THE EFFECT OF STROKE RATE AND FIN HEIGHT ON BOAT VELOCITY, BOAT STABILITY, AND ATHLETE KINEMATICS IN ROWING

by

KHASHAYAR ABBASABADI

BPHE, Payame Noor University, 2017

A THESIS SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE IN KINESIOLOGY

in

THE SCHOOL OF GRADUATE STUDIES

NIPISSING UNIVERSITY

April 2022

Certificate of Examination

NIPISSING UNIVERSITY

SCHOOL OF GRADUATE STUDIES

CERTIFICATE OF EXAMINATION

Certificate of Examination

Supervisor(s):
Dr. Dean Hay

Examiner(s)
Dr. Daniel Bechard

Supervisory Committee:
Dr. Alison Schinkel-Ivy
Dr. Aaron Kociolek

Dr. Mark Wachowiak

The thesis by

Khashayar Abbasabadi

entitled

THE EFFECT OF STROKE AND FIN HEIGHT ON BOAT VELOCITY, BOAT STABILITY, AND ATHLETE KINEMATICS IN ROWING

is accepted in partial fulfillment of the requirements for the degree of

Master of Science in Kinesiology

May 24, 2022	Dr. Brenda Bruner	[redacted]
Date	Chair of the Examination Committee	

(original signatures on file)

Abstract:

Intuitively, poor body stability and technique will negatively impact rowing performance. This study investigated the effects of stroke rate and fin size on rowing velocity, boat stability, and rower kinematics. One male participant rowed repeated trials in a single scull at slow (20) and fast (30) stroke rates per minute with a short fin (18.5 cm) and long fin (24.5 cm). The velocity of the boat and kinematics of the boat and rower were measured with GPS and inertial measurement units (IMUs). The fast stroke rate produced significantly greater velocity, quicker arm motions, and more fluctuations in boat stability. The longer fin produced significantly greater drag, quicker arm motions, and contradictory results with respect to boat stability. As the longer fin did not significantly increase velocity, the drag penalty – especially at fast stroke rates – may not be warranted for experienced rowers who have good balance control.

Acknowledgement

To my MSc Supervisor:

Dr. Dean C. Hay: A prolific man, a true tutor, a constant help who provided great advice from the beginning until the end. Thank you for helping me to grow in academia.

To Fluidesign Company and Nipissing University's Rowing Team and faculty:

I would like to thank Fluidesign for providing the rowing shell used in this study – it is truly appreciated. I would like to thank Nipissing University's rowing team for my athletic scholarships. Also, I want to specially thank our Biomechanics lab technician, Mr. Kevin O'Reilly for his slick fin design.

To my supervisory committee:

I would like to thank my committee members, Dr. Aaron Kociolek, Dr. Alison Schinkel-Ivy, and Dr. Mark Wachowiak, and my external reviewer, Dr. Dan Bechard, for your assistance throughout this process and your valuable comment regarding my thesis.

To those tutors who have influenced my formation as a researcher:

I am much appreciative of time and help contributed by Ms. Veronica Afonso and Ms. Lindsey Voisin of Student Development and Services, PhD candidate Mohsen Tajedini of Texas A&M University, and PhD candidate Alicia M. Gal of Carlton University.

To those family members and friends who provide constant support:

Special thanks to my parents for their love, guidance, patience, and support. Thanks to my friends who have stood by my side in difficult times.

Table of Contents

List of Tables

List of Figures

List of Abbreviations

Abbreviation	Meaning
Ant.	anterior
AP	anteroposterior
Avg	average
CB	center of buoyancy
C_d	coefficient of drag
COM	center of the mass
Deg.	degree
F_B	buoyancy force
F_d	force
F_W	the force of gravity on rowing platform
GPS	global positioning system
Hz	hertz
IMU	inertial measurement units
LWL	waterline length
M	metacenter
m	meters
Max.	maximum
Min.	minimum
ML	mediolateral
Post.	posterior
ROM	range of motion
ROR	right oarlock
s	seconds
SD	standard deviation
SPM	stroke per minute
Star., STBD	starboard
V	Velocity
Vert.	Vertical
W	Watt
ρ	density

Chapter I: Introduction and Background

Baudouin & Hawkins (2002) define success in the sport of rowing as not only achieving high velocity, but also the ability to maintain that high velocity during competition. Maintenance of velocity relies on many factors including the net power output of the rower (Schneider & Hauser, 1981), oar force (Kleshnev, 2010), isometric muscle strength (Secher, 1975), and the preservation of energy by preventing losses from occurring while balancing the boat (Wagner et al., 1993).

The stroke rate is the variable number of rowing strokes per minute and each stroke, defined as a full cycle of rowing movement, consists of two phases: the drive and the recovery. Each phase can be further divided into a number of microphases (e.g., catch position during the drive phase, initiating the pressing on the foot-stretcher during the drive phase, initial arm extension during the recovery phase, commencing sliding the seat towards the bow during the recovery phase, etc.). Each stroke begins at the catch position in the drive phase and continues to the next catch position at the end of the recovery phase (Figure 1.1). Rowers transfer kinetic energy to the water through the blades by holding the oar handles while using the power of their lower limbs to apply force to the foot-stretcher. Rowers complete the drive phase by depressing the oar handles in order to withdraw the oar blades from the water, thus commencing the recovery phase, where the rower then prepares for the next catch by smoothly sliding their seat towards the foot stretcher in the direction of the stern. A perfect stroke is possible only when the boat and rower are in balance, allowing for maximal application of force and a smooth recovery. Three components are important for each stroke: length, stroke frequency and power output. To achieve optimal performance, rowers must prevent sacrificing one of these components for the sake of others. A perfect stroke must be performed with the optimal length and rhythm (i.e., drive/recovery ratio) to maximize power and minimize inertial losses (Kleshnev, 2020).

Figure 1.1

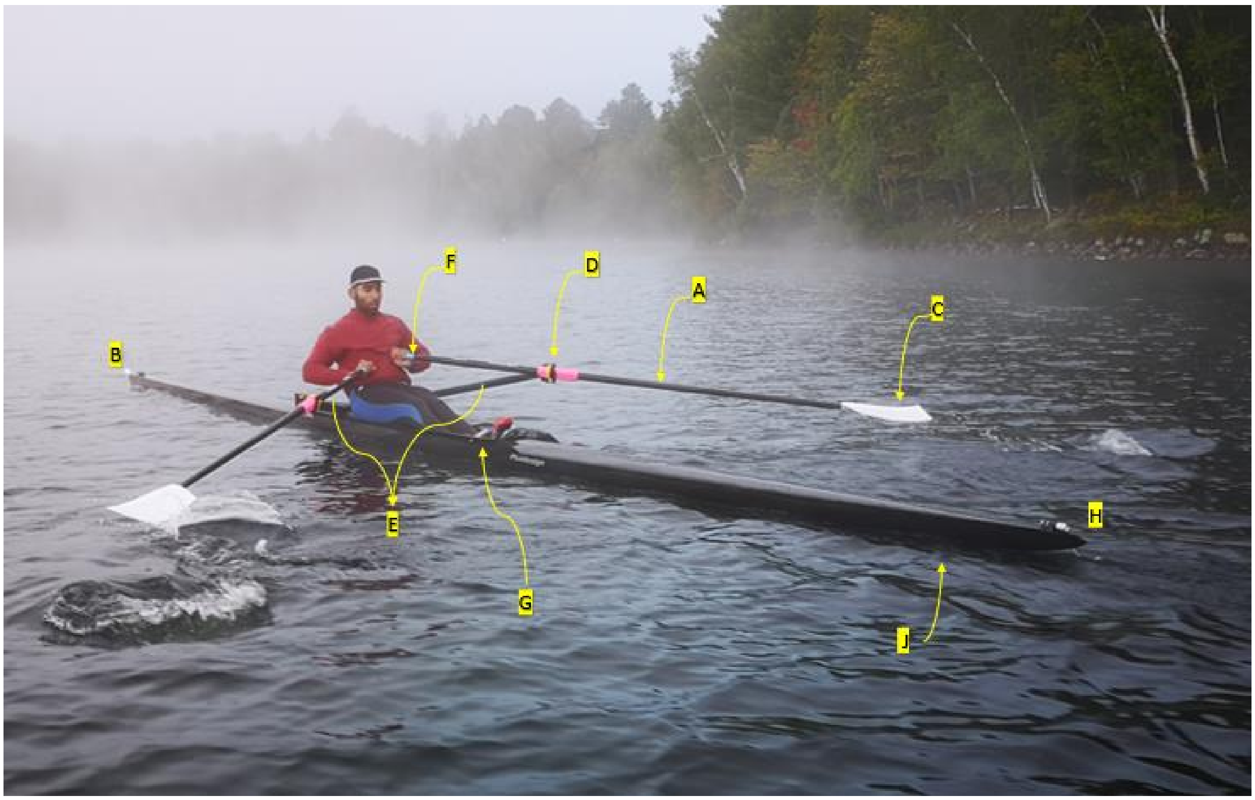
A Rowing Stroke Cycle

Note. Top row is the drive phase and the bottom row is the recovery phase. Photo Credit: Khashayar Abbasabadi.

Setting a rowing boat starts with fixing the rigger (figure 1.2) to the hull and fixing the oarlocks to the rigger. Choosing the appropriate angle of the oarlocks is essential in order to maximize the force applied by the blades through the water. This angle is customized to each athlete based on numerous factors including technique, anthropometric measurements, and experience. The sculls are positioned within the oarlocks. The portion of the shaft medial to the oarlock is called inboard and the portion of the shaft lateral to the oarlock is called outboard. The length of the sculls, the forward/aft position of the seat rails, as well as the position of the foot-stretcher (e.g., angle of the plate, horizontal & vertical position) are also customized to each athlete in order to provide them with favourable leverage and a comfortable range of motion. There are several textbooks about how to set the boat appropriately for each rower (FISA, 2002), but these resources do not adequately address how stability is affected by changes to the boat's configuration (Day et al., 2011a; Day et al., 2011b; Baudouin & Hawkins 2004; Serveto et al., 2009). Stability in this study refers to the ability of the rowing system to respond to the perturbation\motions (i.e., heave, surge, sway, pitch, yaw, roll).

Figure 1.2

The Rowing System Components



Note. A = Oars (sculls); B = Bow; C = Blade; D = Oarlock; E = Rigger; F = Handle (grip); G = Foot-stretcher; H = Stern; J = Location of the fin. Photo Credit: Khashayar Abbasabadi.

As racing shells are designed to be narrow to minimize hydrodynamic drag, they are inherently unstable. Furthermore, small boats such as those used in rowing have many limitations (e.g., weight, size, purpose, etc.) in comparison with larger boats or even ships, and these limitations make them more susceptible to wave motion (France et al., 2003; Minorsky, 1922; Lewandowski, 2004). Rowing shells rely solely on a small fin located at the posterior end (stern) of the hull for longitudinal tracking and stability (Perez & Blanke, 2010).

Considering the impact of the fin on the movement and maneuverability of the boat, it is hypothesized that a larger fin may provide more stability to the rowing boat. Despite the theoretical benefits of a larger fin, there is a lack of research on fin design and its effect on rowing performance. Therefore, this study examined whether rowing performance and stability may be improved by manipulating the size of the fin despite increasing drag to the system.

To measure the effects of fin size, boat velocity, boat stability, and rower stability were evaluated during flat water rowing at slow (20 strokes per minute) and fast (30 strokes per minute) stroke rates using a single-participant, repeated-measures design. GPS was used to measure boat velocity, while wireless inertial measurement units were used to record linear and angular motions of the rower and boat. Stability was evaluated using measures of variability (e.g., max, min, range, standard deviation) within the kinematic data. Differences between conditions for the dependent variables were tested with a repeated-measures analysis of variance.

Although average boat velocity did not significantly differ between fins, maximum boat velocity was significantly greater with the long fin. In addition, the boat was 0.111 m/s faster with the long fin during the slow stroke rate and 0.141 m/s faster with long fin during the fast stroke rate. These differences (20 and 16 seconds, respectively) would be important over a 2000 m race. Stroke rate had a significant effect on boat velocity, with the fast stroke rate producing greater boat speed (0.736 m/s) that would result in a time savings of 106 s over 2000 m.

Statistical analyses of most boat stability variables found no differences between the fins, but significantly increased roll and boat surge was found at the fast stroke rate compared to the slow stroke rate. Greater kinematic measurements (e.g., vertical acceleration of the wrists, anterior acceleration of the trunk) for the long fin suggested that the rower was able to perform some of the stroke cycle microphases faster. The fast stroke rate also produced significantly greater kinematic values of the rower, highlighting that body movements need to be faster to increase stroke rate.

As the participant in this research was an experienced rower with good balance and technique, it is possible that the increased drag of the long fin negated the potential benefits of its increased stability. Results may differ for novices since the improved stability of the long fin may have a greater benefit to rower stability, thereby increasing the rower's ability to propel the boat faster with a consistent and powerful rowing stroke.

Chapter II: Literature Review

2.1 Introduction to the Biomechanics of the Rowing

Kinematics is the analysis of the movement of the body while kinetics is the analysis of forces acting on the body. These two concepts, central to biomechanics, include physical principles of momentum, levers, and stability. Fundamental principles of biomechanics provide us with a critical approach to identifying and evaluating physical activities (Knudson, 2003, 1993, 1991; Knudson & Morrison, 1996; Cooper, 1995; Hay, 1993, 1978).

In competitive rowing, the purpose is to row a specific distance as quickly as possible (Schneider & Hauser, 1981; Sanderson & Martindale, 1986; Smith & Spinks, 1995; Lazauskas, 1997, as cited in Baudouin & Hawkins, 2002). The Olympic and World rowing championship distance of 2000 m requires high levels of both aerobic power and anaerobic capacity (Gayer, 1994). For the fastest boats - eight or quadruple - it takes about six minutes and more than 200 strokes. For a smaller boat such as the single sculls, it takes about seven minutes and more than 240 strokes to complete the distance.

When analyzing the mechanical rowing system, there are three major components (Figure 1.2): the boat, the oar, and the biological system (the rower) that propels the boat (Baudouin & Hawkins, 2004). The kinetic energies in the rowing system are the propulsive force applied by the rower and all drag forces acting on the boat. Ideally, a rower seeks to maximize the propulsive force while minimizing the forces that slow the boat. Forward momentum of the rowing system is primarily produced by the rower (a tail wind or water current may contribute as well). During a 2000 m race, 500 W of average mechanical power output has been reported (Celentano et al., 1974, as cited in Hofmijster et al, 2007; Dal Monte & Komor, 1989, as cited in

Hofmijster et al, 2007), but for intermediate rowers, the power output may be less than half. The levers in the rowing system are the arms and legs of the rower and the oars and riggers of the boat. This system requires an appropriately designed shell to allow the rower to utilize their full leverage while minimizing drag.

In order to effectively use the rower's power output, balancing the system is very important. Excellent stability or "even keel" is when the boat floats upright without unnecessary side-to-side rolling (Heiman et al., 1998). Keeping the balance of the boat is an important part of the rowing technique and poor balance has a direct negative result on the performance. Balance in this study refers to the rowers' skill to maintain the boat at the even keel. An unbalanced boat reduces the work performed at the blade because the rower must expend energy returning the boat to a level position (Nolte & McLaughlin, 2005). Stability is important for both elite and intermediate athletes, as a more stable platform will enable the rower to maintain a more constant speed between strokes, thereby reducing fluctuations in power output and hydrodynamic drag.

Rowing at the elite level looks stable and effortless, but small mistakes may have a great impact on performance. To report the importance of the balance even in the elite level of this sport, I visually inspected the nine different boat classes at the 2011 World Rowing Championships Final A and counted the number of times that rowers visibly lost their perfect stroke (Table 2.1). Overall, only a few strokes in each race resulted in detectable errors. For most of these stroke errors, the effects were minimal, resulting in no changes in position or noticeable decreases in boat speed. However, one of the rowers of the German heavyweight men's quadruple lost his oar entirely right before the finish line. This error cost them one place as they settled for the silver medal. Despite the relatively rare occurrence of stroke errors at the elite level, the repercussions can be severe. Even if there is no obvious change in the result of the race, each missed stroke will negatively impact the rower as their ability to relax during the recovery phase will be impaired, thereby affecting the next stroke. Environmental factors are often the main reason for instability; however, it is possible for the rower to lose their stability even in flat water because of mental factors (e.g., loss of focus, stress, lack of confidence) and fatigue which directly affect technique and weaken balance. Although I cannot confirm instability was the cause of the stroke errors in the races I inspected from the world championships, good balance gives a considerable amount of confidence to the rower so that maximal effort can be produced.

Table 2.1

Loss of Perfect Stroke in 2011 World Rowing Championship

Boat Class	Number of Strokes
Men's Single Scull	1
Men's Double Sculls	5
Lightweight Men's single sculls	3
Men's Four	1
Men's Pair	1
Men's Quadruple sculls	1
Lightweight Men's Quadruple	2
Women's Quadruple Sculls	6
Women's Pair	3

Note. This Table shows the total number of strokes that were visibly compromised during the A finals in each boat class. For example, in the men’s double sculls, the German boat made 5 errors, whereas in the lightweight men’s single sculls, the New Zealand rower missed 2 strokes and the Danish rower missed one stroke.

