters stayed constant for the race’s final 750 m. Surprisingly, the participants in their study did not show an end-spurt to finish the race and seemingly “coasted” to the finish line. The differences between the two studies are likely due to motivational factors (i.e., training camp vs. international competitions) as observed by the differences in average MK1 1000 m race times (i.e., 3:46.3 ± 2.5 s versus 3:34.5 ± 2.8 s).

Although our study is the first to investigate the relationships between stroke parameters and speed in various sprint kayak events, a considerable amount of work in this area has been performed in swimming to better understand speed changes throughout a race (Craig et al., 1985; Laffite et al., 2004; Simbaña-Escobar et al., 2018; Thompson et al., 2004). As swimming speed increases there is an increase in hydrodynamic drag, resulting in an increase in energy lost to the environment (Barbosa et al., 2010; Menting et al., 2019). To overcome additional drag forces acting on the body, athletes are required to expend more energy to maintain their speed which causes them to become increasingly fatigued. This may cause body alignment to change, which also increases the amount of drag encountered (Craig et al., 1985). These concepts are also relevant to other aquatic sports, like sprint kayaking, canoeing and rowing. Currently, there is no evidence linking fatigue and excessive boat movement, nor how these factors affect drag and kayak speed. Perhaps as an athlete becomes fatigued their force output on the paddle, footboard and seat changes. These changes could potentially affect their coordination and how the boat maneuvers in the water, which would likely increase the hydrodynamic drag acting on the boat and decrease speed. Unfortunately, there is little information on paddle, seat and/or footboard force development in sprint kayaking. Although sprint kayak research has investigated paddle force information for multiple decades, there is still no evidence on how the paddle force profile changes throughout a race (Stothart et al., 1986). This information could be critical in understanding why athletes increase their SR (instead of SL) during their end-spurt. Based on these gaps in the literature, future research should investigate how fatigue, boat movement, and drag forces affect sprint kayak performance and pacing strategies.

### ***Practical Applications***

Canoe Sprint is a sport that is dominated with stroke rate watches and hand-held video cameras. With inertial measurement units being widely introduced to the sport, coaches are now able to easily collect high-resolution data that can aid in measuring their athlete’s pacing profiles. This research provides a template for how elite sprint kayakers pace their races in international competitions and shows how these data can be both analyzed and visualized to help athletes and coaches create or alter their current race strategy. For example, the results from this study specify when elite kayakers alter their SR and SL during races of differing distances and durations. By understanding how SR and SL correlate to speed at various sections within the race, coaches can use this new information to help create pacing strategies that may help their athletes develop into more successful sprint kayakers. Finally, the approach taken to analyze these speed and stroke parameter data in the current study can be used in other cyclical sports, both in aquatic and over-ground settings.

### ***Limitations***

Previous research has shown that B-finalists have more race-to-race variability than A-finalists at international regattas, and therefore combining both finals in this study could be viewed as a limitation (Bonetti and Hopkins, 2010). We believe this approach adds to current literature, as analyzing pacing strategies and stroke parameters of A- and B-finalists ensures we obtain data from a truly elite and larger sample (i.e., the best 18 kayakers in the world per group at the time of data collection). It should also be noted that we did not collect physiological or psychological data for this study; therefore, we were unable to determine if athletes "gave up" during their race. Thus, it is possible these results include data from athletes who did not complete the entire race at their full effort. However, since the competitions were elite, international events we do not believe this was a common occurrence. In addition, no anthropometrical, equipment, or strength data were collected; therefore, it was impossible to determine how SR and SL are affected by parameters such as paddle length, grip width, etc. (Hay, 2002). Another limitation of this study was the lack of information available on how SR was calculated from the GPS and IMU data. These SR measurements have yet to be validated.

### ***Conclusions***

Elite single-boat sprint kayakers follow all-out, positive, and seahorse-shaped pacing strategies for MK1 and WK1 200 m, WK1 500 m, and MK1 1000 m races, respectively. Despite previous research inferring that increasing SR will increase speed, our results show that this is not always true, and therefore athletes should ensure they develop their ability to change their SL as well. The results from this study show that elite sprint kayakers alter the relationships between stroke parameters and kayak speed differently depending on the race distance during major international sprint kayak competitions. Specifically, 200 m kayakers rely on SR and SL differently depending on the split of the race they are in, whereas 500 m and 1000 m kayakers both use SR as the primary method of attempting to maintain or increasing their speed late in their races, respectively, despite following two different pacing strategies.

## Acknowledgements

The authors would like to thank Mitacs and Own the Podium through the Mitacs-Accelerate internship program, Intel Corporation and the Nova Scotia Graduate Scholarship for their financial support. The results of the current study do not constitute endorsement of the product by the authors or the journal.

## Disclosure of Interest

The authors report no conflicts of interest.

## Supplemental Material

"*Pacing strategies and relationships between speed and stroke parameters for elite sprint kayakers in single boats*" in the Journal of Sports Sciences.

Note: The following tables show the *p*-values and Cohen's *d* effect sizes calculated from the Tukey's multiple comparisons tests. Each split-to-split comparison has a *p*-value (bottom left cells) and an effect size (top right cells). The critical alpha value for statistical significance was set at $\alpha = 0.05$. **Bold** font indicates a significant *p*-value. The number in parentheses indicates the split number.

### MK1 200

Table 4.4 The p-values (bottom left cells in table) and Cohen's d effect sizes (top right cells in table) calculated from the Tukey's multiple comparisons tests for the MK1 200 m speed analysis. Values correspond to data shown in Figure 4.1A in manuscript.

| Split | 0-100 (1) | 100-200 (2) | 200-300 (3) | 300-400 (4) |
|---|---|---|---|---|
| 0-100 (1) | | -6.7 | -4.1 | 0.1 |
| 100-200 (2) | **<0.0001** | | 2.9 | 5.8 |
| 200-300 (3) | **<0.0001** | **<0.0001** | | 3.6 |
| 300-400 (4) | 0.9415 | **<0.0001** | **<0.0001** | |

Table 4.5 The p-values (bottom left cells in table) and Cohen's d effect sizes (top right cells in table) calculated from the Tukey's multiple comparisons tests for the MK1 200 m SR analysis. Values correspond to data shown in Figure 4.1B in manuscript.

| Split | 0-100 (1) | 100-200 (2) | 200-300 (3) | 300-400 (4) |
|---|---|---|---|---|
| 0-100 (1) | | -2.3 | -1.1 | 0.5 |
| 100-200 (2) | **<0.0001** | | 1.5 | 3.3 |
| 200-300 (3) | **<0.0001** | **<0.0001** | | 1.9 |
| 300-400 (4) | **0.0031** | **<0.0001** | **<0.0001** | |

Table 4.6 The p-values (bottom left cells in table) and Cohen's d effect sizes (top right cells in table) calculated from the Tukey's multiple comparisons tests for the MK1 200 m SL analysis. Values correspond to data shown in Figure 4.1C in manuscript.

| Split | 0-100 (1) | 100-200 (2) | 200-300 (3) | 300-400 (4) |
|---|---|---|---|---|
| 0-100 (1) | | -0.6 | -0.6 | -0.5 |
| 100-200 (2) | **<0.0001** | | 0 | 0 |
| 200-300 (3) | **<0.0001** | 0.9869 | | 0 |
| 300-400 (4) | **0.0012** | 0.9914 | 0.9982 | |

**WK1 200**

Table 4.7 The p-values (bottom left cells in table) and Cohen's d effect sizes (top right cells in table) calculated from the Tukey's multiple comparisons tests for the WK1 200 m speed analysis. Values correspond to data shown in Figure 4.1D in manuscript.

| Split | 0-100 (1) | 100-200 (2) | 200-300 (3) | 300-400 (4) |
|---|---|---|---|---|
| 0-100 (1) | | -4.0 | -2.3 | -0.1 |
| 100-200 (2) | **<0.0001** | | 2.2 | 4.7 |
| 200-300 (3) | **<0.0001** | **<0.0001** | | 2.7 |
| 300-400 (4) | 0.9834 | **<0.0001** | **<0.0001** | |

Table 4.8 The p-values (bottom left cells in table) and Cohen's d effect sizes (top right cells in table) calculated from the Tukey's multiple comparisons tests for the WK1 200 m SR analysis. Values correspond to data shown in Figure 4.1E in manuscript.

| Split | 0-100 (1) | 100-200 (2) | 200-300 (3) | 300-400 (4) |
|---|---|---|---|---|
| 0-100 (1) | | -1.9 | -1.1 | 0 |
| 100-200 (2) | **<0.0001** | | 0.8 | 1.9 |
| 200-300 (3) | **<0.0001** | **<0.0001** | | 1.1 |
| 300-400 (4) | >0.9999 | **<0.0001** | **<0.0001** | |

Table 4.9 The p-values (bottom left cells in table) and Cohen's d effect sizes (top right cells in table) calculated from the Tukey's multiple comparisons tests for the WK1 200 m SL analysis. Values correspond to data shown in Figure 4.1F in manuscript.

| Split | 0-100 (1) | 100-200 (2) | 200-300 (3) | 300-400 (4) |
|---|---|---|---|---|
| 0-100 (1) | | -0.2 | -0.2 | -0.1 |
| 100-200 (2) | 0.1249 | | 0.1 | 0.1 |
| 200-300 (3) | 0.5297 | 0.4410 | | 0 |
| 300-400 (4) | 0.7261 | 0.3519 | 0.7682 | |

## WK1 500

Table 4.10 The p-values (bottom left cells in table) and Cohen's d effect sizes (top right cells in table) calculated from the Tukey's multiple comparisons tests for the WK1 500 m speed analysis. Values correspond to data shown in Figure 4.2A in manuscript.

| Split | 0-100 (1) | 100-200 (2) | 200-300 (3) | 300-400 (4) | 400-500 (5) |
|---|---|---|---|---|---|
| 0-100 (1) |  | 1.0 | 3.3 | 4.2 | 4.8 |
| 100-200 (2) | **<0.0001** |  | 2.5 | 3.5 | 4.3 |
| 200-300 (3) | **<0.0001** | **<0.0001** |  | 1.4 | 2.5 |
| 300-400 (4) | **<0.0001** | **<0.0001** | **<0.0001** |  | 1.2 |
| 400-500 (5) | **<0.0001** | **<0.0001** | **<0.0001** | **<0.0001** |  |

Table 4.11 The p-values (bottom left cells in table) and Cohen's d effect sizes (top right cells in table) calculated from the Tukey's multiple comparisons tests for the WK1 500 m SR analysis. Values correspond to data shown in Figure 4.2B in manuscript.

| Split | 0-100 (1) | 100-200 (2) | 200-300 (3) | 300-400 (4) | 400-500 (5) |
|---|---|---|---|---|---|
| 0-100 (1) |  | 1.4 | 2.1 | 2.4 | 2.5 |
| 100-200 (2) | **<0.0001** |  | 0.7 | 0.9 | 1.1 |
| 200-300 (3) | **<0.0001** | **<0.0001** |  | 0.2 | 0.4 |
| 300-400 (4) | **<0.0001** | **<0.0001** | **0.0181** |  | 0.2 |
| 400-500 (5) | **<0.0001** | **<0.0001** | **0.0032** | **0.0172** |  |

Table 4.12 The p-values (bottom left cells in table) and Cohen's d effect sizes (top right cells in table) calculated from the Tukey's multiple comparisons tests for the WK1 500 m SL analysis. Values correspond to data shown in Figure 4.2C in manuscript.

| Split | 0-100 (1) | 100-200 (2) | 200-300 (3) | 300-400 (4) | 400-500 (5) |
|---|---|---|---|---|---|
| 0-100 (1) |  | -1.1 | -0.9 | -0.4 | 0.1 |
| 100-200 (2) | **<0.0001** |  | 0.2 | 0.7 | 1.1 |
| 200-300 (3) | **<0.0001** | **<0.0001** |  | 0.4 | 0.9 |
| 300-400 (4) | **0.0004** | **<0.0001** | **<0.0001** |  | 0.5 |
| 400-500 (5) | 0.9753 | **<0.0001** | **<0.0001** | **<0.0001** |  |

## MK1 1000

Table 4.13 The p-values (bottom left cells in table) and Cohen's d effect sizes (top right cells in table) calculated from the Tukey's multiple comparisons tests for the MK1 1000 m speed analysis. Values correspond to data shown in Figure 4.3A in manuscript. Note: Table 4.13 has been amended from the published manuscript. Cohen's d values are different than published as of December 3, 2023.

| Split | 0-100 (1) | 100-200 (2) | 200-300 (3) | 300-400 (4) | 400-500 (5) | 500-600 (6) | 600-700 (7) | 700-800 (8) | 800-900 (9) | 900-1000 (10) |
|---|---|---|---|---|---|---|---|---|---|---|
| 0-100 (1) | | 1.2 | 3.4 | 4.7 | 5.4 | 5.8 | 6.1 | 5.5 | 4.4 | 4.3 |
| 100-200 (2) | **<0.0001** | | 2.0 | 3.3 | 4.1 | 4.3 | 4.7 | 4.2 | 3.2 | 3.2 |
| 200-300 (3) | **<0.0001** | **<0.0001** | | 1.4 | 2.2 | 2.4 | 2.9 | 2.4 | 1.5 | 1.7 |
| 300-400 (4) | **<0.0001** | **<0.0001** | **<0.0001** | | 0.9 | 1.0 | 1.5 | 1.1 | 0.3 | 0.7 |
| 400-500 (5) | **<0.0001** | **<0.0001** | **<0.0001** | **<0.0001** | | 0.1 | 0.6 | 0.3 | -0.5 | 0.1 |
| 500-600 (6) | **<0.0001** | **<0.0001** | **<0.0001** | **<0.0001** | >0.9999 | | 0.6 | 0.2 | -0.6 | 0.1 |
| 600-700 (7) | **<0.0001** | **<0.0001** | **<0.0001** | **<0.0001** | **0.0055** | **0.0004** | | -0.3 | -1.0 | -0.3 |
| 700-800 (8) | **<0.0001** | **<0.0001** | **<0.0001** | **<0.0001** | 0.9195 | 0.9384 | 0.1701 | | -0.7 | 0 |
| 800-900 (9) | **<0.0001** | **<0.0001** | **<0.0001** | 0.9351 | 0.2162 | 0.0565 | **<0.0001** | **0.0001** | | 0.5 |
| 900-1000 (10) | **<0.0001** | **<0.0001** | **<0.0001** | **0.0231** | 0.9993 | >0.9999 | 0.9109 | >0.9999 | **0.0053** | |

Table 4.14 The p-values (bottom left cells in table) and Cohen's d effect sizes (top right cells in table) calculated from the Tukey's multiple comparisons tests for the MK1 1000 m SR analysis. Values correspond to data shown in Figure 4.3B in manuscript.

| Split | 0-100 (1) | 100-200 (2) | 200-300 (3) | 300-400 (4) | 400-500 (5) | 500-600 (6) | 600-700 (7) | 700-800 (8) | 800-900 (9) | 900-1000 (10) |
|---|---|---|---|---|---|---|---|---|---|---|
| 0-100 (1) | | 2.3 | 3.5 | 4.0 | 4.3 | 4.3 | 4.4 | 3.9 | 2.9 | 2.7 |
| 100-200 (2) | **<0.0001** | | 1.3 | 2.0 | 2.3 | 2.2 | 2.3 | 1.8 | 0.8 | 0.8 |
| 200-300 (3) | **<0.0001** | **<0.0001** | | 0.6 | 0.9 | 0.9 | 1.0 | 0.5 | -0.4 | -0.2 |
| 300-400 (4) | **<0.0001** | **<0.0001** | **<0.0001** | | 0.3 | 0.2 | 0.3 | -0.1 | -0.9 | -0.7 |
| 400-500 (5) | **<0.0001** | **<0.0001** | **<0.0001** | **<0.0001** | | 0 | 0 | -0.4 | -1.2 | -0.9 |
| 500-600 (6) | **<0.0001** | **<0.0001** | **<0.0001** | **0.0021** | 0.9993 | | 0.1 | -0.4 | -1.2 | -0.9 |
| 600-700 (7) | **<0.0001** | **<0.0001** | **<0.0001** | **0.0013** | 0.9998 | 0.9261 | | -0.4 | -1.2 | -1.0 |
| 700-800 (8) | **<0.0001** | **<0.0001** | **0.001** | 0.8649 | **0.0003** | **0.0005** | **<0.0001** | | -0.8 | -0.6 |
| 800-900 (9) | **<0.0001** | **<0.0001** | 0.1376 | **<0.0001** | **<0.0001** | **<0.0001** | **<0.0001** | **<0.0001** | | 0.1 |
| 900-1000 (10) | **<0.0001** | **<0.0001** | 0.8552 | **0.0008** | **<0.0001** | **<0.0001** | **<0.0001** | **0.0018** | 0.9956 | |

Table 4.15 The p-values (bottom left cells in table) and Cohen's d effect sizes (top right cells in table) calculated from the Tukey's multiple comparisons tests for the MK1 1000 m SL analysis. Values correspond to data shown in Figure 4.3C in manuscript.

| Split | 0-100 (1) | 100-200 (2) | 200-300 (3) | 300-400 (4) | 400-500 (5) | 500-600 (6) | 600-700 (7) | 700-800 (8) | 800-900 (9) | 900-1000 (10) |
|---|---|---|---|---|---|---|---|---|---|---|
| 0-100 (1) |  | -1.9 | -2.1 | -2.0 | -1.8 | -1.8 | -1.6 | -1.3 | -0.8 | -0.5 |
| 100-200 (2) | **<0.0001** |  | -0.2 | -0.1 | 0.1 | 0.1 | 0.3 | 0.6 | 1.2 | 1.3 |
| 200-300 (3) | **<0.0001** | 0.1175 |  | 0.1 | 0.2 | 0.3 | 0.5 | 0.8 | 1.3 | 1.5 |
| 300-400 (4) | **<0.0001** | 0.9828 | 0.8603 |  | 0.2 | 0.2 | 0.4 | 0.7 | 1.2 | 1.4 |
| 400-500 (5) | **<0.0001** | 0.9994 | **0.0024** | **0.0201** |  | 0.1 | 0.2 | 0.6 | 1.1 | 1.2 |
| 500-600 (6) | **<0.0001** | 0.9654 | **0.0054** | **0.0158** | 0.9809 |  | 0.2 | 0.5 | 1.0 | 1.2 |
| 600-700 (7) | **<0.0001** | 0.1479 | **<0.0001** | **<0.0001** | **0.0227** | **0.0001** |  | 0.3 | 0.8 | 1.0 |
| 700-800 (8) | **<0.0001** | **<0.0001** | **<0.0001** | **<0.0001** | **<0.0001** | **<0.0001** | **<0.0001** |  | 0.6 | 0.8 |
| 800-900 (9) | **0.0004** | **<0.0001** | **<0.0001** | **<0.0001** | **<0.0001** | **<0.0001** | **<0.0001** | **<0.0001** |  | 0.2 |
| 900-1000 (10) | 0.0547 | **<0.0001** | **<0.0001** | **<0.0001** | **<0.0001** | **<0.0001** | **<0.0001** | **<0.0001** | **0.0323** |  |

## Link Between Chapter 4 and Chapter 5: Reduce Fatigue by Using Pacing Strategies and Decreasing Hydrodynamic Drag

Chapter 4 results showed elite sprint kayakers change their kayak speed by relying on stroke parameters (i.e., stroke rate and stroke length) differently depending on the phase of the race. An example of this is late in a 500 m or 1000 m race (i.e., approximately 20-30% of the race distance remaining) where athletes in both distances relied more on SR to finish the race than SL. This was an important result, which now allows coaches and athletes to plan their pacing strategy not only from a speed perspective, but also a stroke parameter perspective. To reiterate, the purpose of a well-thought out pacing strategy is to properly regulate intensity levels across the race distance and exercise bout (Roelands et al., 2013; Smits et al., 2014), with the goal of distributing energy expenditure appropriately to delay fatigue (Abbiss & Laursen, 2008; Skorski & Abbiss, 2017; St Clair Gibson et al., 2018).

Using a well-planned pacing strategy will help delay, or at least minimize fatigue; however, it is not the only way to reduce fatigue during a race. Given the same level of aerobic and anaerobic fitness, another method would be to become a more efficient paddler. To do this one must reduce the amount of resistive forces acting on the boat. As it has been highlighted many times throughout this dissertation, measuring resistive forces, or hydrodynamic drag, during paddling is difficult and to date has been relatively overlooked by researchers (Michael et al., 2009). Another approach to measure a proxy for hydrodynamic drag is to quantify boat kinematics during paddling (Wainwright et al., 2014). This is based on the concept that increasing unwanted, or unnecessary boat movements are deterimental to performance. Unnecessary boat movements can be defined as those not acting to help propel the boat in the forward direction, or those not acting in the direction of travel to the finish line. Most research in this area is primarily theoretical, therefore we believed the next logical step was to measure boat kinematics during short distance paddling and relate these movements to kayak speed.

Being able to study these areas of sprint kayak was not possible prior to inertial measurement units and global positioning systems becoming commonplace in the sport. Due to the capabilities of collecting high-resolution acceleration, velocity, position, and angular velocity data more exploration into sprint kayaking technique and pacing strategies can occur. The previous two articles in Chapters 3 and 4 have determined how elite sprint kayakers' pace during racing, whereas the next study investigates how boat kinematics are related to kayak speed in a group of National-to-World Class sprint kayakers.

# CHAPTER 5: The Relationship Between Boat Kinematics and Sprint Kayak Performance

Joshua A. Goreham, Michel Ladouceur

## Abstract

Kayak speed depends on the combination of propulsive and resistive forces; however, the causes of hydrodynamic drag, a resistive force, in sprint kayaking are not well understood. The aims of this research were to determine which six degrees of freedom (DoF) boat kinematics predict kayak speed during the propulsive and resistive phases of the stroke cycle, as well as report normative boat kinematic values (i.e., linear acceleration and angular velocity). Based on the equation for hydrodynamic drag force, we hypothesized that increased forward and vertical impulse (friction drag) as well as pitch and yaw angular impulse (pressure and wave drag) will be significant predictors of sprint kayak speed. Fifteen elite sprint kayak athletes (eight females and seven males, 21.9 ± 5.4 years old, 1.75 ± 0.07 m, 73.0 ± 9.4 kg, 12.7 ± 5.0 years of kayaking experience) completed four, 30-second trials at four different stroke rates (60, 80, 100, and maximum strokes per minute). Kayak speed, three-dimensional linear acceleration (forward, lateral, and vertical), and three-dimensional angular velocity (pitch, yaw, and roll) were measured using an inertial measurement unit combined with a global positioning system. Impulses within the propulsive and resistive phases of ten single strokes (per trial) were calculated, and averaged, for each of the six DoF boat kinematic variables. A stepwise regression was used to predict kayak speed from the six independent variables. Normative data were calculated using mean waveform analysis. Predictors of kayak speed during the propulsive phase of the stroke ($R^2$ = 0.659) included roll (β =0.019; $p$ <0.001), yaw ($\beta = -0.091$; $p$ =0.068), pitch (β =0.061; $p$ =0.005), and vertical acceleration impulses (β =1. 133; $p$ =0.011). Yaw (β =0.191; $p$ <0.001), lateral acceleration ($\beta = -0.737$; $p$ <0.001), and vertical acceleration impulses ($\beta = -1.035$; $p$ =0.016) were significant predictors of kayak speed in the stroke's resistive phase ($R^2$ = 0.568). The results from this study indicate that yaw and vertical acceleration impulses influence kayak speed both in the propulsive and resistive phases of the stroke. Interestingly, they did not always affect kayak speed negatively as hypothesized, and therefore may be a byproduct of movement generated from the propulsive forces the athlete applies to the paddle and water. Further to this point, pitch and roll impulses also had a positive affect on kayak speed during the propulsive phase of the stroke. Lateral acceleration impulse influenced kayak speed negatively during the resistive phase of the stroke, potentially due to increased side-to-side movement velocity which reduces the time spent moving in the forward direction. The only variable to not predict kayak speed was forward acceleration impulses. Coaches and athletes should focus on these variables when attempting to reduce hydrodynamic drag acting on their boat during paddling.

Keywords: hydrodynamic drag, boat kinematics, acceleration, angular velocity, impulse

## Introduction

Much of the sprint kayak literature uses kayak speed as a measure of performance (Goreham et al., 2021; McDonnell et al., 2013a). Many factors influence sprint kayak performance usually by affecting the athlete's ability to propel the boat, or their ability to reduce the number of resistive forces acting on the boat (i.e., hydrodynamic drag). One factor that is related to hydrodynamic drag is the kayak's movement in six degrees of freedom (DoF) (Harbour, 2019; Pendergast et al., 2005, 2003). Interestingly, Michael et al., (2009) reported in their review of the determinants of sprint kayak performance that boat kinematics was an under-studied area in sprint kayak research. They were specifically referring to the measurements of three-dimensional accelerations (i.e., forward, vertical, lateral) and rotations (i.e., pitch, yaw, roll) of the boat. Only one study has reported how boat kinematics affected performance in sprint kayaking. Brown et al., (2011) published a study using notational analysis to discover that boat movement was greater in lesser-skilled athletes compared to elite athletes. Unfortunately, no study has directly measured the relationship between six DoF boat kinematics and performance.

From a hydrodynamic perspective, there can only be three ways to increase kayak speed. The athlete can increase the propulsive forces applied with the paddle, decrease the resistive forces acting on the boat, or do both. Both aspects have been investigated; however, there has been a greater emphasis on propulsive forces (Aitken and Neal, 1992; Bonaiuto et al., 2020; Gomes et al., 2015; Romagnoli et al., 2022) in comparison to the resistive forces in sprint kayaking (Gomes et al., 2015; Gomes et al., 2018). This may be partly due to the increasing availability of instrumented paddles allowing for the quantification of propulsive forces (Bonaiuto et al., 2020; Gomes et al., 2015; Harbour, 2019; Macdermid and Fink, 2017).

Hydrodynamic drag during paddling (i.e., active drag) is dependent on multiple factors as quantified by Equation 8.

Equation 8. $$F_D = ½C_D \rho A v^2$$

where, $F_D$ is the drag force, $C_D$ is the drag coefficient, $\rho$ is the fluid density, $A$ is the kayak's surface area interacting with the fluid, and $v$ is the kayak's velocity. It is difficult to quantify active drag forces during on-water paddling. Although the mechanism (i.e., kinetics) may not be quantified, inertial measurement technology (IMU) allows for the outcome (i.e., the resultant boat movement) to be measured. The kayak's acceleration and angular velocity can be measured in three-dimensions using the accelerometer and gyroscope components of the IMU (Figure 5.1). This allows for high-resolution analysis of intra-stroke boat kinematics which can provide insight on the directions the boat is moving in the water.

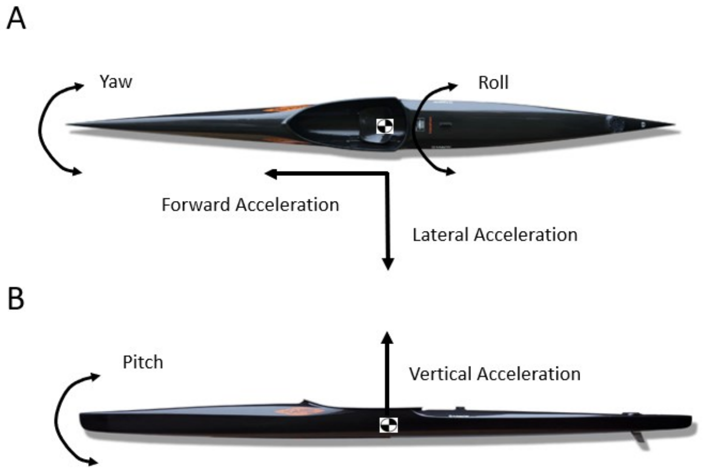


Figure 5.1 Three-dimensional acceleration and angular velocity relative to a sprint kayak's center of mass (CoM) from a (A) transverse and (B) sagittal view.

Resistive forces can be broken down into friction, pressure, and wave drag (Hay, 1993). Each of these types of drag affect the surface area variable of the hydrodynamic drag equation (Equation 8), as they are modulated due to changes in boat movement. Friction drag accounts for most of the hydrodynamic drag (66-73%) and is due to the friction between the kayak's hull and the water (Baker, 2012; Gomes et al., 2018; Jackson, 1995; Michael et al., 2009). Friction drag can be modified by changing the wetted surface area of the boat. Factors that can influence the wetted surface would be the relative height of the boat in comparison with the water level (i.e., a boat sitting lower in the water because of an increased mass) as well as, an increase vertical motion of the boat. Therefore, if an athlete's CoM moves vertically they will have more friction drag acting on their boat.

Pressure drag accounts for approximately 24% of hydrodynamic drag and is due to the separation of water to allow for the hull of the kayak to pass through (Gomes et al., 2015; Gomes et al., 2018; Michael et al., 2009). Pressure drag is also affected by the frontal surface area of the boat (Gomes et al., 2018; Mantha et al., 2013). Measuring the frontal area of the boat in relation to the displacement through the water is difficult; however, an indirect method that measures the yaw angle of the boat during a stroke cycle could be used (Higgens et al., 2016; Wainwright et al., 2015). For example, if the boat has increased rotation around the vertical axis at the boat's CoM (i.e., yaw), it will have a greater frontal surface area in contact with the water in the direction of travel. This would cause pressure drag to increase, and thus kayak speed to decrease.

Wave drag is caused by two types of resistive forces. The first is when the boat produces waves going through the water, and the second is the resistive forces created due to the boat breaking through oncoming waves (Gomes et al., 2018; Michael et al., 2009; Pendergast et al., 2005). In flat water, the creation of waves may cause greater wave drag compared to breaking waves in the same conditions. From a wave creation point of view, a boat that accelerates or rotates more will create more waves, and thus generate a greater amount of wave drag. Therefore, a boat that has more movement (in directions other than the forward direction), should theoretically incur more resistive forces and ultimately go slower for the same amount of propulsive force being applied. All of these factors contributing to hydrodynamic drag may decrease the efficiency of movement, or comparably be an indicator of inefficient technique.