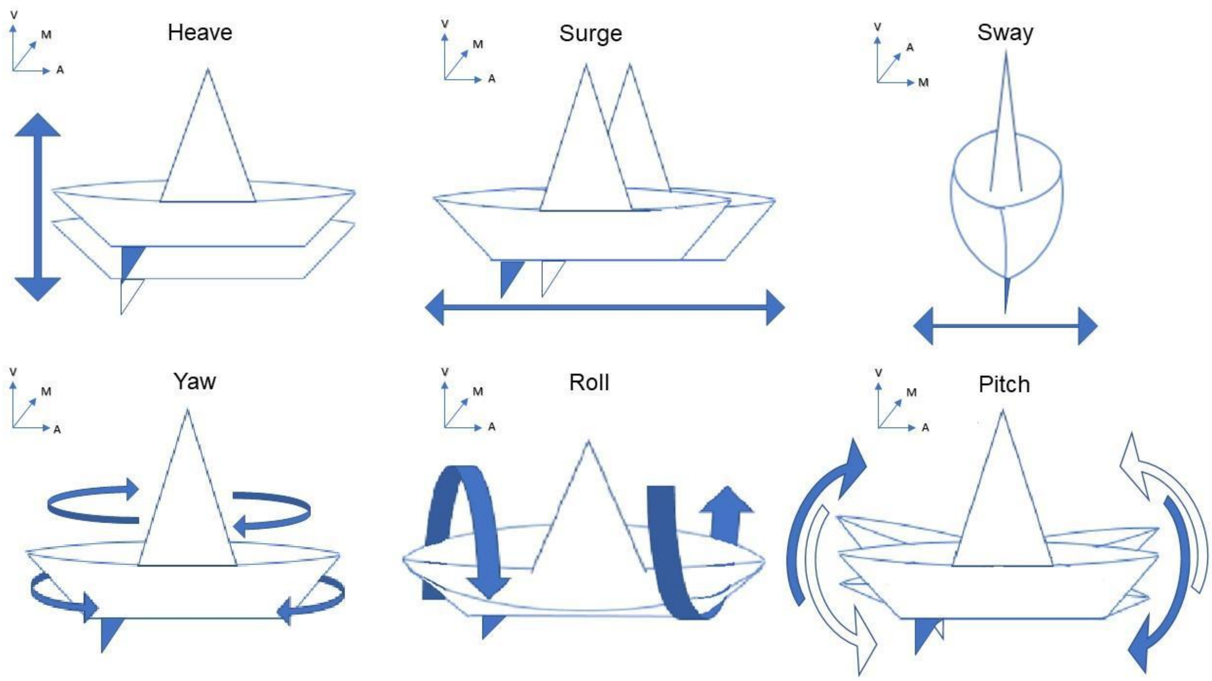
To those who have experienced sitting on a rowing boat, the difficulty of keeping the boat stable is obvious. Even the most talented athletes must put a lot of effort into training, spending days and weeks of rowing on the water to achieve peak performance in this sport. For intermediate rowers, stroke errors due to imbalance are likely to be increased compared to elite rowers. Instability is likely a more significant issue with intermediate and novice athletes as they have spent less time mastering postural control in the boat. The intermediate rower is normally unable to use their physiological capacity because of an inability to keep the boat balanced while exerting their full power. For example, during the drive phase, the rower should pull the handle horizontally to ensure that the blade moves through the water in a straight line, holding a maximum load of water per stroke. This is very hard for an amateur rower to do because when they lose balance – even just by a little – they will move the handle up and down, trying to recover balance during the drive phase. The vertical oscillations of the blade cause turbulence and lead to a less effective load per stroke (Sliasas & Tullis, 2011). A more stable platform, therefore, would allow the rower to focus more on power output and increasing boat velocity.

2.2 Rowing Dynamics

The rowing system can experience the six types of motions that all other water-based vessels encounter (Ibrahim & Grace, 2010). For better understanding of these motions, I drew some nostalgic paper boats in Figure 2.1 that highlight the linear displacement motions (heave, surge, sway) and the angular motions (roll, pitch and yaw) (Spyrou, 2000). Sway along the mediolateral axis is not a linear movement that is particularly important in rowing due to the long and narrow boat design that promotes forward tracking. Heave is linear movement of the boat along the vertical axis and is increased if the blades do not travel horizontally through the water or if the rower's mass slumps downward at the finish of the stroke. Surge is linear movement along the anteroposterior axis. In rowing, boat surge is particularly important as there are large fluctuations in velocity each stroke due to the propulsion and recovery phases. During the recovery phase, the rower's centre of mass moves toward the stern of the boat, thereby accelerating the boat forward. If the rower does not catch the water (begin the propulsion phase) at the precise time that the centre of mass reaches its most posterior point, the boat velocity will drop rapidly, negatively influencing the next stroke.

Figure 2.1

Motions of the Boat



Note. V = Vertical; A = Anteroposterior; M = Mediolateral. The three linear motions (top row) and the three angular motions (bottom row) of the boat are shown. Photo Credit: Khashayar Abbasabadi.

Pitch is rotation of the boat around the mediolateral axis and is similar to heave in that it increases with an uneven path of the blade through the water or due to changes in the center of the mass (COM) as the rower moves forwards (bow pitches downward) and backwards (bow pitches upwards) along the rowing slides. Yaw is the angular motion of the boat around the vertical axis and occurs when uneven pressure is applied to the oars, causing the bow of the boat to rotate away from the oar that is applying greater pressure to the water. In ideal conditions, the rower seeks to minimize yaw, but on river courses or in high cross winds, yaw is used to change direction of the boat. Roll is the rotation of the boat along the anteroposterior axis and is the most difficult movement to control in rowing due to the hull design and high rower COM. The hull cross sectional shape is semi-circular and narrow, which reduces hydrodynamic drag but increases instability (Formaggia et al., 2010). The rower sits on top of a seat which is itself elevated from the waterline because of the wheels underneath it to allow anteroposterior movement of the rower. Excessive roll negatively affects performance (Perez, 2012) because when the boat tilts out of the even keel position it changes the pattern of the rowing technique for the rower.

2.3 Rowing Boat Design

The concept of *platform* means a solid surface or a base that all activity can occur on, but in rowing it refers to the need for the boat to be balanced from side to side (Nolte, 2011). Classic rowboats were wide, wooden vessels that were rowed for different purposes (e.g., daily transport of people and goods through rivers, and recreational and commercial fishing) for more than a millennium.

The hull of the classic rowboat was very stable but also created a great amount of hydrodynamic drag. The boats were heavy and short so they could turn easily to follow the bends of the rivers. Classic rowboats were wide enough to give the necessary levers to row when the oars were attached directly to the body of the boat.

The people who made a living on rowboats started to race for money prizes in the mid-17th Century (Dodd, 1987). On the other hand, universities began rowing clubs as the dedication to rowing training would mentally and physically stimulate the intellectual growth of students (Macmichael, 1870, as cited in Halladay, 1987). In general, rowing was a source of entertainment and pleasure for the public (Dodd, 1987). For example, Halladay (1987) reported that watching prize ring boxing matches and rowing competitions were seen as equally amusing sources of entertainment for the wealthy class.

The traditional rowing stroke primarily consisted of trunk flexion and extension and arm movements. The platform of classic rowboats did not allow the rower to use their full physical capacity because they were unable to properly use their legs as the seat was immobile. Sliding seats were invented in the mid 18th Century and consisted of two parallel rails on which wheels rolled (Dodd, 1992). These wheels were attached to the underside of the seat with a simple chassis (Figure 2.2). The sliding seats immediately lowered race times by a minute and a half due to the extra leg drive described as "a piston and a pair of scissors" (Wigglesworth, 2013, p 86).

Figure 2.2

Modern Sliding Seat Design

Note. Photo Credit: Khashayar Abbasabadi.

As the sport of rowing developed, builders began to change the hull design of boats in order to increase velocity. Minimizing drag was one of the first approaches to increase the velocity of racing shells. In order to minimize drag, rowing boats were built narrower. The problem with a narrow boat is that there is not enough width to have sufficient inboard for the oar. Builders started using outriggers which kept the oarlocks at the required width but allowed for the hull to be narrow. The length of boats was increased, and the shape of the hull became semicircular. For an identical wetted surface area and equal power output, a longer boat is capable of a higher velocity (Buckmann & Harris, 2014; Sponberg, 2011).

A longer, semicircular hull shape reduces the surface area in contact with the water, thereby reducing hydrodynamic drag (Misra, 2015). Although 21st Century boats use carbon fibre and other exotic materials to keep the shell light, the general design principles that were developed over a century ago – namely sliding seats, outriggers, and a long-narrow hull – are still in use. These technological advancements reduce drag and improve velocity, but boat instability – in particular, roll – is increased.

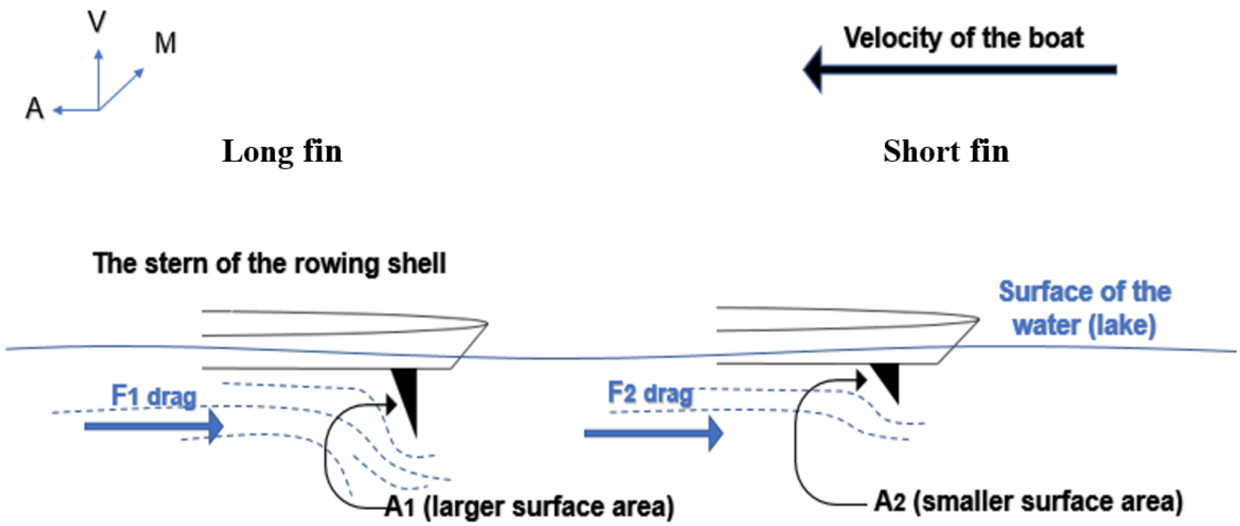
2.3.1 Fin

As the hull design described above is inherently unstable with respect to roll, a small, trapezoidal plate is affixed to the posterior end of the hull which counteracts roll and promotes longitudinal tracking (Perez & Blanke, 2010). The position of the fin has a certain effect on the boat movement. A more forward location will create a shorter turning arc, while a posterior location provides more longitudinal tracking and a longer turning arc (Guisado, 2011). When the boat is moving forward, the fin engages with the water and generates thrust against it. As a result, the fin creates more hold at higher velocity and minimizes roll (Webb, 2005). At low speeds the stabilizing power of the fin drops and when the boat is stationary, effectively no stabilization is possible (Perez, 2005). Side waves and currents easily displace (sway) or rotate (roll, yaw) a moving boat without a fin or stabilizer. Slight imbalances in blade forces will cause a rowing platform to rapidly yaw offline without a fin. Hence, the primary purpose of the fin is to provide longitudinal tracking. Secondarily, the fin reduces roll.

Unfortunately, the stability gained from a fin also comes at a cost because it creates resistance in the water which reduces velocity for a constant power output (Figure 2.3). Bale et al. (2014) compared the height of the electric knifefish's ribbon (dorsal) fin with the cost of transport and velocity. They discovered significant increases of the propelled power by the fish with increasing fin height, while the total corresponding increase in velocity was small. In other words, the increased drag of the longer fin required the fish to put more effort to maintain its velocity. The researchers confirmed their results with an artificial fin model where the cost of transportation increased exponentially with swimming velocity (Bale et al., 2014).

Figure 2.3

Fluid Resistance and the Drag of the Fin in a Rowing System

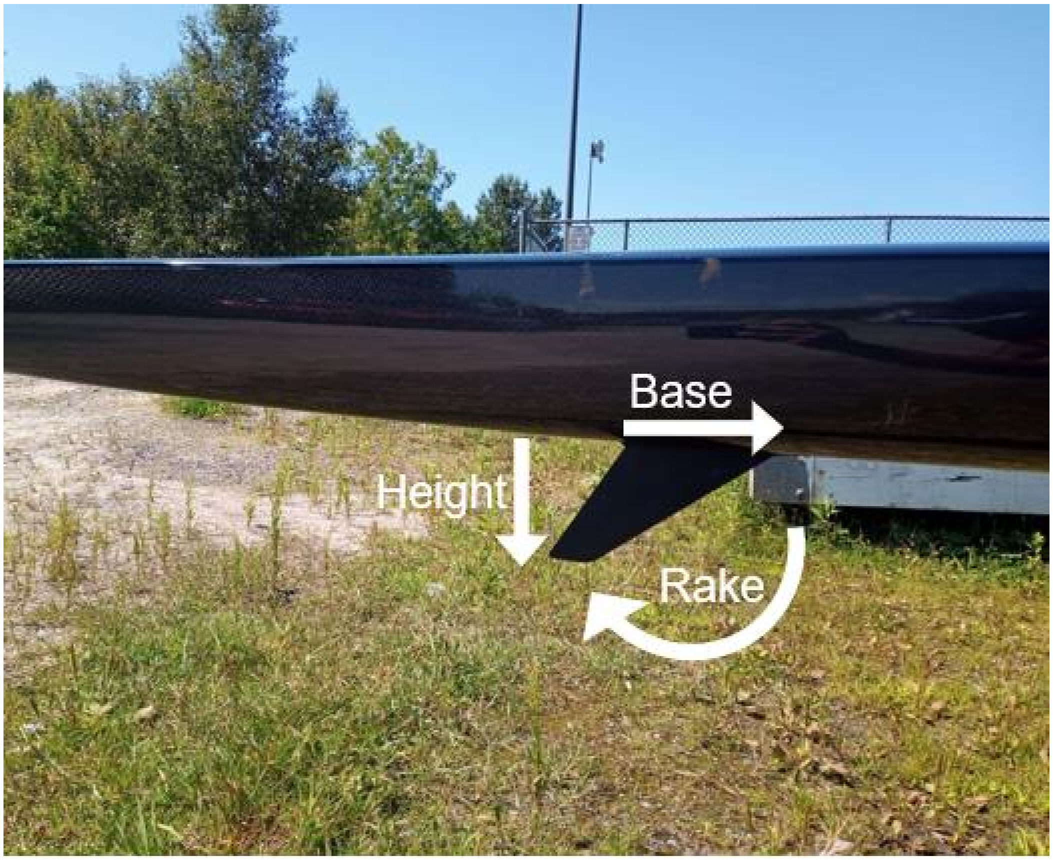


Note. According to Equation 1, increasing surface area creates greater drag. Thus, as A1 is greater than A2, F1 also will be greater than F2. Photo Credit: Khashayar Abbasabadi.

Fins are generally rectangular and categorized by 4 different dimensions: foil, rake, base, and height (Figure 2.4). Each dimension has certain characteristics that affect the boat movement, velocity and stability, and interactions between these dimensions are possible. Although foil shapes are sometimes used for fins (especially in the larger boat classes), for my study I used two fins designed without a foil shape. Therefore, the effect of foil shape on turbulent and laminar flow patterns (Newman, 2018) would theoretically remain similar between fins and, therefore, will not be discussed in this thesis.

Figure 2.4

Fin Dimensions



Note. Photo Credit: Khashayar Abbasabadi.

The base of the fin refers to the anteroposterior length of the fin that is in contact with the hull. As this scale increases, it will increase skin friction drag (Gladstone, 2021; Newman, 2018), therefore, a fin with longer base length will create more hold for the boat. For my study, the base is held constant for the two fin sizes used, so further discussion is not included in this thesis.

Rake refers to the swept-back shape of the fin. A more swept-back fin results in more water engagement on the fin by creating a longer turbulent boundary layer. This creates more lateral stability with the cost of increased forward drag (Newman, 2018). For my study, rake is held constant for the different fin sizes, so further discussion is not included in this thesis.

The height of the fin is defined as the perpendicular distance from the base to the tip of the fin. Changing the height will increase surface area (Equation 1), which will increase drag and provide more stability with respect to roll and yaw (Gladstone, 2021). In my study, fin height was manipulated.

2.4 Drag

Progress of the boat is constrained by the hydrodynamic and aerodynamic drag forces in the rowing system. As the density of the air is much less than water, aerodynamic drag does not have a huge effect in calm conditions. Hydrodynamic drag is the dominant drag force affecting the rowing system (Baudouin & Hawkins, 2003; Sanderson & Martindale, 1986; Lazauskas, 1997). As the fin is the only factor that changed between trials in my study (notwithstanding minor fluctuations in environmental conditions), I do not focus on the rower, boat or oars with respect to drag.

The contribution of the fin in producing drag is in accordance with Newton's third law of motion, such that when the fin moves through the water, the water has an opposite force against the fin (Equation 1).

$$F_d = -\frac{1}{2}\rho v^2 A C_d \qquad (1)$$

Where,

F_d is the drag force of the fin in the water.

The constant of -1/2 indicates this force is in the opposite direction of the boat's velocity.

ρ is the density of the fluid. The density of water is approximately 1.

v refers to the velocity of the object relative to the fluid – which in this case is boat velocity.

A is the area of the object pushing through the water. In my study, the size of the fin was manipulated, thereby affecting *A*.

C_d is the drag coefficient and is lowered by using shapes that minimize turbulent flow such as foils (Newman, 2018). As the profile of the fin was similar between the fins used in my study, I assumed that C_d is constant.

With respect to the fin, the force of drag needs to be considered along two axes: anteroposterior and mediolateral. As the boat travels forward, the frontal surface area (A in equation 1) of the fin will push against the water along the anteroposterior axis. A fin with more height will increase the surface area, thereby increasing drag. For an athlete to maintain the same velocity using a longer fin, more power (propulsion) will be required (Bale et al., 2014). Increasing the height of the fin while keeping the base length constant will also increase the surface area with respect to the mediolateral axis, which will increase skin friction drag (Gladstone, 2021; Newman, 2018). This increased surface area should provide more stability with respect to roll and yaw. By increasing the surface area along the anteroposterior axis, more power will be required to propel the boat forward; however, the concomitant increase in mediolateral surface area should provide more stability for the rower to generate more power.

2.5 Stability in Flotation

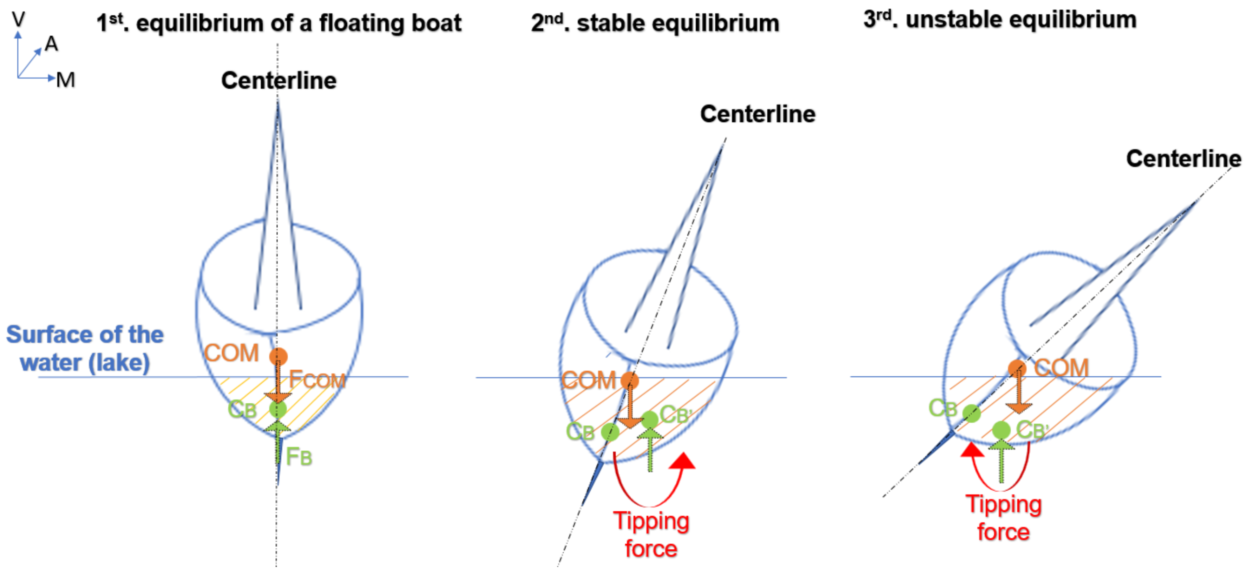
The two vertical forces acting on the boat (excluding environmental factors and the motions of the rower) are gravity and buoyancy, establishing the preferred floating orientation. For example, a log placed in the water will float because the density of the log is less than the water. Gravity will cause the log to roll over and float at its preferred orientation where its center of gravity is positioned at the lowest height (McGinnis, 2013).

2.5.1 Buoyancy

There is an amount of force per area within all fluids that applies in all direction. This force is called fluid pressure. However, this pressure is only upward on the surface of the fluids like water. Thus, when an object's density is less than the water, the upward fluid pressure on that object is the force that keeps that object floating on the surface. In other words, according to Newton's laws of motion, the downward force of gravity acting on the mass of the boat is opposed by the upwards force produced by the fluid pressure (Figure 2.5). This force is defined as buoyancy (Chassignet et al., 2012).

Figure 2.5

Stability in Flotation



***Note*:** The COM and the orange vertical downward arrow indicates the weight of the boat. The center of buoyancy (CB) and the vertical upward green arrow indicates the force of buoyancy. The new center of buoyancy (CB') occurs during roll according to the changed location of the immersed part of the boat (the orange hash lines). The red arrow indicates the direction of the tipping force which occurs when the COM and CB are not vertically aligned. Photo Credit: Khashayar Abbasabadi.

2.5.2 Center of Buoyancy

Center of buoyancy (CB in Figure 2.5) is the centroid of the center of gravity of the displaced volume of the water by the immersed part of the boat and is equal to the sum of the distributed force of water over the hull. The boat will stay in its preferred orientation, upright and stable (Figure 2.5, 1st), when the COM and centre of buoyancy are vertically aligned on the centerline. This equilibrium position is called even keel (Kang & Hasegawa, 2007).

When a boat has rolled to one side, the center of buoyancy changes to a new point (CB'), on the same side due to an increase in the volume of displaced water on that side (marked with orange hatches in Figure 2.5). During roll, the boat possesses one of three types of balance depending on the position of CB': stable equilibrium, neutral equilibrium, and unstable equilibrium. When a boat starts to roll, a tipping force is created by a difference in the alignment of the COM and the CB. Stable equilibrium occurs at the beginning stage of the roll (2nd position on Figure 2.5). In stable equilibrium, the tipping force tends to turn the boat back to the even keel position. This is possible because CB' is lateral to the COM, creating a net tipping force in the opposite direction to the roll.

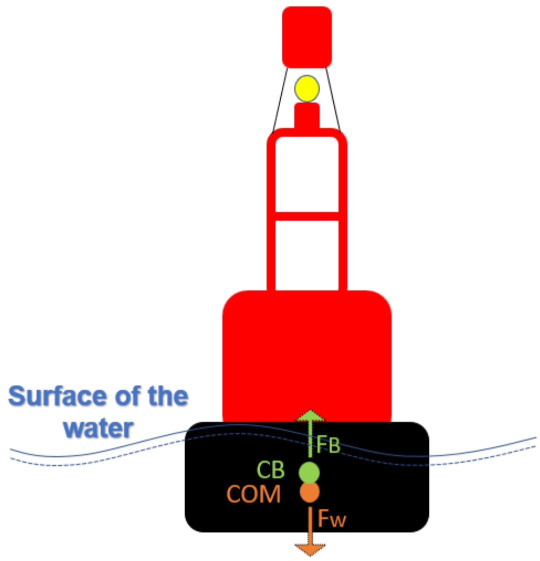
Once a boat passes neutral equilibrium during a roll, COM is lateral to CB', creating a tipping force that is in the same direction as the roll. This state, known as unstable equilibrium (3rd position in Figure 2.5) will capsize a boat if a correcting force is not applied (in the case of rowing, the athlete must make changes to their posture and/or apply forces through the blades to counteract the tipping force).

For a semicircular hull used in rowing, metacentre (M) is defined as the intersection between the center line and an imaginary vertical line from the CB' (Alamian et al, 2019). In stable equilibrium, M is above the COM on the center line (Figure 5.2, right). A boat with this configuration creates a tipping force in the opposite direction to the roll – thereby restoring an upright position. When M and COM are vertically collinear points, the boat is in neutral position and, in the absence of an additional tipping force, the boat will remain in its current orientation. In unstable equilibrium M is located below the COM. This position indicates that a tipping force will capsize the boat as it is in the same direction as the roll.

The most stable position for a floating object is when its COM is located below the CB (M is located above COM). A marine buoy light, where the mass density is distributed in the bottom of the structure, will never capsize (Figure 2.6). Even in stormy weather, it will roll over like a floating log and return to its preferred upright orientation.

Figure 2.6

Marine Buoy Light



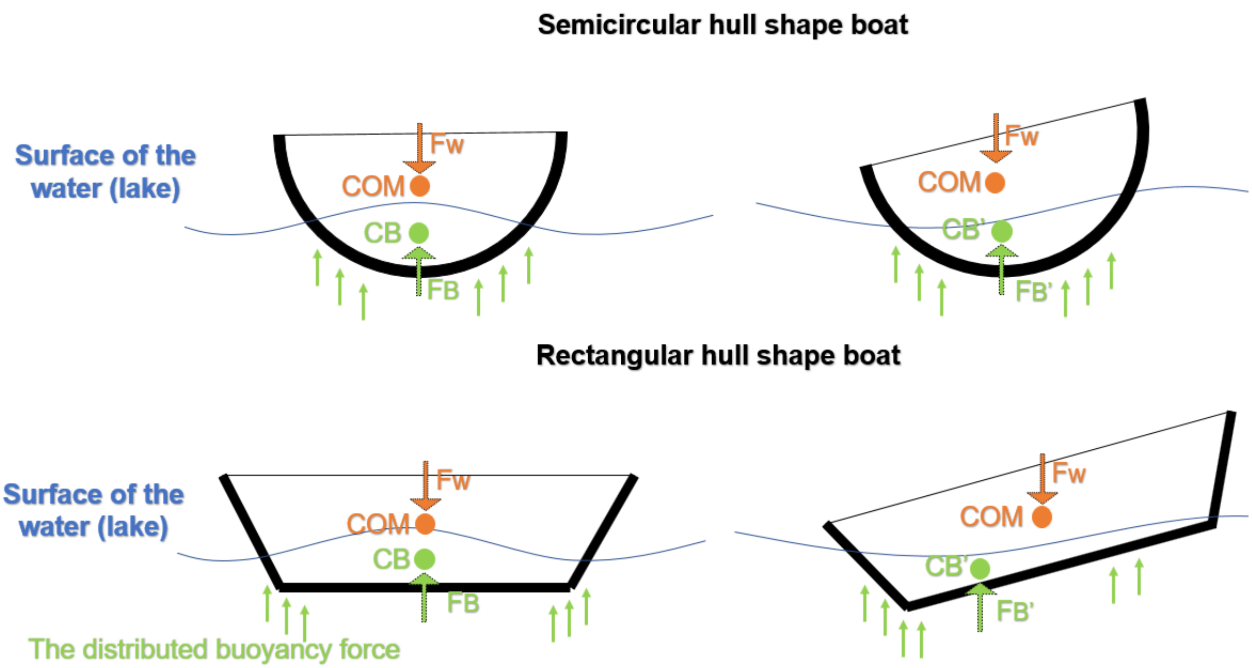
Note. As the COM is located inferior CB, marine buoy light will always remain upright, even in stormy weather. Photo Credit: Khashayar Abbasabadi.

Designing a hull with more stability or mechanically stabilizing the boat is a very complex approach. Hydrostatic and hydrodynamic characteristics of the watercraft depend on the submerged volume, center of buoyancy and pressure distribution under the wetted surface of hull, and center of gravity. The distributed pressure can bring more stability to a boat if the hull shape is a rectangular (Figure 2.7). As mentioned, the center of buoyancy is constantly changing while the boat is rolling. With a rectangular hull shape, the distribution of pressure on the hull will increase on the side that is rolling towards the water, creating a tipping force in the opposite direction. With a semicircular hull, pressure distribution remains symmetrical during roll, resulting in no counteracting tipping force.

In competitive rowing, the COM is located higher than the CB due to the hull design and the position of the rower above the waterline, making the system inherently unstable – in other words, M is *always* lower than COM. For recreational rowing boats, wider hull designs are used because of their increased stability as the system's M is either above, or close to level with, COM during normal usage conditions. According to Equation 1, increasing the wetted surface (A) area of hull (by making it wider) will increase the drag, making for a slower boat. As success in the sport of rowing is achieved with the greatest velocity (Baudouin & Hawkins, 2002), a boat with less wetted surface area is preferred. The trade-off is increased instability.

Figure 2.7

Hull Shape and Roll Stability



Note. This Figure illustrates the displacement of the CB' for different hull shapes of the boat. The distributed buoyancy force acting on the outer part of the hull of the rectangular hall shape boat restores the boat to even keel. In a semicircular hull, however, as the buoyancy force remains symmetrical during roll, no counteracting tipping force is present. This Figure is adapted from Harvard Natural Sciences Lecture Demonstrations (n.d). Photo Credit: Khashayar Abbasabadi.

2.6 Kinematics of the Rowing Stroke

Scullers use their muscles symmetrically (Chudecka et al., 2015) and a common belief among rowers is that rowing is powered largely by the lower limbs (60%) followed by the trunk (30%) and upper limbs (10%) (Turner, 2018). Starting the drive phase at the catch, the rower begins with flexed hips and knees, with the trunk slightly flexed, and the shoulders flexed and elbows extended in order to attain a maximum reach. Then, by locking the blades in the water, the rower prepares for a long, strong, and solid drive. The effectiveness of applied power to the water through the handles depends on the skill of the rower as up to a third of this energy may be lost in the flow of water around the blade (Affeld et al., 1993). Therefore, it is crucial for them to catch the water properly and pull through the water with confidence while maintaining their balance in order to minimize the loss of the waterflow around the blades.

Pressing the foot-stretcher in the drive phase begins with plantar flexion, and knee and hip extension followed by extension of the trunk. Shoulder extension and elbow flexion are used to pull the handles toward the chest, finishing the drive phase (Kleshnev, 2020). As the rower leans back towards the bow at the end of the drive phase, the bow will dip into the water increasing the drag on the hull of the boat. There is a trade-off between maximizing the length of the stroke with a pronounced back extension and maintaining level trim of the boat by reducing back extension at the cost of a shorter stroke. Although there are differences in techniques taught internationally, the most common trend is to shorten the length of the stroke by maintaining a more upright posture of the trunk at the finish.

At the end of the drive phase the rower pushes down on the handles to release the blades from the water and commences the recovery phase. The recovery phase is initiated by extending the elbows, flexing the trunk, and rotating the oars parallel to the surface of the water. This shifts the COM of the system towards the stern, elevating the bow through positive pitch motion. Some coaches suggest that the rower must do this part of the recovery phase as quickly and as smoothly as possible in order to minimize the duration of bow submersion. Following this, hip and knee flexion facilitate the sliding of the seat (and rower COM) towards the stern. During this phase, the rower prepares the oars for reentry by rotating the oars so that they are perpendicular to the surface of the water. During both phases of the rowing stroke, good technique is believed to be efficient by producing the largest sustainable propulsive force for the lowest muscular effort.

2.7 Factors Affecting Performance of the Rowing Stroke

Baudouin & Hawkins (2002) defined success in rowing as achieving and maintaining high velocity for 2000 m during competition. This necessitates the rower to develop good technical skills and balance in order to minimize the cost of energy and drag while maximizing their contribution of power to the forward velocity of the boat.

There are several ways for the rower to minimize drag force. The rower can increase and maintain the velocity of the boat during the recovery phase precisely by their movements (Celentano et al., 1974 & Dudhia, 2000 as cited in Baudouin & Hawkins, 2002). For example, the velocity of the boat may be better maintained during the recovery phase if the rower actively pulls the boat toward themselves using their feet instead of simply allowing the seat to slide towards the catch. Avoiding certain behaviours can also have a positive impact on velocity maintenance. For instance, a smooth reach towards the catch position while preventing the blades from contacting the water surface will not only aid in stability but will also decrease drag and minimize speed variation of the rower's body movements (Smith & Loschner, 2002). This is impactful as the rower is often five to seven times heavier than the boat, and consequently any sudden body movements or even a change in their body movement's speed has an instantaneous effect on the velocity of the boat (Baudouin & Hawkins, 2004; Celentano et al., 1974; Zatsiorsky & Yakunin, 1991). Celentano et al. (1974) suggested adopting a faster stroke rate to minimize the chance of such oscillations (32 - 42 strokes per minute [SPM] is a common stroke rate for single sculling during competition), but also indicated that there may be physiological limits to stroke rate due to the force-velocity relationship of muscle contraction.

To achieve peak performance and minimize energy costs, the rower seeks to minimize fluctuations in boat speed (Senator, 1981; Sanderson & Martindale, 1986; Smith & Spinks, 1995). With each speed oscillation, according to Equation 1, the drag force will exponentially increase, indicating the inefficacy of speed variation (Sanderson & Martindale, 1986). The rower, therefore, by minimizing inefficient movements and rapid changes to their COM can lessen their contribution to boat drag.

Baudouin & Hawkins (2003) and Wagner, et al. (1993) reported an excessive energy loss in the balancing of the boat. The preferred orientation of the boat in order to row is in a stable equilibrium that is close to the even keel position. Any roll motion can easily disturb the balance of the boat. Rolls are mostly caused by the waves and changes in seat pressure due to the coronal plane hip movements of the rower. As a boat rolls, the CB and COM positions change, affecting both the direction and magnitude of the tipping force. As discussed above, when the COM is lateral to the CB, the boat will be unstable and roll in the direction of the COM. The rower must constantly work to keep their COM above the centre line of the boat, or, when the boat begins to roll, move their COM medial to the CB to create a restorative tipping force. This is referred to as dynamic balance in this paper.

2.8 Dynamic Balance

The rower can correct boat roll with lateral trunk flexion, and subtle movements of their shoulders and arms during the drive phase to change the pressure of the blades in the water. Although the oar is the propulsive device for the drive phase, it is also a major contributor to balance during the recovery phase (Notle, 2011). Like a stick in the hands of a tightrope walker, the rower can utilize the oars to adjust their COM.

If the boat leaves the even keel position during the drive phase while the rower is pulling the handles and pressing the foot stretcher with maximum force, the rower will then be required to change their rowing pattern in order to maintain balance. For example, when the boat rolls off balance, the athlete may rotate their pelvis and/or trunk around the anteroposterior axis. This positioning, especially when paired with the increased load of drive phase, predisposes the athlete to lower back injuries (Buckeridge, 2012). In the above scenario, asymmetrical muscle activation may result in the inability to achieve a perfect stroke and reduces the propulsive power of the athlete during the drive phase.

A common misconception about this sport is that rowing is a safe sport compared to contact sports. However, rowing has its specific injuries at different athletic levels, from collegiate athletes who often suffer knee injuries, to elite athletes, where the most common injury is to the lower back (Smoljanovic et al., 2009; Wilson et al., 2010). The majority of problems stem from overuse of biological structures in combination with poor mechanics and technique. Smoljanović, et al. (2018) reported that the most common site of injury for master rowers was the lower back (32.6%). Rowing injuries can be attributed to different causes such as excessive load in one session or excessive resistance training. Also, an unrestrained volume of weekly training can cause delayed onset muscle soreness leading to injury (Cheung et al., 2003).