Another important variable in the hydrodynamic drag equation (Equation 8) is velocity. Changes in velocity occur when an athlete takes a stroke, and if the propulsive forces generated by the athlete exceed the resistive forces acting on the athlete-paddle-boat system, the boat accelerates. The boat will continue to accelerate until resistive forces exceed propulsive forces and causes the boat to slow down. Since hydrodynamic drag is proportional to velocity squared, from an energy conservation perspective it is in the athlete's best interest to minimize the fluctuations in velocity. It can also be expected that the kayak changes velocity differently during the propulsive and resistive phases of the stroke; however, no one has measured this to date.

As discussed, there are two primary variables within the hydrodynamic drag equation that can be modulated by the athlete. These include the position and the change in velocity of the boat. One way to measure these variables is by using an accelerometer and gyroscope within an IMU and a global positioning system (GPS) attached to the boat. Unfortunately, boat position and orientation in six DoF is difficult to quantify over long periods of paddling due to the potential integration error (i.e., drift) accumulated from these sensor's measurements. Also, being on an unsteady surface (i.e., water) makes it difficult to re-calibrate the IMU to a known position.

Since the goal of sprint kayaking is to travel in a straight line from one position on the start line to the finish line as quick as possible, it can be assumed that any movement deviation from that straight line is wasted energy. Considering this concept another solution to measure boat kinematics in six DoF is to measure the impulse of the boat. Typically, impulse is measured by calculating the area under a force-time curve; however, during kayaking the athlete's body mass does not change during a session and thus the force due to body mass (i.e., body weight) can be ignored. Therefore, the linear portion of the impulse can be calculated by integrating each stroke's acceleration-time waveforms in three DoF (i.e., from forward, lateral, vertical acceleration measurements). IMU gyroscopes already measure angular velocity, thus the rotational portion of the impulse can be found by calculating the amplitude range in the angular velocity-time waveforms measured by the gyroscope in three DoF (i.e., pitch, yaw, roll).

The specific aim of this study was to determine which six DoF boat kinematics, measured by calculating impulse, predict kayak speed during the propulsive and resistive phases of the stroke cycle. We hypothesized that resistive forces affecting friction (forward and vertical acceleration), and pressure and wave drag (pitch and yaw angular velocity) will affect mean kayak speed the most. A secondary aim was to report normative boat kinematics values measured by an IMU (i.e., acceleration and angular velocity) from a group of National-to-World Class level sprint kayakers.

## Methods

### *Participants*

Fifteen elite sprint kayak athletes (eight females and seven males, 21.9 ± 5.4 years old, 1.747 ± 0.066 m, 73.0 ± 9.4 kg, 12.7 ± 5.0 years of kayaking experience) participated in this study. All participants consented to participating in the study in accordance with Dalhousie University's Research Ethics Board. To be included in the study, participants were required to have competed for more than one year, had not capsized their boat in the past year, and complete a minimum of five on-water training sessions per week during a typical training week.

### *Experimental Protocol*

Data were collected on a marked 1000 m sprint kayak racecourse with participants using their own personal kayaks. The experimental protocol began with an individualized ten-minute warm-up, followed by a five-minute rest period (Figure 5.2). The participant then randomly completed four, 30-second trials at four different SRs (60 strokes per minute (spm), 80 spm, 100 spm, and maximum spm), with a three-minute rest period between trials. These SRs were selected as they are often used in training (60 spm, 80 spm) and in competition (100 spm, maximum spm). Participants started the trial from a static position and were instructed to increase their SR slowly until they reached the intended SR for the trial in approximately ten seconds. For the trial to be analyzed the average SR for the trial's final twenty seconds was required to be within ±5 spm of the intended SR and the kayak speed during this period was required to not change by more than 5% of the average trial speed. Participants were informed of their SR in real time via verbal cues from the lead investigator based on measurements from SR watch (Interval 2000 Split/Rate Watch, Nielsen-Kellerman Co., Boothwyn, PA).

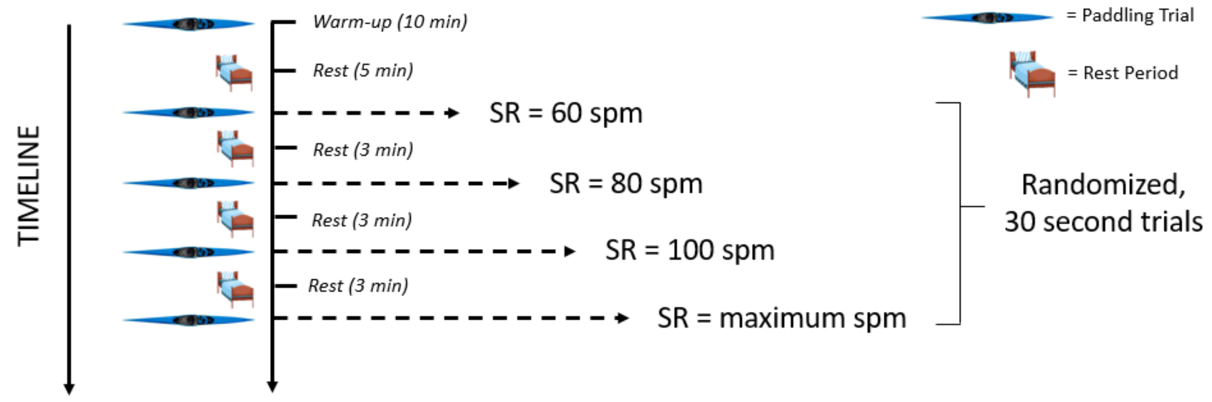


Figure 5.2 The experimental protocol. SR, stroke rate; spm, strokes per minute; min, minutes.

All data were collected in calm environmental conditions (15.9 ± 4.0˚C air temperature, 13.8 ± 2.2˚C water temperature, 1.03 ± 0.91 m•s$^{-1}$ tail wind). Kayak speed, acceleration, and angular velocity data were collected for each trial using a device with an inertial measurement unit (IMU; LMS330DL, STMicroelectronics©, Indiana, USA) and a 5 Hz GPS/GNSS module (LS20030, LOCOSYS Technology Inc., Taipei County, Taiwan). The IMU contained a tri-axial accelerometer measuring acceleration at ±2 g and a tri-axial gyroscope measuring angular velocity at ±2000 degrees per second (˚•s$^{-1}$) over a full-scale dynamic range. Both accelerometer and gyroscope data were sampled at 50 Hz. The device was attached to the kayak using 3M™ Dual Lock™ re-closable fasteners on the midline of the longitudinal axis of the kayak, 0.15 m posterior to the kayak's seat. The mean biases of the accelerometer from the midline of the kayak were 2.2˚±0.9˚, 3.8˚±2.9˚, and 0.2˚±0.7˚ in the forward, lateral, and vertical axes, respectively. The biases were removed from the acceleration signals prior to further analysis. The IMU's coordinate system was as follows. The forward direction was along the positive y-axis, the right lateral direction was along the positive x-axis, and the upward vertical direction was along the positive z-axis. Positive angular rotations followed the right-hand rule, meaning positive roll was the kayak rolling to the right, positive yaw was the kayak yawing to the left, and positive pitch was the kayak's bow pitching in the upward direction.

***Data Analysis***

Kayak acceleration and angular velocity data were filtered using a low-pass, 4th order Butterworth filter at 6 Hz (Holt et al., 2021). Individual single strokes were identified as the peak forward acceleration of each stroke in each trial (MATLAB; *findpeaks* function) (McDonnell et al., 2012). The reciprocal of the elapsed time between each stroke (i.e., stroke time) determined the instantaneous stroke rate. The analysis range included ten consecutive strokes that met the appropriate SR range and constant speed criteria (Figure 5.3). A sensitivity analysis was conducted on a subset of participant trials to ensure the analysis method provided similar results throughout the population. For acceleration and angular velocity variables, the average difference between analysis ranges was 0.003 g and 0.735°•$s^{-1}$, respectively.

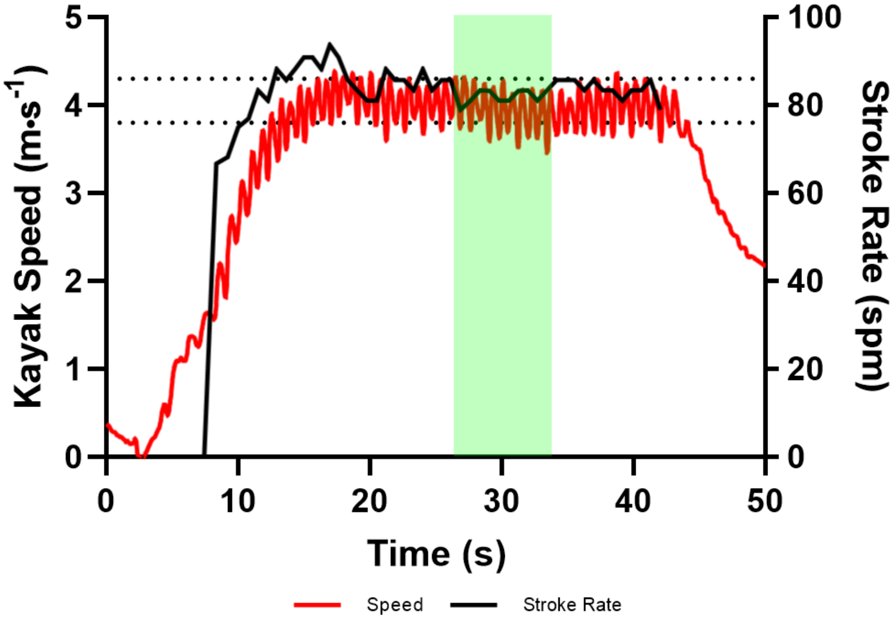


Figure 5.3 Example of an individual participant's trial at 80 spm. The participant's kayak speed and stroke rate is indicated by the solid red and black lines, respectively. The horizontal dotted lines indicate the maximum and minimum stroke rate range for the trial (i.e., 80 ± 5 spm). The green highlighted area indicates the time where the participant met the analysis guidelines, and thus highlights the ten strokes analyzed for the trial. M•$s^{-1}$, meters per second; spm, strokes per minute; s, seconds.

Individual strokes within the analysis range were cut based on specific start and end points. The start of an individual stroke was defined as the first sample after forward kayak acceleration became positive (i.e., greater than 0 g). The end of an individual stroke was defined as the sample before forward kayak acceleration became positive again. Each stroke was then divided into both propulsive and resistive phases. The propulsive phase was defined as positive forward acceleration and the resistive phase was defined as negative forward acceleration (Figure 5.4). All acceleration (i.e., forward, lateral, and vertical) and angular velocity (i.e., pitch, roll, and yaw) variables for each individual stroke were then cut based on the calculated time points. Prior to calculating the impulse, acceleration units were converted from g to $m \bullet s^{-2}$ by multiplying the measured values by 9.81 $m \bullet s^{-2}$. No unit conversion was needed for angular velocity data as those data were collected in degrees per second ($^{\circ} \bullet s^{-1}$).

The magnitude of the impulse for both propulsive and resistive phases were calculated differently between the linear accelerations and the angular velocity waveforms. For the linear acceleration waveforms, the integral of the linear acceleration waveform were calculated in MATLAB (*trapz* function) to determine the magnitude of the impulse for each acceleration variable. For the angular velocity waveforms, the magnitude of the change in angular velocity amplitudes (i.e., impulse) were calculated by subtracting the minimum angular velocity from the maximum angular velocity. The average impulse for all variables were then calculated by averaging the values for all ten individual strokes in the trial. The average impulse was used for statistical analysis. To note, since left and right lateral acceleration, roll, and yaw waveforms are opposite to one another, the left signals were inverted for these movements prior to impulse and range calculations.

A pilot study was completed to determine if critical features found in left and right strokes forward acceleration profiles were equal (Goreham and Ladouceur, 2022). The study showed forward acceleration asymmetry indices of 8.0±11.7% to 19.3±12.4% existed for critical features (i.e., range, minimum, and maximum forward acceleration) combined. A one-way repeated measures ANOVA with linear trend analyses showed all critical feature ASI's increased with SR. However, although asymmetries between left and right strokes existed, further investigation showed left and right stroke acceleration profiles in three planes (forward, lateral, and vertical) were strongly correlated with one another (i.e., Pearson's correlation coefficient between 0.44 and 0.93). Due to the strong correlations and the risk of multicollinearity, it was decided that left and right strokes should be averaged for data analysis for the current study.

For graphical purposes acceleration and gyroscope stroke data were normalized to 100% stroke cycle to show the population's mean waveforms. Kayak speed for the trial was calculated by averaging instantaneous speed over the full analysis range. All data were analyzed in MATLAB (R2022a, MathWorks®, Natick, USA).

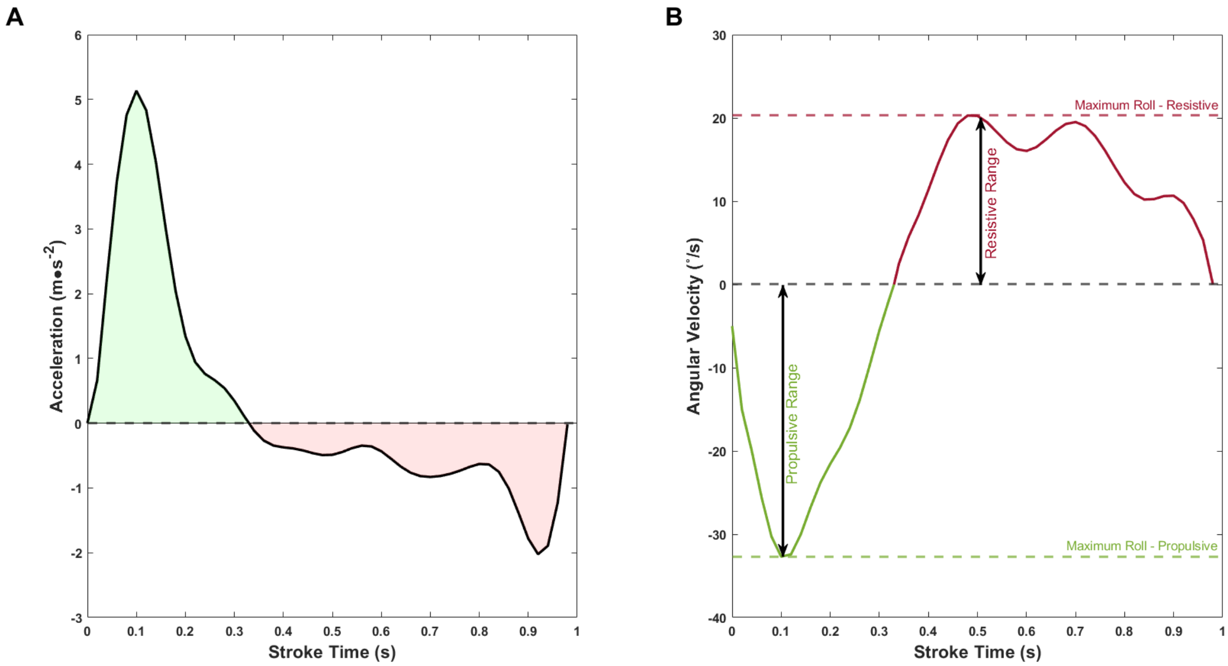


Figure 5.4 Example of a (A) forward acceleration waveform and a (B) roll angular velocity waveform from one individual right stroke. The stroke is divided into propulsive (green) and resistive (red) phases.

### *Statistical Analysis*

Two stepwise regression analyses were conducted to determine the amount each independent variable (i.e., the magnitude of impulse) predicted mean kayak speed during the stroke's propulsive and resistive phases. The assumptions of stepwise regression were all met by ensuring the following. The relationships between each independent variable and kayak speed were linear. Multicollinearity was tested by ensuring the variance inflation factor was below 4 for all independent variables. Normality of residuals were tested using D'Agostino-Pearson omnibus test. Homoscedasticity was tested using predicted kayak speed vs. absolute residual plots. Statistical analysis was conducted in SPSS (version 28.0.1.1 (15), IBM SPSS Statistics, Chicago, IL, USA) and GraphPad Prism 9 (v.9.4.0 (673), GraphPad Software, San Diego, CA, USA).

## Results

Participants spent 42.8±10.1% of the stroke cycle in the propulsive phase. Using the magnitude of impulse for all six DoF, stepwise regression analyses predicted kayak speed in both the propulsive ($R^2$ = 0.659) and resistive ($R^2$ = 0.568) phases of the kayak stroke (

Table 5.1 and Table 5.2). The stepwise regression identified roll, yaw, pitch, and vertical acceleration impulses as significant predictors of kayak velocity during the propulsive phase of the stroke (

Table 5.1). As such, the regression equation (Equation 9) identifying the predictors of kayak speed during the propulsive phase, with the coefficient of each term found in

Table 5.1, can be written as:

Equation 9.

$$\text{Kayak Speed} = 3.517 + 0.019*\text{Roll} + -0.091*\text{Yaw} + 0.061*\text{Pitch} + 1.133*\text{Vertical Acceleration}$$

Table 5.1 Stepwise regression results for the impulse of the propulsive phase of the kayak stroke ($R^2$ = 0.659).

| Variable | Estimate | SE | 95% CI | $\lvert t\rvert$ | $p$-value | VIF | Relative % Contribution |
|---|---|---|---|---|---|---|---|

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Intercept | 3.517 | 0.200 | 3.12 to 3.92 | 17.62 | <0.001** | | |
| Roll | 0.019 | 0.003 | 0.013 to 0.024 | 6.79 | <0.001** | 1.36 | 74.2 |
| Yaw | -0.091 | 0.049 | -0.189 to 0.007 | -1.86 | 0.068 | 1.37 | 13.6 |
| Pitch | 0.061 | 0.021 | 0.019 to 0.104 | 2.91 | 0.005* | 1.22 | 6.1 |
| Vertical Acceleration | 1.133 | 0.432 | 0.267 to 2.00 | 2.62 | 0.011* | 1.30 | 6.1 |

$* \ p < 0.05, \ ** \ p < 0.001$; SE, standard error; CI, confidence intervals; $|t|$, t-statistic; VIF, variance inflation factor; Relative % Contribution, relative contribution to model $R^2$.

The stepwise regression identified yaw, lateral and vertical acceleration impulses as significant predictors of kayak velocity during the resistive phase of the stroke (Table 5.2). As such, the regression equation (Equation 10) identifying the predictors of kayak speed during the resistive phase, with the coefficient of each term found in Table 5.2, can be written as:

Equation 10.

$$\text{Kayak Speed} = 3.70 + 0.191*\text{Yaw} + -0.737*\text{Lateral Acceleration} + -1.035*\text{Vertical Acceleration}$$

Table 5.2 Stepwise regression results for the impulse of the resistive phase of the kayak stroke ($R^2 = 0.568$).

| Variable | Estimate | SE | 95% CI | $\|t\|$ | $p$-value | VIF | Relative % Contribution |
|---|---|---|---|---|---|---|---|
| Intercept | 3.70 | 0.196 | 3.30 to 4.09 | 18.88 | <0.001** | | |
| Yaw | 0.191 | 0.034 | 0.123 to 0.259 | 5.64 | <0.001** | 1.01 | 48.4 |
| Lateral Acceleration | -0.737 | 0.144 | -1.025 to -0.448 | -5.12 | <0.001** | 1.03 | 43.3 |
| Vertical Acceleration | -1.035 | 0.417 | -1.869 to -0.200 | -2.48 | 0.016* | 1.04 | 8.3 |

$* \ p < 0.05, \ ** \ p < 0.001$; SE, standard error; CI, confidence intervals; $|t|$, t-statistic; VIF, variance inflation factor; Relative % Contribution, relative contribution to model $R^2$.

Graphical representation of the predicted vs. actual speed values for both propulsive and resistive phases of the stroke from the stepwise regressions are shown in

Figure 5.5. The normative linear acceleration and rotational angular velocity waveforms are shown in Figure 5.6.

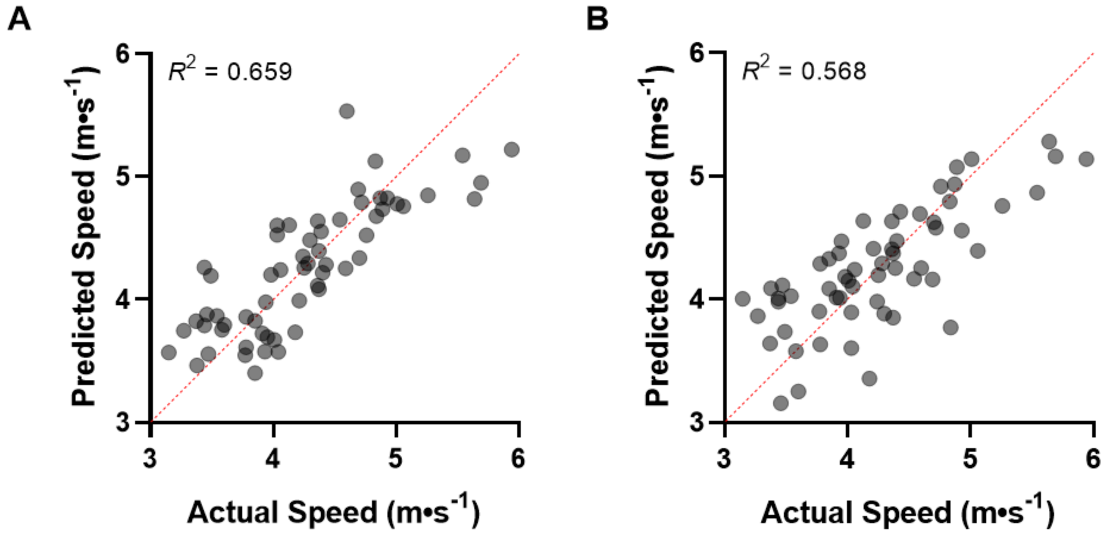


Figure 5.5 Predicted speed (calculated from the stepwise regressions) vs. the actual speed during the (A) propulsive phase and (B) resistive phase of the kayak stroke. Red dashed line, line of identity.

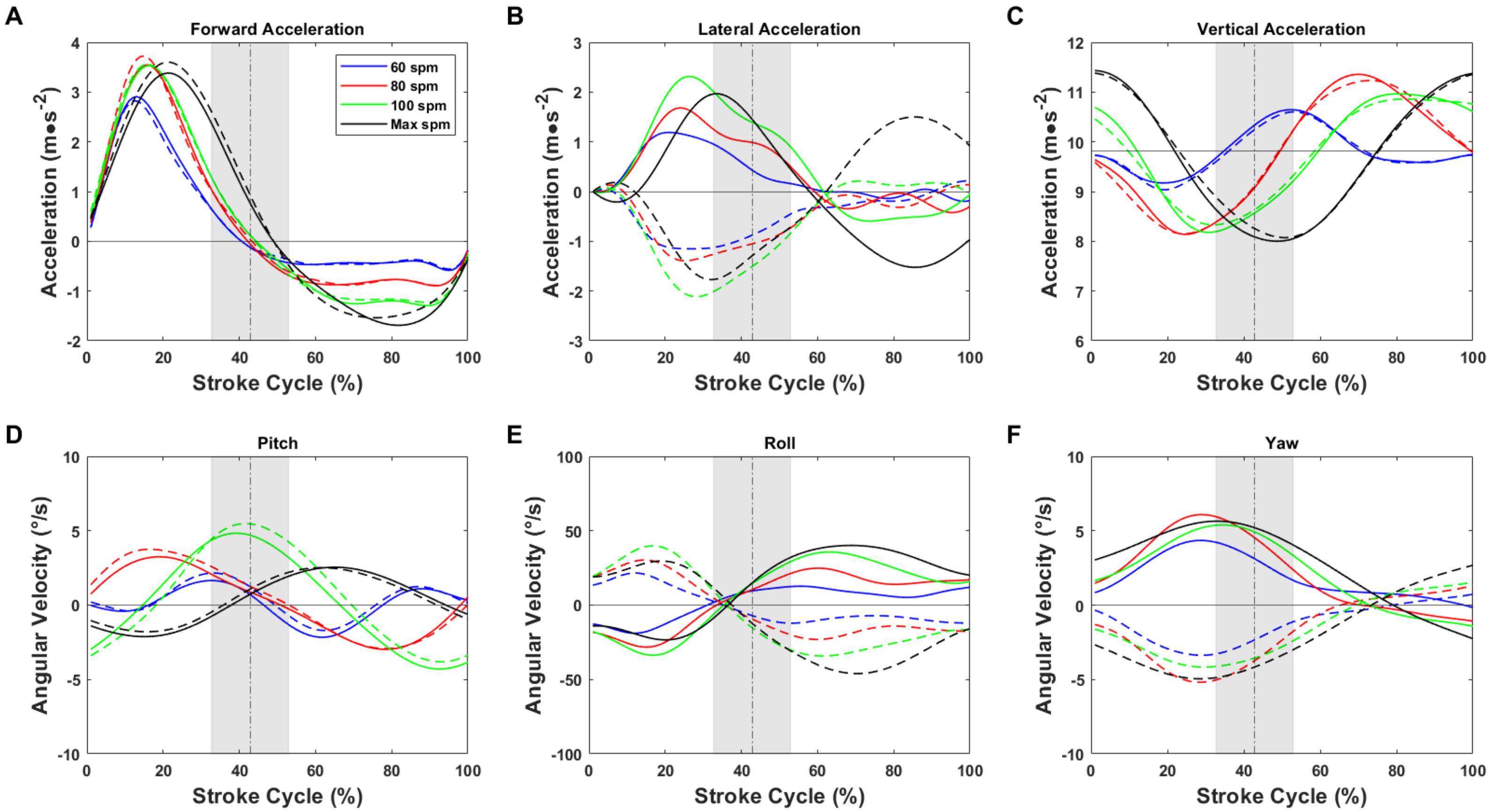


Figure 5.6 Average kayak acceleration (A-C) and angular velocity (D-F) waveforms normalized to stroke cycle for both the right (solid line) and left (dashed line) strokes. Each SR condition is indicated by a different colour line (60 spm = blue, 80 spm = red, 100 spm = green, maximum spm = black). Horizontal dashed-dotted line indicates 0 m•s$^{-2}$ for acceleration panels (or 9.81 m•s$^{-2}$ in the case of vertical acceleration) and 0°•s$^{-1}$ for angular velocity panels. Vertical dotted-dashed line indicates the average end of propulsive phase (and beginning of resistive phase) of the stroke, whereas the vertical grey band indicates ±1 SD.

## Discussion

The results showed that yaw impulse magnitudes were negatively associated with kayak speed during the propulsive phase of the stroke and positively associated with kayak speed during the resistive phase. Interestingly, the magnitude of the vertical acceleration impulses had the opposite effect as yaw (i.e., a positive association with kayak speed during the resistive phase and a negative association during the resistive phase). The magnitudes of the roll and pitch impulses were associated positively with kayak speed during the propulsive phase of the stroke, but not associated with kayak speed during the resistive phase. Lastly, the magnitude of lateral acceleration impulse was only associated negatively to kayak speed during the resistive phase of the stroke. Contrary to our hypothesis, results indicated that forward acceleration impulses did not influence kayak speed in neither phase of the stroke.

Our hypothesis regarding yaw impulse having a negative affect on kayak speed was only partially correct. Specifically, we hypothesized that increased yaw impulse would affect pressure and wave drag, thus having a negative association with kayak speed. Interestingly, this only occurred during the propulsive phase of the stroke, as yaw impulse had a positive affect on kayak speed during the resistive phase. The results suggest correcting the kayak's heading quicker during the resistive phase may have a positive affect on kayak speed (i.e., to reduce yaw impulse).

A similar result occurred with pitch impulse, as greater pitch impulse during the propulsive phase was associated with kayak speed. The increase in pitch movement velocity may be due to faster athletes having more forceful propulsion during their strokes which causes pitch velocity to increase through greater velocity magnitudes. Both pitch and yaw impulses could also be related to the athlete's CoM movements; however, this was not measured in this study and is an important topic to investigate in future research.

Another important result from this research was that roll impulse during the propulsive phase had the greatest contribution to kayak speed (74.2%). Although this was not hypothesized, there seems to be a strong rationale for this result. As mentioned, when discussing pitch above, the faster athlete's greater roll impulse may be explained by their ability to generate greater propulsive forces and power output during the stroke cycle. Rotating the body laterally to apply large forces to the water on one side of the kayak likely causes a roll rotation. The results indicate that paddlers who do this quicker (in the propulsive phase of the stroke) have faster kayak speeds. The reason this was not hypothesized was because this has less to do with resistive forces acting on the overall system, and more to do with overall propulsion. This was an unanticipated, yet interesting result since this study was designed using a hydrodynamic drag lens.

Vertical acceleration impulses were also associated with kayak speed. However, negative vertical acceleration impulses (i.e., the kayak's CoM accelerating downward into the water) had a positive affect on kayak speed during the propulsive phase, which was not expected. A potential explanation for this result has been mentioned above for pitch and roll. As faster athletes apply force to the paddle blade the kayak accelerates deeper into the water. The hypothesized result did occur during the resistive phase though, as greater vertical acceleration impulse (acting upwards) during this phase had a negative affect on kayak speed. This result may be due to more vertical acceleration rebound caused by buoyancy forces, which causes wave generation and subsequently accelerates the kayak upwards instead of forward in the intended direction of travel. The same can be hypothesized for lateral acceleration impulses, as greater impulses in the lateral direction had a negative affect on kayak speed. More movement laterally takes time away from moving forward towards the finish line.

Our approach to solving the relationship between boat kinematics and kayak speed was to use six DoF impulse as a predictor variable. Based on the impulse-momentum theorem, impulse is equal to the change in momentum, and since the mass of the athlete-boat-paddle does not change during the kayak stroke, it can be ignored generating an approximation of the impulse equation. Thus, the primary variable of interest is the change in velocity. Due to the exponential relationship between velocity and drag (Equation 8), the increase in velocity would cause drag to increase during that phase of the stroke, which would reduce the amount of time during the stroke the boat is accelerating in the forward direction. Changes in velocity, or velocity fluctuations, have been shown to have a negative effect on performance in rowing and swimming, and our results suggest that the same is true for some directions and movements in sprint kayaking (Baudouin and Hawkins, 2002; Cuijpers et al., 2017; Morais et al., 2023). Surprisingly, results from our study did not show forward acceleration impulse to have an affect on kayak speed. Based on the literature and theories listed above, we expected athletes with a large catch during the propulsive phase (or a greater rate of force development) to have a negative influence on kayak speed; however, this was not found. Future research should investigate this further.