Moreover, an injury might happen in the absence of stability (McNeely, 2009). An imperfect stroke due to boat imbalance may cause a rower to use their muscles in an uncoordinated way. In the moment that the boat departs from the even keel position during the drive phase, the rower must instantaneously change the action in their muscles to maintain balance. This sudden change of action can cause twisting of muscle fibers (Byrne et al., 2004). Hence, the maintenance of balance in rowing is important not only for maximizing velocity, but also for reducing injury.

Stability is one of the key determinants of performance in rowing. There are several studies analysing the rowing dynamic on a rowing machine, but there is only a small amount of research that focuses on stability while on water. Gravenhorst et al. (2011) reported that the same crew was 7 seconds faster over 1000 m with a boat that had less pitch motion. Tessendorf et al. (2011) used IMU sensors and found a negative linear correlation between stroke rate and stroke length. Kleshnev (2010) studied the rowing microphases between experienced athletes and Olympic champions and reported that the Olympic champions could reach their maximum power output in the initial microphase of the drive phase. Although there has been research on rowing technique, a thorough knowledge of the correlation between kinematic stability and performance on the water is lacking. Also, implementing different approaches to improve boat stability, such as measuring how different fin sizes affect boat stability, is a subject that has seemingly not yet been studied.

Developing a better understanding of the kinematics of the rowers with respect to stability could help coaches and athletes improve their performance. Moreover, it would also provide a clearer image of weakness and advantages of different rowing techniques. To study the kinematics of the rower, a new methodology must be developed in order to interpret the body motions and different techniques that rowers take to maintain their balance. After a better understanding of these methodologies and their consequences, rowers may be better able to detect and improve technical errors, thereby improving performance.

Chapter III: Purpose and Hypotheses

3.1 Purpose

i) Examine how fin size affects boat velocity and stability in an experienced sculling athlete.

ii) As a long fin should create a more stable platform for the participant by reducing yaw and roll of the boat, the secondary purpose examines the kinematics of the rower to determine if fin size affects rowing technique.

3.2 Hypotheses

i) Boat velocity will be increased with a long fin.

ii) Boat stability will be increased with a long fin.

iii) The stroke kinematic variability will be reduced with a long fin.

Chapter IV - Methodology

4.1 Participant

This study was approved by the Nipissing University's research ethics committee (NUREB 102824) and carried out as a pilot study with one male participant (height: 188 cm; mass: 90 kg; age: 29 years) due to limitations and delays caused by the COVID-19 pandemic. He was a rower with national and international competitive experience and presented with no musculoskeletal issues in this investigation (Richer et al., 2016).

4.2 Instrumentation

A middleweight single scull (Fluidesign, London) and Croaker oars (Croaker, Australia) were used by the participant. The boat's setting (i.e., angle and the length of the oars, rigging, foot stretcher position, height of the oarlocks) were adjusted to the participant's anthropometric measurements. The research was conducted using two different fins, one with a height of 24.5 cm and one with a height of 18.5 cm but were otherwise identical in shape with respect to base length, width, rake, and foil (Figure 4.1).

Figure 4.1

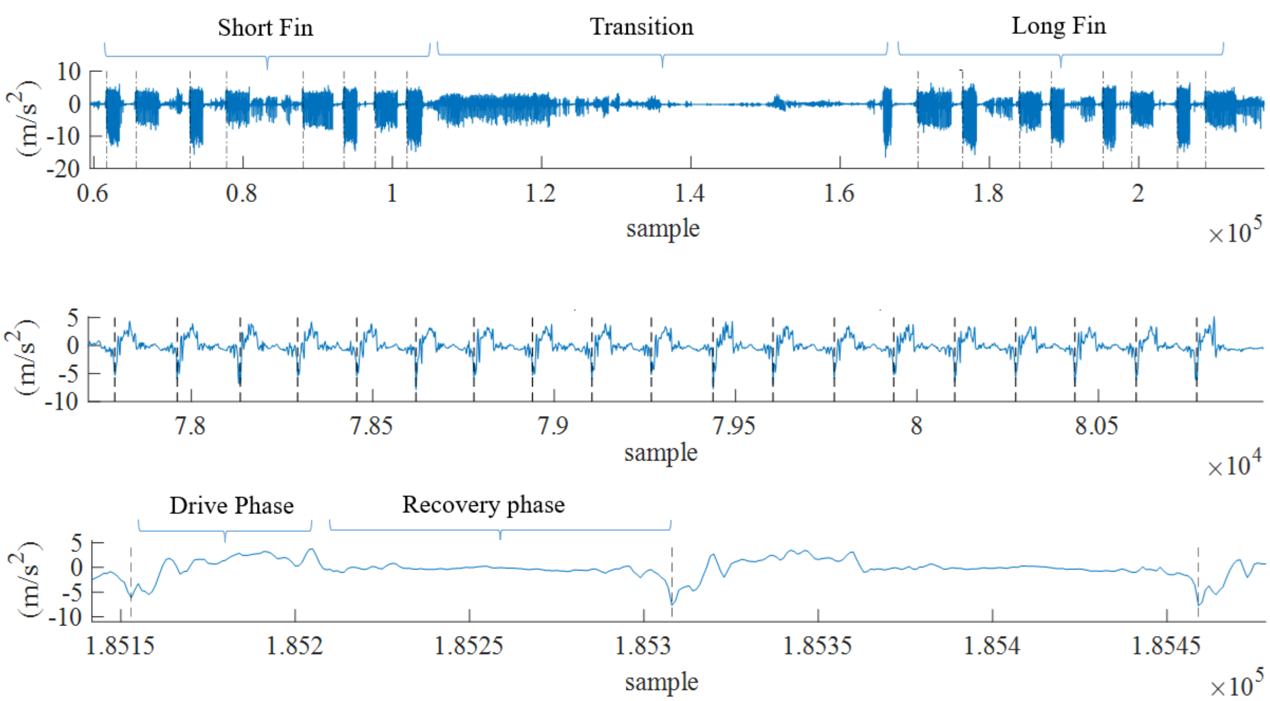
Long and Short Experimental Fins

Note. Photo Credit: Khashayar Abbasabadi.

This research was conducted on Trout Lake in North Bay, Ontario. Therefore, inertial measurement units (IMUs) (MBIENTLAB, San Francisco) were used to record the linear accelerations and angular velocities of the boat and participant during trials (figure 4.2). Data were sampled at a frequency of 50 Hz (Groh et al, 2014) using the data logging function through the MetaBase software via smartphone. These data were then transferred to a computer for processing and analysis. Boat position and velocity were recorded by a global positioning system (GPS) during the experiment sampled at 1 Hz (Ambit 2, Suunto, Finland). The raw data files were exported to a computer for processing and analysis.

Figure 4.2

Anteroposterior Acceleration Data from the Bow Sensor



Note. The top graph illustrates a whole data collection session (i.e. two eight trials for each fin and the rest between them). The figure in the middle randomly chose to illustrate a trial and 15 stroke cycles and it performed in slow stroke rate and with a short fin. The bottom figure is two random stroke cycles from the middle figure. The vertical dotted black lines indicate the start of a stroke cycle. This figure is just a sample to demonstrate how start points are defined using the "findpeaks" function in Matlab. These data were collected in December 2021 during a pilot testing.

4.3 Procedures

The participant was informed of the benefits and risks and the series of steps involved in this investigation prior to arriving at Trout Lake. The participant signed an informed consent prior to the session (hard copy). All instruments were sanitized prior to data collection and appropriate COVID-19 protocols was in place prior to, and during, data collection.

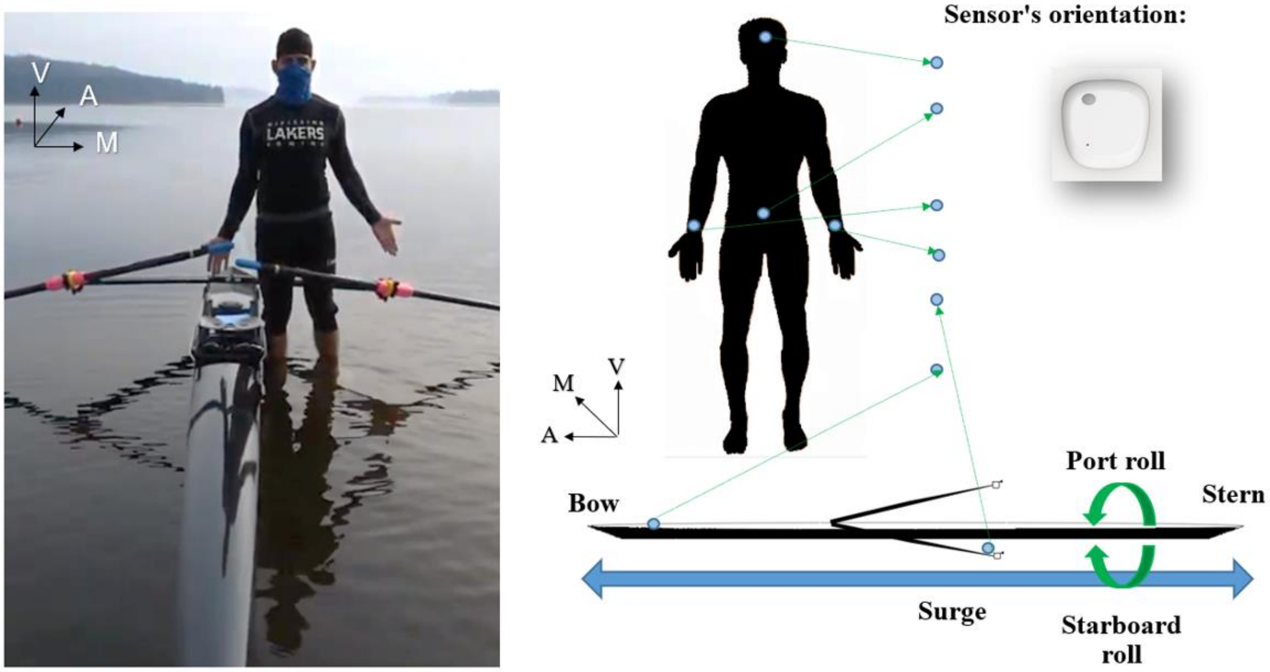
4.3.1 Initial Preparation

The fully charged IMU sensors were safely sheathed in their waterproof covers. The boat was equipped with four fixed IMU sensors (figure 4.3). Two sensors were placed on the right oarlock, and two were placed on the bow end of the boat (40 cm from the end and centered). The oarlock position was selected to measure boat roll angular velocity and vertical acceleration of the rigger. The bow was selected to measure anteroposterior and vertical acceleration and pitch and yaw angular velocity. Two sensors were used at each location to provide redundancy in case of problems with one of the sensors. These locations were selected as the magnitude of the listed motions were expected to be greatest at the respective boat locations.

The participant wore 4 belts containing IMU sensors on the head, posterior pelvis, and posterior wrists (Figure 4.3) as they are regions associated with rowing stability (Sforza et al., 2012). Adjustments to the belts were made as necessary during on-land warm-up so that the orientations of the sensors would remain fixed for the trials. The pelvis was selected for evaluating the stability of the participant's trunk. The wrists were selected as vertical oscillations of the hands may indicate instability as the rower adjusts oar position to maintain balance. The head sensor was selected as it is the most distal part of the trunk from the boat; lateral deviations of the head would indicate instability of the participant.

Figure 4.3

IMU Sensor Positions



Note. The blue circles indicate IMUs sensor locations. Photo Credit: Khashayar Abbasabadi.

4.3.2 Data Collection

The participant was asked to follow his normal on-land warm-up routine, followed by rowing on the water with a combination of slow and fast stroke rate efforts of varying intensities. Once the participant felt comfortable with the boat set up and was ready for the trials, the boat was put on stretchers at the water's edge and one of the two experimental fins (Figure 4.1) was attached to the hull at random.

Following this, the participant was asked to perform 4 trials each in counter-balanced order at 18 and 30 strokes per minute at maximal effort for approximately 250 m. The participant did not have real-time objective measurement of his stroke rate as it was decided that it was more important to have the participant focus on rowing technique and not on a digital display in the cockpit. Following each trial, the participant was given rest of at least two minutes or until the participant declared his readiness for the next trial. Following completion of the 8 trials, the participant returned to shore where the other fin was attached. The 8-trial procedure was repeated for the second fin. Data were collected on two consecutive days. On day 2, the fin order was reversed to minimize the effect of fatigue on the trials. In total, 32 trials were completed. A description of each trial including the start time, fin depth and stroke rate were manually recorded in order to facilitate data analysis.

4.4 Data processing

Primary data processing was performed in MATLAB (version R2021a, MathWorks, Natik MA, USA) and Excel software. MATLAB was used for signal processing of time-series data of the IMUs to determine 15 consecutive stroke cycles for each trial. Once the strokes were determined, the following variables were calculated for each stroke from the accelerometer and gyroscope data: mean, standard deviation, minimum, maximum, and range (Dubus, 2012; Tessendorf et al., 2011). The mean and standard deviation were then calculated for each of the variables, resulting in a single value for each variable for each trial. For example, the maximum vertical acceleration of the boat (bow sensor) for each stroke cycle was calculated, then the mean of those 15 values was taken as a dependent variable measure of boat stability (in this case, pitch). Only meaningful outputs (i.e., values that were logically associated with velocity and stability) were used for statistical analysis.

Excel software was used to analyze the data obtained from the GPS device. As the start and stop times of each trial were known, the total GPS signal within each trial was used to calculate the dependent values of mean, standard deviation, maximum and minimum velocity.

4.4.1 Boat Velocity Dependent Variables

Mean velocity was the primary dependent variable to measure performance. The additional calculated dependent variables, which included *SD velocity*, and *maximum*, *minimum*, and *range of velocity*, provided additional insights to how the boat speed fluctuated within stroke cycles.

4.4.2 Boat Stability Dependent Variables

4.4.2.1 Surge, Pitch and Heave

The bow sensor data were used to measure boat stability with respect to surge, heave, and pitch. *Anterior peak* acceleration is a measure of positive surge during the drive phase, while *posterior peak* acceleration is a measure of negative surge during the recovery. Total AP acceleration changes during a stroke cycle in boat surge are indicated by the dependent variable, *AP range*. 'Range' in data processing for this study refers to the range between the maximum and minimum peak in a stroke cycle. *Anterior SD peak* is a measure of surge fluctuations during the drive phase, *posterior SD peak* is a measure of surge fluctuations during the recovery phase, and *AP SD* is a measure of the overall variability in surge throughout the rowing cycle. Significant results with respect to these variables would suggest differences in the participant COM within the rowing cycle that could be attributed to variability in power application and/or inconsistency of the participant's slide speed.

Due to the 7.9 m length of the boat, changes in pitch which may have a meaningful effect on boat speed were relatively small with respect to the measurement sensitivity of the IMUs on the bow. In other words, as the participant's COM shifted fore and aft, the bow pitched down and up, respectively, but due to the relatively long hull design, the angular displacement was only a few degrees. As the IMU output was in degrees/s, these fluctuations were quite small and provided inconclusive statistical results. The fore and aft movement of the participant's COM, however, did produce relatively large fluctuations in vertical acceleration at the bow. Therefore, boat pitch and heave are considered analogous. *Upward peak* is a measure of positive pitch (heave) of the boat as the participant's COM moves to the stern prior to the catch, while *downward peak* is a measure of the negative pitch (heave) of the boat as the participant moves toward the bow at the end of the drive phase. *Vertical range* is a measure of the overall pitch (heave) throughout the rowing cycle. The *upward and downward SD peak* variables are indicators of fluctuations in the participant's COM between strokes.

4.4.2.2 Roll

The right oarlock sensor was used to measure roll as it is the most distal location from the long axis of the boat. As the oarlock is ideally horizontal throughout the rowing stroke, rolling motions of the hull due to mediolateral shifting of the participant's COM will cause the oarlock to rise or fall. Both angular velocity and linear acceleration data, therefore, can be used to measure boat stability with respect to roll. From the angular velocity data, *starboard roll peak* is a measure of upward movement of the oarlock. From the acceleration data, *upward peak* is analogous to starboard roll, so it is expected that a significant result in one would be found in the other. Downward movement of the oarlock is measured by *port roll peak* from the gyroscope data and *downward peak* from the accelerometer data. However, as the IMU gyroscope output was angular velocity, the sensitivity to perturbations is less than the linear acceleration data. Differentiation of the angular velocity data may have provided more sensitivity between conditions, but was not performed in this study. The *vertical range* from acceleration data and *roll SD* from the gyroscope data provide overall information about roll fluctuations throughout a stroke cycle.

4.4.3 Rower's Kinematic Dependent Variables

4.4.3.1 Left and Right wrist sensors

Wrist sensor data were used to quantify the participant's arm movements throughout the rowing stroke. *Anterior peak, anterior SD peak* and *upward peak* are the variables associated in drive phase as the wrists move upward and towards the chest during the catch phase. *Posterior peak, posterior SD peak* and *downward peak* are the variables associated with the recovery phase as the wrists move downward and away from the chest.

Anterior SD peak is likely a measure of elbow flexion fluctuation during the drive phase as the acceleration of the wrist is caused by the elbow joint. Therefore, posterior SD peak is likely a measure of elbow extension fluctuation during the recovery phase. Significant results with respect to these variables would suggest differences in consistency of the flow of AP movement of the wrists (e.g., a greater anterior SD peak would indicate more jerky movements during the drive phase). *AP range* is a measure of total changes in AP acceleration. Total changes in vertical acceleration of the wrists are indicated by the dependent variable, *vertical range*.