Furthermore, it should be noted that the predicted model fits the actual kayak speed data worse at lower and higher kayak speeds (Figure 5.5). This may be due to differences in kayak speed within the studied population, and therefore should be tested further. However, it could also be that there is a limit to how well boat kinematics predict kayak speed. For example, it may be possible that at a certain speed more (or less) boat movement does not affect kayak speed and other factors may have greater importance.

The results from this study add to a growing body of literature on hydrodynamic drag in sprint kayaking. In fact, this is the first study to quantify linear acceleration and angular velocity impulse during on-water sprint kayaking. The results also provide meaningful information that can be used in future computational models, as some published studies have assumed boat kinematics stayed constant during on-water paddling when modelling kayak performance (Barros et al., 2021; Gomes et al., 2018; Nakashima et al., 2017; Therrien et al., 2012).

The results from this study generally agreed with what was previously reported by a notational analysis of club, national, and international sprint kayakers during on-water competitions (Brown et al., 2011). Their data reported less skilled athletes had more overall boat motion than their elite counterparts. However, they also reported that club level athletes had more side-to-side rotation (i.e., roll) than the international athletes. It is important to note that our study did not measure absolute kayak movement, and therefore a direct comparison between studies cannot be made. That said, our results indicated more roll impulse was associated with faster kayak speeds during the propulsive phase of the stroke. In other words, faster kayakers have a greater change in roll angular velocity than slower athletes at the start of the stroke cycle. From a technical standpoint and mentioned above, it could be that more powerful athletes generate greater levels of propulsion which causes the boat to roll quicker than less powerful, and potentially slower athletes. That said, our results agree with their findings during the resistive phase of the stroke. It is worth noting that the populations in the two studies were not completely similar, as there were no club-level athletes in the current study.

Researchers are beginning to instrument kayaks with force measuring devices which will help explain the mechanisms behind why the intra-stroke velocity fluctuates during on-water paddling (Bonaiuto et al., 2020; Bugeya Miller, 2021; Klitgaard et al., 2021; Nilsson and Rosdahl, 2016). Our results do not explain the mechanisms; however, they do show the resultant boat kinematics and how they affect kayak performance. Future research should relate both kinematics and kinetics from the athlete, paddle, and kayak to determine methods to modify the specific boat movements that affect performance. Until instrumented kayaks are more prevalent, our study shows IMU's can be used to collect important kinematics data to help improve technique and kayaking performance. Specifically, the IMU can be used to quantify excessive change in kayak velocity, which can be useful for coaches to determine if their feedback to the athlete is affecting change in boat kinematics or not.

### *Limitations*

The data analyzed in this study were collected for only ten strokes during steady state paddling. This may be seen as a limitation as sprint kayak races include a greater number of strokes, at different intensities. Thus, the results do not account for the starting phase of a race nor when the athlete is potentially fatigued during the later portion of the race. It is possible that these portions of the race may show different results. The study also combined data from male and female sprint kayakers, and thus no technique differences due to sex were examined (Baker et al., 1998). Finally, the IMUs used in this study did not contain a magnetometer, and thus instantaneous orientation was not captured. We were able to relate impulse (i.e., change in velocity) to kayak speed; however, due to signal drift when integrating the acceleration and angular velocity waveforms we were unable to obtain the kayak's absolute position, heading, or angle. Future research should attempt to verify our results by measuring position with an IMU.

Fortunately, the normative data we have shown in Figure 5.6 still provides coaches and athletes with a good depiction of National-to-World Class sprint kayakers boat kinematics. These data can be collected with any IMU that contains a tri-axial accelerometer and gyroscope, and inferences on technique can be made.

### *Conclusion*

Boat kinematics variables predict kayak speed differently depending on the phase of the stroke. In the propulsive phase, significant predictors included roll, yaw, pitch, and vertical acceleration impulses. In the resistive phase, kayak speed was predicted by yaw, lateral acceleration, and vertical acceleration impulses. The results of this study will help inform coaches and athletes on which boat kinematics are important to focus on when attempting to increase their kayak speed. Furthermore, this study was the first to provide normative linear and rotational boat kinematics waveforms of fifteen National-to-World Class sprint kayakers. This information can also be used to correct sprint kayaking technique with the goal of enhancing performance.

### Acknowledgements

The authors would like to thank Mitacs and Own the Podium through the Mitacs-Accelerate internship program for their financial support.

## Section 2: The Development of an On-Water Kinetic Measurement System for Sprint Kayaking

The second section of this dissertation includes two validation studies that were completed to develop an on-water kinetic measurement system for sprint kayaking. The first study (*Chapter 6*) was completed to validate a low cost IMU system to eventually measure on-water athlete body kinematics to better understand sprint kayaking technique. The second study in this section (*Chapter 7*) was completed to validate an instrumented paddle to quantify on-water propulsive paddle forces and power output.

# CHAPTER 6: The Validation of a Low-Cost Inertial Measurement Unit System to Quantify Simple and Complex Upper-Limb Joint Angles

Joshua A. Goreham, Kathleen F.E. MacLean, Michel Ladouceur

This chapter is published in the *Journal of Biomechanics*. The author has the appropriate rights to include this article in their dissertation (Appendix C).

Citation:

Goreham JA, MacLean KF, Ladouceur M. The validation of a low-cost inertial measurement unit system to quantify simple and complex upper-limb joint angles. Journal of Biomechanics. 2022 Mar 1;134:111000.

## Abstract

The purpose of this research was to validate the use of a low-cost IMU system to measure upper-limb joint angles by comparing it to passive optical motion capture measures. Fifteen participants (five females; 25.9 ± 4.7 years) completed one trial of four simple range of motion (ROM) movements (elbow flexion/extension, shoulder abduction/adduction, shoulder flexion/extension, and shoulder internal/external rotation), and three complex functional daily tasks [hand to: back pocket (HBP), contralateral shoulder (HCS), head (HTH)]. Movements were measured, simultaneously, using fourteen OptiTrack cameras and five Notch® IMUs. The mean joint angle difference between devices ranged from 0.10˚ ± 3.11˚ for the HBP shoulder internal/external movement to 44.95˚ ± 3.50˚ for the simple ROM shoulder internal/external rotation movement. Nine of sixteen movement and plane comparisons showed significant differences between the device-specific movement cycle waveforms. Eleven of the comparisons showed either fixed and/or proportional biases (fixed only: 9; proportional only: 1; both fixed and proportional: 1). Due to multiple movements having large amplitude errors, low waveform similarities, and/or statistically significant mean differences between the Notch® IMUs and the gold-standard motion capture devices, we cannot recommend that Notch® IMUs are valid devices for measuring upper-limb joint angles during simple ROM and complex functional daily tasks.

Keywords

inertial sensors, wearables, biomechanics, joint kinematics, movement

## Introduction

New state-of-the-art motion capture technologies are being pushed to market at staggering rates. Specifically, inertial measurement units (IMUs) are becoming very popular in clinical and sport settings, as they provide a portable, user-friendly alternative method to measure human movement (Windt et al., 2020). As an emerging and evolving technology, many IMU systems are on the market, with varying reliability, validity, and price points. Therefore, from an ethical standpoint, it is important to validate new IMUs prior to their application in patient healthcare or athletic technique decision-making (Sperlich and Holmberg, 2017).

Although IMUs may be an answer to ensure movement data are collected in ecologically valid settings, they also have limitations. Primary limitations of IMUs are ferromagnetic disturbances (de Vries et al., 2009) and drift errors due to signal integration (Camomilla et al., 2018; Filippeschi et al., 2017) needing appropriate data analysis methods (i.e., filters) to provide accurate IMU data. IMUs are also associated with more kinematic errors (e.g., gimbal lock) when compared with optical motion capture techniques (Filippeschi et al., 2017). These errors are less common when measuring lower body angles because of reduced and less complex range of motion (ROM) and more cyclical motion (Rau et al., 2000). This could be a reason why IMUs have been shown to have increased accuracy in measuring lower body joint angles compared to upper body joint angles (Al-Amri et al., 2018; Cooper et al., 2009; Kluge et al., 2017; Mayagoitia et al., 2002; O’Donovan et al., 2007; Teufl et al., 2018). Within the upper limb, movements measured with IMUs in the sagittal (i.e., flexion/extension) and frontal planes (i.e., abduction/adduction) have shown better validity than in the transverse planes (i.e., internal/external rotation) (Cutti et al., 2008; El-Gohary and McNames, 2012; Ligorio et al., 2017; Morrow et al., 2017; Picerno et al., 2019; Poitras et al., 2019; van Andel et al., 2008). Furthermore, IMU accuracy is also dependent on the task’s complexity (e.g., single plane vs. multi-planar movements, speed of movement, etc.) (Kim and Nussbaum, 2013; Poitras et al., 2019; Walmsley et al., 2018). Finally, to ensure the IMU is measuring the motion of the underlying segment, it is important to relate the sensor’s technical coordinate system to the body’s anatomical coordinate system (i.e., sensor-to-segment calibration).

To combat the issues listed above, many technology companies create their own proprietary algorithms to take the factors listed above into account. This causes a problem for end-users, as it often difficult to confirm the technology's validity prior to using the product. There is a current need to validate these technologies externally to provide end-users the confidence that they are measuring what the device intends to measure. The purpose of this study was to validate Notch® IMUs, a low-cost system (<$500 USD) with smartphone real-time kinematic tracking capabilities, against a criterion-measure. Upper limb 3D joint angle waveform amplitudes and ROM measured using the Notch® were compared to a criterion-measure during both simple, single-planar movements and complex, functional daily task movements.

## Methods

Fifteen healthy adults (five females, 25.9 ± 4.7 years old, 75.2 ± 14.5 kg and 1.731 ± 0.085 m) participated in this criterion validity study, which was approved by Dalhousie University's Research Ethics Board. Participants wore tight fitting clothing and completed one laboratory visit, where upper limb kinematics were collected simultaneously using five IMUs (Notch®, New York, USA) and a fourteen-camera passive optical motion capture system (OptiTrack, NaturalPoint Inc., Corvallis, USA). Data from both devices were sampled at 40 Hz for a duration of 5 seconds. Each participant's right upper limb and thorax were fitted with nine reflective markers located on their xiphoid process, suprasternal notch, 7th cervical vertebrae, 8th thoracic vertebrae, acromion process, lateral and medial epicondyles of the humerus and the radial and ulnar styloids.

Static and dynamic sensor calibrations were conducted prior to beginning each experimental protocol. As per the manufacturer's guidelines, the purpose of these calibrations was to ensure optimal performance in changing environments (i.e., to reduce the potential effect of ferromagnetic materials on the sensor's performance). Each IMU was mounted in a rigid plastic case that was attached to manufacturer-made straps. The strap was then attached to the participant's body segment using overlapping Velcro (Figure 6.1A). An IMU was placed on the right and left forearms and upper arms at 50% of the distance between distal and proximal segment landmarks, and the sternum (Figure

6.1A). Notch® data collection was initiated using the Notch® Pioneer application on an iPhone 8 device (Apple Inc., Cupertino, USA).

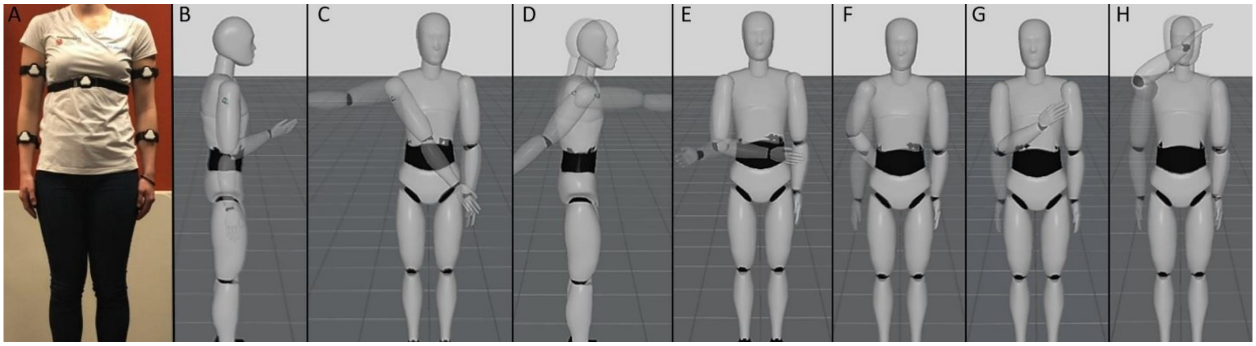


Figure 6.1 Figure showing example of Notch® IMU placement (A), and each of the seven upper body movements analyzed. The movements include B. elbow flexion/extension (EFE), C. shoulder abduction/adduction (SAA), D. shoulder flexion/extension (SFE), E. shoulder internal/external rotation (SIER), F. hand to back pocket (HBP), G. hand to the contralateral shoulder (HCS). H. hand to the top of head (HTH).

A "steady pose" was collected prior to each movement trial where participants stood with feet shoulder width apart, and palms facing their thighs (Figure 6.1A). The purpose of the steady pose was for the Notch® IMUs to collect the body orientation and match it to a predefined skeleton pose within the Notch® algorithms. Starting from the steady pose position, each participant completed one trial of each of the four simple movements and three complex movements using the right arm. Simple movements were defined as movements occurring in only one plane, whereas complex movements occurred in more than one plane (Poitras et al., 2019). The simple movements included: (1) elbow flexion/extension (EFE; Figure 6.1B), (2) shoulder abduction/adduction (SAA; Figure 6.1C), (3) shoulder anterior flexion/extension (SFE; Figure 6.1D), and (4) shoulder internal/external rotation with 0° humerus abduction and 90° elbow flexion (SIER; Figure 6.1E). The complex movements included: (1) hand to back pocket (HBP; Figure 6.1F), (2) hand to the contralateral shoulder (HCS; Figure 6.1G), and (3) hand to the top of head (HTH; Figure 6.1H). All trials were randomized.

Notch® IMUs use proprietary sensor fusion, filtering methods, and algorithms to calculate joint angles. Three-dimensional position data collected using optical motion capture were cubic splined and low-pass filtered (4th order Butterworth filter; cut-off:

8 Hz). Right elbow and shoulder joint angles were calculated using Visual3D software (v6.01.36, C-Motion Inc., Germantown, USA) using standard segment definition and Euler rotation sequences (Wu et al., 2005). Joint angles were measured in the sagittal (flexion/extension), frontal (abduction/adduction), and transverse (internal/external rotation) planes.

Device signals were synchronized by finding similar joint angle magnitudes as signal cut points. For example, the trial start and end points were determined when joint angle acceleration was above (start) and below (end) $50^{\circ}\cdot s^{-2}$. Data were time-normalized to 100% of the movement duration. Both Notch® and criterion-measured angular data offsets were set to 0˚ at trial initiation. Custom MATLAB (R2020a, MathWorks®, Natick, USA) scripts were used for all data analyses. Movement trials for all 15 participants were analyzed except for the HTH movement (n=14; one participant's marker set was corrupt) and the simple SIER movement (n=10; five participants followed an incorrect movement order).

Two separate statistical techniques were used to detect differences in joint angles measured by Notch® IMUs and the criterion-measure with statistical significance ( $\alpha$) set at 0.05. One-dimensional statistical parametric mapping (SPM; spm1d version M.0.4.7; www.spm1d.org) was used to detect significant differences in angle amplitude between devices at 1% time-normalized intervals (Pataky, 2012). A modified Bland-Altman method of differences (Ludbrook, 2010) was used to determine differences between the ROM measured by both devices. All Bland-Altman analyses were conducted in GraphPad Prism (v. 9.0.0., GraphPad Software, San Diego, USA). Data normality were checked using the D'Agostino-Pearson normality test. Non-parametric data were analyzed using the Wilcoxon Signed Ranked test.

## Results

### *Waveform Analysis*

Nine of sixteen movement and plane comparisons showed significant differences between the Notch® and criterion-measured movement cycle waveforms. A significant difference between devices was found in all simple movement waveforms, ranging between 17.9˚ and 40.2˚ (EFE: $P<0.001$; SAA: $P<0.001$; SFE: $P=0.024$; SIER: $P=0.001$;

Figure 6.2). Significant differences between waveforms appeared for 15% or less of each movement cycle.

For the complex movements, the HBP movement (Figure 6.2) showed a significant difference between devices in the EFE plane (32.6˚; *P*<0.001) and the SIER plane (18.7˚; *P*=0.003). The HCS movement (Figure 6.2) showed a significant difference between devices in the EFE plane (16.1˚; *P*<0.001) and the SAA plane (27.6˚; *P*<0.001). The HTH movement (Figure 6.2) only showed a significant difference between devices in the SFE plane (25.9˚; *P*<0.001). Significant differences between waveforms occurred during the maximum joint angle amplitude for all movements and planes, except for HBP SIER, where the difference occurred during the final 10% of the movement cycle.

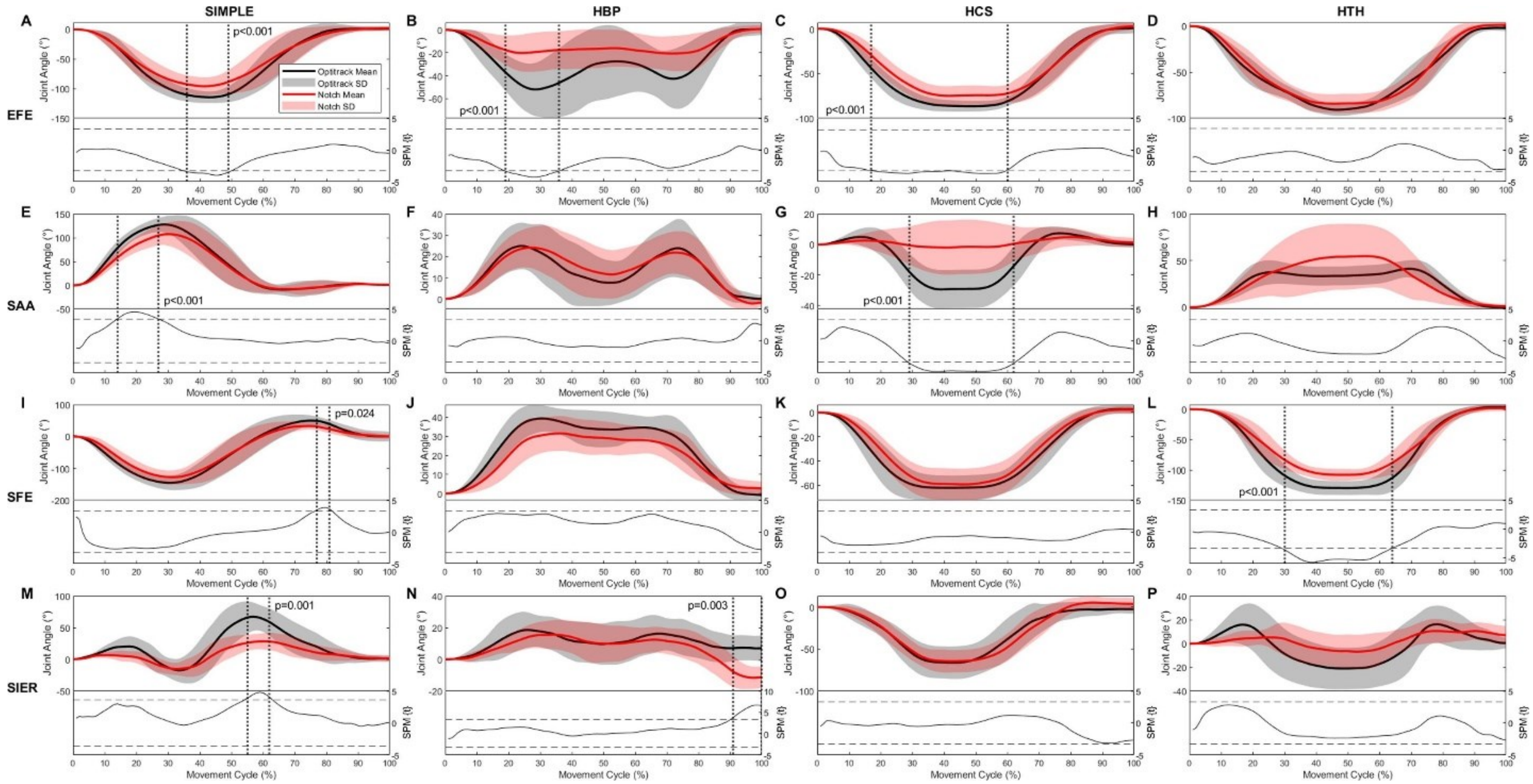


Figure 6.2 Joint angle waveform comparisons between the Notch® and criterion device using statistical parametric mapping. Rows indicate the joint plane being analyzed (e.g., EFE data are shown in panels A, B, C, D), whereas columns indicate the movement being analyzed (e.g., hand to contralateral shoulder (HCS) data are shown in panels C, G, K, O). Thick solid lines indicate the mean joint angle waveform for Notch® (red) and OptiTrack (black). Shaded areas indicate one standard deviation from the mean joint angle waveform. Thin solid line reported below averaged waveforms indicates the SPM *z*-scores, with critical *z*-scores denoted by dashed lines. Vertical dotted lines indicate portion of movement cycle where significant differences between devices exist.

### *Range of Motion Analysis*

Of the 16 movement and plane comparisons, eleven showed either fixed and/or proportional biases between devices (fixed only: 9; proportional only: 1; both fixed and proportional: 1; Table 6.1). All simple movements were shown to have fixed bias, but not proportional bias. The mean ROM difference between devices for the simple movements ranged between 17.55° ± 3.28° (EFE) and 44.95° ± 3.50° (SIER). For the complex movements, HBP had one plane show proportional bias (EFE) and one plane show fixed bias (SFE) between devices. The mean ROM difference between devices for the HBP movement ranged between 0.10° ± 3.11° (SIER) and 8.70° ± 1.58° (SFE). Two planes in the HCS movement showed fixed bias between devices (EFE, SAA), whereas no planes showed proportional bias. The mean ROM difference between devices for the HCS movement ranged between -1.53° ± 4.75° (SIER) and 21.24° ± 4.14° (SAA). The HTH movement had one plane show proportional bias (SAA) and three shoulder planes show fixed bias between devices. The mean ROM difference between devices for the HTH movement ranged between 3.34° ± 3.48° (EFE) and 21.88° ± 3.10° (SFE). In all complex movements, the shoulder joint plane with the greatest average ROM (i.e., primary joint motion) had either proportional or fixed bias. Bland-Altman graphs can be found in the supplementary material (Figure 6.3).

Table 6.1 Bland-Altman method of difference results for Notch® vs. criterion-measured ROM data.

| | Proportional Bias | | | | Fixed Bias | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Condition | *r* | *b* | *P* (OLS) | Proportional Bias? | Mean Difference ± SEM (˚) | 95% CI (˚) | *P* (t-test) | ES | Fixed Bias? |
| S-EFE | 0.44 | -0.42 | 0.1011 | No | 17.55 ± 3.28 | 10.52, 24.57 | 0.0001 | 0.67 | Yes |
| S-SAA | 0.14 | -0.14 | 0.6138 | No | 24.48 ± 4.83 | 14.12, 34.83 | 0.0002 | 0.65 | Yes |
| S-SFE | 0.13 | 0.08 | 0.6463 | No | 34.11 ± 3.81 | 25.95, 42.27 | <0.0001 | 0.85 | Yes |
| S-SIER | 0.33 | 0.17 | 0.3560 | No | 44.95 ± 3.50 | 37.03, 52.87 | <0.0001 | 0.95 | Yes |
| | | | | | | | | | |
| HBP-EFE | 0.64 | 0.82 | 0.0100 | Yes | - | -39.22, 20.98 | 0.5532 | - | No |
| HBP-SAA | 0.47 | 0.40 | 0.0798 | No | 3.05 ± 2.36 | -2.01, 8.10 | 0.2167 | 0.11 | No |
| HBP-SFE | 0.40 | -0.36 | 0.1353 | No | 8.70 ± 1.58 | 5.30, 12.09 | <0.0001 | 0.68 | Yes |
| HBP-SIER | 0.16 | -0.30 | 0.5665 | No | 0.10 ± 3.11 | -6.56, 6.77 | 0.9739 | 0.00 | No |
| | | | | | | | | | |
| HCS-EFE | 0.25 | -0.50 | 0.3624 | No | 9.91 ± 3.18 | 3.09, 16.73 | 0.0076 | 0.41 | Yes |
| HCS-SAA | 0.23 | 0.33 | 0.4103 | No | 21.24 ± 4.14 | 12.35, 30.12 | 0.0002 | 0.65 | Yes |
| HCS-SFE | 0.39 | -0.25 | 0.1463 | No | 3.49 ± 1.97 | -0.74, 7.72 | 0.0983 | 0.18 | No |
| HCS-SIER | 0.18 | 0.23 | 0.5216 | No | -1.53 ± 4.75 | -11.71, 8.66 | 0.7524 | 0.01 | No |
| | | | | | | | | | |
| HTH-EFE | 0.47 | -0.87 | 0.0912 | No | 3.34 ± 3.48 | -4.18, 10.86 | 0.3544 | 0.07 | No |
| HTH-SAA | 0.85 | -1.22 | 0.0001 | Yes | - | 25.51, 78.86 | 0.0001 | - | Yes |
| HTH-SFE | 0.21 | 0.22 | 0.4791 | No | 21.88 ± 3.10 | 15.19, 28.56 | <0.0001 | 0.79 | Yes |
| HTH-SIER | 0.36 | 0.46 | 0.2126 | No | *14.70 ± 14.13* | *10.87, 26.97* | *0.0002* | 0.65 | Yes |

*r*, product-moment correlation coefficient; *b*, ordinary least squares (OLS) slope of the Bland-Altman method of differences plots; *P* (OLS), *P* value for the OLS slope (vs. 0); SEM, Standard Error of Mean; CI, confidence interval; *P* (t-test), *P* value for the one-sample t-test on the mean differences or y-intercept (vs. 0); ES, effect size; $P < 0.05$; *italicized* data calculated from Wilcoxon Signed Rank Test; If no proportional bias present, 95% CI is of mean difference and ES is partial eta squared; If proportional bias present, 95% CI is of y-intercept; S, simple; HBP, hand to back pocket; HCS, hand to contralateral shoulder; HTH, hand to head; EFE, elbow flexion/extension; SAA, shoulder abduction/adduction; SFE, shoulder flexion/extension; SIER, shoulder internal/external rotation.

## Discussion

### *Waveform Analysis*

Significant differences between the Notch® and criterion-measured movement cycle waveforms were present in nine of sixteen movement and plane comparisons. These differences occurred at the maximum amplitude of each movement, except for the SIER plane during the HBP movement. Qualitatively, it seems that Notch® and the criterion-measure did not follow the same waveform patterns for some movements (Figure 6.2); however, these differences in joint angle magnitudes are within the fixed bias reported. Errors at maximum ROM could be due to the absent sensor placement guidelines for the Notch® system. Although the lack of sensor placement guidelines has been noted previously (Walmsley et al., 2018), joint angle measurement accuracy could benefit from them. Furthermore, errors like kinematic crosstalk due to joint axis misalignment (Piazza and Cavanagh, 2000), gimbal lock (Woltring, 1994), and skin motion artefact (Cutti et al., 2008) are common when analyzing upper-limb kinematics (Rau et al., 2000). These errors could also be contributing to the disagreement between the Notch® and criterion-measure.

### *Range of Motion Analysis*

The Notch® system showed proportional and/or fixed biases in eleven movements or planes in comparison to the criterion-measure. Unlike previous research, less fixed bias was present during complex movements compared to simple movements. This may be due to the task instruction, as participants were asked to reach their maximum ROM for the simple movements. In contrast, participants were only instructed to complete the task during complex movements, which may not have required large amounts of ROM. In each of the complex movements, the shoulder joint plane with the greatest average ROM had proportional or fixed bias. These results suggest the Notch® device may be invalid when measuring movements with large ROM. Furthermore, a recent systematic review of the literature concluded that the variability in IMU joint angle errors for the upper limb provide conflicting results (Poitras et al., 2019). The range in joint angle errors were variable between studies and were also dependent on the plane of movement. In the present study, large mean ROM differences were found across all three planes of movement. As kinematic errors associated with the Notch® were not restricted to a single plane of movement, they may be due to a combination of factors such as total ROM, sensor placement, and associated kinematic crosstalk.

The study results are comparable to those shown in previous research. In a similar study, Pérez et al., (2010) validated the commonly used Xsens IMU system against a camera-based criterion measure to determine its ability to measure upper limb joint angles. Mean joint angle errors of 13.4˚, 17.2˚, 60.4˚, and 5.8˚ were reported for simple SFE, SAA, SIER, and EFE movements, respectively. In another study, Robert-Lachaine et al., (2020) measured full-body joint angle limits of agreement between a low-cost IMU system and a camera-based criterion-measure during manual handling tasks. Elbow flexion-extension movements showed joint angle limits of agreement of -11.1 ± 16.2˚, whereas SAA, SFE, and SIER movements were -1.2 ± 26.3˚, 1.3 ± 18.6˚, and -4.3 ± 23.6˚, respectively. An important difference between the current study and the study by Robert-Lachaine et al., (2020) is the types of calibration procedures completed. For example, their device required four different calibration poses, whereas the Notch® device only requires one calibration pose. Previous research has shown the importance of an appropriate calibration procedure when measuring joint angles with IMUs (Ligorio et al., 2017).

### ***Limitations***

There are three primary limitations to this research. As no data analysis or algorithm information is provided by Notch®, the first limitation is that it is possible the rotation sequences and the anatomical frame definitions selected for the criterion-measure analysis did not match the Notch® methods. This could account for some differences between modalities. To minimize the effect of these factors, we used the Euler rotation sequence that provided joint angles that best matched the Notch® joint angle data (i.e., elbow: ZXY; shoulder: YXZ). This often meant that the first axis rotation was set to be the axis with the movement's largest ROM. However, it should be stressed that Notch® algorithms are proprietary and we believed the next best approach was to use the best match between joint angles. The second limitation is that the trials were only 5 seconds in duration, which does not address the potential for signal drift. Therefore, the results of this study must only be implemented for short duration movements. Future research should investigate the amount of drift present in longer duration movements. The final limitation is that Notch® could change their proprietary joint angle calculations, thus the results of this study would need to be reconsidered. However, there is a possibility this could happen with all technology that relies on firmware updates. Therefore, it is important for end-users to be cognizant of these changes prior to collecting and interpreting data.