Upward peak is a measure of the participant's speed at the catch microphase. Larger values for this variable may indicate a faster catch due to increased system stability. Downward peak is a measure of the participant's speed at the push-down/release microphase. Larger values for this variable may indicate a faster push down/release due to increased system stability. *Upward SD peak* and *downward SD peak* are measures of the wrists' fluctuation during the catch and push-down phases, respectively. The *vertical SD* is a measure of overall vertical variability of the wrists throughout the stroke cycle.

4.2.3.2 Head Sensor

Head sensor data were used to measure the participant's upper-body movements of anteroposterior and lateral swing. The gyroscope data for the first day was lost, therefore only acceleration data was analyzed. *Anterior peak* and *anterior SD peak* are measures of the participant's upper body acceleration during the drive phase and *posterior peak* and *posterior SD peak* are measures of participant's upper body acceleration during the recovery phase. These values are most likely due to hip extension/flexion as the neck movements are minimal during a rowing stroke.

4.2.3.3 Lower Back Sensor

Lower back sensor data were used to measure changes in the participant's COM in fore and aft movements, and mediolateral linear and angular motions in response to roll. The participant's movement along the AP axis coincides with heave and pitch motions of the boat. For example, *anterior peak* is a measure of the participant's trunk acceleration during the drive phase, and *anterior SD peak* is a measure of consistency in trunk acceleration during the drive phase (due to knee and hip extension fluctuation). These variables coincide with downward heave/pitch of the bow as the participant moves towards the bow. *Posterior peak* is a measure of the participant's trunk acceleration during the recovery phase, and *posterior SD peak* is a measure of consistency in trunk acceleration during the recovery phase (due to knee and hip flexion fluctuation). These variables coincide with upward heave/pitch of the bow as the participant moves towards the stern. Total changes in AP acceleration of the participant's COM are indicated by the dependent variable, *AP range*. Significant results with respect to this variable would suggest differences in the participant COM within the rowing cycle that could be attributed to variability in power application and/or inconsistency of the participant's slide speed.

Total changes in ML acceleration of the lower back are indicated by the dependent variable, *ML range*. From the gyroscope data, trunk rotation towards right oarlock was defined as *port roll* and the opposite was *starboard roll*. Total fluctuations in roll motion are indicated by *roll SD*. Significant results with respect to these variables would suggest differences in the participant's ML lower back movement that could be attributed to variability in roll angular velocity of the boat and/or core instability of the participant.

4.5 Data Analysis

Statistical analysis was performed in SPSS (version 27, IBM Corp., Armonk, N.Y., USA). A two-factor (fin size × stroke rate) repeated-measures ANOVA was performed in SPSS software on the dependent variables (alpha = 0.05). As there are only two conditions for each factor, there was no need to perform *post hoc* tests for significant main effects. Significant interactions between factors were interpreted as required, but *post hoc* tests were not conducted. The F statistic, p value, estimated marginal means, and $\pm$ 95% confidence intervals (CIs) are presented in tables and figures. Where appropriate, time-series graphs that highlight meaningful trends are also presented.

Chapter V: Results

The results are divided into three sections: velocity of the boat (5.1), stability of the boat (5.2), and stability of the participant (5.3). In almost all cases, there was a significant effect of stroke rate on the dependent variables, with the greater values found in the fast stroke rate condition. Therefore, only dependent variables with a significant main effect for fin and/or significant interactions are plotted from the ANOVA results. All the negative values (i.e., minimum peaks, posterior acceleration, downward acceleration, port acceleration, port roll) were multiplied by -1 before statistical analysis, so that all values that are presented in tables and figures are positive.

5.1 Velocity of the Boat

A significant main effect of stroke rate was found for all velocity variables (Table 5.1). Also, a significant main effect of fin was found for maximum velocity (Table 5.1). The fast stroke rate was 0.866 m/s greater than the slow stroke rate and the long fin was 0.186 m/s greater than the short fin (Figure 5.1.1). Significant main effects of stroke rate and fin were found for stroke frequency (Table 5.1).

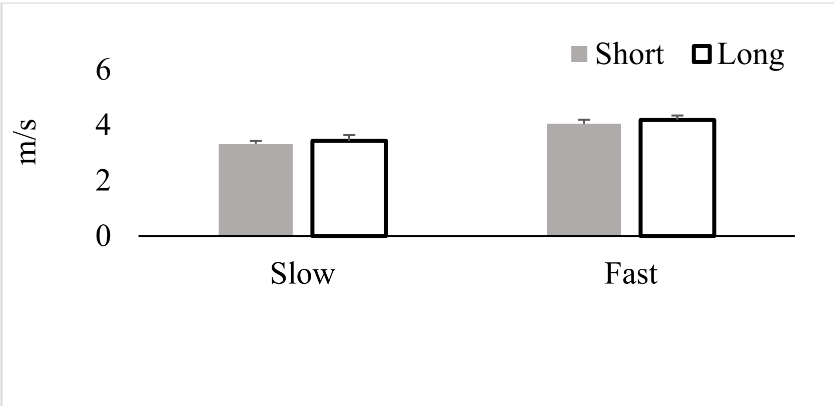
Table 5.1

Velocity ANOVA Results

	Stroke Rate		Fin		Interaction	
	F	*p*	*F*	*p*	*F*	*p*
Mean velocity	349	**<0.001**	1.86	0.214	0.464	0.518
SD velocity	17.0	**0.004**	1.29	0.293	0.320	0.589
Maximum velocity	278	**<0.001**	5.78	**0.047**	2.90	0.133
Minimum velocity	150.0	**<0.001**	1.9	0.208	0.125	0.734
Velocity range	1167	**<0.001**	3.76	0.094	1.36	0.281
Stroke frequency	677	**<0.001**	36.2	**0.001**	4.31	0.076

Figure 5.1.1

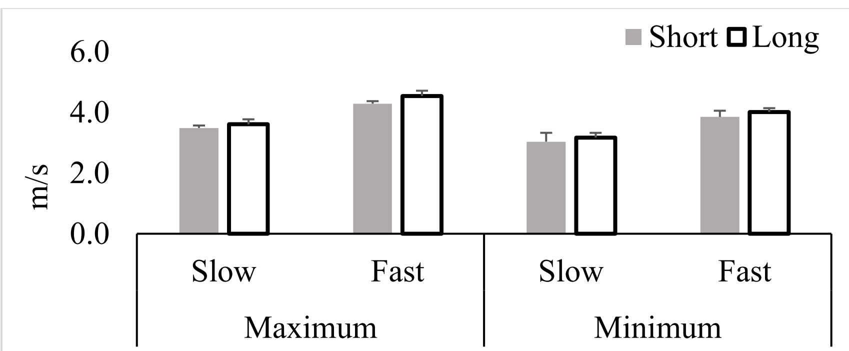
Mean Velocity



Note. A significant main effect for stroke rate ($p < 0.001$) was found. There was no significant main effect for fin ($p = 0.214$) or interaction ($p = 0.518$). F values are presented in Table 5.1.

Figure 5.1.2

Maximum and Minimum Velocity



Note. For maximum velocity, significant main effects of stroke rate ($p < 0.001$) and fin ($p = 0.047$) were found. There was no significant interaction between stroke rate and fin ($p = 0.133$). For minimum velocity, a significant main effect for stroke rate was found. There was no significant main effect for fin ($p = 0.208$) or interaction ($p = 0.734$). F values are presented in Table 5.1.

5.2 Stability of the Boat

5.2.1 Inter-Sensor Reliability

To determine inter-sensor reliability, *t*-tests were performed on the AP range variable for each of the experimental conditions between the bow sensor and right oarlock. Both locations were expected to produce similar results due to the rigid nature of the rowing shell. Significant differences between sensors were found for: slow stroke rate and short fin (t_7 = 2.36, <0.001); slow stroke rate and long fin (t_7 = 2.36, <0.001); fast stroke rate and short fin, (t_7 = 2.36, .001); fast stroke rate and long fin, (t_7 = 2.36, <0.001). The magnitude of these differences were relatively small (approximately 7% overall) considering that the sensor locations were not close to each other and the relatively larger effect of pitch on the bow sensor may have affected AP results. Visual inspection of the bow and ROR AP range results (Figure 5.2.1) also shows that the difference between sensors is relatively small. Therefore, for subsequent presentation of the surge and pitch results for the boat, only the bow sensor data are presented.

5.2.2 Bow Sensor

A summary of ANOVA results is presented in Table 5.2.1 for the bow sensor. A significant main effect of stroke rate was found for all variables except for upward peak and upward SD peak. A significant main effect for fin was found for the posterior peak (Table 5.2.1). Posterior peak with the long fin was 0.481 m/s^2 greater than the short fin (Figure 5.2.2). In accordance with this finding, AP range was 0.655 m/s^2 greater with the long fin (Table 5.2.1, Figure 5.2.1).

A significant main effect for fin and a significant interaction between fin and stroke rate were found for AP SD (Table 5.2.1). AP SD with long fin was 0.201 m/s^2 greater than short fin. AP SD with long fin was 0.304 m/s^2 greater than short fin in fast stroke rate, but proportionally greater (0.098 m/s^2) in slow stroke rate (Figure 5.2.3).

A significant main effect of stroke rate was found for downward peak acceleration for the bow sensor (Table 5.2.1). Downward peak acceleration in fast stroke rate was 0.971 m/s^2 greater than slow stroke rate (Figure 5.2.4). Conversely, there was no significant effect of stroke rate on upward peak acceleration.

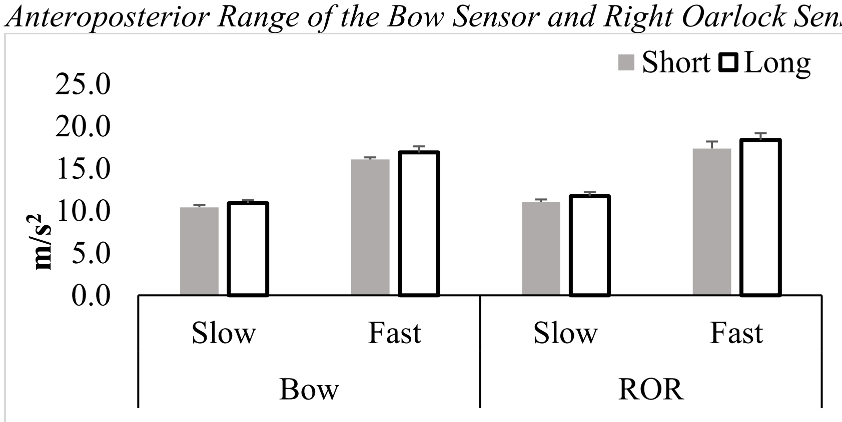
Table 5.2.1

Bow Sensor Acceleration ANOVA Results

	Stroke Rate		Fin		Interaction	
	F	*p*	*F*	*p*	*F*	*p*
Ant. Peak	48	**<0.001**	4.95	0.061	4.10	0.082
Post. Peak	2610	**<0.001**	5.99	**0.044**	0.09	0.772
AP Range	1262	**<0.001**	9.62	**0.017**	0.682	0.436
Ant. SD Peak	11.9	**0.011**	0.202	0.667	2.97	0.128
Post. SD Peak	16.2	**0.005**	0.264	0.623	0.61	0.461
AP SD	652	**<0.001**	16.5	**0.005**	6.53	**0.038**
Upward Peak	2.15	0.186	2.11	0.189	1.30	0.291
Downward Peak	75.7	**<0.001**	1.62	0.243	0.336	0.581
Vert. Range	35.7	**0.001**	0.738	0.159	0.038	0.852
Upward SD Peak	5.47	0.052	0.148	0.712	0.019	0.894
Downward SD Peak	5.74	**0.048**	0.225	0.649	0.041	0.845

Figure 5.2.1

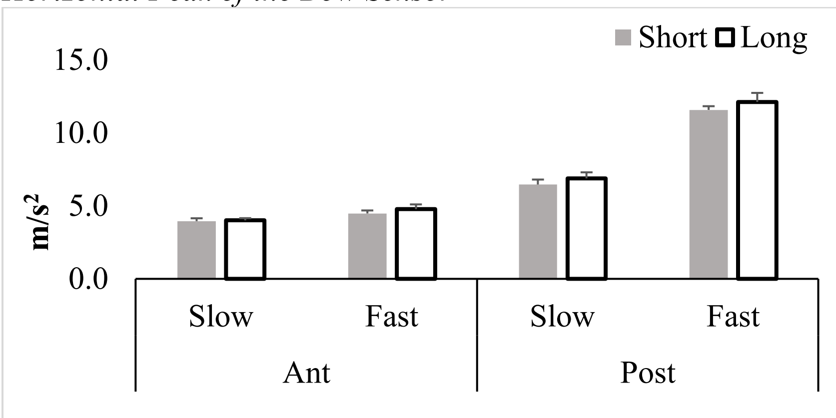
Anteroposterior Range of the Bow Sensor and Right Oarlock Sensor



Note. For bow sensor, significant main effects for stroke rate ($p < 0.001$) and fin ($p = 0.017$) were found for bow sensor. There was no significant interaction ($p = 0.436$). F values are presented in Table 5.2.1. For right oarlock sensor, significant main effects for stroke rate ($p < 0.001$) and fin ($p = 0.024$) were found. There was no significant interaction ($p = 0.582$). *F* values are presented in Table 5.2.2.

Figure 5.2.2

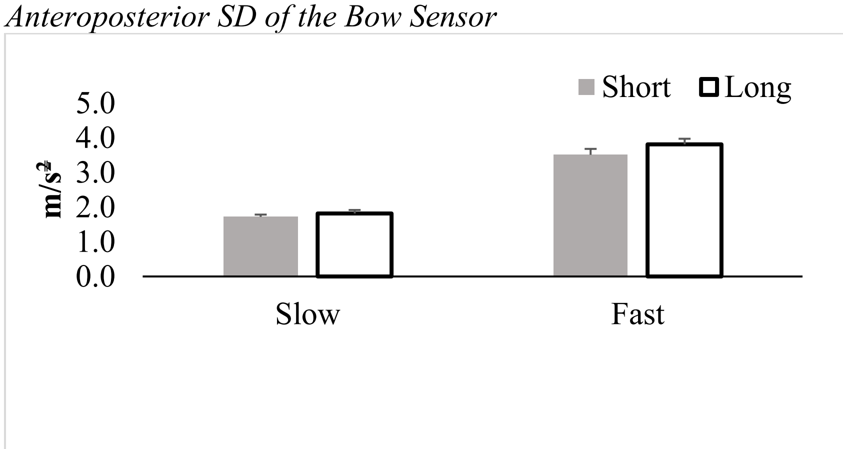
Horizontal Peak of the Bow Sensor



Note. For anterior peak, a significant main effect was found for stroke rate ($p < 0.001$). There was no significant main effect for fin ($p = 0.061$) or interaction ($p = 0.082$) for anterior acceleration. For posterior peak, significant main effects for stroke rate ($p < 0.001$) and fin ($p = 0.044$) were found. There was no significant interaction ($p = 0.772$). F values are presented in Table 5.2.1.

Figure 5.2.3

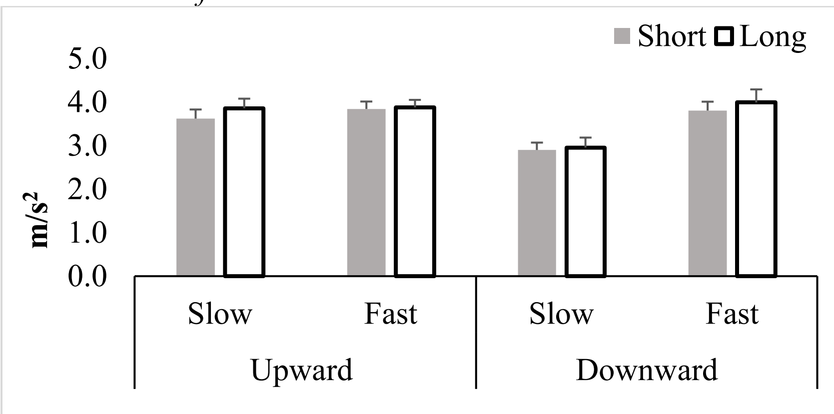
Anteroposterior SD of the Bow Sensor



Note. Significant main effects for stroke rate ($p < 0.001$) and fin ($p = 0.005$) were found. A significant interaction ($p = 0.038$) was found. F values are presented in Table 5.2.1.

Figure 5.2.4

Vertical Peak of the Bow Sensor



Note. For upward peak, there were no significant main effects of stroke rate (p = 0.186), fin (p = 0.189), or interaction (p = 0.291). For downward peak, there was a significant main effect for stroke rate ($p < 0.001$), but no significant main effect for fin (p = 0.243) or interaction (p = 0.581). F values are presented in Table 5.2.1.

5.2.3 Right Oarlock Sensor

A summary of ANOVA results is presented in Table 5.2.1 for the ROR sensor. A significant main effect of stroke rate was found for all variables except for upward SD peak and downward SD peak. As discussed in 5.2.1, the ROR AP values were calculated to test inter-sensor reliability. Similar to the bow sensor, a significant main effect of fin was found for AP range (Table 5.2.2). AP range was 0.835 m/s^2 greater with long fin (Figure 5.2.1).

A significant interaction between fin and stroke rate was found for upward peak (Table 5.2.2). The long fin was 0.737 m/s^2 greater than short fin during slow stroke rate, but only 0.083 m/s^2 greater during fast stroke rate (Figure 5.2.5). A significant interaction between fin and stroke rate was also found for upward SD peak (Table 5.2.2). Upward SD peak with long fin was 0.315 m/s^2 greater than short fin in slow stroke rate, but 0.253 m/s^2 less during the fast stroke rate (Figure 5.2.6).