### *Conclusion*

The Notch® IMU system showed both proportional and fixed biases in joint angle ROM during simple and complex tasks, and significant differences in 9 of 16 movements and planes when comparing upper-limb angle movement waveforms against criterion-measure waveforms. The results indicated that the Notch® IMU system showed more fixed bias for simple movements and more errors during movements with larger ROM. The differences in measured upper-limb angles between Notch® IMUs and the optical motion capture system varied considerably depending on the movement, joint, and plane being measured. These results should be considered when using Notch® IMUs to measure upper-limb joint angles in research or applied settings.

### Acknowledgements

The authors would like to acknowledge funding from Mitacs (Accelerate Fellowship), Own the Podium (Innovation for Gold program), and the Nova Scotia Graduate Scholarship. The study sponsors were not involved in the study design, in the collection, in the analysis or interpretation of the data, in the writing of the manuscript or in the decision to submit the manuscript for publication. The results of the current study do not constitute endorsement of the product by the authors or the journal.

### Disclosure of Interest

The authors report no conflicts of interest. There has been no financial support for this work that could have influenced its outcome.

## Supplementary Material

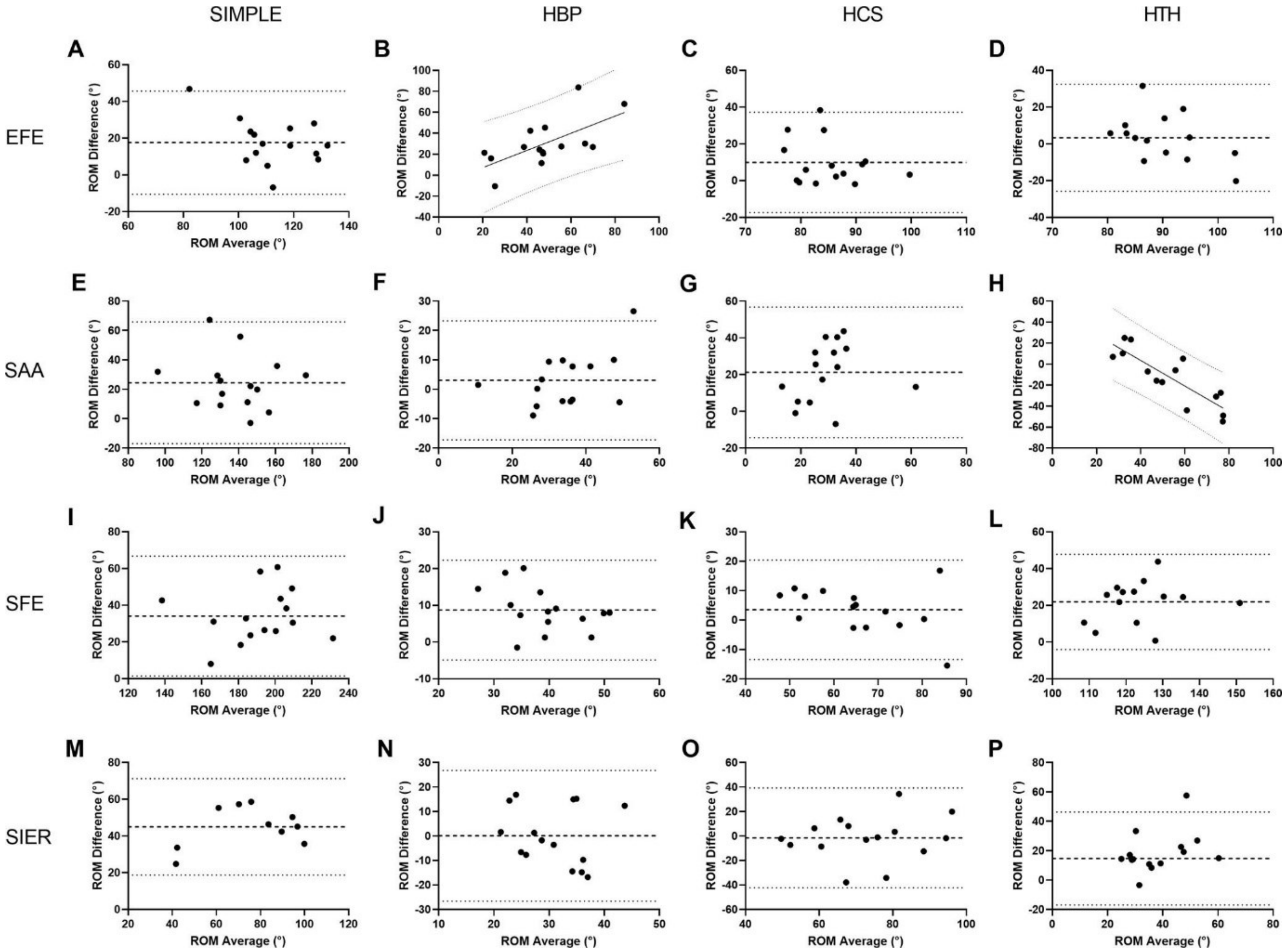


Figure 6.3 Bland-Altman method of difference analysis plots for Notch® vs. criterion-measured ROM data. Rows indicate the joint plane being analyzed (e.g., EFE data are shown in panels A, B, C, D), whereas columns indicate the movement being analyzed (e.g., hand to contralateral shoulder (HCS) data are shown in panels C, G, K, O). For conditions with no proportional bias the mean difference in ROM between devices and the upper and lower 95% confidence limits are represented with a dashed line and dotted lines, respectively. For conditions with proportional bias the OLS line of best fit is represented by a solid line with 95% predictive limits in smaller dotted lines. Positive y-axis values indicate the criterion device having a greater ROM than the Notch® device. EFE, elbow flexion/extension; SAA, shoulder abduction/adduction; SFE, shoulder flexion/extension; SIER, shoulder internal/external rotation; SIMPLE, simple movements; HBP, hand to back pocket; HCS, hand to contralateral shoulder; HTH, hand to top of head.

# CHAPTER 7: The Validation of a Commercial Wireless Power Meter for Sprint Kayaking

Joshua A. Goreham, Ryan J. Frayne, Kayla Bugeya Miller, Michel Ladouceur

## Abstract

Purpose: Two experiments were used to determine the construct and concurrent validity of a commercial kayak paddle shaft power meter (OGL) for measuring force and power output in female sprint kayakers. Methods and Results: *Construct validity:* Seven female participants used the same OGL paddle to complete 30-second trials at different stroke rates (60, 80, 100, maximum strokes per minute) while a global positioning system measured kayak velocity. Regression analysis provided a large coefficient of determination ($R^2 \geq 0.83$) between mean power and mean velocity ($f(x) = 6.892x^3$). *Concurrent validity:* Two known weight combinations were used to calibrate the paddle (wide range: 51.5-394.9 N; narrow range: 100.6-247.7 N), whereas both left and right sides of the shaft were statically loaded eight separate times with known weights (51.5 N to 394.9 N at 49.1 N intervals) to test its concurrent validity. The right side of the shaft had proportional bias ($p<0.001$) and the left side of the shaft had fixed bias (65.7±21.1 N, $p=0.017$) when calibrated with a narrow range. Neither shaft side had proportional bias, but both shaft sides had small, fixed biases (left: -18.3±7.4 N, $p=0.043$; right: -9.3±3.0 N, $p=0.018$) when calibrated with a wide range. Conclusion: the study establishes that even though the OGL reports power values that appear to have construct validity up to $4.6\text{m}\bullet\text{s}^{-1}$, calibration with a range of weights that encompasses the projected applied forces is needed to improve the accuracy of the force measurement, and thus the power calculation, by the OGL.

Keywords: power, force, elite, female, athletes, on-water

## Introduction

As innovative technology becomes available, on-water measurement of paddle forces and power are becoming popular in sprint kayaking. These measurements are highly beneficial to performance evaluation because they quantify the mechanical workload required to be successful, while other external variables may be affected by changes in the environment (i.e., velocity, stroke rate (SR), etc.) (Hogan et al., 2020a). Power output is often measured in other cyclical sports; however, it remains uncommon in on-water sprint kayaking even though average power output is related to an increase in sprint kayaking performance on a kayak ergometer (Bishop et al., 2002; Michael et al., 2009, 2008). Researchers and practitioners have been searching for a tool to measure on-water propulsive forces from a kayak paddle since at least the 1980's (Stothart et al., 1986). There have been many iterations of instrumented paddles and power meters, but no single paddle is widely accepted as a gold standard. One study suggested that a lack of products available with an "acceptable level of validity" was the primary reason (McDonnell et al., 2013). For the interpretations of values from a measurement system, and inferences based on these measurements to be meaningful, it is critical that the evaluation measures demonstrate acceptable validity and reliability. There are several types of measurement validity, and this research focuses on construct and concurrent validity. Establishing the degree to which a measure assesses the hypothetical construct it is intended to reflect is central to construct validity. Whereas, comparing the measured values to a known "gold standard" is the tenet of concurrent validity.

Multiple recent studies have used a specific power meter (Kayak Meter Pro, One Giant Leap (OGL), Nelson, NZ) to measure the propulsive force and power of a sprint kayak stroke (Hogan et al., 2021, 2020b, 2020a; Kong et al., 2020; Macdermid et al., 2019; Winchcombe et al., 2019). The OGL paddle has six strain gauges and an inertial measurement unit, which calculate force output and power using proprietary algorithms (Winchcombe et al., 2019). The exact use of the paddle varies between studies, but it is commonly used to monitor training load, physiological testing (Hogan et al., 2021, 2020b, 2020a; Macdermid et al., 2019; Winchcombe et al., 2019), and/or kayak stroke kinetics (Kong et al., 2020). Macdermid and Fink (2017) established the construct validity of the OGL paddle by comparing its measurements to the cubic relationship between power output and velocity in aquatic locomotion (Barbosa et al., 2010; Di Prampero et al., 1974; Michael et al., 2009). This relationship can be explained further by reducing the equation of power. To increase kayak velocity, the kayaker must overcome the hydrodynamic drag forces resisting the athlete-kayak-system; therefore, increasing the overall power output. Since power is equal to force multiplied by velocity, we can substitute drag force into the equation. Drag force ($D_F$) is equal to Equation 11,

Equation 11. $$D_F = {}^1/_2 \rho A K v^2$$

where $\rho$ is equal to water density, $A$ is kayak surface area, $K$ is drag coefficient and $v$ is velocity. By multiplying both sides of the equation by $v$, power (P) becomes Equation 12,

Equation 12. $$P = {}^1/_2 \rho A K v^3$$

which makes it proportional to velocity cubed (Macdermid and Fink, 2017).

Unfortunately, the study looked at the power meters in slalom kayak training, and thus may not be transferable to elite level sprint kayaking (Hogan et al., 2021, 2020b, 2020a; Kong et al., 2020; Winchcombe et al., 2019). For example, the low on-water paddling velocities collected during their validation (i.e., maximum velocity of 2.49 $m \cdot s^{-1}$) are well below that of race velocities for female 200 m sprint kayakers ($4.95 \pm 0.46$ $m \cdot s^{-1}$) (Goreham et al., 2021). Furthermore, the study used a narrow range of known forces during their experiment, with only three known weights tested to a maximum of 155.9 N. This amount of force is significantly lower than the mean peak forces applied to the water by elite sprint kayakers at velocities of $4.14 \pm 0.25$ $m \cdot s^{-1}$ ($301.1 \pm 23.1$ N) (Bonaiuto et al., 2020).

The purpose of this study was to determine the OGL power meter measurement validity for on-water sprint kayak. A first experiment extended the construct validity of the OGL power meter by including velocities that are comparable to levels found in sprint kayak. It was hypothesized that the OGL paddle's mean power output would have a strong cubic relationship with mean kayak velocity. If found to have acceptable construct validity, a second experiment determined the concurrent validity of the paddle force measurements. It was hypothesized that the OGL paddle's force outputs would not be significantly different from applied known weight forces. Finally, a supplementary data acquisition was carried-out to determine if a wider range of calibration weights would provide better concurrent validity than the suggested range of calibration weights.

## Methods

### *Construct Validity*

### *Participants*

Seven elite female sprint kayak athletes (21.6 ± 4.6 years old, 1.69 ± 0.04 m, 66.8 ± 5.4 kg, 12.7 ± 5.1 years of kayaking experience) participated in the construct validity portion of the study. All participants consented to participating in the study in accordance with Dalhousie University's Research Ethics Board (No. 2020-5127).

### *Experimental Protocol*

Data were collected on a marked 1000 m sprint kayak racecourse with participants using their personal kayaks and a short, stiff OGL power meter with Brača IV (765) blades. The paddle was calibrated with two known weights (i.e., 100.6 N and 247.7 N) as per the manufacturer's guidelines. Prior to testing the distances between the blade tips and middle knuckles of each hand, blade tip to blade tip, blade tip to shaft datums, the blade twist, and the blade type were recorded in the OGL web application. The experimental protocol began with a ten minute, individual-led warm-up, followed by a five-minute rest period. The participant then completed four, 30-second trials at four different SRs (random order: 60 strokes per minute (spm), 80 spm, 100 spm, and maximum spm), with a three-minute rest period between trials (Figure 7.1A). These SRs were selected as they are often used in training (60 spm, 80 spm) and in competition (100 spm, maximum spm). Participants started the trial from a static position and were instructed to increase their SR slowly until they reached the intended trial SR (within 10 seconds). The average SR during the final twenty seconds of the trial was required to be within ±5 strokes per minute of the intended SR to be analyzed.

All data were collected in calm environmental conditions (15.8 ± 3.5˚C air temperature, 14.3 ± 2.1˚C water temperature, 0.73 ± 0.51 m•s$^{-1}$ tail wind). OGL paddle data were collected using a Samsung Galaxy Tab S2 tablet with OGL's web-based software. Force and power output from the paddle was measured at 50 Hz during each stroke's water phase. Kayak velocity data were collected for each trial using an inertial measurement unit (IMU; LMS330DL, STMicroelectronics$^{©}$, Indiana, USA) with a 5 Hz GPS/GNSS module. The IMU was attached to the kayak using Velcro on the midline of the longitudinal axis of the boat, 0.15 m posterior to the kayak's cockpit. The IMU contained a tri-axial accelerometer measuring acceleration at ±2 g over a full-scale dynamic range. Accelerometer data were sampled at 50 Hz and peak-detection algorithms were used to calculate SR.

### ***Data Analysis***

Power output data were obtained during ten stroke cycles (i.e., five strokes on the left side and five strokes on the right side) while paddling at the trial's intended SR. Mean power output was subdivided into three groups: the mean power of ten strokes, and the mean power of five left and five right strokes separately. Mean kayak velocity was calculated by averaging the kayak's velocity in the forward direction between the catch of the first stroke to the catch of the eleventh stroke.

### ***Statistical Analysis***

The mean stroke power as a function of mean kayak velocity was used to establish the construct validity of the OGL paddle. As such, a linear regression between mean power output and mean velocity with no squared or linear component, and a $y$-intercept of 0 was calculated for all ten strokes and the left and right strokes separately. A coefficient of determination ($R^2$) was used to determine the goodness of fit for each linear regression (Chicco et al., 2021). Statistical analyses were conducted in GraphPad Prism software (v.9.1.0, GraphPad Software, San Diego, USA).

### ***Concurrent Validity***

### ***Paddle Calibration Procedure***

The OGL power meter with Brača IV (765) blades was set up according to manufacturer's guidelines (i.e., zero offset and scale factor) and calibrated using a narrow and wide weight range. The known weights used for the narrow weight calibration were

100.6 N (10.25 kg) and 247.7 N (25.25 kg), whereas the known weights for the wide weight calibration were 51.5 N (5.25 kg) and 394.9 N (40.25 kg). The paddle shaft was placed horizontally on two fulcrums with one fulcrum supporting the top hand position and the other fulcrum supporting the blade centre. Weightlifting plates were suspended at the bottom hand position with a small rope and metal carabiners (mass: 0.25 kg). Measurement lengths of 0.880 m, 0.345 m, 0.240 m, 1.330 m, 0.780 m, and 2.110 m were used for the blade tip to datum, datum to datum, blade tip to blade support, blade tip to shaft support, blade tip to calibration weight, and blade tip to blade tip, respectively. The blade twist was set to 60° right hand twist for both validations. All measurements were recorded in the OGL web application.

### ***Experimental Protocol***

Concurrent validation testing of the OGL power meter was conducted on both the right and left shaft sides, after each (narrow and wide) calibration procedures. Eight known weights (ranging from 51.5 N to 394.9 N, separated by 49.1 N increments) were hung at hand positions on both right and left shaft sides in a randomized order (Figure 7.2A). The weights were suspended using the same attachment system and locations used during the calibration procedure. All trials were recorded at 50 Hz and for 10-seconds.

### ***Statistical Analysis***

A linear regression was completed between the measured OGL paddle forces and the applied known weights (i.e., criterion measure). The linear regression's coefficient of determination was calculated for the left and right shaft sides and calibration type. Bland-Altman method of differences analyses were completed to determine if fixed and proportional bias were present in the force measurements (Ludbrook, 2010). The presence of proportional bias was determined by using an ordinary least square regression (OLS) and using an $F$ test to determine if the slope of the method of differences data was significantly different than '0'. If proportional bias was present, then fixed bias was determined using an $F$ test to establish if the y-intercept of the OLS regression between methods was different from '0' (Ludbrook, 2010). If there was no proportional bias, then fixed bias was determined using a one-sample t-test comparing mean difference between methods data to '0', and effect sizes were measured using partial eta squared ($\eta^2$)

(Ludbrook, 2010). Bland-Altman analyses were conducted in GraphPad Prism. All datasets were confirmed to follow normal distributions based on D’Agostino-Pearson normality tests. Statistical significance (critical $\alpha$) was set at 0.05.

## Results

### *Construct Validity*

The on-water construct validity experiment results for mean SR, velocity, force, and power output for all strokes, and left and right shaft sides are shown in Table 7.1. The coefficient of determination ($R^2$) value from the linear regression (cubic relationship: Power=$x \bullet v^3$) between mean paddle power and mean velocity, was 0.83 (individual range: 0.83 to 0.99; RMSE=70.9) for all ten strokes (Figure 7.1B) and was 0.85 (RMSE=68.7) for the left side of the shaft and 0.75 (RMSE=89.4) for the right side of the shaft (Figure 7.1C). The coefficient value ± standard error of measurement (SEM) and the 95% confidence intervals (CI) of the combined shaft linear regression equation ($x$) were 6.892 ± 0.183 (CI: 6.517 to 7.268). The coefficient values ± SEM (and 95% CI) for the left and right shafts regressions were 7.104 ± 0.177 (CI: 6.740 to 7.461) and 6.681 ± 0.231 (CI: 6.207 to 7.154), respectively). Furthermore, the uncertainty in the regression model was not discussed together with the minimum meaningful error that the authors are willing to accept for different ranges of power and velocity.

Table 7.1 Average stroke rate, velocity, force, and power outputs, and maximum force output measured in all and left and right strokes during on-water construct validation.

| Variable | 60 spm | 80 spm | 100 spm | Maximum spm |
|---|---|---|---|---|
| Stroke Rate (spm) | 61.90 ± 1.89 | 83.02 ± 1.96 | 101.53 ± 2.78 | 124.04 ± 12.83 |
| Velocity (m•s$^{-1}$) | 3.42 ± 0.14 | 3.89 ± 0.06 | 4.32 ± 0.08 | 4.61 ± 0.22 |
| Mean Power All Strokes (W) | 297.7 ± 57.5 | 416.8 ± 64.2 | 536.7 ± 93.7 | 669.4 ± 174.4 |
| Mean Power Left Strokes (W) | 313.4 ± 57.1 | 434.9 ± 57.8 | 549.1 ± 100.3 | 685.1 ± 181.4 |
| Mean Power Right Strokes (W) | 282.0 ± 71.5 | 398.6 ± 87.7 | 524.2 ± 105.7 | 653.7 ± 177.9 |
| Mean Force All Strokes (N) | 168.0 ± 51.8 | 185.3 ± 55.4 | 203.4 ± 64.2 | 207.0 ± 69.4 |
| Maximum Force All Strokes (N) | 270.8 ± 84.8 | 284.4 ± 86.9 | 307.7 ± 93.4 | 320.0 ± 101.6 |

Mean or maximum ± standard deviation; spm, strokes per minute; m•s$^{-1}$, meters per second; W, watts; N, Newtons.

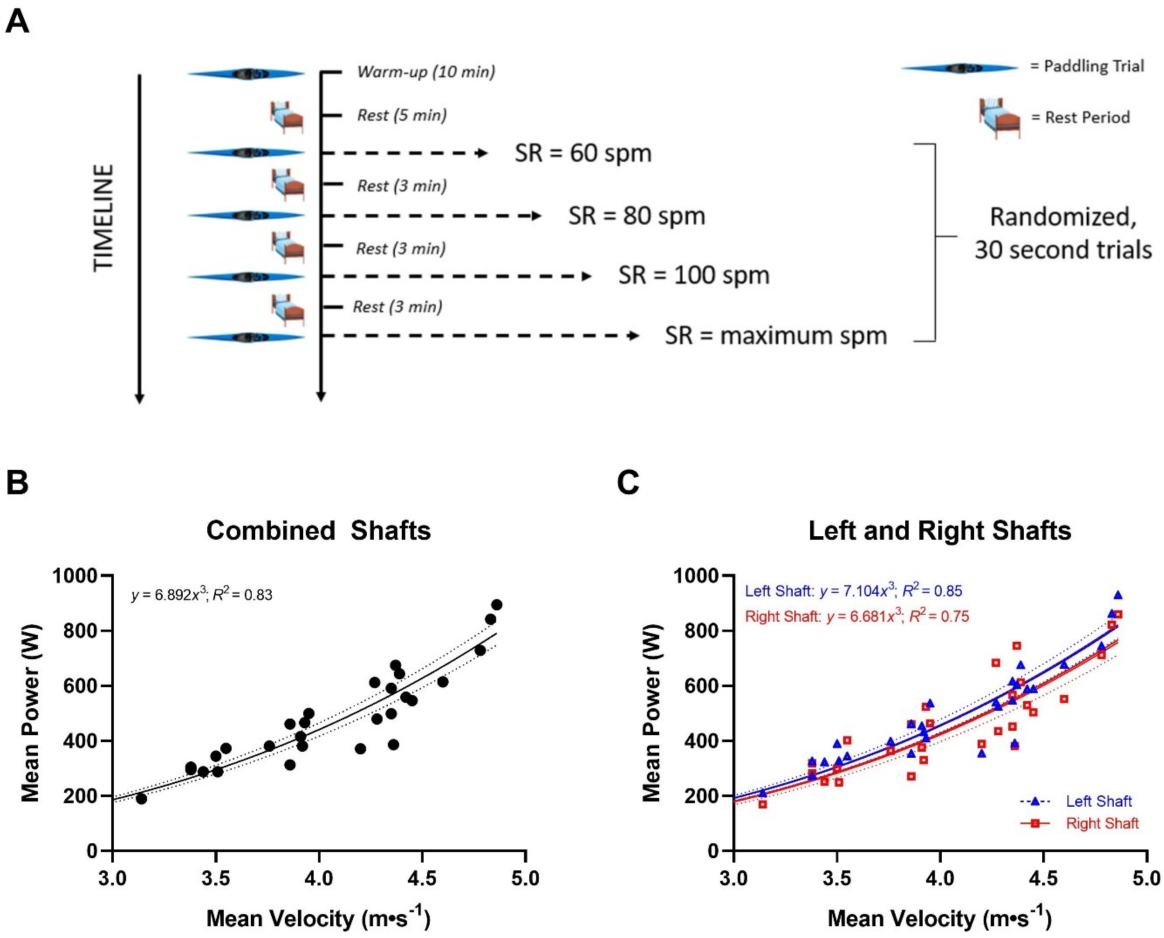


Figure 7.1 A. The experimental protocol for the construct validation portion of the study. SR, stroke rate; spm, strokes per minute; min, minutes. Mean velocity vs. mean power outputs measured from (B) the average of all ten strokes (circles) and (C) the right (squares) and left (triangles) shaft sides, separately. Red and blue lines indicate the cubic function's line of best fit for the right and left sides of the shaft, respectively. Dotted lines indicate 95% confidence bands. $R^2$, coefficient of determination; W, watts; m•s$^1$, meters per second.

### *Concurrent Validity*

The slopes of the linear regression analyses (Measured Force=$x$•Known Force+constant) from the wide weight range calibration were the closest to the optimal slope of 1, with mean slopes ± SEM (and 95% CI) of 0.98 ± 0.03 (CI: 0.91 to 1.04) for the right side of shaft and 0.95 ± 0.07 (CI: 0.78 to 1.11) for the left side of shaft (Figure 7.2D and Figure 7.2E). The mean slopes ± SEM (and 95% CI) of the linear regression analyses from the narrow weight range calibration were larger (left side of shaft = 1.25 ± 0.17 (CI: 0.83 to 1.68); right side of shaft = 1.31 ± 0.06 (CI: 1.17 to 1.44) than the wide calibration (Figure 7.2B and Figure 7.2C). The mean $y$-intercept values ± SEM (and 95% CI) of the linear regression analyses were -12.73 N ± 14.05 (CI: -47.12 to 21.65) for the right side of shaft and 9.93 N ± 43.29 (CI: -96.0 to 115.9) for the left side of shaft for the narrow calibration, and -3.75 N ± 6.81 (CI: -20.41 to 12.92) for the right side of shaft and -6.23 N ± 16.9 (CI: -47.59 to 35.12) for the left side of shaft for the wide calibration (Figure 7.2B-E). The Bland-Altman method of differences identified that the narrow calibration right side of the shaft condition was the only condition to display proportional bias and the only condition to have no fixed bias (Table 7.2).

Table 7.2 Bland-Altman method of difference results for known force vs. OGL-measured force.

| | Proportional Bias | | | | Fixed Bias | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Force Range - Shaft | *r* | *b* | *P* (OLS) | Proportional Bias? | Mean Difference ± SEM (N) | 95% CI (N) | *P* (t-test) | ES | Fixed Bias? |
| Narrow – Right | 0.93 | 0.27 | <0.001 | Yes | - | -41.7, 16.6 | 0.397 | - | No |
| Narrow – Left | 0.66 | 0.28 | 0.076 | No | 65.7 ± 21.1 | 15.9, 115.5 | 0.017 | 0.58 | Yes |
| Wide – Right | 0.31 | -0.02 | 0.448 | No | -9.3 ± 3.0 | -16.4, -2.2 | 0.018 | 0.57 | Yes |
| Wide – Left | 0.23 | -0.04 | 0.588 | No | -18.3 ± 7.4 | -35.8, -0.8 | 0.043 | 0.47 | Yes |

Narrow force range, 100.6 N to 247.7 N; Wide force range, 51.5 N to 394.9 N; *r*, product-moment correlation coefficient; *b*, ordinary least squares (OLS) slope of the Bland-Altman method of differences plots; *P* (OLS), *P* value for the OLS slope (vs. 0); SEM, Standard Error of Mean; CI, confidence interval; *P* (t-test), *P* value for the one-sample t-test on the mean differences or y-intercept (vs. 0); ES, effect size; $P < 0.05$; If no proportional bias is present, 95% CI is of mean difference and ES is partial eta squared; If proportional bias present, 95% CI is of y-intercept.

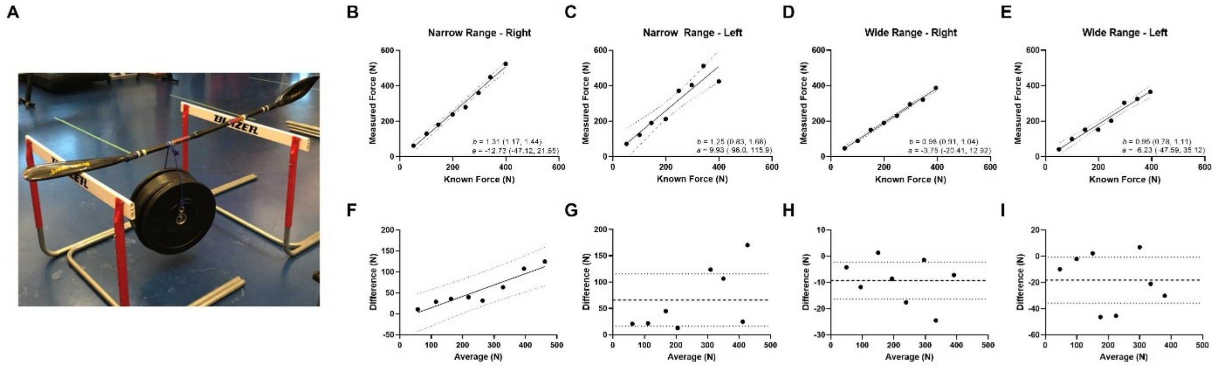


Figure 7.2 An example of the concurrent validation experimental setup. A. An example of the concurrent validation experimental setup. Linear regression data (Panels B-E) and Bland-Altman method of differences data (Panels F-I) between known forces and OGL-measured forces for the left and right shaft sides for both calibrations (narrow force range: 100.6 N to 247.7 N, and wide force range: 51.5 N to 394.9 N). *a*, y-intercept; *b*, slope; numbers in parentheses, 95% confidence intervals.

## Discussion

This study aimed to validate the OGL power meter paddle because of its increased usage during sprint kayak training (Hogan et al., 2020a; Winchcombe et al., 2019). The results showed that the OGL power meter had both fixed and proportional bias when comparing measured forces to known forces under static loading conditions. However, only fixed bias was present when the paddle was calibrated with a wider calibration range compared to fixed bias or proportional bias when calibrating using a narrower range. Furthermore, the mean difference between the known and measured forces were approximately 3 to 7 times more when the paddle was calibrated with the narrow range of weights. Therefore, it can be argued that a mean error of approximately 10 to 20 N is small and can be used by athletes in training. As such, the calibration range should encompass the expected force ranges produced by the athletes being tested. Although the results showed the OGL paddle to have both construct and concurrent validity (when calibrated with a wide range of forces), it also showed the importance of considering the calibration procedures prior to collecting data with athletes.

The results from this study also showed that there was a strong cubic relationship between the OGL paddle's mean power output and the athlete's mean kayak velocity during on-water testing. However, an important concept to consider is the construct validity does not validate the absolute power values. The construct validity results indicate that the OGL power meter results match what is expected from the cubic power-velocity relationship. Based on the concurrent validity results, if the power meter is not calibrated with an appropriate range of weights, the measured forces may have a large bias. Since power is calculated from the measured forces, the power measurements will also be biased. This concept is also relevant for the research by Macdermid and Fink (2017).

This study conducted similar concurrent and on-water construct validation protocols as Macdermid and Fink (2017). A crucial difference between studies was the inclusion of elite female sprint kayakers during the on-water construct validity assessment. For example, they showed the OGL paddle was a valid tool to measure mean power output while paddling at low kayak velocities (i.e., <2.5 m•s$^{-1}$), whereas our study showed the OGL paddle was valid at higher velocities (i.e., between 3.42 ± 0.14 and 4.61 ± 0.22 m•s$^{-1}$) (Macdermid and Fink, 2017). Secondly, the coefficient of determination of the cubic relationships between mean power output and mean kayak velocity was slightly greater in their study ($R^2 = 0.98$) compared to the current study ($R^2 = 0.83$). The difference between studies may be due to the number of participants tested. Our study tested seven elite female sprint kayakers, whereas their study tested a single male participant. Other factors that may have influenced the coefficient of determination differences may have been the athlete's kayaking technique and anthropometrics. The current study is an extension of the previously published data, as the OGL paddle's power output is now validated to velocities more appropriate to elite sprint kayakers (approximately 4.6 m•s$^{1}$). Future research should investigate this relationship at paddling velocities reaching 5.81 ± 0.54 m•s$^{-1}$ (Goreham et al., 2021), such as elite male K1 200 m sprint kayakers.

The current study and Macdermid and Fink (2017) both used static known weights to assess concurrent validity; however, the current study had eight weight trials and a larger maximal weight (394.9 N) compared to three known weights and a maximum weight of 155.9 N (Macdermid and Fink, 2017). These differences may explain why they identified a strong relative agreement between the known and measured forces with mean difference errors between 0.12% and 1.4%, while the current study identified greater absolute mean differences (Table 7.2) (Macdermid and Fink, 2017). In relative terms, the mean difference errors in the current study were between 0.9-11.7% for the right side of the shaft and 2.3-23.4% for the left side of the shaft.

Although no analytical goal was chosen for this study, multiple studies investigating other technology's validity (e.g., IMU and GPS) have stated a mean percentage difference less than 5% is good, whereas percentages between 5-10% are moderate, and any value above 10% is poor (Brosnan et al., 2021; Crang et al., 2021). Again, it is suggested users of the OGL power meter calibrate their paddles with a range of forces equal to that of the kayakers they are testing.

An example of the importance of properly calibrating the OGL paddle prior to use was noticeable in a recent publication that measured bilateral force asymmetries while sprint kayaking in crew boats (Kong et al., 2020). The article presented a figure where raw force asymmetries of approximately 50 to 100 N were evident. The result from our study gives confidence that the OGL paddle can provide mean force differences of approximately 10 to 20 N under static loading conditions. By increasing the calibration force range, we saw the absolute mean difference of the left side of the shaft drop from 65.7 ± 21.1 N to 18.3 ± 7.4 N. Although no information was presented about how calibration was completed in the Kong et al. (2020) study, if they calibrated with a narrow range then their asymmetry observations may have been the biproduct of absolute mean difference errors rather than true athlete asymmetry. This further suggests the importance of internally validating equipment to ensure athlete recommendations to coaches are accurate (Brosnan et al., 2021).

### *Limitations*

There were two study limitations from a statistical analysis perspective. First, an a priori sample size calculation was not completed. Second, the residuals from the left shaft power measurements did not follow a normal distribution; therefore, a robust regression was also conducted on these data. The coefficient of the cubic function for the left shaft changed from 7.104 (linear regression) to 7.155 (robust regression). Since the robust regression coefficient was well within the confidence intervals of the linear regression (i.e., 6.740 to 7.461) the difference was not deemed to have a large effect on the overall results of the study. Finally, all participants used one OGL paddle with one set of blades, to which some athletes may not have been accustomed. However, all athletes were given ample time to warmup with the paddle before completing the trials, and no athlete stated it was difficult to paddle with the OGL paddle. Due to these reasons, we do not believe the paddle characteristics affected the results. However, by testing one OGL paddle during this experiment it introduced another limitation to the research, which was that only female athletes were studied. Due to the shorter length of the paddle, it typically only allowed for females to be tested. Although we do not expect to more differences when male sprint kayakers are tested, we have demonstrated the need to calibrate the instrument in the range of forces to be experienced. As such the range of weights for the calibration needed for male sprint kayakers may be different, but the principle remains the same.

### ***Conclusions***

In conclusion, the study establishes that even though the OGL reports power values that appear to have construct validity up to 4.6 $m \cdot s^{-1}$, calibration with a range of weights that encompasses the projected applied forces is needed to improve the accuracy of the force measurement, and power calculation, by the OGL.

### Acknowledgements

The authors would like to thank the athletes who participated in this study, and Will George from the Canadian Sport Institute Ontario for his support with equipment.

### Disclosure of Interests

The authors have no conflicts of interest to report.

# CHAPTER 8: Conclusion

The original goal of this doctoral research was to quantify the kinematics and kinetics of the athlete-paddle-boat system during on-water paddling. The completion of this goal was highly dependent on the use of valid equipment and technology. Unfortunately, as highlighted in Section 2 of this dissertation, an inertial measurement system used to quantify body kinematics did not have the validity required for research-grade data collection to investigate one of the original research goals (i.e., the measurement of on-water 3D body kinematics). In addition, a wireless instrumented paddle was found to have acceptable concurrent validity only when calibrated with a wider range of calibration weights than those listed in the device's user manual. Therefore, although the goal of collecting on-water body kinematics and boat kinetics did not occur during this dissertation, meaningful validation work occurred which will inform the process of developing the system moving forward. Furthermore, the over-arching topic of this doctoral research was to investigate the biomechanical determinants of sprint kayaking performance. Therefore, while validation work was being completed, other important research regarding the kinematics of sprint kayaking was being completed as well. As shown in the deterministic model (Figure 1.2) the topics are connected, yet broad.

In total, five research studies were presented in two sections in this dissertation. The first section included three studies with goals of investigating sprint kayak pacing strategies, the relationships between stroke parameters and performance, and the role of boat kinematics in generating resistive forces and the relationships with kayak speed. It is important to note that all three studies included elite sprint kayakers as participants, which is rare in sport science research, and is a strength of this work. The second section included two studies focused on validating two separate measurement devices which may advance sport science research in the future. The first was an inertial measurement system to measure body kinematics during simple and complex upper-limb movements. The second device was a wireless instrumented paddle, which was designed to quantify both power and force output during the kayak stroke. The following sub-sections will summarize the key results and conclusions from each study.

## Chapter Summaries

### *Section 1 – The Kinematics of Sprint Kayaking*

The first two studies in this section were conducted to investigate the pacing strategies sprint kayakers used and how they alter the stroke parameters, of SR and SL, during international competitions. As shown in the deterministic model, these studies are highly linked. Specifically, pacing strategies were influenced by how an athlete alters their stroke parameters. For example, shown in both Chapters 3 and 4, athletes used end-spurts to complete longer races (i.e., 1000 m). The results from Chapter 4 also indicated the relationship between SR and kayak speed was greater at the final portion of the race distance, thus athletes used that strategy instead of increasing their SL to finish the race.

The final study in this section investigated the relationships between boat kinematics and kayak speed. The results from this study are indirectly related to pacing strategies as well. For example, the results indicated that boat movements in specific directions have a strong relationship with kayak speed. Thus, for energy conservation purposes, it would benefit athletes to maximize the movements that are related to an increase in boat speed and minimize the movements that are related to a decrease in boat speed. Although this was not directly measured, it can be hypothesized that reducing hydrodynamic drag (due to unnecessary boat movements) throughout the race distance will help an athlete from being increasingly fatigued when an end-spurt is needed. In particular, vertical and lateral acceleration impulses, and pitch, roll, and yaw impulses were found to be important for performance.

### *Chapter 3 – Using Principal Component Analysis to Investigate Pacing Strategies in Elite International Canoe Kayak Sprint Races*

Prior to conducting this study there was little information published on how sprint kayakers' complete races from a pacing perspective. Therefore, the first aim of this study was to use publicly available high-resolution boat velocity data, collected from GPS units, to investigate the pacing strategies currently being used by elite sprint kayakers at major international competitions. The primary result from this analysis was that pacing strategies depend on the race distance, and more importantly from a physiology standpoint, the duration of the race (Abbiss and Laursen, 2008). As hypothesized, shorter duration races (i.e., 200 m or ~38 s) saw athletes use an all-out pacing strategy, whereas athletes used positive pacing strategies for medium duration races (i.e., 500 m or ~1 min 45 s). Interestingly, the hypothesis for longer duration races (i.e., 1000 m or ~3 min 38 s) was based on previous research, in that athletes would follow a reverse J-shaped strategy (Borges et al., 2013). This was not what the current study showed, as our results indicated athletes followed a sea-horse shaped pacing strategy in 1000 m races. This result is important and novel, because it highlighted the importance of the end-spurt in sprint kayaking research, and as it has never been measured before despite being mentioned in an influential study published four decades ago (Plagenhoef, 1979). The reason for this result was likely due to the methodology in which velocity data were collected. Previous race data have been collected using low-resolution split data, where one velocity split would be recorded every 250 m raced in 500 m and 1000 m races. By introducing GPS technology to the sport, high-resolution data now allows for more detailed analyses, which will help athletes develop a more detailed race plan. This also fills a gap in the pacing literature for all racing sports, as one researcher originally called for higher split resolution almost thirty years ago (Foster et al., 1994).

The second aim of this study was to determine if a form of functional data analysis could detect differences in the pacing strategies between medallists and non-medallists. It is believed that this study was the first to use principal component analysis (PCA) to investigate pacing strategies in any sport. This analysis determined that there were significant differences in pacing strategies between medallists and non-medallists in the 1000 m race distance. The primary result was that medallists were able to produce an end-spurt at approximately the 700 m mark of the race, whereas the non-medallists could not. This becomes an energy availability problem for athletes and coaches, as some athletes clearly were unable to maintain the pace set out by them nor their competitors for the full duration of the 1000 m race distance. This adds to the literature in two primary ways. First, it highlights the need to have a well-thought out pacing strategy prior to racing. Second, it highlights the importance of being able to maintain a certain pace and be able to complete an end-spurt if the competition requires the athlete to do so. Therefore, although this study did not investigate training methods, the novel results discovered will hopefully inform them.

### *Chapter 4 – Pacing Strategies and Relationships Between Speed and Stroke Parameters for Elite Sprint Kayakers in Single Boats*

The PCA results from Chapter 3 highlighted that pacing plays a greater role in longer duration races (i.e., 1000 m) than in shorter duration races (i.e., 200 m and 500 m). This was based on the amount of variance explained in principal component 1 (i.e., PC1), as it explained more variance in the shorter races (97.4% and 91.3%) than it did in the longer 1000 m race (77.3%). This may sound obvious as long-distance races are longer in duration and therefore there is more time to change strategies within the race. However, the results from Chapter 4 showed that although both male and female 200 m athletes followed all-out pacing strategies, they did not rely on (i.e., depend on) the same stroke parameters and timing to do so. Specifically, male athletes relied more on SL during the first 100 m of the race and more on SR during the second 100 m of the race, whereas female athletes relied primarily on SR throughout the entire race. There is currently little evidence to suggest why this is; however, it may have something to do with anthropometrics like arm span and body mass, but this is still unclear (Shin, 2020). This concept should be a focus of future research. However, it is important to note that 200 m sprint kayak races are no longer raced at the Olympic Games, and therefore less emphasis will likely be placed on those events by National canoe sprint federations moving forward.

The novelty of this study was that it was the first to show how the relationship between kayak speed and stroke parameters (i.e., SR and SL) changes at different time points within a race. As has been stated many times in this dissertation and in the existing literature, the relationship between SR and kayak speed is strong, especially over short durations of paddling. However, it is important as a field that this concept does not get used as a generic statement which leads athletes and coaches to assume that speed will always increase anytime SR is increased. The study results should promote athletes and coaches to choose appropriate timing as when to increase either SR or SL during a race to enhance performance. An example of this is late in a 500 m or 1000 m race, with approximately 20-30% of the race distance remaining, where athletes in both race distances relied more on SR to finish the race than SL. The mechanism behind this was not studied, but based on swimming research, it could be due to increasing fatigue where propulsive forces and power output decline (Laffite et al., 2004; Thompson et al., 2004). In fact, a recent study analyzing body kinematics during ergometer paddling found some shoulder, trunk, and hip joint angle waveforms significantly changed from the beginning of a 500 m time trial compared to the end of the trial (Bertozzi et al., 2021). Stroke length (i.e., anterior reach in this study's case) and paddle velocity significantly decreased at the end of the trial as well, indicating fatigue modulates these parameters during simulated sprint kayak racing. These results are important initial steps in better understanding the outcomes of Chapter 4 of this thesis, and a major overall aim of this dissertation.

It is unfortunate that the validation results of measuring body kinematics with an IMU system were not accurate enough (at least to a research-grade level) to be used in a follow-up study. Meaningful discoveries could likely come from a study that combines body kinematics, boat kinematics, and stroke kinetics during sprint kayaking time trials and races. A large portion of this thesis was based on the effect of resistive forces during on-water paddling, and although Chapter 5 investigated this concept indirectly, it would have been a nice addition to the sprint kayaking literature of better understanding why athletes rely on SR and SL during different parts of the race. As highlighted previously, it could be that active drag increases as athletes become fatigued due to the increase in unnecessary body movements. As technology becomes more accurate, some of the study's results may be better informed by combining instantaneous stroke parameters, force and power output, and boat and body kinematics.

Another important factor to discuss regarding this topic is athlete individuality, and how our results may change if we did not use a group analysis to answer the research question. For example, research by Shin, (2020) showed coaches were interested in the topic, and therefore she studied whether SR or SL was more important in determining kayak speed in elite kayakers. In a similar study design to Chapter 5 of this dissertation, the researcher found SR had a greater correlation with kayak speed ($r = 0.87$, $p < 0.01$) than SL did ($r = 0.67$, $p < 0.01$) when analyzed as a group. However, in another analysis using a subset of participants the researcher found that some athletes had greater correlations between SL and kayak speed than between SR and kayak speed. These results indicate the importance of determining the relationships between stroke parameters and kayak speed on an individual athlete level rather than a group level. Future research should investigate this concept further, and coaches should be aware of the potential differences between each athlete.

Finally, it should be noted that the research discussed in Chapters 3 and 4 of this dissertation is contingent on the measured pacing profiles of elite sprint kayakers. Due to the large participant pool in this research, we did not physically ask each athlete what their pacing strategy or intentions were prior to or following their races. Although this information would greatly enhance the understanding of pacing strategies in this population, it may not be possible to get the true intentions of an athlete following a race. For example, athletes who did not meet their goals may not be truthful in what their plan was, or the athlete may not say publicly what they actually intended to do. Future research may warrant this approach, but for now we believe the results from these studies will help inform coaches and athletes as prepare for their future races.

### *Chapter 5 – The Relationship Between Boat Kinematics and Sprint Kayak Performance*

The results of the section's final study fill a gap that was identified in the sprint kayak literature. This is primarily because researchers have been calling for more information on boat kinematics for more than a decade, and this is the first study to investigate three-dimensional boat kinematics and relate them to kayak speed. Likely the most impactful result from this doctoral work was that boat kinematics (in some directions) predict sprint kayak speed more than others. Although it is difficult to quantify active drag during on-water paddling, we took the approach of hypothesizing which kinematics would affect boat speed the most based on theory. For example, it has been well documented throughout this dissertation and the literature that excessive boat movement likely affects hydrodynamic drag. It was hypothesized that forward and vertical acceleration (both effect friction drag) and pitch and yaw angular velocity (both effect pressure and wave drag) will be significant predictors of kayak speed. The hypothesis was partially correct, as predictors of kayak speed during the propulsive phase of the stroke included roll, yaw, pitch, and vertical acceleration impulses. In addition, yaw, lateral and vertical acceleration impulses were significant predictors of kayak speed in the resistive phase of the stroke. The primary difference from what was hypothesized was roll impulse played a bigger role in predicting kayak speed, and that pitch and vertical acceleration impulses were actually related to faster kayak speeds in the propulsive phase of the stroke. These results are likely due to the resulting movements from the applied propulsive forces. This is important because it now provides knowledge users information about which variables to focus on when attempting to increase their kayak speed. Essentially, coaches and athletes can use this information to refine the athlete's technique.

The approach we took to solve this research question is important for the field, and for sports biomechanics in general. Sprint kayak technique is a powerful and complex motion, therefore, using technology is important for detecting technical flaws as they may otherwise go missed by the coach's eye. We used an IMU with GPS to conduct this research, which showed that more information could be gathered, and ultimately used to detect areas in kayaking technique that can be improved upon. The only other study to measure boat kinematics in sprint kayaking literature was a notational analysis by Brown et al., (2011). Therefore, our results will hopefully motivate other researchers to study boat kinematics in a similar way by using IMU technology.

### *Section 2 – The Development of an On-Water Kinetic Measurement System for Sprint Kayaking*

The two studies in this section were completed to determine the validity of two new pieces of technology. The results showed that the Notch® IMU system was not valid for the intended use of this research (i.e., the measurement of on-water 3D body kinematics), and that the OGL power meter was only valid when calibrated with a wider than instructed calibration weight range. These results were unfortunate for not only the originally proposed research, but also from an overall biomechanics and sport science perspective as well. Increasing amounts of technology are becoming commercially available everyday with the promise of providing biomechanists, sport scientists, coaches, and all other users with accurate biomechanical data. Unfortunately, as shown in this research, there are situations where these products are not valid, and thus the insights gathered from their data will not be correct or useable for this research and/or practice. Some researchers have even gone on to state this is unethical, by giving users a false sense of data accuracy (Sperlich and Holmberg, 2017). The results from the studies in this section of the thesis add to the body of literature, but also reminds readers that it is critical to validate new technology for your specific purpose prior to conducting data collection on athletes and participants.

### *Chapter 6 – The Validation of a Low-Cost Inertial Measurement Unit System to Quantify Simple and Complex Upper-Limb Joint Angles*

One of the original objectives of this dissertation was to measure the body kinematics of sprint kayakers' during on-water paddling to assess their technique. Prior to beginning to study the objective, the equipment used to measure body kinematics was required to be validated. By conducting a validation study in a controlled laboratory environment, the Notch® IMUs were found to have poor joint angle waveform comparisons with the criterion measure (i.e., optical motion capture) during both simple and complex upper-limb movements and tasks. More specifically, when comparing the Notch® and criterion measure, statistical parametric mapping techniques showed nine of sixteen movement and plane waveform comparisons were significantly different from each other. Furthermore, there were proportional and/or fixed biases in ROM measures in eleven movements and/or planes. The movements completed in this study were both simple, single-joint movements, and complex, multi-joint movements which are common in daily functional tasks. It was deemed this level of accuracy in common movements was not sufficient to continue with the proposed research plan of measuring on-water body kinematics of sprint kayakers during complex sport-specific movements.

### *Chapter 7 – The Validation of a Commercial Wireless Power Meter for Sprint Kayaking*

Another original objective of this doctoral thesis was to quantify propulsive paddle forces and power output during on-water sprint kayaking. Like Chapter 6, a validation study was required prior to conducting research to explore this objective. One of the main results from this research was that thorough user guidelines (whether provided or not) are important for accurate data collection and analysis. For example, in this study two different validation techniques were used to determine the validity of the OGL power meter. The first compared force measurements to known weights, and unfortunately, when following the user guidelines for calibrating the power meter, the right shaft had proportional bias ($p<0.001$) and the left shaft had fixed bias (65.7±21.1 N, $p=0.017$). Only by changing the user guidelines and calibrating the power meter by a larger range of known weights were we able to obtain a better level of accuracy.

It is important to note that a lot has changed from a technology standpoint over the period of completing this thesis. For example, when beginning this research project in 2018 the only commercially available power meter built for kayaking was the OGL power meter. Since then, the e-kayak system and the PaddleMate system have entered the market. From an overall usability standpoint, the prospect of using the PaddleMate system in the daily training environment seems to be promising, as the strain gauge technology is enclosed into a small device that fits into a bracket that is permanently attached to the athlete's personal paddle. From my experience collecting data for this thesis, this technology will likely gather greater interest and uptake from coaches and athletes. I learned that it is important for technology to be easy to use in order to have impact with the sport. However, as shown in Chapter 7, it is also important for the device to be valid and reliable and thus all new power meters should be validated in-house by the manufacturer and by independent researchers and practitioners before using them with athletes.

### *Limitations*

An obvious limitation of this research was that some equipment did not provide the validity required to explore some important originally proposed research questions (i.e., the measurement of on-water 3D body kinematics). Despite this, this work extends the knowledge that can be used to enhance sprint kayak performance, as other researchers will not have to complete the same steps as was required in this research.

As with all research, the results are only transferrable to similar conditions or cohorts in which data were collected. The majority of the research in this thesis was conducted on National-to-World Class sprint kayakers. This is seen as a benefit for most, but it should be noted that the results may not be useful for all sprint kayakers. For example, the results may not be appropriate for developing athletes who are not considered to be at the National-level yet. Specifically, the skill levels that are needed to benefit from this work were not investigated. There are multiple examples where this statement fits within the research completed. One example is the baseline level of a boat kinematic variable needed to generate a specific kayak speed. It is possible that a certain amount of strength or propulsive force output is needed to apply a rotational force to generate enough roll impulse to increase kayak speed. Another example is related to the pacing strategies acquired from World Class sprint kayakers. There are likely minimum aerobic and anaerobic thresholds that must be met in order to execute specific pacing strategies (e.g., completing an end-spurt during a 1000 m race).

A large portion of this research used new technology to answer research questions. This will continue in scientific disciplines as new technology is developed. One important concept readers of this thesis should be aware of is the tendencies of some technology companies regarding their proprietary information. A lot of time and resources are used to develop new technology and algorithms; therefore, it is reasonable that companies are not always forthright in providing information about their products to scientists free-of-charge. This occurred during two studies in this thesis (i.e., Chapter 6 and Chapter 4). In Chapter 6, the methods in which Notch® calculated joint angles were not provided; whereas, in Chapter 4, there was no information on how SR was calculated from the publicly available data source. Scientists must continue to use creative but sound scientific methods to test whether a measurement tool can be used to answer their research questions. It should also be mentioned that if a scientist is provided with proprietary information, it is possible that the company could change the algorithms or data analysis methods without warning. Therefore, it is important to read firmware updates to ensure their changes do not influence study results or data collection procedures. Finally, it is believed that it is in the company's best interest to be as transparent as possible with their algorithms. From this author's perspective, understanding how and what data is being collected and used to calculate specific performance parameters gives confidence that what is being reported is the intended metric and may actually influence widespread use.

With new technology comes increased amounts of data. This can be seen as something promising to look forward to for scientists, especially those who require large amounts of data to conduct statistical analyses. An example of this in the current thesis was in Chapter 3. Due to the lack of data for some canoe sprint disciplines, pacing strategy data from different boat classes (canoe and kayak), sexes (male and female), and number of athletes (single and crew boats) needed to be combined. This may be seen as a limitation in this work, as in Chapter 4 it was shown that despite male and female single kayak athletes following similar pacing strategies, they relied on SR and SL differently during the 200 m race. With more data being available, more in-depth analyses can be conducted for specific populations.

### ***Future Research***

The research completed in this doctoral thesis has provided the groundwork to be able to continue investigating themes within the newly-adapted deterministic model (Figure 1.2). One of the most important results from this research was the effect of boat kinematics on kayak speed. By identifying which kinematic variables were significant predictors of kayak speed allows future research to investigate the mechanisms causing these relationships. Although theories on why each significant boat kinematics predictor affected kayak speed were hypothesized, they were not specifically tested. Some of this work has already begun, with researchers in our laboratory and other laboratories around the world measuring forces and moments acting at the seat, footboard, and paddle during ergometer paddling, and the footboard and paddle during on-water paddling (Bonaiuto et al., 2020; Bugeya Miller, 2021). As this work progresses it will continue to inform coaches and other knowledge users on what is causing excessive boat movement and how it can be minimized. For example, some work showing the effect of body mass on hydrodynamic drag exists; however, this specific example investigated passive drag, not active drag (Gomes et al., 2018). In this one specific case, as we better understand how vertical seat forces oscillate during the stroke cycle while paddling on-water, the more information will be uncovered about minimizing active hydrodynamic drag.

Two out of the five studies in this thesis were validation studies, and one of the goals is that their results will inform other researchers looking to investigate on-water paddling technique using IMUs and instrumented paddles. Due to the abilities of IMUs to measure body kinematics and the development of new technologies and algorithms, it is likely that future research in this area will be conducted using markerless motion capture techniques. This new approach has been implemented in daily activities, like walking, but also in high performance sport activities as well (Armitano-Lago et al., 2022; Kanko et al., 2021). The primary benefit of this data collection method is that there is very little disturbance to the athlete completing their movement tasks. This causes the ecological validity of this method to be superior to some traditional methods; however, the accuracy of the technology will still need to be quantified. It is obvious that this approach lends well to collecting sport movements on land, but it is possible that this technique will be conducted during on-water kayaking in the near future. One of the downfalls noted in the sprint kayak literature is that many studies investigating technique on-water are limited to a very small volume capture area, which only allows for one or two strokes to be collected per trial. It can be expected that a kayak will be instrumented with multiple high-speed cameras (e.g., GoPro cameras) soon, which will allow for a constant capture volume that can collect kinematics data on-water over long periods of time (Miyazaki et al., 2023). The added ability to combine athlete body kinematics data with kinetics data from the paddle, seat, and footboard will help researchers determine the true effect of body movements on boat kinematics and hydrodynamic drag, and finally relate that information to kayak performance.

Furthermore, the two validation studies (Chapter 6 and Chapter 7) outline both methodological and statistical guidelines that can be used by other researchers and practitioners when validating both biomechanics and sports science technology. The research methods employed can be replicated using most technologies that need to be validated. Specifically, Chapter 6 tested the criterion validity of a low-cost IMU system to measure upper-extremity joint angles. Future research using technology to measure joint ROM can use both the ROM comparison method and the joint angle waveform comparison method. These methods used the Bland-Altman method of differences and statistical parametric mapping (SPM) analyses respectively, which as shown, are both statistical tests that can give applicable insights into the validity of a measurement device. Chapter 7 tested the OGL power meter's construct and concurrent validity. In doing so, the chapter highlights statistical methods that can be used in the future for both power- and force-measuring devices. In the experiment validating on-water power output measurement, a simple construct (i.e., theory) was explored using a linear regression, cubic function, and a coefficient of determination. There is often no clear method or guidelines to validate all types of technology; however, the methods used in this dissertation will hopefully help guide future research in this area.

One of the studies that investigated the pacing strategies of elite sprint kayakers was completed using kayak speed, whereas the other used kayak speed and traditional stroke parameters (i.e., SR and SL). These studies add context and resolution to the existing pacing literature, considering previous literature only included studies with very few split times per race. By adding the abilities of GPS and IMU technology, more comparisons within each race can be made. For example, race dynamics between competitors can now be investigated, as well as inter-stroke effects, like inter-stroke steadiness (Abellán-Aynés et al., 2022). That said, as paddles with force and power measuring capabilities continue to be developed, a bigger impact on performance is expected to be created by combining kinetics data with speed, SR, and SL data. For example, the results in Chapter 4 showed that SR had a stronger correlation with kayak speed later in the women's K1 500 m and men's K1 1000 m races. This information is important for athletes and coaches as an increase in SR seems to be the approach elite sprint kayakers use to enable their end-spurt; however, they would benefit further from understanding the mechanisms behind why this occurs. By determining exactly when an athlete's force output is declining in the race, it could allow them to know when they need to increase their movement velocity to maintain or increase their power output to finish the race.

There are many areas that were highlighted in the deterministic model and literature review section in this thesis that future research can investigate. Immediate topics to investigate are listed in the paragraphs above; however, other areas will continue to develop. This seems to be escalating lately, and as new technology is deployed it will likely continue to do so.

### ***Conclusion***

Overall, the results of the research outlined in this dissertation adds to the knowledge in the sprint kayak and sports biomechanics literature. More specifically, knowledge has been gained that is relevant to the over-arching topic of this doctoral research, which was to enhance the understanding around the biomechanical determinants of sprint kayaking performance. Unfortunately, the goal of developing an instrumented paddle-athlete-boat system, which would include paddle kinetics, boat kinematics, and body kinematics, was not met. However, this was an ambitious plan, and steps in the right direction have been made in this dissertation. As innovative technology is developed one wish is that this research will be built upon by other researchers in the future. It is obvious from the literature that more information exists on the propulsive work done by a sprint kayaker than what exists regarding the resistive work. It is believed that a better understanding of kayak performance could be created by conducting more research on the interaction between propulsive and resistive work during paddling, instead of focusing solely on the propulsive factors.

# References

Abbiss, C.R., Laursen, P.B., 2008. Describing and understanding pacing strategies during athletic competition. Sport. Med. 38, 239–252. https://doi.org/10.2165/00007256-200838030-00004

Abbiss, C.R., Straker, L., Quod, M., Martin, D., Laursen, P., 2008. Examining pacing profiles in elite female road cyclists using exposure variation analysis. Br. J. Sports Med. 44, 437–442. https://doi.org/10.1136/bjsm.2008.047787

Abellán-Aynés, O., López-Plaza, D., Martínez-Aranda, L.M., Alacid, F., 2022. Inter-stroke steadiness: a new kinematic variable related to 200m performance in young canoeists. Sport. Biomech. 00, 1–13. https://doi.org/10.1080/14763141.2022.2071327

Aitken, D.A., Neal, R.J., 1992. An on-water analysis system for quantifying stroke force characteristics during kayak events. Int. J. Sport Biomech. 8, 165–174. https://doi.org/10.1123/ijsb.8.2.165

Al-Amri, M., Nicholas, K., Button, K., Sparkes, V., Sheeran, L., Davies, J.L., 2018. Inertial measurement units for clinical movement analysis: Reliability and concurrent validity. Sensors 18, 719. https://doi.org/10.3390/s18030719

Armitano-Lago, C., Willoughby, D., Kiefer, A.W., 2022. A SWOT analysis of portable and low-cost markerless motion capture systems to assess lower-limb musculoskeletal kinematics in sport. Front. Sport. Act. Living 3, 1–14. https://doi.org/10.3389/fspor.2021.809898

Baker, J., 2012. Biomechanics of paddling. ISBS Proc. Arch. 30, 101–104.