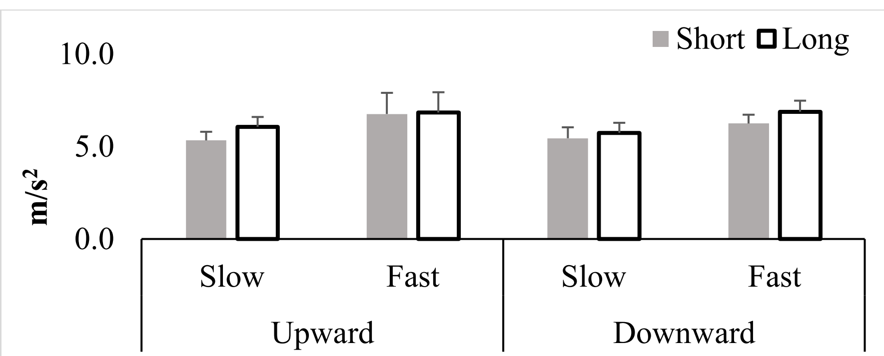
Table 5.2.2

Right Oarlock Sensor ANOVA Results

	Stroke Rate		Fin		Interaction	
	F	*p*	*F*	*p*	*F*	*p*
Acceleration						
AP Range	621	**<0.001**	8.16	**0.024**	0.334	0.582
Upward Peak	9.66	**0.017**	4.24	0.078	6.76	**0.035**
Downward Peak	40.5	**<0.001**	1.76	0.226	4.00	0.085
Vert. Range	25.4	**0.001**	2.64	0.148	0.604	0.463
Upward SD Peak	0.480	0.511	0.14	0.721	17.9	**0.004**
Downward SD Peak	0.515	0.496	0.73	0.421	0.026	0.877
Angular Velocity						
Star. Roll Peak	16.0	**0.005**	0.12	0.739	2.37	0.168
Port Roll Peak	22.7	**0.002**	1.290	0.293	1.29	0.292
Roll SD	122	**<0.001**	0.081	0.785	1.05	0.339

Figure 5.2.5

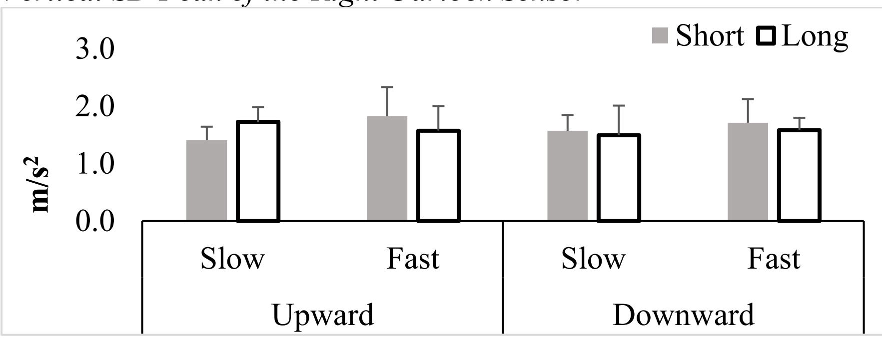
Vertical Peak of the Right Oarlock Sensor



Note. For upward peak, a significant main effect for stroke rate (p = 0.017) and a significant interaction (p = 0.035) were found. There was no significant main effect for fin (p = 0.078). For downward peak, a significant main effect for stroke rate (p < 0.001) was found, but not for fin (p = 0.225) or interaction (p = 0.078). F values are presented in Table 5.2.2.

Figure 5.2.6

Vertical SD Peak of the Right Oarlock Sensor



Note. For upward SD peak, a significant interaction (p = 0.004) was found. There were no significant main effects for stroke rate (p = 0.511) or fin (p = 0.721). For downward SD peak, there were no significant main effects for stroke rate (p = 0.496), fin (p = 0.421), or interaction (p = 0.877). F values are presented in Table 5.2.2.

5.3 Kinematics of the Rower

Tables 5.3.1 to 5.3.4 present the results related to the ANOVA analysis of sensors on the participant (i.e., left/right wrists, head, and lower back). The analysis of the left wrist indicates that several of the kinematic measurements were affected by the fin length (see Table 5.3.2, i.e., mean peak for anterior acceleration, mean peak for posterior acceleration, anteroposterior range). This contrasted with the right wrist in which the fin length did not affect any of the anteroposterior kinematic measurements (see Table 5.3.1).

5.3.1 Right Wrist Sensor

A summary of ANOVA results is presented in Table 5.3.1 for the right wrist sensor. A significant main effect of stroke rate was found for all variables except for posterior SD peak and downward SD peak. A significant interaction between fin and stroke rate was found for anterior peak (Table 5.3.1). Anterior peak with short fin was 0.538 m/s^2 greater than long fin during the slow stroke rate, but 2.25 m/s^2 less during fast stroke rate (Figure 5.3.1). A significant main effect of fin was found for upward peak (Table 5.3.1). Upward peak with long fin was 2.85 m/s^2 greater than short fin (Figure 5.3.2).

A significant main effect of fin and significant interaction were found for vertical range (Table 5.3.1). Vertical range with long fin was 2.39 m/s^2 greater than short fin during the slow stroke rate and 4.39 m/s^2 greater during the fast stroke rate (Figure 5.3.3). In accordance with this finding, a significant main effect of fin and a significant interaction were also found for vertical SD (Table 5.3.1). Vertical SD with long fin was 0.170 m/s^2 greater than short fin during the slow stroke and 0.799 m/s^2 during the fast stroke rate (Figure 5.3.4).

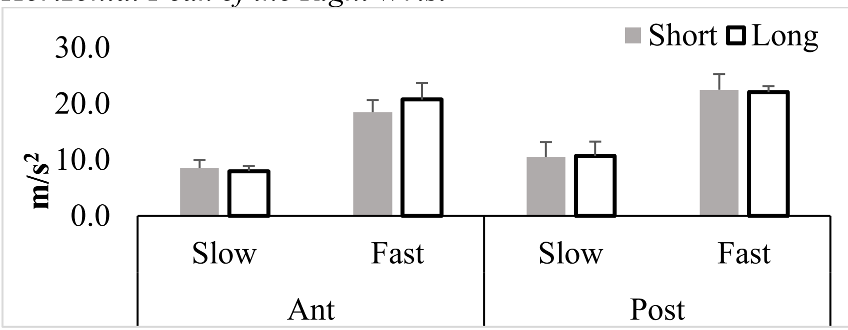
Table 5.3.1

Right Wrist Sensor ANOVA Results

	Stroke Rate		Fin		Interaction	
	F	*p*	*F*	*p*	*F*	*p*
Acceleration						
Ant. Peak	135	**<0.001**	1.38	0.277	5.60	**0.050**
Post. Peak	862	**<0.001**	0.026	0.877	0.369	0.563
AP Range	334	**<0.001**	0.501	0.502	2.37	0.167
Ant. SD Peak	36.8	**0.001**	0.070	0.799	0.081	0.784
Post SD Peak	0.3	0.604	0.316	0.592	0.534	0.489
Upward Peak	41.2	**<0.001**	22.1	**0.002**	2.47	0.160
Downward Peak	69.5	**<0.001**	2.26	0.176	2.57	0.153
Vert. Range	84.1	**<0.001**	14.7	**0.006**	9.46	**0.018**
Upward SD Peak	7.93	**0.026**	3.95	0.087	1.24	0.302
Downward SD Peak	2.03	0.197	3.55	0.102	0.301	0.600
Vert. SD	312	**<0.001**	29.2	**0.001**	21.9	**0.002**

Figure 5.3.1

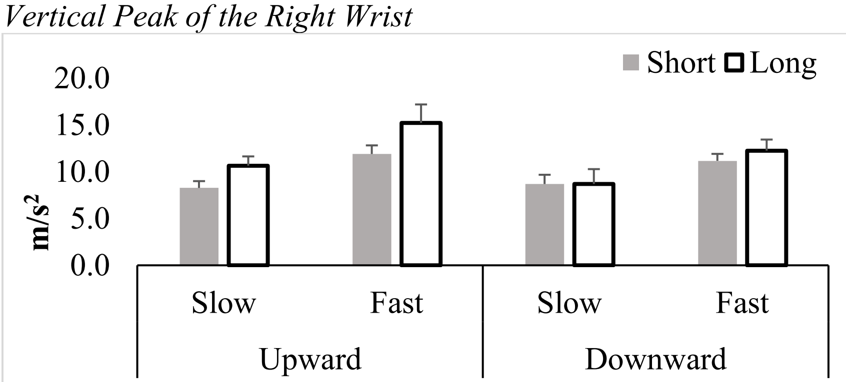
Horizontal Peak of the Right Wrist



Note. For anterior peak a significant main effect for stroke rate (p < 0.001) and a significant interaction (p = 0.050) were found, but there was no significant main effect for fin (p = 0.277). For posterior peak, a significant main effect for stroke rate (p < 0.001) was found, but there was no significant main effect for fin (p = 0.877) or interaction (p = 0.563). F values are presented in Table 5.3.1.

Figure 5.3.2

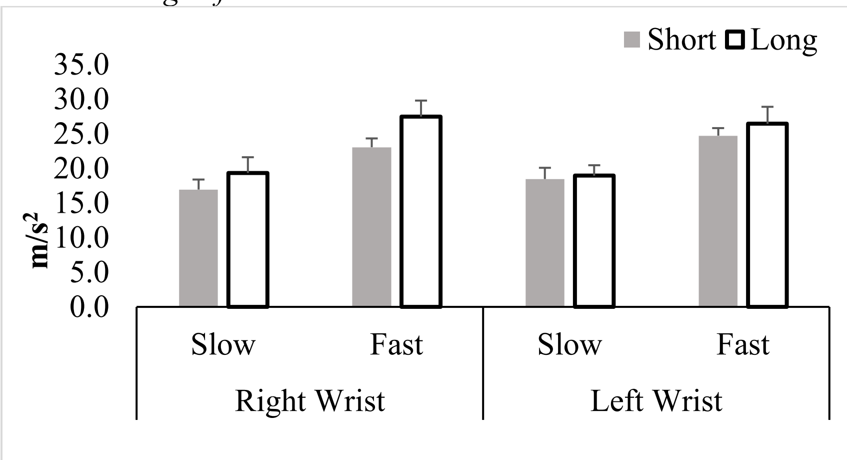
Vertical Peak of the Right Wrist



Note. For upward peak, significant main effects for stroke rate (p < 0.001) and fin (p = 0.002) were found, but there was no significant interaction (p = 0.160). For downward peak, a significant main effect for stroke rate (p < 0.001) was found, but there was no significant main effect for fin (p = 0.176) or interaction (p = 0.153). F values are presented in Table 5.3.1.

Figure 5.3.3

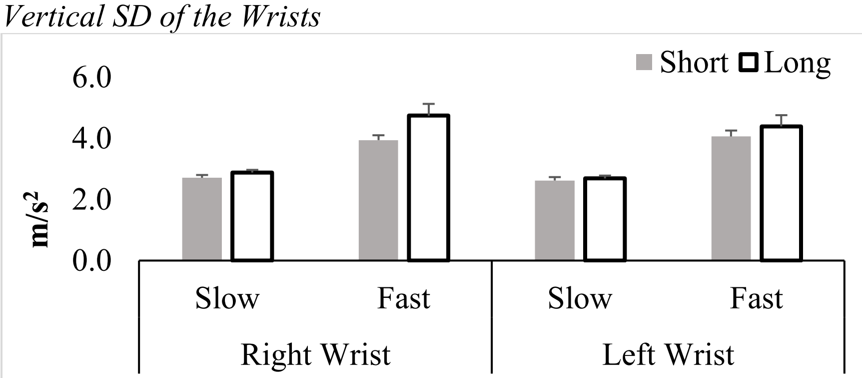
Vertical Range of the Wrists



Note. For right wrist, significant main effects for stroke rate ($p < 0.001$) and fin ($p = 0.006$) and a significant interaction ($p = 0.018$) were found. F values are presented in Table 5.3.1. For left wrist, a significant main effect for stroke rate ($p < 0.001$) was found, but there was no significant main effect for fin ($p = 0.078$) or interaction ($p = 0.078$). *F* values are presented in Table 5.3.2.

Figure 5.3.4

Vertical SD of the Wrists



Note. For right wrist, significant main effects for stroke rate ($p < 0.001$) and fin ($p = 0.006$) and a significant interaction ($p = 0.018$) were found. F values are presented in Table 5.3.1. For left wrist, significant main effects for stroke rate ($p < 0.001$) and fin ($p = 0.039$) were found, but there was no significant interaction ($p = 0.123$). *F* values are presented in Table 5.3.2.

5.3.2 Left Wrist Sensor

A summary of ANOVA results is presented in Table 5.3.2 for the left wrist sensor. A significant main effect of stroke rate was found for all variables except for posterior SD peak, upward SD peak, and downward SD peak. A significant interaction was found for anterior peak

(Table 5.3.2). Anterior peak with long fin was only 0.167 m/s^2 greater than short fin during slow stroke rate, but 1.16 m/s^2 greater during fast stroke rate (Figure 5.3.5). A significant interaction was found for posterior peak (Table 5.3.2). Posterior peak with long fin was only 1.052 m/s^2 greater than short fin during the slow stroke rate, but 2.52 m/s^2 greater during the fast stroke rate (Figure 5.3.5). In accordance with these results, a significant interaction was found for AP range (Table 5.3.2). AP range with long fin was only 1.22 m/s^2 greater than short fin during the slow stroke rate, but 3.67 m/s^2 greater during the fast stroke rate (Figure 5.3.6).

A significant interaction between fin and stroke rate was found for upward peak (Table 5.3.2). Upward peak with long fin was only 0.348 m/s^2 greater than short fin during the slow stroke rate, but 1.35 m/s^2 greater during the fast stroke rate (Figure 5.3.7). A significant main effect of fin was found for vertical SD (Table 5.3.1). Vertical SD with long fin was 0.200 m/s^2 greater than short fin (Figure 5.3.4).

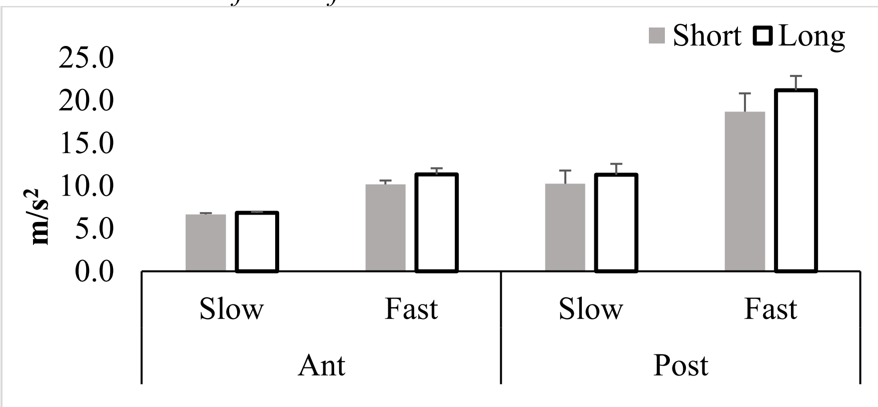
Table 5.3.2

Left Wrist Sensor ANOVA Results

	Stroke Rate		Fin		Interaction	
	F	*p*	*F*	*p*	*F*	*p*
Acceleration						
Ant. Peak	373	**<0.001**	16.5	**0.005**	7.46	**0.029**
Post. Peak	287	**<0.001**	12.0	**0.010**	6.55	**0.038**
AP Range	346	**<0.001**	16.2	**0.005**	7.4	**0.030**
Ant. SD Peak	29.3	**0.001**	0.2	0.709	0.333	0.582
Post. SD Peak	0.064	0.807	1.5	0.265	2.41	0.164
Upward Peak	62.4	**<0.001**	6.43	**0.039**	6.89	**0.034**
Downward Peak	49.1	**<0.001**	0.6	0.480	0.149	0.711
Vert. Range	63.2	**<0.001**	4.23	0.078	4.25	0.078
Upward SD Peak	0.139	0.720	1.57	0.250	0.330	0.584
Downward SD Peak	1.01	0.348	0.056	0.820	4.14	0.081
Vert. SD	222	**<0.001**	6.40	**0.039**	3.07	0.123

Figure 5.3.5

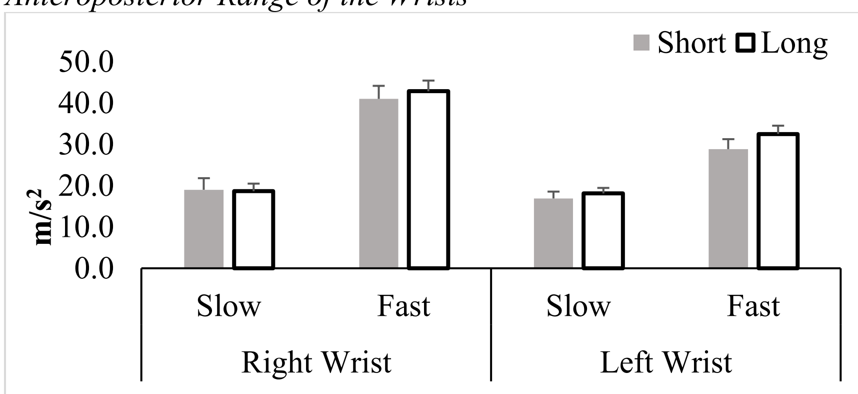
Horizontal Peak of the Left Wrist



Note. For anterior peak, significant main effects for stroke rate ($p < 0.001$) and fin ($p = 0.005$) and a significant interaction ($p = 0.029$) were found. For posterior peak, significant main effects for stroke rate ($p < 0.001$) and fin ($p = 0.010$) and a significant interaction ($p = 0.038$) were found. *F* values are presented in Table 5.3.2.

Figure 5.3.6

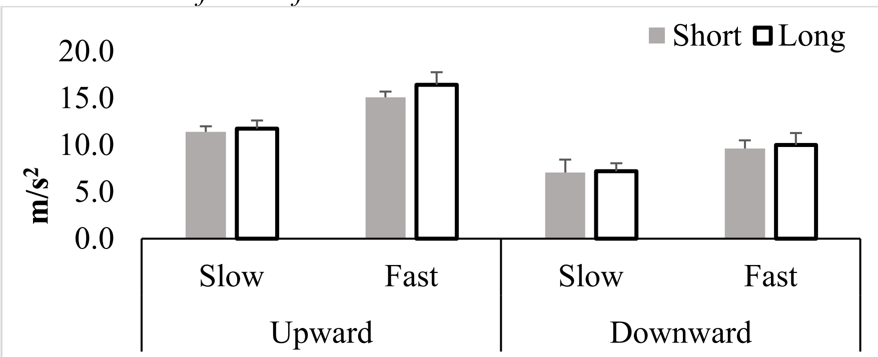
Anteroposterior Range of the Wrists



Note. For right wrist, a significant main effect for stroke rate ($p < 0.001$) was found but there was no significant main effect for fin ($p = 0.501$) or significant interaction ($p = 0.167$). F values are presented in Table 5.3.1. For left wrist, significant main effects for stroke rate ($p < 0.001$) and fin ($p = 0.005$) and a significant interaction between stroke rate and fin ($p = 0.030$) were found. *F* values are presented in Table 5.3.2.

Figure 5.3.7

Vertical Peak of the Left Wrist



Note. For upward peak, significant main effects for stroke rate ($p < 0.001$) and fin ($p = 0.039$) and a significant interaction ($p = 0.034$) were found. For downward peak, a significant main effect for stroke rate ($p < 0.001$) was found but there was no significant main effect for fin ($p = 0.480$) or significant interaction ($p = 0.711$). *F* values are presented in Table 5.3.2.

5.3.3 Head Sensor

A summary of ANOVA results is presented in Table 5.3.3 for the head sensor. There was only one significant variable: main effect of stroke rate for anterior peak. Anterior peak in fast stroke rate was 0.202 m/s^2 greater than slow stroke.

Table 5.3.3

Head Sensor ANOVA Results

	Stroke Rate		Fin		Interaction	
	F	*p*	*F*	*p*	*F*	*p*
Acceleration						
Ant. Peak	13.00	**0.009**	1.45	0.267	0.48	0.512
Post. Peak	3.8	0.092	4.88	0.063	2.8	0.138
Ant. SD Peak	0.22	0.657	0.22	0.656	0.242	0.638
Post. SD Peak	2.000	0.200	0.16	0.699	1.9	0.208

5.3.4 Lower Back Sensor

A summary of ANOVA results is presented in Table 5.3.4 for the lower back sensor. A significant main effect of stroke rate was found for all variables. A significant main effect of fin was found for anterior SD peak (Table 5.3.4). Anterior SD with long fin was 0.071 m/s^2 greater than short fin (Figure 5.3.8).

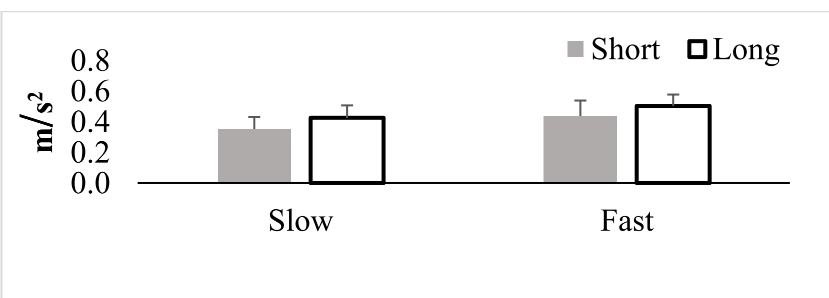
Table 5.3.4

Lower Back sensor ANOVA results

	Stroke Rate		Fin		Interaction	
	F	*p*	*F*	*p*	*F*	*p*
Acceleration:						
Ant. Peak	22.6	**0.002**	2.350	0.169	0.01	0.942
Post. Peak	465	**<0.001**	1.71	0.232	3.09	0.122
AP Range	441	**<0.001**	0.591	0.467	2.12	0.189
Ant. SD Peak	5.72	**0.048**	5.98	**0.044**	0.006	0.941
Post. SD Peak	59.1	**<0.001**	0.309	0.596	0.113	0.747
ML Range	33.8	**0.001**	3.26	0.114	1.59	0.248
Angular Velocity:						
Port Roll Peak	8.920	**0.020**	0.318	0.591	0.001	0.981
Star. Roll Peak	12.60	**0.009**	0.12	0.744	0.48	0.512
Roll SD	29.1	**0.001**	0.902	0.374	0.654	0.445

Figure 5.3.8

Anterior SD Peaks for the Lower Back Sensor



Note. Significant main effects for stroke rate (p = 0.048) and fin (p = 0.044) were found. There was no significant interaction between stroke rate and fin (p = 0.941). F values are presented in Table 5.3.4.

Chapter VI Discussion

In this study, stroke rate and fin length were evaluated in terms of their relationship with the kinematic measurement values obtained from the movement of the boat and body of the rower. For the majority of dependent variables, there was an expected significant main effect for stroke rate. Rowing at a faster stroke rate will produce greater fluctuations in the rower's COM, limb movements will be faster, and the potential for variability in the rowing stroke will be increased (Dawson et al., 1998). However, the results do not present a clear relationship between fin length and performance, nor between fin length and stability. Interpretation of the results is provided in more detail below.

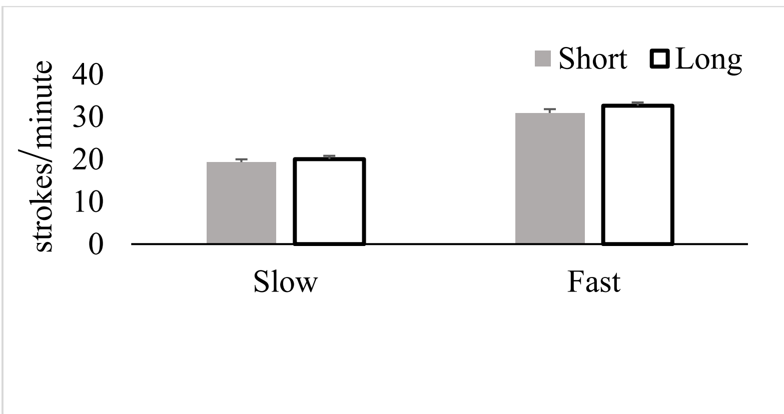
6.1 Velocity of the Boat

The participant was asked to maintain a stroke frequency of 18 for the slow condition and 30 for the fast condition; however, real-time stroke frequency data was not provided as the goal was to have the rower focusing on technique, rather than rate. Average stroke frequency for each trial was calculated from obtained acceleration data of the bow sensor. There was a main effect of stroke rate (Table 5.1.1), with velocity being significantly higher in fast stroke rate (0.736 m/s) than slow stroke rate, which would result in a 1:46 faster time over 2000 m. This result was expected as Martin & Bernfield (1980) found a significant positive relationship between stroke rate and average velocity.

There was a significant main effect of fin for stroke frequency (Table 5.1.1), which was unexpected. The average stroke frequency with short fin was 19.3 s/m for slow stroke rate and 30.9 s/m for fast stroke rate. The average stroke frequency with long fin was 20.1 s/m for slow stroke rate and 32.7 s/m for fast stroke rate (Figure 6.1). As the stroke frequency was significantly greater for the long fin, yet mean velocity was unchanged (Table 5.1), it can be concluded that the long fin did cause a noticeable increase in drag. At fast stroke rate, the difference in stroke frequency between fins increased. To overcome the exponential increase in drag as velocity increased (Eq. 1), the participant needed to increase stroke frequency with the long fin. This is in agreement with Bale et al. (2014), who found that an increased fin height results in significant increased propelled power by the knife fish while the total corresponding increase in velocity was small.

Figure 6.1

ANOVA result for stroke frequency



Note. Significant main effects for stroke rate ($p < 0.001$) and fin ($p = 0.001$) were found. There was no significant interaction between stroke rate and fin ($p = 0.076$). F values are presented in Table 5.1.

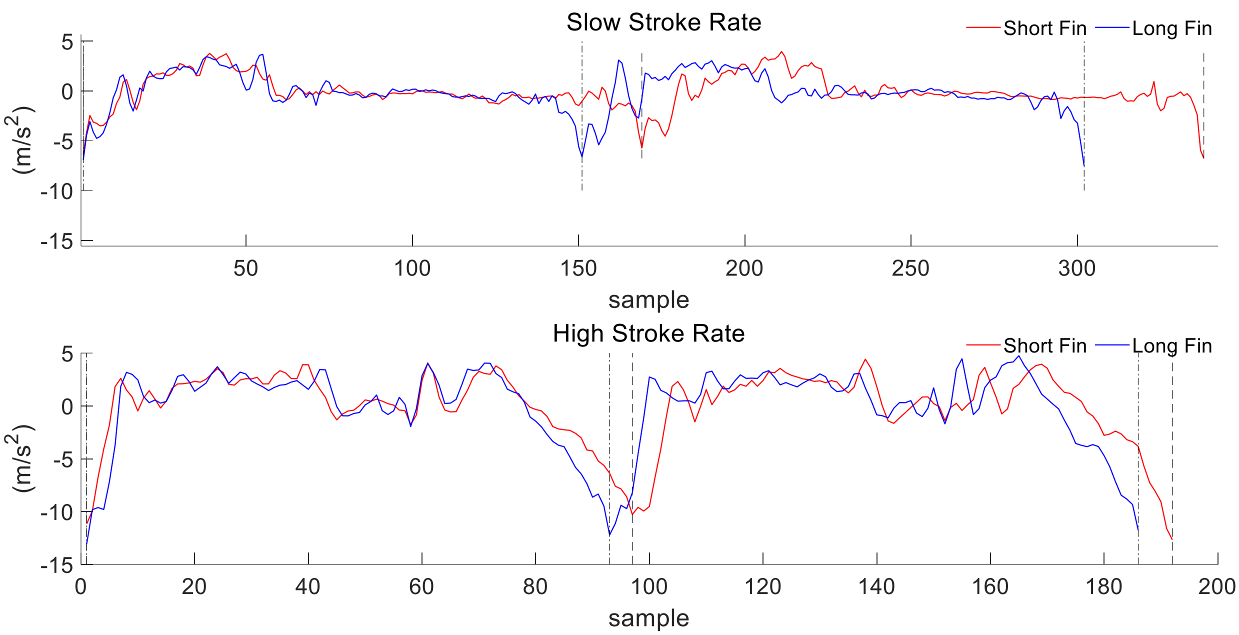
A significant main effect of fin for posterior peak acceleration (for bow sensor) suggested that the boat was presenting a greater deceleration (negative surge) with the long fin (Table 5.1.1, Figure 5.1.1). Range of velocity approached significance ($p = 0.094$), also suggesting that the long fin produced more drag as relatively greater change between maximum and minimum velocity (greater surge) was presented with long fin (Table 5.3). Essentially, rowing in the presence of a greater drag will be harder, but a higher maximum velocity (Table 5.1) suggested that the rower was able to exert greater force and reached a higher peak velocity with the long fin.

Anterior peak acceleration for the bow sensor (Table 5.2.1, Figure 5.2.1) approached a significant main effect for fin, with long fin 0.174 m/s^2 greater than short fin. These peaks for anterior acceleration were visually inspected to be at the beginning of the drive phase (Figure 6.1). This was immediately after the negative posterior peak microphase during the catch that was caused by the rower's change of direction momentum (Kleshnev, 2010). Tessendorf et al. (2011) suggested in order to perform a perfect stroke, rowers must be consistent during the drive phase and avoid jerky peaks in their force application. Kleshnev (2010) also suggested that a greater acceleration during the first microphase of the drive phase will result in a higher overall velocity (Figure 6.5). In other words, a good rowing technique starts with a strong pressure at the initial phase and must be kept consistent until the end of the drive phase to attain the highest overall velocity. The significantly greater AP range and AP SD values for the long fin suggest that within-stroke and between-stroke fluctuations were greater due to the increased drag of the long fin. To compensate, the rower was pulling harder at the catch and moving more rapidly during the recovery to maintain boat speed.

Although the mean velocity was not significant between the fins, there was a meaningful change that could make a difference in a race result. For example, the velocity was 0.111 m/s faster with long fin during the slow stroke rate which would result in a 20 seconds savings over 2000 m. The long fin during the high stroke rate was 0.141 m/s faster, which is 16 seconds faster over 2000 m. As the distance traveled in each trial was approximately 250 m, it is unknown if the higher stroke frequency used with the long fin would be sustainable for 2000 m. If it were, however, then the time savings observed in this study would be important during competition. Furthermore, it is possible that the inclusion of a larger participant pool would have produced statistical significance.

Figure 6.2

Raw AP Acceleration data of Bow Sensor from Two Random Stroke Cycles



Note. Two random strokes for each fin beginning at the catch are shown for slow stroke rate (top) and high stroke rate (bottom). The (-.) line illustrates the stroke starts for long fin and (--) illustrates the stroke starts for short fin. Greater anterior peaks for high stroke rate were found. Also, a greater acceleration with long fin for the anterior peak (positive value) was observed. In accordance with the results, a greater posterior peak (negative value) and AP range for high stroke rate and long fin were also visible in this figure.

6.2 Stability

6.2.1 Stroke rate

The anteroposterior range of motion (ROM) in rowing is constrained by the foot-stretcher location and the rower’s anthropometric measurements. The overall goal for a rower is to perform a long catch while maintaining balance. Changes in anteroposterior kinematic measurements of the stroke cycle microphases can make a noticeable change in the way the boat moves (Tessendorf et al, 2011). In this study, a significant main effect for stroke rate was found for the downward peak for bow sensor (Table 5.2.1). This result suggested that the rower was bouncing the bow (negative pitch) into the water more during the high stroke rate due to the trunk accelerating toward the bow in the drive phase (Table 5.3.4). Accordingly, if the rower could shorten the anteroposterior ROM at the end of the drive phase microphase (i.e., shorten the finish by maintaining an upward trunk position and/or by not fully extending the legs), they might be able to control this negative downward momentum. The non-significant finding for stroke rate on positive pitch (bow sensor upward peak), suggests that COM shift to the stern of the boat at the catch does not affect pitch to the same extent as the anterior COM shift at the finish of the stroke. Gravenhorst et al (2011) in a study of the correlation between stability and velocity reported that the boat with smaller pitch angular velocity was 7 seconds faster over 1000 m. From the results in this study, it is clear that increased stroke rate produced more boat velocity, but it also negatively affected the stability of the boat with respect to pitch/heave. Whether or not this can be minimized by altering the rowing stroke is an area for future research.

The dependent variables associated with boat roll are useful approximators of boat stability, with smaller values indicating greater stability. In this study the higher stroke rate resulted in significantly greater values for most of the measures associated with boat roll (Table 5.2.2). Cuijpers et al. (2017) suggested differences in amplitude and timing of force application during the drive phase changes the net torque around the system COM and that results in additional motions of the boat (e.g., surge, pitch, roll). At the higher stroke rate, the rower's arm movements (Tables 5.3.1 and 5.3.2) and trunk (Table 5.3.4) accelerated significantly faster. If the timing of the right and left arm movements were asynchronous, or the trunk shifted from the midline, then a lateral shift in the COM would cause the boat to roll. At a higher stroke rate, the same degree of movement error would have a greater negative effect on boat roll because the greater acceleration of the body segments would create more linear and/or angular momentum from the midline of the boat.

6.2.2 Fin

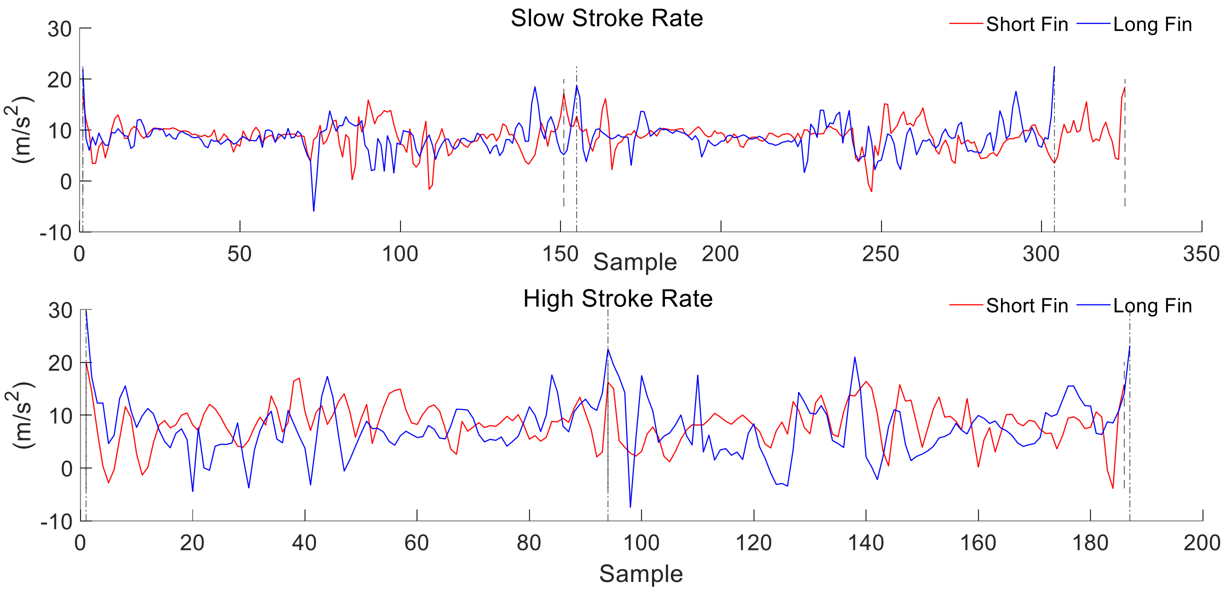
The confounding factor in this study is that the stroke (FREQUENCY) between fins were different. It is difficult to determine if the kinematic differences were due to the higher stroke frequencies of the long fin, or if the long fin enabled the participant to row quicker due to increased stability of the boat. During high stroke rate, vertical range with the long fin was 14.28 m/s^2 greater for right wrist, and 13.75 m/s^2 greater for left wrist compared to the short fin results (Figure 5.3.3). At 30 SPM, the hands must travel the same distance and perform the same pattern but almost 30% faster than at 20 SPM. Kleshnev (2010) conducted a study on microphases of stroke cycles between Olympic champions and rowers who were in the finals of the world championship but could not achieve successful performance on the water although they had a very good physiological work capacity (Figure 6.5). Kleshnev (2010) reported the first crew performed with a higher handle and trunk velocity as well as producing a much quicker force application during the initial drive phase microphase, resulting in greater overall boat acceleration (Figure 6.5). In this study, a greater initial microphase of the drive phase was found for anterior peak for the wrists (Figures 5.3.1 and 5.3.5) and a greater anterior peak for the boat with the long fin (Figure 5.2.2).