Baker, J., 1998. The evaluation of biomechanic performance related factors and on-water tests, in: International Seminar on Kayak-Canoe Coaching and Science. pp. 50–66.

Baker, J., Rath, D., Sanders, R., Kelly, B., 1998. A three-dimensional analysis of male and female elite sprint kayak paddlers. ISBS Proc. Arch. 17, 53–56.

Barbosa, T.M., Bragada, J.A., Reis, V.M., Marinho, D.A., Carvalho, C., Silva, A.J., 2010. Energetics and biomechanics as determining factors of swimming performance: Updating the state of the art. J. Sci. Med. Sport 13, 262–269. https://doi.org/10.1016/j.jsams.2009.01.003

Barros, F., Viriato, N., Veiga Rodrigues, C., Ferrás, L.L., Vaz, M.A.P., Afonso, A.M., 2021. Numerical study of hydrodynamic resistance on a sportive sprint hull. Semin. Ciências Exatas e Tecnológicas 42, 131. https://doi.org/10.5433/1679-0375.2021v42n2p131

Baudouin, A., Hawkins, D., 2002. A biomechanical review of factors affecting rowing performance. Br. J. Sports Med. 36, 396–402.

Begon, M., Lacouture, P., Colloud, F., 2008. 3D kinematic comparison between on-water and on ergometer kayaking. ISBS Proc. Arch. 26, 502–505.

Bertozzi, F., Porcelli, S., Marzorati, M., Pilotto, A.M., Galli, M., Sforza, C., Zago, M., 2021. Whole-body kinematics during a simulated sprint in flat-water kayakers. Eur. J. Sport Sci. 1–23. https://doi.org/10.1080/17461391.2021.1930190

Bishop, D., 2000. Physiological predictors of flat-water kayak performance in women. Eur. J. Appl. Physiol. 82, 91–97. https://doi.org/10.1007/s004210050656

Bishop, D., Bonetti, D., Dawson, B., 2002. The influence of pacing strategy on VO2 and supramaximal kayak performance. Med. Sci. Sport. Exerc. 34, 1041–1047. https://doi.org/10.1097/00005768-200206000-00022

Bjerkefors, A., Tarassova, O., Rosén, J.S., Zakaria, P., Arndt, A., 2017. Three-dimensional kinematic analysis and power output of elite flat-water kayakers. Sport. Biomech. 17, 414–427. https://doi.org/10.1080/14763141.2017.1359330

Blanca, M.J., Alarcón, R., Arnau, J., Bono, R., Bendayan, R., 2017. Non-normal data: Is ANOVA still a valid option? Psicothema 29, 552–557. https://doi.org/10.7334/psicothema2016.383

Bonaiuto, V., Gatta, G., Romagnoli, C., Boatto, P., Lanotte, N., Annino, G., 2020. A pilot study on the e-kayak system: A wireless DAQ suited for performance analysis in flatwater sprint kayaks. Sensors (Switzerland) 20, 1–17. https://doi.org/10.3390/s20020542

Bonetti, D., Hopkins, W., 2010. Variation in performance times of elite flat-water canoeists from race to race. Int. J. Sports Physiol. Perform. 5, 210–217.

Bonito, P., Sousa, M., Ferreira, F.J., Justo, J.F., Gomes, B.B., 2022. Magnitude and shape of the forces applied on the foot rest and paddle by elite kayakers. Sensors 22. https://doi.org/10.3390/s22041612

Borges, T.O., Bullock, N., Coutts, A.J., 2013. Pacing characteristics of international sprint kayak athletes. Int. J. Perform. Anal. Sport 13, 353–364.

Brandon, S.C.E., Graham, R.B., Almosnino, S., Sadler, E.M., Stevenson, J.M., Deluzio, K.J., 2013. Interpreting principal components in biomechanics: Representative extremes and single component reconstruction. J. Electromyogr. Kinesiol. 23, 1304–1310. https://doi.org/10.1016/j.jelekin.2013.09.010

Brosnan, R.J., Watson, G., Stuart, W., Twentyman, C., Kitic, C.M., Schmidt, M., 2021. The validity, reliability, and agreement of global positioning system units — Can we compare research and applied data? J. Strength Cond. Res. https://doi.org/10.1519/JSC.0000000000004139

Brown, M.B., Lauder, M., Dyson, R., 2011. Notational analysis of sprint kayaking: Differentiating between ability levels. Int. J. Perform. Anal. Sport 11, 171–183. https://doi.org/10.1080/24748668.2011.11868538

Brown, M.R., Delau, S., Desgorces, F.D., 2010. Effort regulation in rowing races depends on performance level and exercise mode. J. Sci. Med. Sport 13, 613–617. https://doi.org/10.1016/j.jsams.2010.01.002

Bugeya Miller, K., 2021. Assessment of a sprint kayaker's kinetic asymmetries at increasing stroke rates. MSc Thesis. Dalhousie University, Halifax.

Burnley, M., Jones, A.M., 2018. Power–duration relationship: Physiology, fatigue, and the limits of human performance. Eur. J. Sport Sci. 18, 1–12. https://doi.org/10.1080/17461391.2016.1249524

Camomilla, V., Bergamini, E., Fantozzi, S., Vannozzi, G., 2018. Trends supporting the in-field use of wearable inertial sensors for sport performance evaluation: A systematic review. Sensors 18, 873. https://doi.org/10.3390/s18030873

Casado, A., Renfree, A., 2018. Fortune favors the brave. Tactical behaviors in the middle distance running events at the 2017 IAAF world championships. Int. J. Sports Physiol. Perform. 13, 1386–1391. https://doi.org/10.1123/ijspp.2018-0055

Chicco, D., Warrens, M.J., Jurman, G., 2021. The coefficient of determination R-squared is more informative than SMAPE, MAE, MAPE, MSE and RMSE in regression analysis evaluation. PeerJ Comput. Sci. 7, 1–24. https://doi.org/10.7717/PEERJ-CS.623

Chow, J.W., Knudson, D. V., 2011. Use of deterministic models in sports and exercise biomechanics research. Sport. Biomech. 10, 219–233. https://doi.org/10.1080/14763141.2011.592212

Cooper, G., Sheret, I., McMillian, L., Siliverdis, K., Sha, N., Hodgins, D., Kenney, L., Howard, D., 2009. Inertial sensor-based knee flexion/extension angle estimation. J. Biomech. 42, 2678–2685. https://doi.org/10.1016/j.jbiomech.2009.08.004

Corbett, J., 2009. An analysis of the pacing strategies adopted by elite athletes during track cycling. Int. J. Sports Physiol. Perform. 4, 195–205.

Craig, A.B., Skehan, P.L., Pawelczyk, J.A., Boomer, W.L., 1985. Velocity, stroke rate, and distance per stroke during elite swimming competition. Med. Sci. Sports Exerc. https://doi.org/10.1249/00005768-198512000-00001

Crang, Z.L., Duthie, G., Cole, M.H., Weakley, J., Hewitt, A., Johnston, R.D., 2021. The validity and reliability of wearable microtechnology for intermittent team sports: A systematic review. Sport. Med. 51, 549–565. https://doi.org/10.1007/s40279-020-01399-1

Cuijpers, L.S., Passos, P.J.M., Murgia, A., Hoogerheide, A., Lemmink, K.A.P.M., de Poel, H.J., 2017. Rocking the boat: does perfect rowing crew synchronization reduce detrimental boat movements? Scand. J. Med. Sci. Sport. 27, 1697–1704. https://doi.org/10.1111/sms.12800

Cutti, A.G., Giovanardi, A., Rocchi, L., Davalli, A., Sacchetti, R., 2008. Ambulatory measurement of shoulder and elbow kinematics through inertial and magnetic sensors. Med. Biol. Eng. Comput. 46, 169–178. https://doi.org/10.1007/s11517-007-0296-5

Day, A., Campbell, I., Clelland, D., Doctors, L.J., Cichowicz, J., 2011. Realistic evaluation of hull performance for rowing shells, canoes, and kayaks in unsteady flow. J. Sports Sci. 29, 1059–1069. https://doi.org/10.1080/02640414.2011.576691

de Koning, J.J., Bobbert, M.F., Foster, C., 1999. Determination of optimal pacing strategy in track cycling with an energy flow model. J. Sci. Med. Sport 2, 266–277. https://doi.org/10.1016/S1440-2440(99)80178-9

de Vries, W.H.K., Veeger, H.E.J., Baten, C.T.M., van der Helm, F.C.T., 2009. Magnetic distortion in motion labs, implications for validating inertial magnetic sensors. Gait Posture 29, 535–541. https://doi.org/10.1016/j.gaitpost.2008.12.004

Di Prampero, P.E., Pendergast, D.R., Wilson, D.W., Rennie, D.W., 1974. Energetics of swimming in man. J. Appl. Physiol. 37, 1–5. https://doi.org/10.1152/jappl.1974.37.1.1

El-Gohary, M., McNames, J., 2012. Shoulder and elbow joint angle tracking with inertial sensors. IEEE Trans. Biomed. Eng. 59, 2635–2641. https://doi.org/10.1109/TBME.2012.2208750

Fernandes, R.A., Alacid, F., Gomes, A.B., 2021. Validation of a global positioning system with accelerometer for canoe / kayak sprint kinematic analysis. Sport. Biomech. 00, 1–12. https://doi.org/10.1080/14763141.2021.2005128

Fernandez-Nieves, A., De Las Nieves, F.J., 1998. About the propulsion system of a kayak and of Basiliscus Basiliscus. Eur. J. Phys. 19, 425–429. https://doi.org/10.1088/0143-0807/19/5/003

Filippeschi, A., Schmitz, N., Miezal, M., Bleser, G., Ruffaldi, E., Stricker, D., 2017. Survey of motion tracking methods based on inertial sensors: A focus on upper limb human motion. Sensors 17, 1257. https://doi.org/10.3390/s17061257

Fleming, N., Donne, B., Fletcher, D., Mahony, N., 2012. A biomechanical assessment of ergometer task specificity in elite flatwater kayakers. J. Sport. Sci. Med. 11, 16–25.

Foster, C., Schrager, M., Snyder, A.C., Thompson, N.N., 1994. Pacing strategy and athletic performance. Sport. Med. An Int. J. Appl. Med. Sci. Sport Exerc. 17, 77–85. https://doi.org/10.2165/00007256-199417020-00001

Garland, S., 2005. An analysis of the pacing strategy adopted by elite competitors in 2000 m rowing. Br. J. Sports Med. 39, 39–42. https://doi.org/10.1136/bjsm.2003.010801

Gastin, P.B., 2001. Energy system interaction and relative contribution during maximal exercise. Sport. Med. 31, 725–741. https://doi.org/0112-1642/01/0010-0725

Gee, T.I., French, D.N., Gibbon, K.C., Thompson, K.G., 2013. Consistency of pacing and metabolic responses during 2000-m rowing ergometry. Int. J. Sports Physiol. Perform. 8, 70–76. https://doi.org/10.1123/ijspp.8.1.70

Glazier, P.S., Robins, M.T., 2012. Comment on "Use of deterministic models in sports and exercise biomechanics research" by Chow and Knudson (2011). Sport. Biomech. 11, 120–122. https://doi.org/10.1080/14763141.2011.650189

Gomes, B.B., 2015. Biomechanical determinants of kayak paddling performance in single-seat and crew boats. PhD Thesis. University of Porto, Porto.

Gomes, B.B., Conceição, F.A.V., Pendergast, D.R., Sanders, R.H., Vaz, M.A.P., Vilas-Boas, J.P., 2015a. Is passive drag dependent on the interaction of kayak design and paddler weight in flat-water kayaking? Sport. Biomech. 14, 394–403. https://doi.org/10.1080/14763141.2015.1090475

Gomes, B.B., Machado, L., Ramos, N. V., Conceição, F.A.V., Sanders, R.H., Vaz, M.A.P., Vilas-Boas, J.P., Pendergast, D.R., 2018. Effect of wetted surface area on friction, pressure, wave and total drag of a kayak. Sport. Biomech. 17, 453–461. https://doi.org/10.1080/14763141.2017.1357748

Gomes, B.B., Ramos, N.V., Conceição, F.A., Sanders, R.H., Vaz, M.A., Vilas-boas, J.P., 2015b. Paddling force profiles at different stroke rates in elite sprint kayaking. J. Appl. Biomech. 31, 258–263. https://doi.org/10.1123/jab.2014-0114

Gomes, B.B., Ramos, N. V, Conceição, F., Sanders, R., Vilas-boas, J.P., 2020. Paddling time parameters and paddling efficiency with the increase in stroke rate in kayaking. Sport. Biomech. 00, 1–9. https://doi.org/10.1080/14763141.2020.1789204

Gomes, B.B., Viriato, N., Sanders, R., Conceição, F., Vaz, M., 2011. Analysis of the on-water paddling force profile of an elite kayaker. Port. J. Sport Sci. 11, 255–257.

Goreham, J.A., Ladouceur, M., 2022. The analysis of forward acceleration asymmetries during on-water sprint kayaking. ISBS Proc. Arch. 40, 247–250.

Goreham, J.A., Landry, S.C., Kozey, J.W., Smith, B., Ladouceur, M., 2020. Using principal component analysis to investigate pacing strategies in elite international canoe kayak sprint races. Sport. Biomech. 1–16. https://doi.org/10.1080/14763141.2020.1806348

Goreham, J.A., Landry, S.C., Kozey, J.W., Smith, B., Ladouceur, M., 2018. Functional data analysis: a new method to investigate pacing strategies in elite canoe kayak sprint. ISBS Proc. Arch. 36, 426.

Goreham, J.A., Miller, K.B., Frayne, R.J., Ladouceur, M., 2021. Pacing strategies and relationships between speed and stroke parameters for elite sprint kayakers in single boats sprint kayakers in single boats. J. Sports Sci. 00, 1–8. https://doi.org/10.1080/02640414.2021.1927314

Gray, G.L., Matheson, G.O., McKenzie, D.C., 1995. The metabolic cost of two kayaking techniques. Int. J. Sports Med. 16, 250–254. https://doi.org/10.1055/s-2007-973000

Hanley, B.A., Stellingwerff, T., Hettinga, F.J., 2019. Successful pacing profiles of Olympic and IAAF world championship middle-distance runners across qualifying rounds and finals. Int. J. Sports Physiol. Perform. 14, 894–901. https://doi.org/10.1123/ijspp.2018-0742

Harbour, E., 2019. The evaluation of an instrumented paddle device for analysising kayak sprint performance. MSc Thesis. Auckland University of Technology, Auckland.

Harrison, S.M., Cleary, P.W., Cohen, R.C.Z., 2019. Dynamic simulation of flat water kayaking using a coupled biomechanical-smoothed particle hydrodynamics model. Hum. Mov. Sci. 64, 252–273. https://doi.org/10.1016/j.humov.2019.02.003

Hatfield, G.L., Hubley-Kozey, C.L., Astephen Wilson, J.L., Dunbar, M.J., 2011. The effect of total knee arthroplasty on knee joint kinematics and kinetics during gait. J. Arthroplasty 26, 309–318. https://doi.org/10.1016/j.arth.2010.03.021

Hay, J.G., 2002. Cycle rate, length, and speed of progression in human locomotion. J. Appl. Biomech. 18, 257–270.

Hay, J.G., 1993. The Biomechanics of Sports Techniques, 4th ed. Prentice Hall, Englewood Cliffs, NJ.

Helmer, R.J., Farouil, A., Baker, J., Blanchonette, I., 2011. Instrumentation of a kayak paddle to investigate blade/water interactions. Procedia Eng. 13, 501–506. https://doi.org/10.1016/j.proeng.2011.05.121

Hettinga, F.J., de Koning, J.J., Schmidt, L.J., Wind, N.A., MacIntosh, B.R., Foster, C., 2011. Optimal pacing strategy: from theoretical modelling to reality in 1500-m speed skating. Br. J. Sports Med. 45, 30–35. https://doi.org/10.1136/bjsm.2009.064774

Higgens, A., Conway, L., Banks, J., Taunton, D., Hudson, D., Turnock, S., 2016. Development of a kayak race prediction including environmental and athlete effects, in: Procedia Engineering: 11th Conference of the International Sports Engineering Associations, ISEA 2016. Elsevier B.V., pp. 305–310. https://doi.org/10.1016/j.proeng.2016.06.296

Hill, H., 2002. Dynamics of coordination within elite rowing crews: Evidence from force pattern analysis. J. Sports Sci. 20, 101–117. https://doi.org/10.1080/026404102317200819

Hill, H., Fahrig, S., 2009. The impact of fluctuations in boat velocity during the rowing cycle on race time. Scand. J. Med. Sci. Sport. 19, 585–594. https://doi.org/10.1111/j.1600-0838.2008.00819.x

Hofmijster, M.J., Landman, E.H., Smith, R.M., Van Soest, A.J., 2007. Effect of stroke rate on the distribution of net mechanical power in rowing. J. Sports Sci. 25, 403–411. https://doi.org/10.1080/02640410600718046

Hogan, C., Binnie, M.J., Doyle, M., Lester, L., 2020a. Heart rate and stroke rate misrepresent supramaximal sprint kayak training as quantified by power. Eur. J. Sport Sci. 0, 1–10. https://doi.org/10.1080/17461391.2020.1771430

Hogan, C., Binnie, M.J., Doyle, M., Lester, L., Peeling, P., 2020b. Comparison of training monitoring and prescription methods in sprint kayaking. Int. J. Sports Physiol. Perform. 15, 654–662. https://doi.org/10.1123/ijspp.2019-0190

Hogan, C., Binnie, M.J., Doyle, M., Peeling, P., 2021. Mean maximal power from an on-water 1000-m time-trial predicts lactate threshold power in well- trained flat-water sprint kayak athletes. Eur. J. Sport Sci. 1–22. https://doi.org/10.1080/17461391.2021.1880648

Holt, A.C., Ball, K., Siegel, R., Hopkins, W.G., Aughey, R.J., 2021. Relationships between measures of boat acceleration and performance in rowing, with and without controlling for stroke rate and power output. PLoS One 16, 1–16. https://doi.org/10.1371/journal.pone.0249122

Hopkins, W., Marshall, S., Batterham, A., Hanin, J., 2009. Progressive statistics for studies in sports medicine and exercise science. Med. Sci. Sports Exerc. 41, 3–12. https://doi.org/10.1249/MSS.0b013e31818cb278

Hureau, T.J., Romer, L.M., Amann, M., 2018. The ‘sensory tolerance limit’: A hypothetical construct determining exercise performance? Eur. J. Sport Sci. 18, 13–24. https://doi.org/10.1080/17461391.2016.1252428

Ishiko, T., 1971. Biomechanics of Rowing. Med. Sport 6, 249–252. https://doi.org/10.1159/000392181

Jackson, P., Locke, N., Brown, P., 1992. The hydrodynamics of paddle propulsion, in: 11th Australasian Fluid Mechanics Conference. pp. 1197–1200.

Jackson, P.S., 1995. Performance prediction for Olympic kayaks. J. Sports Sci. 13, 239–245. https://doi.org/10.1080/02640419508732233

Janssen, I., Sachlikidis, A., 2010. Validity and reliability of intra-stroke kayak velocity and acceleration using a GPS-based accelerometer. Sport. Biomech. 9, 47–56. https://doi.org/10.1080/14763141003690229

Jolliffe, I.T., 2002. Principal Component Analysis, Second Edition, Springer Series in Statistics. https://doi.org/10.1007/b98835

Kanko, R.M., Laende, E.K., Strutzenberger, G., Brown, M., Selbie, W.S., DePaul, V., Scott, S.H., Deluzio, K.J., 2021. Assessment of spatiotemporal gait parameters using a deep learning algorithm-based markerless motion capture system. J. Biomech. 122, 110414. https://doi.org/10.1016/j.jbiomech.2021.110414

Kendal, S., Sanders, R., 1992. The technique of elite flatwater kayak paddlers using the wing paddle. Int. J. Sport Biomech. 8, 233–250. https://doi.org/10.1123/ijsb.8.3.233

Kim, S., Nussbaum, M.A., 2013. Performance evaluation of a wearable inertial motion capture system for capturing physical exposures during manual material handling tasks. Ergonomics 56, 314–326. https://doi.org/10.1080/00140139.2012.742932

Kleshnev, V., 2006. Method of analysis of speed, stroke rate and stroke distance in aquatic locomotions. ISBS Proc. Arch. 24, 1–5.

Kleshnev, V., 1998. Estimation of biomechanical parameters and propulsive efficiency of rowing, Australian Institute of Sport.

Klitgaard, K.K., 2021. Kinetics and kinematics of sprint kayaking on-water. PhD Thesis. Aalborg University, Aalborg.

Klitgaard, K.K., Hauge, C., Oliveira, A.S., Heinen, F., 2020. A kinematic comparison of on-ergometer and on-water kayaking. Eur. J. Sport Sci. 0, 1–10. https://doi.org/10.1080/17461391.2020.1831617

Klitgaard, K.K., Rosdahl, H., Brund, R.B., Hansen, J., de Zee, M., 2021. Characterization of leg push forces and their relationship to velocity in on-water sprint kayaking. Sensors 21, 1–11. https://doi.org/10.3390/s21206790

Kluge, F., Gaßner, H., Hannink, J., Pasluosta, C., Klucken, J., Eskofier, B.M., 2017. Towards mobile gait analysis: Concurrent validity and test-retest reliability of an inertial measurement system for the assessment of spatio-temporal gait parameters. Sensors 17, 1522. https://doi.org/10.3390/s17071522

Kong, P.W., Tay, C.S., Pan, J.W., 2020. Application of instrumented paddles in measuring on-water kinetics of front and back paddlers in K2 sprint kayaking crews of various ability levels. Sensors (Switzerland) 20, 1–14. https://doi.org/10.3390/s20216317

Konings, M.J., Noorbergen, O.S., Parry, D., Hettinga, F.J., 2016. Pacing behaviour and tactical positioning in 1500 m short-track speed skating. Int. J. Sports Physiol. Perform. 11, 122–129.

Kwak, S.G., Kim, J.H., 2017. Central limit theorem: the cornerstone of modern statistics. Korean J. Anesthesiol. 70, 144–156. https://doi.org/10.4097/kjae.2017.70.2.144

Laffite, L.P., Vilas-Boas, J.P., Demarle, A., Silva, J., Fernandes, R., Billat, V.L., 2004. Changes in physiological and stroke parameters during a maximal 400-m free swimming test in elite swimmers. Can. J. Appl. Physiol. 29, S17–S31.

Landry, S.C., McKean, K.A., Hubley-Kozey, C.L., Stanish, W.D., Deluzio, K.J., 2007. Neuromuscular and lower limb biomechanical differences exist between male and female elite adolescent soccer players during an unanticipated run and crosscut maneuver. Am. J. Sports Med. 35, 1888–1900. https://doi.org/10.1177/0363546507307400

Lees, A., 2002. Technique analysis in sports: A critical review. J. Sports Sci. 20, 813–828. https://doi.org/10.1080/026404102320675657

Ligorio, G., Zanotto, D., Sabatini, A.M., Agrawal, S.K., 2017. A novel functional calibration method for real-time elbow joint angles estimation with magnetic-inertial sensors. J. Biomech. 54, 106–110. https://doi.org/10.1016/j.jbiomech.2017.01.024

Limonta, E., Squadrone, R., Rodano, R., Marzegan, A., Veicsteinas, A., Merati, G., Sacchi, M., 2010. Tridimensional kinematic analysis on a kayaking simulator: Key factors to successful performance. Sport Sci. Health 6, 27–34. https://doi.org/10.1007/s11332-010-0093-7

Logan, S., Holt, L., 1985. The flatwater kayak stroke. Natl. Strength Cond. Assoc. 7, 4–11.

Löppönen, A., Vänttinen, T., Haverinen, M., Linnamo, V., 2022. The effect of paddle stroke variables measured by trainesense SmartPaddle® on the velocity of the kayak. Sensors 22, 1–12.

Loschner, C., Smith, R., Galloway, M., 2000. Intra-stroke boat orientation during single skulling. ISBS Proc. Arch. 18, 1–4.

Ludbrook, J., 2010. Confidence in Altman-Bland plots: A critical review of the method of differences. Clin. Exp. Pharmacol. Physiol. 37, 143–149. https://doi.org/10.1111/j.1440-1681.2009.05288.x

Macdermid, P.W., Fink, P., 2017. The validation of a paddle power meter for slalom kayaking. Sport. Med. Int. Open 01, E50–E57. https://doi.org/10.1055/s-0043-100380

Macdermid, P.W., Osborne, A., Stannard, S.R., 2019. Mechanical work and physiological responses to simulated flat water slalom kayaking. Front. Physiol. 10, 1–9. https://doi.org/10.3389/fphys.2019.00260

Mann, R.V., Kearney, J.T., 1980. A biomechanical analysis of the Olympic-style flatwater kayak stroke. Med. Sci. Sports Exerc. https://doi.org/10.1249/00005768-198023000-00010

Mantha, V.R., Silva, A.J., Marinho, D.A., Rouboa, A.I., 2013. Numerical simulation of two-phase flow around flatwater competition kayak design-evolution models. J. Appl. Biomech. 29, 270–278. https://doi.org/10.1123/jab.29.3.270

Mayagoitia, R.E., Nene, A.V., Veltink, P.H., 2002. Accelerometer and rate gyroscope measurement of kinematics: an inexpensive alternative to optical motion analysis systems. J. Biomech. 35, 537–542. https://doi.org/10.1016/S0021-9290(01)00231-7

McDonnell, L.K., Hume, P.A., Nolte, V., 2013a. A deterministic model based on evidence for the associations between kinematic variables and sprint kayak performance. Sport. Biomech. 12, 205–220. https://doi.org/10.1080/14763141.2012.760106

McDonnell, L.K., Hume, P.A., Nolte, V., 2013b. Place time consistency and stroke rates required for success in K1 200-m sprint kayaking elite competition. Int. J. Perform. Anal. Sport 13, 38–50. https://doi.org/10.1080/24748668.2013.11868630

McDonnell, L.K., Hume, P.A., Nolte, V., 2012. An observational model for biomechanical assessment of sprint kayaking technique. Sport. Biomech. 11, 507–523. https://doi.org/10.1080/14763141.2012.724701

McGibbon, K.E., Pyne, D.B., Shephard, M.E., Thompson, K.G., 2018. Pacing in swimming: A systematic review. Sport. Med. 48, 1621–1633. https://doi.org/10.1007/s40279-018-0901-9

Menting, S.G., Elferink-Gemser, M., Huijgen, C.B., Hettinga, F.J., 2019. Pacing in lane-based head-to-head competitions: A systematic review on swimming. J. Sports Sci. 37, 2287–2299. https://doi.org/10.1080/02640414.2019.1627989

Michael, J.S., Rooney, K.B., Smith, R.M., 2012. The dynamics of elite paddling on a kayak simulator. J. Sports Sci. 30, 661–668. https://doi.org/10.1080/02640414.2012.655303

Michael, J.S., Rooney, K.B., Smith, R.M., 2008. The metabolic demands of kayaking: A review. J. Sport. Sci. Med. 7, 1–7.

Michael, J.S., Smith, R.M., Rooney, K.B., 2009. Determinants of kayak paddling performance. Sport. Biomech. 8, 167–179. https://doi.org/10.1080/14763140902745019

Miyazaki, S., Yamako, G., Kimura, R., Punchihewa, N.G., Kawaguchi, T., Arakawa, H., Chosa, E., 2023. Development of a video camera-type kayak motion capture system to measure water kayaking. PeerJ 11, 1–15. https://doi.org/10.7717/peerj.15227

Morrow, M., Lowndes, B., Fortune, E., Kaufman, K., Hallbeck, M., 2017. Validation of inertial measurement units for upper body kinematics. J. Appl. Biomech. 33, 227–232. https://doi.org/10.1183/09031936.00063810.The

Mytton, G.J., Archer, D.T., Turner, L., Skorski, S., Renfree, A., Thompson, K.G., St Clair Gibson, A., 2015. Increased variability of lap speeds differentiate medallists and non-medallists in middle distance running and swimming events. Int. J. Sports Physiol. Perform. 10, 369–373. https://doi.org/10.1123/ijspp.2014-0207

Nakashima, M., Kitazawa, A., Nakagaki, K., Onoto, N., 2017. Simulation to clarify the effect of paddling motion on the hull behavior of a single kayak in a sprint race. Sport. Eng. 20, 133–139. https://doi.org/10.1007/s12283-016-0222-x

Newell, K., 1986. Constraints on the development of coordination, in: Motor Development in Children: Aspects of Coordination and Control. pp. 341–360.

Nilsson, J.E., Rosdahl, H.G., 2016. Contribution of leg-muscle forces to paddle force and kayak speed during maximal-effort flat-water paddling. Int. J. Sports Physiol. Perform. 11, 22–27. https://doi.org/10.1123/ijspp.2014-0030

Niu, L., Kong, P.W., Tay, C.S., Lin, Y., Wu, B., Ding, Z., Chiu, C., 2019. Evaluating on-water kayak paddling performance using optical fiber technology. IEEE Sens. J. 19, 11918–11925. https://doi.org/10.1109/JSEN.2019.2927304

O'Donovan, K.J., Kamnik, R., O'Keeffe, D.T., Lyons, G.M., 2007. An inertial and magnetic sensor based technique for joint angle measurement. J. Biomech. 40, 2604–2611. https://doi.org/10.1016/j.jbiomech.2006.12.010

Ong, K., Elliott, B., Ackland, T., Lyttle, A., 2006. Performance tolerance and boat set-up in elite sprint kayaking. Sport. Biomech. 5, 77–94. https://doi.org/10.1080/14763141.2006.9628226

Paquette, M., Bieuzen, F., Billaut, F., 2020. Effect of a 3-weeks training camp on muscle oxygenation, VO2 performance in elite sprint kayakers. Front. Sport. Act. Living 2, 1–13. https://doi.org/10.3389/fspor.2020.00047

Pataky, T.C., 2012. One-dimensional statistical parametric mapping in Python. Comput. Methods Biomech. Biomed. Engin. 15, 295–301. https://doi.org/10.1080/10255842.2010.527837

Pendergast, D., Mollendorf, J., Zamparo, P., Termin, A., Bushnell, D., Paschke, D., 2005. The influence of drag on human locomotion in water. Undersea Hyperb. Med. 32, 45–57.

Pendergast, D., Zamparo, P., di Prampero, P.E., Capelli, C., Cerretelli, P., Termin, A., Craig, A., Bushnell, D., Paschke, D., Mollendorf, J., 2003. Energy balance of human locomotion in water. Eur. J. Appl. Physiol. 90, 377–386. https://doi.org/10.1007/s00421-003-0919-y

Pérez, R., Costa, Ú., Torrent, M., Solana, J., Opisso, E., Cáceres, C., Tormos, J.M., Medina, J., Gómez, E.J., 2010. Upper limb portable motion analysis system based on inertial technology for neurorehabilitation purposes. Sensors 10, 10733–10751. https://doi.org/10.3390/s101210733

Petrovic, M., Garcia-Ramos, A., Janicijevic, D., Pérez-Castilla, A., Knezevic, O., Mirkov, D., 2020. The force-velocity relationship assessed during the single-stroke kayak test can discriminate between 200-m and longer distance (500 and 1000-m) specialists in canoe sprint. Int. J. Sports Physiol. Perform. 1–8.

Piazza, S.J., Cavanagh, P.R., 2000. Measurement of the screw-home motion of the knee is sensitive to errors in axis alignment. J. Biomech. 33, 1029–1034. https://doi.org/10.1016/S0021-9290(00)00056-7

Picerno, P., Caliandro, P., Iacovelli, C., Simbolotti, C., Crabolu, M., Pani, D., Vannozzi, G., Reale, G., Rossini, P.M., Padua, L., Cereatti, A., 2019. Upper limb joint kinematics using wearable magnetic and inertial measurement units: an anatomical calibration procedure based on bony landmark identification. Sci. Rep. 9, 1–10. https://doi.org/10.1038/s41598-019-50759-z

Pickett, C.W., Abbiss, C., Zois, J., Blazevich, A.J., 2020. Pacing and stroke kinematics in 200-m kayak racing. J. Sports Sci. 00, 1–9. https://doi.org/10.1080/02640414.2020.1859242

Plagenhoef, S., 1979. Biomechanical analysis of Olympic flatwater kayaking and canoeing. Res. Quarterly. Am. Alliance Heal. Phys. Educ. Recreat. Danc. 50, 443–459. https://doi.org/10.1080/00345377.1979.10615632

Poitras, I., Dupuis, F., Bielmann, M., Campeau-Lecours, A., Mercier, C., Bouyer, L.J., Roy, J.S., 2019. Validity and reliability of wearable sensors for joint angle estimation: A systematic review. Sensors 19, 1555. https://doi.org/10.3390/s19071555

Prétot, C., Carmigniani, R., Hasbroucq, L., Labbé, R., Boucher, J., Clanet, C., 2022. On the physics of kayaking. Appl. Sci. 12, 8925.

Rau, G., Disselhorst-Klug, C., Schmidt, R., 2000. Movement biomechanics goes upwards: from the leg to the arm. J. Biomech. 33, 1207–1216. https://doi.org/10.1016/S0021-9290(00)00062-2

Redwood-Brown, A., Brown, H.L., Oakley, B., Felton, P.J., 2021. Determinants of boat velocity during a 200 m race in elite Paralympic sprint kayakers. Int. J. Perform. Anal. Sport 00, 1–13. https://doi.org/10.1080/24748668.2021.1986351

Renfree, A., Martin, L., Richards, A., St Clair Gibson, A., 2012. All for one and one for all! Disparity between overall crew's and individual rowers' pacing strategies during rowing. Int. J. Sports Physiol. Perform. 7, 298–300. https://doi.org/10.1123/ijspp.7.3.298

Robert-Lachaine, X., Mecheri, H., Muller, A., Larue, C., Plamondon, A., 2020. Validation of a low-cost inertial motion capture system for whole-body motion analysis. J. Biomech. 99, 109520. https://doi.org/10.1016/j.jbiomech.2019.109520

Roelands, B., de Koning, J., Foster, C., Hettinga, F., Meeusen, R., 2013. Neurophysiological determinants of theoretical concepts and mechanisms involved in pacing. Sport. Med. 43, 301–311. https://doi.org/10.1007/s40279-013-0030-4

Romagnoli, C., Ditroilo, M., Bonaiuto, V., Annino, G., Gatta, G., 2022. Paddle propulsive force and power balance : a new approach to performance assessment in flatwater kayaking to performance assessment in flatwater kayaking. Sport. Biomech. 00, 1–14. https://doi.org/10.1080/14763141.2022.2109505

Sanders, R.H., Kendal, S.J., 1992. A description of Olympic flatwater kayak stroke technique. Aust. J. Sci. Med. Sport 24, 25–30.

Sanderson, B., Martindale, W., 1986. Towards optimizing rowing technique. Med. Sci. Sports Exerc. 18, 454–468. https://doi.org/10.1249/00005768-198608000-00016

Sandford, G.N., Pearson, S., Allen, S. V., Malcata, R.M., Kilding, A.E., Ross, A., Laursen, P.B., 2018. Tactical behaviors in men's 800-m olympic and world-championship medalists: A changing of the guard. Int. J. Sports Physiol. Perform. 13, 246–249. https://doi.org/10.1123/ijspp.2016-0780

Seiler, S., 2015. 150 years of rowing faster: What are the sources of more and more speed? BMC Sports Sci. Med. Rehabil. 7, 2052. https://doi.org/10.1186/2052-1847-7-s1-o12

Shapiro, R., Kearney, J.T., 1986. Anatomical and physiological factors in elite female kayakers. ISBS Proc. Arch. 4, 129–137.

Shin, C., 2020. Biomechanical factors affecting individuals' performance in sprint kayaking. PhD Thesis. University of Lincoln, Lincoln.

Shin, C., Willmott, A.P., Mullineaux, D.R., 2018. Does Isoinertial ergometry profiling represent on-water sprint capacity in kayakers? ISBS Proc. Arch. 36, 342–345.

Simbaña-Escobar, D., Hellard, P., Seifert, L., 2018. Modelling stroking parameters in competitive sprint swimming: Understanding inter- and intra-lap variability to assess pacing management. Hum. Mov. Sci. 61, 219–230. https://doi.org/10.1016/j.humov.2018.08.002

Sinclair, P.J., Greene, A.J., Smith, R., 2009. The Effects of horizontal and vertical forces on single scull boat orientation while rowing. ISBS Proc. Arch. 27, 1–4.

Skorski, S., Abbiss, C.R., 2017. The manipulation of pace within endurance sport. Front. Physiol. 8, 1–8. https://doi.org/10.3389/fphys.2017.00102

Smits, B.L., Pepping, G.-J., Hettinga, F.J., 2014. Pacing and decision making in sport and exercise: The roles of perception and action in the regulation of exercise intensity. Sport. Med. 44, 763–775. https://doi.org/10.1007/s40279-014-0163-0

Soper, C., Hume, P.A., 2004. Towards an ideal rowing technique for performance. Sport. Med. 34, 825–848. https://doi.org/10.2165/00007256-200434120-00003

Sperlich, B., Holmberg, H.C., 2017. Wearable, yes, but able...?: it is time for evidence-based marketing claims! Br. J. Sports Med. 51, 1240. https://doi.org/10.1136/bjsports-2016-097295

Sperlich, J., Baker, J., 2002. Biomechanical testing in elite canoeing. ISBS Proc. Arch. 20, 44–47.

Sprigings, E., McNair, P., Mawston, G., Sumner, D., Boocock, M., 2006. A method for personalising the blade size for competitors in flatwater kayaking. Sport. Eng. 9, 147–153. https://doi.org/10.1007/BF02844116

St Clair Gibson, A., Schabort, E.J., Noakes, T.D., 2001. Reduced neuromuscular activity and force generation during prolonged cycling. Am. J. Physiol. Regul. Integr. Comp. Physiol. 281, 187–196. https://doi.org/10.1111/j.1748-1716.1967.tb03720.x

St Clair Gibson, A., Swart, J., Tucker, R., 2018. The interaction of psychological and physiological homeostatic drives and role of general control principles in the regulation of physiological systems, exercise and the fatigue process – The Integrative Governor theory. Eur. J. Sport Sci. 18, 25–36. https://doi.org/10.1080/17461391.2017.1321688

Stoter, I.K., MacIntosh, B.R., Fletcher, J.R., Pootz, S., Zijdewind, I., Hettinga, F.J., 2016. Pacing strategy, muscle fatigue and technique in 1500 m speed skating and cycling time-trials. Int. J. Sports Physiol. Perform. 11, 337–343. https://doi.org/10.1123/ijspp.2014-0603

Stothart, J. P., Reardon, F.D., Thoden, J.S., 1986. A system for the evaluation of on-water stroke force development during canoe and kayak events. ISBS Proc. Arch. 4, 146–152.

Stothart, J.P., Reardon, F.D., Thoden, J.S., 1986. Paddling ergometer kinematics of elite kayakers. ISBS Proc. Arch. 4, 125–128.

Sumner, D., Sprigings, E.J., Bugg, J.D., Heseltine, J.L., 2003. Fluid forces on kayak paddle blades of different design. Sport. Eng. 6, 11–19. https://doi.org/10.1007/BF02844156

Teufl, W., Miezal, M., Taetz, B., Fröhlich, M., Bleser, G., 2018. Validity, test-retest reliability and long-term stability of magnetometer free inertial sensor based 3D joint kinematics. Sensors 18, 1980. https://doi.org/10.3390/s18071980

Therrien, M., Colloud, F., Begon, M., 2012. Effect of stroke rate on paddle tip path in kayaking. Mov. Sport. Sci. - Sci. Mot. 75, 113–120. https://doi.org/10.1051/sm/2011156

Thiel, C., Foster, C., Banzer, W., de Koning, J., 2012. Pacing in Olympic track races: Competitive tactics versus best performance strategy. J. Sports Sci. 30, 1107–1115. https://doi.org/10.1080/02640414.2012.701759

Thompson, K.G., Maclaren, D.P.M., Lees, A., Atkinson, G., 2004. The effects of changing pace on metabolism and stroke characteristics during high-speed breaststroke swimming. J. Sports Sci. 22, 149–157. https://doi.org/10.1080/02640410310001641467

Toussaint, H.M., Carol, A., Kranenborg, H., Truijens, M.J., 2006. Effect of fatigue on stroking characteristics in an arms-only 100-m front-crawl race. Med. Sci. Sports Exerc. 38, 1635–1642. https://doi.org/10.1249/01.mss.0000230209.53333.31

Tullis, S., Galipeau, C., Morgoch, D., 2018. Detailed on-water measurements of blade forces and stroke efficiencies in sprint canoe, in: The 12th Conference of the International Sports Engineering Association. pp. 306–314. https://doi.org/10.3390/proceedings2060306 u-blox AG, 2015. PAM-7Q u-blox 7 GPS Antenna Module [WWW Document]. Data Sheet. URL https://www.u-blox.com/sites/default/files/PAM-7Q_DataSheet_%28UBX-13002455%29.pdf (accessed 5.22.20).

Vadai, G, Gingl, Z., Mingesz, R., Makan, G., 2013. Performance estimation of kayak paddlers based on fluctuation analysis of movement signals. 2013 22nd Int. Conf. Noise Fluctuations, ICNF 2013 2–5. https://doi.org/10.1109/ICNF.2013.6579010

Vadai, G., Makan, G., Gingl, Z., Mingesz, R., Mellar, J., Szepe, T., Csamango, A., 2013. On-water measurement and analysis system for estimating kayak paddlers' performance, in: 2013 36th International Convention on Information and Communication Technology, Electronics and Microelectronics. pp. 131–136.

van Andel, C.J., Wolterbeek, N., Doorenbosch, C.A.M., Veeger, D. (H E.J.), Harlaar, J., 2008. Complete 3D kinematics of upper extremity functional tasks. Gait Posture 27, 120–127. https://doi.org/10.1016/j.gaitpost.2007.03.002

Van Someren, K.A., Howatson, G., 2008. Prediction of flatwater kayaking performance. Int. J. Sports Physiol. Perform. 3, 207–218. https://doi.org/10.1139/h03-039

Van Someren, K.A., Palmer, G.S., 2003. Prediction of 200-m sprint kayaking performance. Can. J. Appl. Physiol. 28, 505–517. https://doi.org/10.1139/h03-039

Veiga, S., Rodriguez, L., González-Frutos, P., Navandar, A., 2019. Race strategies of open water swimmers in the 5-km, 10-km, and 25-km races of the 2017 FINA World Swimming Championships. Front. Psychol. 10, 654. https://doi.org/10.3389/fpsyg.2019.00654

Wagner, J., Bartmus, U., Marées, H. de, 1993. Three-axes gyro system quantifying the specific balance of rowing. Int. J. Sports Med. 14, S35–S38. https://doi.org/10.1055/s-2007-1021222

Wainwright, B., Cooke, C., Low, C., 2015. Performance related technique factors in Olympic sprint kayaking. ISBS Proc. Arch. 33, 1275–1278.

Wainwright, B., Cooke, C., Low, C., 2014. A deterministic model for Olympic sprint kayaking, in: Bases 2013 Abstracts, Journal of Sports Sciences. p. s107. https://doi.org/10.1080/02640414.2014.896604

Walmsley, C.P., Williams, S.A., Grisbrook, T., Elliott, C., Imms, C., Campbell, A., 2018. Measurement of upper limb range of motion using wearable sensors: A systematic review. Sport. Med. - Open 4, 1–22. https://doi.org/10.1186/s40798-018-0167-7

Warmenhoven, J., Cobley, S., Draper, C., Harrison, A.J., Bargary, N., Smith, R., 2017. Assessment of propulsive pin force and oar angle time-series using functional data analysis in on-water rowing. Scand. J. Med. Sci. Sport. 27, 1688–1696. https://doi.org/10.1111/sms.12871

Warmenhoven, J, Cobley, S., Draper, C., Smith, R., 2018a. Over 50 years of researching force profiles in rowing: What do we know? Sport. Med. 48, 2703–2714. https://doi.org/10.1007/s40279-018-0992-3

Warmenhoven, J, Harrison, A., Robinson, M.A., Vanrenterghem, J., Bargary, N., Smith, R., Cobley, S., Draper, C., Donnelly, C., Pataky, T., 2018b. A force profile analysis comparison between functional data analysis, statistical parametric mapping and statistical non-parametric mapping in on-water single sculling. J. Sci. Med. Sport 21, 1100–1105. https://doi.org/10.1016/j.jsams.2018.03.009

Warmenhoven, J., Smith, R., Draper, C., Harrison, A.J., Bargary, N., Cobley, S., 2018. Force coordination strategies in on-water single sculling: Are asymmetries related to better rowing performance? Scand. J. Med. Sci. Sport. 28, 1379–1388. https://doi.org/10.1111/sms.13031

Winchcombe, C.E., Binnie, M.J., Doyle, M.M., Hogan, C., Peeling, P., 2019. Development of an on-water graded exercise test for flat-water sprint kayak athletes. Int. J. Sports Physiol. Perform. 14, 1244–1249. https://doi.org/10.1123/ijspp.2018-0717

Windt, J., MacDonald, K., Taylor, D., Zumbo, B.D., Sporer, B.C., Martin, D.T., 2020. “To Tech or Not to Tech?” A critical decision-making framework for implementing technology in sport. J. Athl. Train. 55, 902–910. https://doi.org/10.4085/1062-6050-0540.19

Wing, A.M., Woodburn, C., 1995. The coordination and consistency of rowers in a racing eight. J. Sports Sci. 13, 187–197. https://doi.org/10.1080/02640419508732227

Woltring, H.J., 1994. 3-D attitude representation of human joints: A standardization proposal. J. Biomech. 27, 1399–1414. https://doi.org/10.1016/0021-9290(94)90191-0

Worsey, M.T.O., Espinosa, H.G., Shepherd, J.B., Thiel, D. V., 2019. A systematic review of performance analysis in rowing using inertial sensors. Electron. 8. https://doi.org/10.3390/electronics8111304

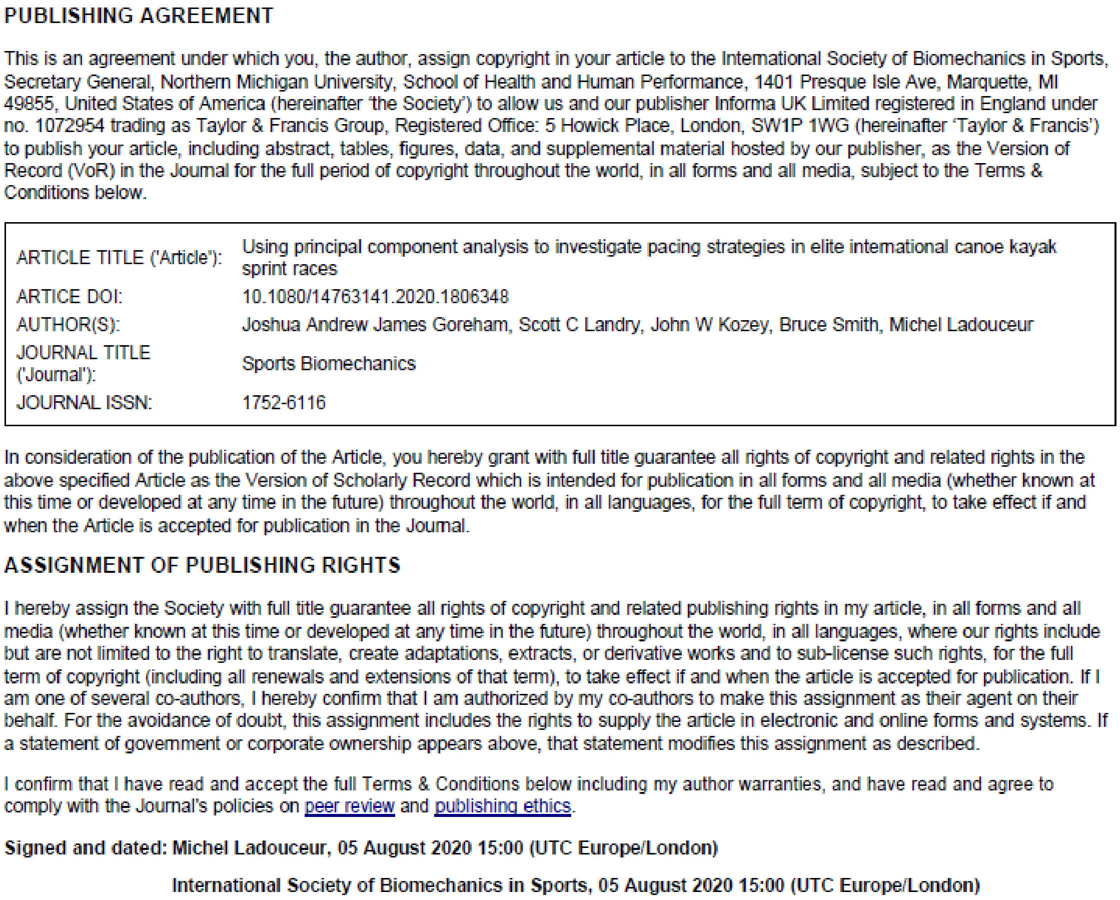
Wu, G., van der Helm, F.C., Veeger, H.E., Makhsous, M., Van Roy, P., Anglin, C., Nagels, J., Karduna, A.., McQuade, K., Wang, X., Werner, F., Buchholz, B., 2005. ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion - Part II: shoulder, elbow, wrist and hand. J. Biomech. 38, 981–992. https://doi.org/10.1016/j.jbiomech.2004.05.042

Zatsiorsky, V.M., 2008. Biomechanics in sport: Performance enhancement and injury prevention, 9th ed. John Wiley & Sons.

Zatsiorsky, V.M., Yakunin, N., 1991. Mechanics and Biomechanics of Rowing: A Review. J. Appl. Biomech. 7, 229–281. https://doi.org/10.1123/ijsb.7.3.229

Zouhal, H., Lahaye, S.L., Abderrahaman, A.B., Minter, G., Herbez, R., Castagna, C., 2012. Energy system contribution to Olympic distances in flat water kayaking (500 and 1,000 m) in highly trained subjects. J. Strength Cond. Res. 26, 825–831. https://doi.org/10.1519/JSC.0b013e31822766f7

# Appendix A: Publishing Agreement for Chapter 3



## PUBLISHING AGREEMENT

This is an agreement under which you, the author, assign copyright in your article to the International Society of Biomechanics in Sports, Secretary General, Northern Michigan University, School of Health and Human Performance, 1401 Presque Isle Ave, Marquette, MI 49855, United States of America (hereinafter 'the Society') to allow us and our publisher Informa UK Limited registered in England under no. 1072954 trading as Taylor & Francis Group, Registered Office: 5 Howick Place, London, SW1P 1WG (hereinafter 'Taylor & Francis') to publish your article, including abstract, tables, figures, data, and supplemental material hosted by our publisher, as the Version of Record (VoR) in the Journal for the full period of copyright throughout the world, in all forms and all media, subject to the Terms & Conditions below.

| | |
|---|---|
| ARTICLE TITLE ('Article'): | Using principal component analysis to investigate pacing strategies in elite international canoe kayak sprint races |
| ARTICE DOI: | 10.1080/14763141.2020.1806348 |
| AUTHOR(S): | Joshua Andrew James Goreham, Scott C Landry, John W Kozey, Bruce Smith, Michel Ladouceur |
| JOURNAL TITLE ('Journal'): | Sports Biomechanics |
| JOURNAL ISSN: | 1752-6116 |

In consideration of the publication of the Article, you hereby grant with full title guarantee all rights of copyright and related rights in the above specified Article as the Version of Scholarly Record which is intended for publication in all forms and all media (whether known at this time or developed at any time in the future) throughout the world, in all languages, for the full term of copyright, to take effect if and when the Article is accepted for publication in the Journal.

## ASSIGNMENT OF PUBLISHING RIGHTS

I hereby assign the Society with full title guarantee all rights of copyright and related publishing rights in my article, in all forms and all media (whether known at this time or developed at any time in the future) throughout the world, in all languages, where our rights include but are not limited to the right to translate, create adaptations, extracts, or derivative works and to sub-license such rights, for the full term of copyright (including all renewals and extensions of that term), to take effect if and when the article is accepted for publication. If I am one of several co-authors, I hereby confirm that I am authorized by my co-authors to make this assignment as their agent on their behalf. For the avoidance of doubt, this assignment includes the rights to supply the article in electronic and online forms and systems. If a statement of government or corporate ownership appears above, that statement modifies this assignment as described.

I confirm that I have read and accept the full Terms & Conditions below including my author warranties, and have read and agree to comply with the Journal's policies on peer review and publishing ethics.

**Signed and dated: Michel Ladouceur, 05 August 2020 15:00 (UTC Europe/London)**

**International Society of Biomechanics in Sports, 05 August 2020 15:00 (UTC Europe/London)**

**THIS FORM IS A LEGALLY BINDING DOCUMENT. WE RECOMMEND THAT YOU RETAIN A COPY OF IT AND CONSULT A LEGAL ADVISOR IF YOU HAVE ANY QUESTIONS.**

## ASSIGNMENT OF COPYRIGHT: TERMS & CONDITIONS

### DEFINITION

1. Your article is defined as comprising (a) your Accepted Manuscript (AM) in its final form; (b) the final, definitive, and citable Version of Record (VoR) including the abstract, text, bibliography, and all accompanying tables, illustrations, data, and media; and (c) any supplemental material hosted by our publisher. This assignment and these Terms & Conditions constitute the entire agreement and the sole understanding between you and us ('agreement'); no amendment, addendum, or other communication will be taken into account when interpreting your and our rights and obligations under this agreement, unless amended by a written document signed by both of us.

### TAYLOR & FRANCIS' RESPONSIBILITIES

2. If deemed acceptable by the Editors of the Journal, we shall prepare and publish your article in the Journal. We may post your accepted manuscript in advance of the formal publication of the VoR. We reserve the right to make such editorial changes as may be necessary to make the article suitable for publication, or as we reasonably consider necessary to avoid infringing third-party rights or breaching any laws; and we reserve the right not to proceed with publication for whatever reason.
3. Taylor & Francis will deposit your Accepted Manuscript (AM) to any designated institutional repository including PubMedCentral (PMC) with which Taylor & Francis has an article deposit agreement; see 4 iv (a) below.

### RIGHTS RETAINED BY YOU AS AUTHOR

4. These rights are personal to you, and your co-authors, and cannot be transferred by you to anyone else. Without prejudice to your rights as author set out below, you undertake that the fully reference-linked VoR will not be published elsewhere without our prior written consent. You assert and retain the following rights as author(s):
    i. The right to be identified as the author of your article, whenever and wherever the article is published, such rights including moral rights arising under § 77, Copyright, Designs & Patents Act 1988, and, so far as is legally possible, any corresponding rights we may have in any territory of the world.
    ii. The right to retain patent rights, trademark rights, or rights to any process, product or procedure described in your article.
    iii. The right to post and maintain at any time the Author's Original Manuscript (AOM; your manuscript in its original and unrefereed form; a 'preprint').
    iv. The right to post at any time after publication of the VoR your AM (your manuscript in its revised after peer review and accepted for publication form; a 'postprint') as a digital file on your own personal or departmental website, provided that you do not use the VoR published by us, and that you include any amendments or deletions or warnings relating to the article issued or published by us; and with the acknowledgement: 'The Version of Record of this manuscript has been published and is available in <JOURNAL TITLE> <date of publication> http://www.tandfonline.com/<Article DOI>.'
        a. Please note that embargoes apply with respect to posting the AM to an institutional or subject repository. For further information, please see our list of journals with applicable embargo periods. For the avoidance of doubt, you are not permitted to post the final published paper, the VoR published by us, to any site, unless it has been published as Open Access on our website.
        b. If, following publication, you or your funder pay an Article Publishing Charge for retrospective Open Access publication, you may then opt for one of three licenses: CC BY, CC BY-NC, or CC BY-NC-ND; if you do not respond, we shall assign a CC BY licence. All rights in the article will revert to you as author.
    v. The right to share with colleagues copies of the article in its published form as supplied to you by the publisher as a digital eprint or printed reprint on a non-commercial basis.
    vi. The right to make printed copies of all or part of the article on a non-commercial basis for use by you for lecture or classroom purposes provided that such copies are not offered for sale or distributed in any systematic way, and provided that acknowledgement to prior publication in the Journal is given.
    vii. The right, if the article has been produced within the scope of your employment, for your employer to use all or part of the article internally within the institution or company on a non-commercial basis provided that acknowledgement to prior publication in the Journal is given.
    viii. The right to include the article in a thesis or dissertation that is not to be published commercially, provided that acknowledgement to prior publication in the Journal is given.
    ix. The right to present the article at a meeting or conference and to distribute printed copies of the article to the delegates attending the meeting provided that this is not for commercial purposes and provided that acknowledgement to prior publication in the Journal is given.
    x. The right to use the article in its published form in whole or in part without revision or modification in personal compilations, or other publications of your own work, provided that acknowledgement to prior publication in the Journal is given.
    xi. The right to expand your article into book-length form for publication provided that acknowledgement to prior publication in the Journal is made explicit (see below). Where permission is sought to re-use an article in a book chapter or edited collection on a commercial basis a fee will be due, payable by the publisher of the new work. Where you as the author of the article have had the lead role in the new work (i.e., you are the author of the new work or the editor of the edited collection), fees will be waived. Acknowledgement to prior publication in the Journal should be made explicit (see below):

**Acknowledgement**: This <chapter or book> is derived in part from an article published in <JOURNAL TITLE> <date of publication> <copyright <the Society>, available online: http://www.tandfonline.com/<Article DOI>

If you wish to use your article in a way that is not permitted by this agreement, please contact permissionrequest@tandf.co.uk

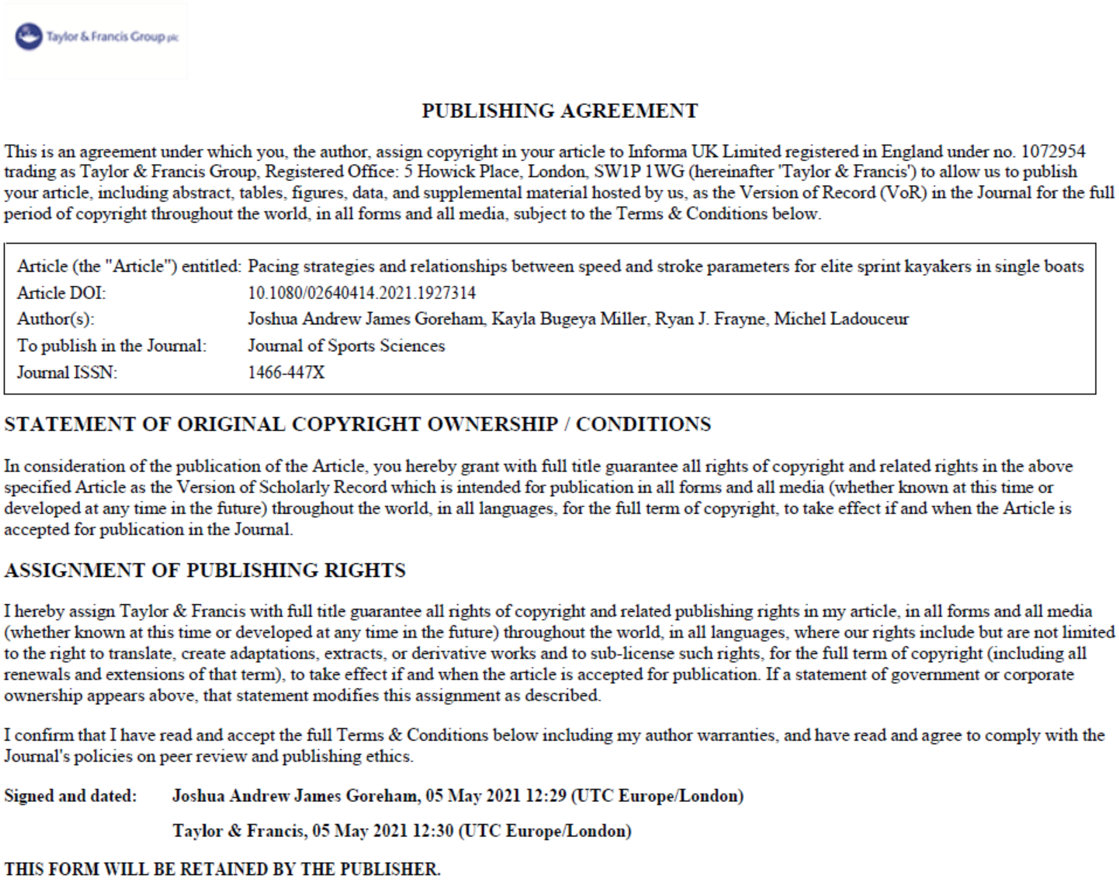
**WARRANTIES MADE BY YOU AS AUTHOR**

5. You warrant that:
   - i. All persons who have a reasonable claim to authorship are named in the article as co-authors including yourself, and you have not fabricated or misappropriated anyone's identity, including your own.
   - ii. You have been authorized by all such co-authors to sign this agreement as agent on their behalf, and to agree on their behalf the priority of the assertion of copyright and the order of names in the publication of the article.
   - iii. The article is your original work, apart from any permitted third-party copyright material you include, and does not infringe any intellectual property rights of any other person or entity and cannot be construed as plagiarizing any other published work, including your own published work.
   - iv. The article is not currently under submission to, nor is under consideration by, nor has been accepted by any other journal or publication, nor has been previously published by any other journal or publication, nor has been assigned or licensed by you to any third party.
   - v. The article contains no content that is abusive, defamatory, libellous, obscene, fraudulent, nor in any way infringes the rights of others, nor is in any other way unlawful or in violation of applicable laws.
   - vi. Research reported in the article has been conducted in an ethical and responsible manner, in full compliance with all relevant codes of experimentation and legislation. All articles which report in vivo experiments or clinical trials on humans or animals must include a written statement in the Methods section that such work was conducted with the formal approval of the local human subject or animal care committees, and that clinical trials have been registered as applicable legislation requires.
   - vii. Any patient, service user, or participant (or that person's parent or legal guardian) in any research or clinical experiment or study who is described in the article has given written consent to the inclusion of material, text or image, pertaining to themselves, and that they acknowledge that they cannot be identified via the article and that you have anonymized them and that you do not identify them in any way. Where such a person is deceased, you warrant you have obtained the written consent of the deceased person's family or estate.
   - viii. You have complied with all mandatory laboratory health and safety procedures in the course of conducting any experimental work reported in your article; your article contains all appropriate warnings concerning any specific and particular hazards that may be involved in carrying out experiments or procedures described in the article or involved in instructions, materials, or formulae in the article; your article includes explicitly relevant safety precautions; and cites, if an accepted Standard or Code of Practice is relevant, a reference to the relevant Standard or Code.
   - ix. You have acknowledged all sources of research funding, as required by your research funder, and disclosed any financial interest or benefit you have arising from the direct applications of your research.
   - x. You have obtained the necessary written permission to include material in your article that is owned and held in copyright by a third party, which shall include but is not limited to any proprietary text, illustration, table, or other material, including data, audio, video, film stills, screenshots, musical notation and any supplemental material.
   - xi. You have read and complied with our policy on publishing ethics.
   - xii. You have read and complied with the Journal's Instructions for Authors.
   - xiii. You have read and complied with our guide on peer review.
   - xiv. You will keep us and our affiliates indemnified in full against all loss, damages, injury, costs and expenses (including legal and other professional fees and expenses) awarded against or incurred or paid by us as a result of your breach of the warranties given in this agreement.
   - xv. You consent to allowing us to use your article for marketing and promotional purposes.

**GOVERNING LAW**

6. This agreement (and any dispute, proceeding, claim or controversy in relation to it) is subject to English law and the parties hereby submit to the exclusive jurisdiction of the Courts of England and Wales.

# Appendix B: Publishing Agreement for Chapter 4



Taylor & Francis Group plc

## PUBLISHING AGREEMENT

This is an agreement under which you, the author, assign copyright in your article to Informa UK Limited registered in England under no. 1072954 trading as Taylor & Francis Group, Registered Office: 5 Howick Place, London, SW1P 1WG (hereinafter 'Taylor & Francis') to allow us to publish your article, including abstract, tables, figures, data, and supplemental material hosted by us, as the Version of Record (VoR) in the Journal for the full period of copyright throughout the world, in all forms and all media, subject to the Terms & Conditions below.

| | |
|---|---|
| Article (the "Article") entitled: | Pacing strategies and relationships between speed and stroke parameters for elite sprint kayakers in single boats |
| Article DOI: | 10.1080/02640414.2021.1927314 |
| Author(s): | Joshua Andrew James Goreham, Kayla Bugeya Miller, Ryan J. Frayne, Michel Ladouceur |
| To publish in the Journal: | Journal of Sports Sciences |
| Journal ISSN: | 1466-447X |

## STATEMENT OF ORIGINAL COPYRIGHT OWNERSHIP / CONDITIONS

In consideration of the publication of the Article, you hereby grant with full title guarantee all rights of copyright and related rights in the above specified Article as the Version of Scholarly Record which is intended for publication in all forms and all media (whether known at this time or developed at any time in the future) throughout the world, in all languages, for the full term of copyright, to take effect if and when the Article is accepted for publication in the Journal.

## ASSIGNMENT OF PUBLISHING RIGHTS

I hereby assign Taylor & Francis with full title guarantee all rights of copyright and related publishing rights in my article, in all forms and all media (whether known at this time or developed at any time in the future) throughout the world, in all languages, where our rights include but are not limited to the right to translate, create adaptations, extracts, or derivative works and to sub-license such rights, for the full term of copyright (including all renewals and extensions of that term), to take effect if and when the article is accepted for publication. If a statement of government or corporate ownership appears above, that statement modifies this assignment as described.

I confirm that I have read and accept the full Terms & Conditions below including my author warranties, and have read and agree to comply with the Journal's policies on peer review and publishing ethics.

**Signed and dated:** **Joshua Andrew James Goreham, 05 May 2021 12:29 (UTC Europe/London)**

**Taylor & Francis, 05 May 2021 12:30 (UTC Europe/London)**

**THIS FORM WILL BE RETAINED BY THE PUBLISHER.**

# ASSIGNMENT OF COPYRIGHT: TERMS & CONDITIONS

## DEFINITION

1. Your article is defined as comprising (a) your Accepted Manuscript (AM) in its final form; (b) the final, definitive, and citable Version of Record (VoR) including the abstract, text, bibliography, and all accompanying tables, illustrations, data, and media; and (c) any supplemental material hosted by Taylor & Francis. This assignment and these Terms & Conditions constitute the entire agreement and the sole understanding between you and us ('agreement'); no amendment, addendum, or other communication will be taken into account when interpreting your and our rights and obligations under this agreement, unless amended by a written document signed by both of us.

## TAYLOR &FRANCIS' RESPONSIBILITIES

2. If deemed acceptable by the Editors of the Journal, we shall prepare and publish your article in the Journal. We may post your accepted manuscript in advance of the formal publication of the VoR. We reserve the right to make such editorial changes as may be necessary to make the article suitable for publication, or as we reasonably consider necessary to avoid infringing third-party rights or breaching any laws; and we reserve the right not to proceed with publication for whatever reason.
3. Taylor & Francis will deposit your Accepted Manuscript (AM) to any designated institutional repository including PubMedCentral (PMC) with which Taylor & Francis has an article deposit agreement; see 4 iv (a) below.

## RIGHTS RETAINED BY YOU AS AUTHOR

4. These rights are personal to you, and your co-authors, and cannot be transferred by you to anyone else. Without prejudice to your rights as author set out below, you undertake that the fully reference-linked Version of Record (VOR) will not be published elsewhere without our prior written consent. You assert and retain the following rights as author(s):
   i. The right to be identified as the author of your article, whenever and wherever the article is published, such rights including moral rights arising under § 77, Copyright, Designs & Patents Act 1988, and, so far as is legally possible, any corresponding rights we may have in any territory of the world.
   ii. The right to retain patent rights, trademark rights, or rights to any process, product or procedure described in your article.
   iii. The right to post and maintain at any time the Author's Original Manuscript (AOM; your manuscript in its original and unrefereed form; a 'preprint').
   iv. The right to post at any time after publication of the VoR your AM (your manuscript in its revised after peer review and accepted for publication form; a 'postprint') as a digital file on your own personal or departmental website, provided that you do not use the VoR published by us, and that you include any amendments or deletions or warnings relating to the article issued or published by us; and with the acknowledgement: 'The Version of Record of this manuscript has been published and is available in <JOURNAL TITLE> <date of publication> http://www.tandfonline.com/<Article DOI>.'
      a. Please note that embargoes apply with respect to posting the AM to an institutional or subject repository. For further information, please see our list of journals with applicable embargo periods. For the avoidance of doubt, you are not permitted to post the final published paper, the VoR published by us, to any site, unless it has been published as Open Access on our website.
      b. If, following publication, you or your funder pay an Article Publishing Charge for retrospective Open Access publication, you may then opt for one of three licenses: CC BY, CC BY-NC, or CC BY-NC-ND; if you do not respond, we shall assign a CC BY licence. All rights in the article will revert to you as author.
   v. The right to share with colleagues copies of the article in its published form as supplied to you by Taylor & Francis as a digital eprint or printed reprint on a non-commercial basis.
   vi. The right to make printed copies of all or part of the article on a non-commercial basis for use by you for lecture or classroom purposes provided that such copies are not offered for sale or distributed in any systematic way, and provided that acknowledgement to prior publication in the Journal is given.
   vii. The right, if the article has been produced within the scope of your employment, for your employer to use all or part of the article internally within the institution or company on a non-commercial basis provided that acknowledgement to prior publication in the Journal is given.
   viii. The right to include the article in a thesis or dissertation that is not to be published commercially, provided that acknowledgement to prior publication in the Journal is given.
   ix. The right to present the article at a meeting or conference and to distribute printed copies of the article to the delegates attending the meeting provided that this is not for commercial purposes and provided that acknowledgement to prior publication in the Journal is given.
   x. The right to use the article in its published form in whole or in part without revision or modification in personal compilations, or other publications of your own work, provided that acknowledgement to prior publication in the Journal is given.
   xi. The right to expand your article into book-length form for publication provided that acknowledgement to prior publication in the Journal is made explicit (see below). Where permission is sought to re-use an article in a book chapter or edited collection on a commercial basis a fee will be due, payable by the publisher of the new work. Where you as the author of the article have had the lead role in the new work (i.e., you are the author of the new work or the editor of the edited collection), fees will be waived. Acknowledgement to prior publication in the Journal should be made explicit (see below):

      **Acknowledgement:** This <chapter or book> is derived in part from an article published in <JOURNAL TITLE> <date of publication> <copyright Taylor & Francis>, available online: http://www.tandfonline.com/<Article DOI>

If you wish to use your article in a way that is not permitted by this agreement, please contact permissionrequest@tandf.co.uk

## WARRANTIES MADE BY YOU AS AUTHOR

5. You warrant that:
   i. All persons who have a reasonable claim to authorship are named in the article as co-authors including yourself, and you have not

fabricated or misappropriated anyone's identity, including your own.

ii. You have been authorized by all such co-authors to sign this agreement as agent on their behalf, and to agree on their behalf the priority of the assertion of copyright and the order of names in the publication of the article.

iii. The article is your original work, apart from any permitted third-party copyright material you include, and does not infringe any intellectual property rights of any other person or entity and cannot be construed as plagiarizing any other published work, including your own published work.

iv. The article is not currently under submission to, nor is under consideration by, nor has been accepted by any other journal or publication, nor has been previously published by any other journal or publication, nor has been assigned or licensed by you to any third party.

v. The article contains no content that is abusive, defamatory, libelous, obscene, fraudulent, nor in any way infringes the rights of others, nor is in any other way unlawful or in violation of applicable laws.

vi. Research reported in the article has been conducted in an ethical and responsible manner, in full compliance with all relevant codes of experimentation and legislation. All articles which report in vivo experiments or clinical trials on humans or animals must include a written statement in the Methods section that such work was conducted with the formal approval of the local human subject or animal care committees, and that clinical trials have been registered as applicable legislation requires.

vii. Any patient, service user, or participant (or that person's parent or legal guardian) in any research or clinical experiment or study who is described in the article has given written consent to the inclusion of material, text or image, pertaining to themselves, and that they acknowledge that they cannot be identified via the article and that you have anonymized them and that you do not identify them in any way. Where such a person is deceased, you warrant you have obtained the written consent of the deceased person's family or estate.

viii. You have complied with all mandatory laboratory health and safety procedures in the course of conducting any experimental work reported in your article; your article contains all appropriate warnings concerning any specific and particular hazards that may be involved in carrying out experiments or procedures described in the article or involved in instructions, materials, or formulae in the article; your article includes explicitly relevant safety precautions; and cites, if an accepted Standard or Code of Practice is relevant, a reference to the relevant Standard or Code.

ix. You have acknowledged all sources of research funding, as required by your research funder, and disclosed any financial interest or benefit you have arising from the direct applications of your research.

x. You have obtained the necessary written permission to include material in your article that is owned and held in copyright by a third party, which shall include but is not limited to any proprietary text, illustration, table, or other material, including data, audio, video, film stills, screenshots, musical notation and any supplemental material.

xi. You have read and complied with our policy on publishing ethics.

xii. You have read and complied with the Journal's Instructions for Authors.

xiii. You have read and complied with our guide on peer review.

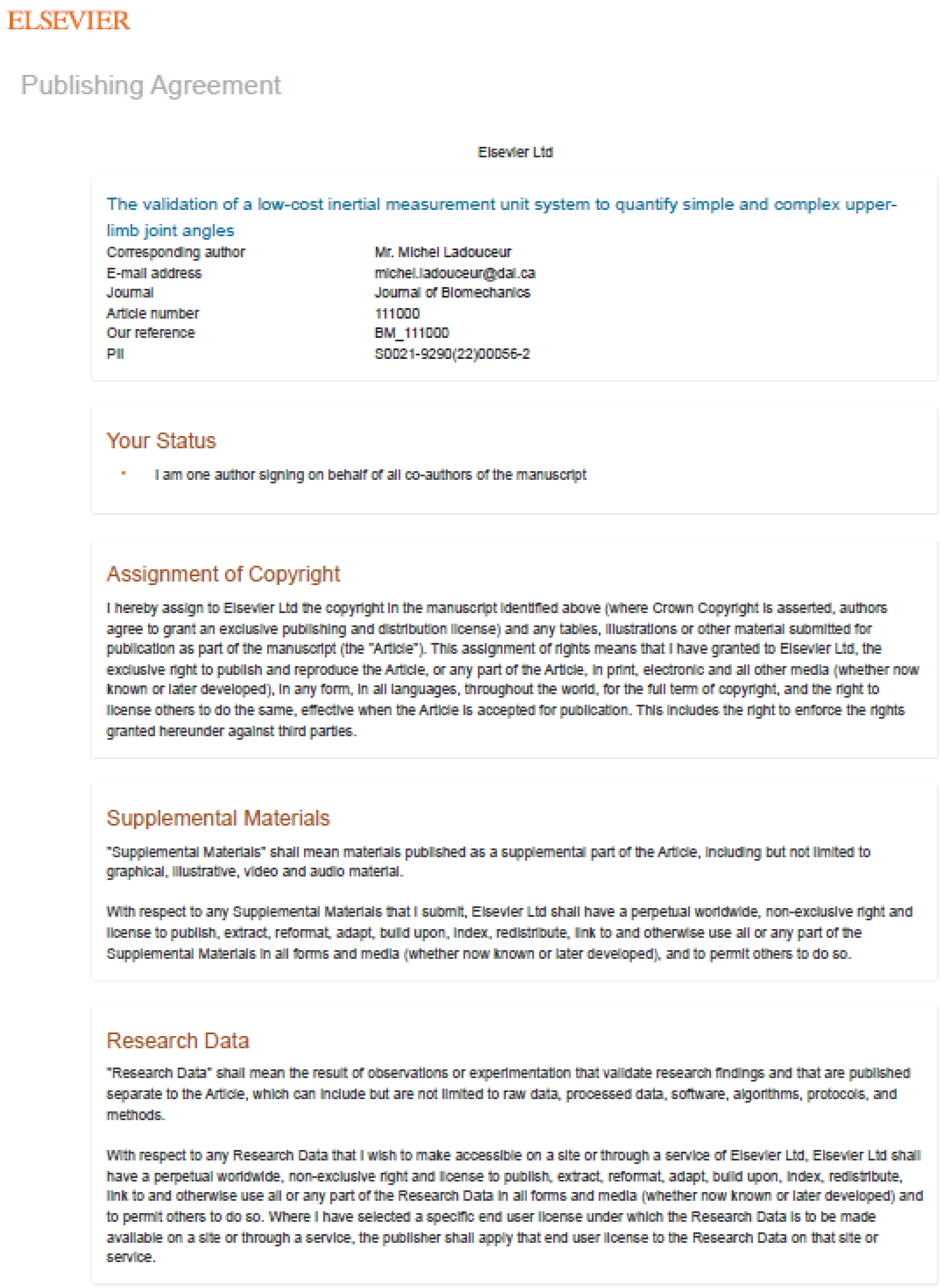
xiv. You will keep us and our affiliates indemnified in full against all loss, damages, injury, costs and expenses (including legal and other professional fees and expenses) awarded against or incurred or paid by us as a result of your breach of the warranties given in this agreement.

xv. You consent to allowing us to use your article for marketing and promotional purposes.

## GOVERNING LAW

6. This agreement (and any dispute, proceeding, claim or controversy in relation to it) is subject to English law and the parties hereby submit to the exclusive jurisdiction of the Courts of England and Wales.

# Appendix C: Publishing Agreement for Chapter 6



ELSEVIER

## Publishing Agreement

Elsevier Ltd

### The validation of a low-cost inertial measurement unit system to quantify simple and complex upper-limb joint angles

| | |
|---|---|
| Corresponding author | Mr. Michel Ladouceur |
| E-mail address | michel.ladouceur@dal.ca |
| Journal | Journal of Biomechanics |
| Article number | 111000 |
| Our reference | BM_111000 |
| PII | S0021-9290(22)00056-2 |

### Your Status

- I am one author signing on behalf of all co-authors of the manuscript

### Assignment of Copyright

I hereby assign to Elsevier Ltd the copyright in the manuscript identified above (where Crown Copyright is asserted, authors agree to grant an exclusive publishing and distribution license) and any tables, illustrations or other material submitted for publication as part of the manuscript (the "Article"). This assignment of rights means that I have granted to Elsevier Ltd, the exclusive right to publish and reproduce the Article, or any part of the Article, in print, electronic and all other media (whether now known or later developed), in any form, in all languages, throughout the world, for the full term of copyright, and the right to license others to do the same, effective when the Article is accepted for publication. This includes the right to enforce the rights granted hereunder against third parties.

### Supplemental Materials

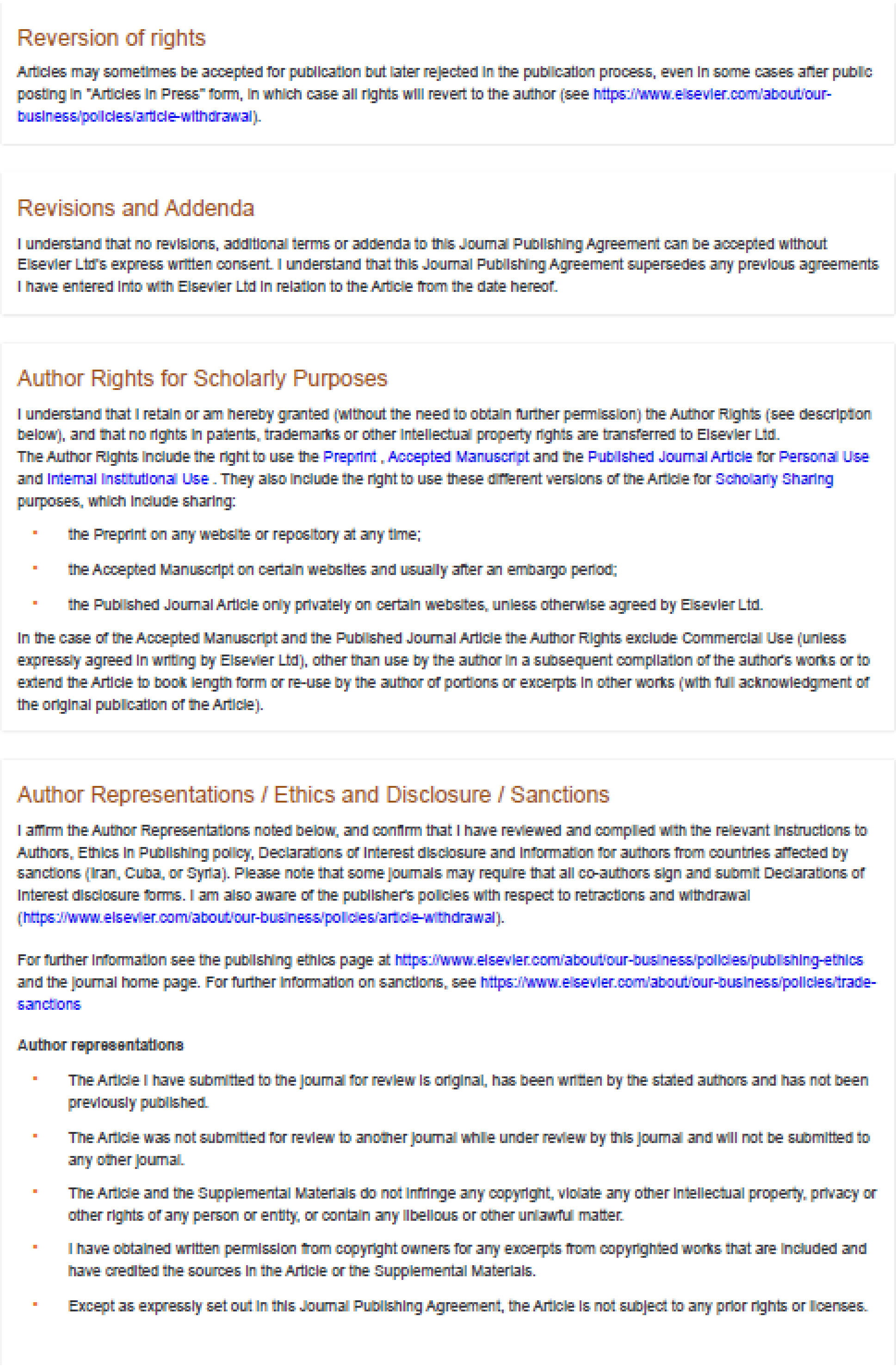
"Supplemental Materials" shall mean materials published as a supplemental part of the Article, including but not limited to graphical, illustrative, video and audio material.

With respect to any Supplemental Materials that I submit, Elsevier Ltd shall have a perpetual worldwide, non-exclusive right and license to publish, extract, reformat, adapt, build upon, index, redistribute, link to and otherwise use all or any part of the Supplemental Materials in all forms and media (whether now known or later developed), and to permit others to do so.

### Research Data

"Research Data" shall mean the result of observations or experimentation that validate research findings and that are published separate to the Article, which can include but are not limited to raw data, processed data, software, algorithms, protocols, and methods.

With respect to any Research Data that I wish to make accessible on a site or through a service of Elsevier Ltd, Elsevier Ltd shall have a perpetual worldwide, non-exclusive right and license to publish, extract, reformat, adapt, build upon, index, redistribute, link to and otherwise use all or any part of the Research Data in all forms and media (whether now known or later developed) and to permit others to do so. Where I have selected a specific end user license under which the Research Data is to be made available on a site or through a service, the publisher shall apply that end user license to the Research Data on that site or service.



## Reversion of rights

Articles may sometimes be accepted for publication but later rejected in the publication process, even in some cases after public posting in "Articles in Press" form, in which case all rights will revert to the author (see https://www.elsevier.com/about/our-business/policies/article-withdrawal).

## Revisions and Addenda

I understand that no revisions, additional terms or addenda to this Journal Publishing Agreement can be accepted without Elsevier Ltd's express written consent. I understand that this Journal Publishing Agreement supersedes any previous agreements I have entered into with Elsevier Ltd in relation to the Article from the date hereof.

## Author Rights for Scholarly Purposes

I understand that I retain or am hereby granted (without the need to obtain further permission) the Author Rights (see description below), and that no rights in patents, trademarks or other intellectual property rights are transferred to Elsevier Ltd.
The Author Rights include the right to use the Preprint , Accepted Manuscript and the Published Journal Article for Personal Use and Internal Institutional Use . They also include the right to use these different versions of the Article for Scholarly Sharing purposes, which include sharing:

- the Preprint on any website or repository at any time;
- the Accepted Manuscript on certain websites and usually after an embargo period;
- the Published Journal Article only privately on certain websites, unless otherwise agreed by Elsevier Ltd.

In the case of the Accepted Manuscript and the Published Journal Article the Author Rights exclude Commercial Use (unless expressly agreed in writing by Elsevier Ltd), other than use by the author in a subsequent compilation of the author's works or to extend the Article to book length form or re-use by the author of portions or excerpts in other works (with full acknowledgment of the original publication of the Article).

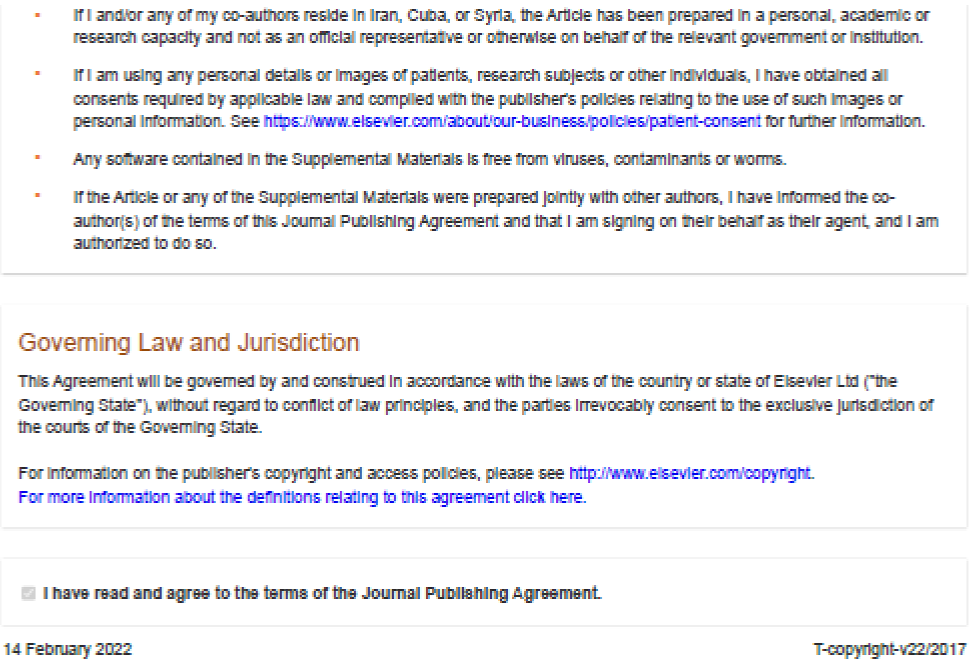
## Author Representations / Ethics and Disclosure / Sanctions

I affirm the Author Representations noted below, and confirm that I have reviewed and complied with the relevant Instructions to Authors, Ethics in Publishing policy, Declarations of Interest disclosure and information for authors from countries affected by sanctions (Iran, Cuba, or Syria). Please note that some journals may require that all co-authors sign and submit Declarations of Interest disclosure forms. I am also aware of the publisher's policies with respect to retractions and withdrawal (https://www.elsevier.com/about/our-business/policies/article-withdrawal).

For further information see the publishing ethics page at https://www.elsevier.com/about/our-business/policies/publishing-ethics and the journal home page. For further information on sanctions, see https://www.elsevier.com/about/our-business/policies/trade-sanctions

**Author representations**

- The Article I have submitted to the journal for review is original, has been written by the stated authors and has not been previously published.
- The Article was not submitted for review to another journal while under review by this journal and will not be submitted to any other journal.
- The Article and the Supplemental Materials do not infringe any copyright, violate any other intellectual property, privacy or other rights of any person or entity, or contain any libellous or other unlawful matter.
- I have obtained written permission from copyright owners for any excerpts from copyrighted works that are included and have credited the sources in the Article or the Supplemental Materials.
- Except as expressly set out in this Journal Publishing Agreement, the Article is not subject to any prior rights or licenses.



- If I and/or any of my co-authors reside in Iran, Cuba, or Syria, the Article has been prepared in a personal, academic or research capacity and not as an official representative or otherwise on behalf of the relevant government or institution.
- If I am using any personal details or images of patients, research subjects or other individuals, I have obtained all consents required by applicable law and complied with the publisher's policies relating to the use of such images or personal information. See https://www.elsevier.com/about/our-business/policies/patient-consent for further information.
- Any software contained in the Supplemental Materials is free from viruses, contaminants or worms.
- If the Article or any of the Supplemental Materials were prepared jointly with other authors, I have informed the co-author(s) of the terms of this Journal Publishing Agreement and that I am signing on their behalf as their agent, and I am authorized to do so.

## Governing Law and Jurisdiction

This Agreement will be governed by and construed in accordance with the laws of the country or state of Elsevier Ltd ("the Governing State"), without regard to conflict of law principles, and the parties irrevocably consent to the exclusive jurisdiction of the courts of the Governing State.

For information on the publisher's copyright and access policies, please see http://www.elsevier.com/copyright.
For more information about the definitions relating to this agreement click here.

☑ **I have read and agree to the terms of the Journal Publishing Agreement.**

14 February 2022 T-copyright-v22/2017