While the participant in this study was able to row at a higher frequency with the long fin and produce a modest increase in boat velocity, boat stability and rower kinematic results are difficult to interpret. Downward peak values for the right oar lock were higher for the long fin for both stroke rates, but not significantly so (Figure 5.2.5). Conversely, upward SD peak for the right oarlock sensor suggests a greater fluctuation with long fin during the slow stroke rate but less fluctuation with long fin during the high stroke rate (Figure 5.2.6). Similarly, the upward peak for right oarlock sensor suggests that the boat was rolling with proportionally greater acceleration with long fin at the slow stroke rate (Figure 5.2.5). These results coincide with greater upward peak with the long fin for the wrist sensors. In a visual inspection of the microphases, these peaks were during the catch (Figure 6.3, Figure 6.4). Thus, this inspection suggests the rower was performing the catch with a higher speed. Greater anterior peaks were found for the right (2.25 m/s^2) and left (1.16 m/s^2) wrist sensors with the long fin at high stroke rate (Figure 5.3.1, Figure 5.3.5). These peaks generally occurred during the microphase of the drive immediately following the catch. It is possible that the participant was able to move his arms with greater acceleration around the catch phase because the boat was more stable with the long fin.

None of the variables for the head were significantly different between fins. For the lower back, only anterior SD peak was significantly different between fins. As 12 of the 13 variables between the two sensors were not different, it seems that changes in arm movements were responsible for the higher frequencies observed with the long fin. As the trunk and legs have more mass than the arms, the participant was likely able to reduce physiological workload by moving the arms more quickly to compensate for the increased drag of the long fin. Further research with improved analysis techniques (for example, calculating COM displacement and velocity) may provide greater insights to the motor control strategies rowers use under different drag factors and at different stroke rates.

Figure 6.3

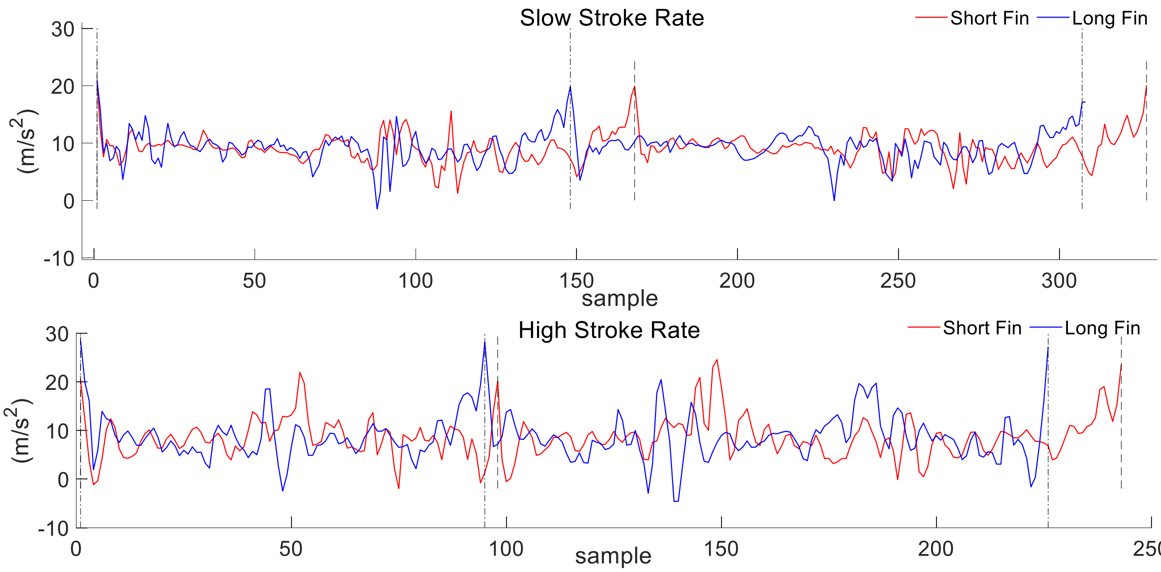
Two Random Stroke Cycles from Raw Signal for Vertical Acceleration for Right Wrist Sensor



Note. Two random strokes for each fin beginning at the catch are shown for slow stroke rate (top) and high stroke rate (bottom). The (-.) line illustrates the stroke starts for long fin and (--) illustrates the stroke starts for short fin. Greater vertical peaks for high stroke rate were found. Also, a greater acceleration with long fin for the upward peak (positive value) was observed. In accordance with the results, a greater vertical range and vertical SD for high stroke rate and long fin were also visible in this figure.

Figure 6.4

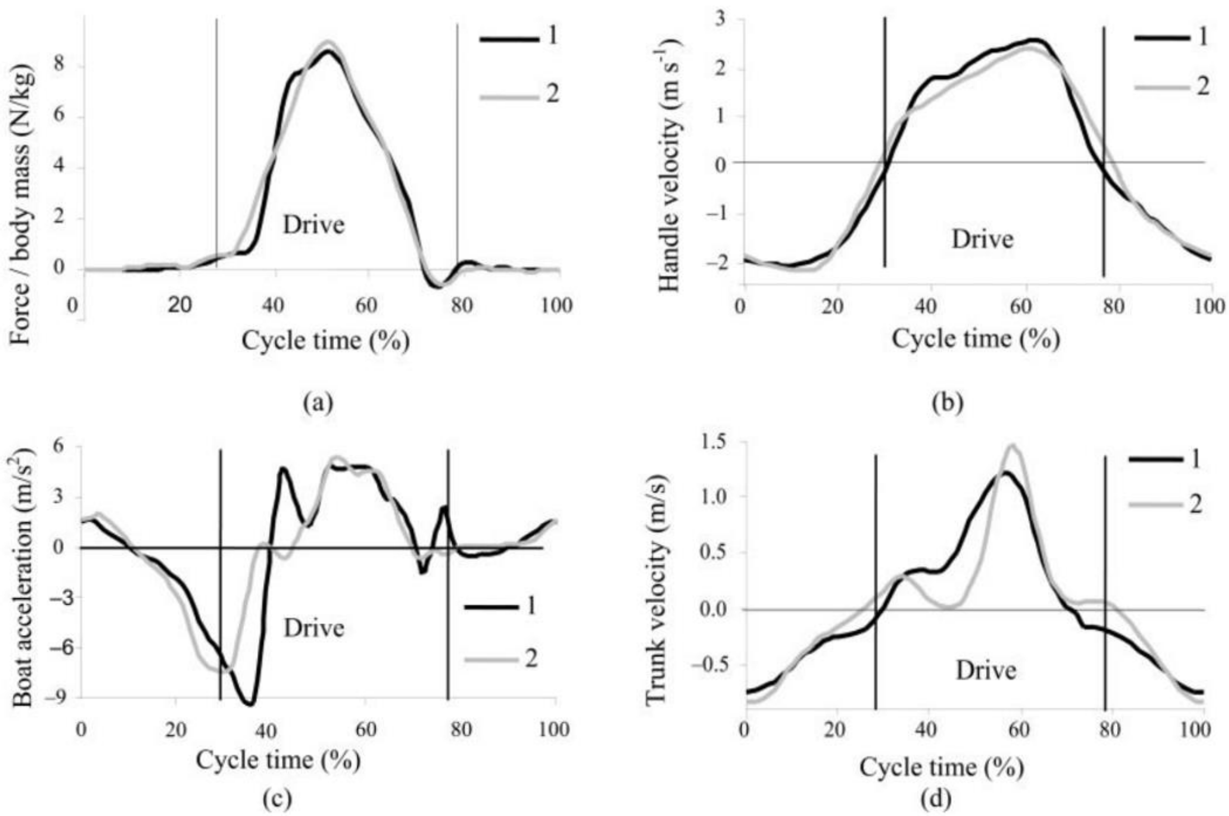
Two Random Stroke Cycles from Raw Signal for Vertical Acceleration for Left Wrist Sensor



Note. Two random strokes for each fin beginning at the catch are shown for slow stroke rate (top) and high stroke rate (bottom). The (-.) line illustrates the stroke starts for long fin and (--) illustrates the stroke starts for short fin. Greater vertical peaks for high stroke rate were found. Also, a greater acceleration with long fin for the upward peak (positive value) was observed. In accordance with the results, a greater vertical SD for high stroke rate and long fin were also visible in this figure.

Figure 6.5

Acceleration Microphases of the Drive Phase for Two Examples of Rowing Technique



Note. Line number one illustrates the first crew's curve (Olympic champions). Line number two illustrates second crew's curve (those athletes were in world championships final several times). The vertical black lines are separating the drive phase from the recovery phase. This data was collected in a stroke rate close to 32 for both crews. First crew reached 70 per cent of their maximal force at 23.1 per cent of the drive phase while second crew reached their 70 per cent at 29 per cent of the drive phase (a). A greater rise in handle velocity (b) and trunk velocity (d) for first crew were also coincide with the rapid rise in force velocity (a). a deeper and later negative peak (c) was observed at the catch for the first crew (1.1 m/s^2 greater than second crew) but a greater first peak was also observed for the first crew (2.4 m/s^2 greater than second crew). This figure is adopted from Kleshnev (2010). Reprinted with permission from Sage Publishing.

6.3 Considerations and Limitations

I faced several limitations during this study that must be addressed. COVID-19 and safety protocols delayed data collection until late in the fall. With cold temperatures, the participant's rowing performance may have been negatively affected. Furthermore, this study was supposed to recruit at least 6 participants, but because of the safety protocol, I had to do repeated trials for one participant. Future studies can present a stronger result if data collection of larger groups of rowers (e.g., rowers with different skill levels) is conducted.

Additionally, my experimental fin designs were not perfect as they were not industrially manufactured. They were mounted over the existing fin, likely causing more resistance than a narrow profile fin design would.

I used Mbientlab MetaMotionRL model IMU sensors and they could only record 500,000 samples approximately (i.e., 8 MB internal memory). As I was recording both acceleration and gyroscope, I was able to record approximately 250,000 samples each. Considering the data collection was taking place in roughly 75 minutes, I lowered my sampling frequency to 50 Hz. Thus, that gave me a window of about 80 minutes to record the kinematics of the rowing platform. Otherwise, I would prefer to use a sampling frequency of 100-200 Hz to obtain a clearer resolution (Bosch et al, 2015; Dubus, 2012). Furthermore, the GPS data were collected at 1 Hz, which provided poor resolution for within-stroke fluctuations of velocity.

The participant did not use a stroke coach device and he was asked to focus on the technical aspects while he tried to maintain 20 SPM for slow stroke rate and 30 SPM for fast stroke rate by his feeling.

6.3.1 Challenges of IMU Usage

There were a number of errors and challenges that occurred with IMU sensors. First, frequency sampling was not consistent between the sensors, despite all sensors set to record at 50 Hz. Thus, syncing trial starts based on the timeline from the bow sensor resulted in inaccurate data from a number of other sensors. This problem required me to select the start times for each sensor by individual inspection of the raw timeseries data.

The data logging function through the MetaBase software via smartphone or using the raspberry p was problematic, as only 2 sensors could be set as a functioning group, requiring me to start groups of sensors separately. Downloading the collected data from each IMU sensor (32 megabytes of internal memory) took approximately 20 minutes. Also, four sensors lost the gyroscope data during the downloading session.

6.4 Future Directions of the Research

It is recommended to use a stroke monitoring device for future studies to eliminate the confounding factor in this study. By keeping the stroke rate fixed between fin conditions, future researchers may be able to focus on how changes in rower COM and power output are affected.

Developing an algorithm for integration of the values obtained from IMU sensors (e.g., velocity, distance, roll angle) and analyzing them in microphase accuracy would be beneficial to rowing professionals. For example, the acceleration of pressing the foot-stretcher pattern or the correlation of acceleration in timing at the catch versus the boat displacement may help to improve performance. Understanding the trade-off between stability and velocity would introduce a rapid approach to develop stability skills for amateur rowers. For example, amateur rowers might prefer a more stable platform despite increasing hull drag. Thus, it becomes important to investigate how the individual features (e.g., anthropometric measurements, gender, etc.) of the multiple rowers and fin length will affect stability and velocity.

Also, researchers could study the correlation of kinematic measurement values utilizing IMU sensors (e.g., acceleration, rotation, velocity, and the distance that the boat travels, movement of the rowers, etc.). The association of kinetic and kinematic measurements obtained using various instruments in a rowing platform may reveal the implication of stroke microphases more comprehensively. Furthermore, development of a robust system to monitor the efficacy of the technique for daily use in rowers' real life (Anderson et al, 2005) will require more complex data analysis algorithms than the ones used in this study.

6.5 Summary

In a rowing competition it is important to reach high velocity and maintain this velocity for two kilometers to achieve successful results. However, the key is to reach that high velocity in the most efficient manner and with the least amount of effort (Baudouin & Hawkins, 2002). As the majority of rowing research has used on-land ergometers (Soper & Hume, 2004), IMU sensors were used in this study to measure acceleration and angular velocity data from one participant in a natural rowing environment.

A fast stroke rate significantly increased velocity and created more fluctuations in boat stability and the movement patterns of the rower. In rowing, the stability of the boat due to the movement of COM of the rowers decreases during the fast stroke rate (in the rowing competition environment). This is in contrast with other sports such as cycling where the bicycle becomes more stable as the self-correcting gyroscopic effect of the spinning wheels increases with speed.

A longer fin – which was hypothesized to increase stability and thereby improve performance – created more drag and did not clearly affect boat stability. With the longer fin, the participant rowed at a faster frequency that was achieved primarily by increasing arm speed. A meaningful (but not significant) increase in velocity with the long fin was most likely due to the faster stroke frequency. Future research, using more complex data analysis algorithms should be able to provide additional insights to the relationships between performance, stability, stroke rate, and boat design.

References

Affeld, K., Schichl, K., & Ziemann, A. (1993). Assessment of rowing efficiency. *International Journal of Sports Medicine*, 14(S 1), S39-S41.

Alamian, R., Shafaghat, R., & Safaei, M. R. (2019). Multi-objective optimization of a pitch point absorber wave energy converter. *Water*, 11(5), 969.

Anderson, R., Harrison, A., & Lyons, G. M. (2005). Rowing: Accelerometry-based feedback-can it improve movement consistency and performance in Rowing?. *Sports biomechanics*, 4(2), 179-195.

Bale, R., Shirgaonkar, A. A., Neveln, I. D., Bhalla, A. P. S., MacIver, M. A., & Patankar, N. A. (2014). Separability of drag and thrust in undulatory animals and machines. *Scientific Reports*, 4(1), 1-11.

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

Baudouin, A. G., & Hawkins, D. A. (2003). Biomechanical analysis of on-water rowing performance. *Medicine & Science in Sports & Exercise*, 35(5), S62.

Baudouin, A., & Hawkins, D. (2004). Investigation of biomechanical factors affecting rowing performance. *Journal of biomechanics,* 37(7), 969-976.

Bosch, S., Shoaib, M., Geerlings, S., Buit, L., Meratnia, N., & Havinga, P. (2015, September). Analysis of indoor rowing motion using wearable inertial sensors. *Proceedings of the 10th EAI International Conference on Body Area Networks* (pp. 233-239).

Buckeridge, E., Hislop, S., Bull, A., & McGregor, A. (2012). Kinematic asymmetries of the lower limbs during ergometer rowing. *Medicine & Science in Sports & Exercise,* 44(11), 2147-2153.

Buckmann, J. G., & Harris, S. D. (2014). An experimental determination of the drag coefficient of a Mens 8+ racing shell. *SpringerPlus*, 3(1), 1-7.

Byrne, C., Twist, C., & Eston, R. (2004). Neuromuscular function after exercise-induced muscle damage. *Sports Medicine,* 34(1), 49-69.

Chassignet, E. P., Cenedese, C., & Verron, J. (Eds.). (2012). *Buoyancy-driven flows*. Cambridge University Press.

Cheung, K., Hume, P. A., & Maxwell, L. (2003). Delayed onset muscle soreness. *Sports Medicine*, 33(2), 145-164.

Chudecka, M., Lubkowska, A., Leźnicka, K., & Krupecki, K. (2015). The use of thermal imaging in the evaluation of the symmetry of muscle activity in various types of exercises (symmetrical and asymmetrical). *Journal of Human Kinetics,* 49(1), 141-147.

Cooper, J. M. (1995). Biomechanics of human movement. McGraw-Hill Humanities, Social Sciences & World Languages.

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?. *Scandinavian journal of medicine & science in sports*, 27(12), 1697-1704.

Dawson, R. G., Lockwood, R. J., Wilson, J. D., & Freeman, G. (1998). The rowing cycle: Sources of variance and invariance in ergometer and on-the-water performance. *Journal of motor behavior*, 30(1), 33-43.

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

Day, A. H., Campbell, I., Clelland, D., & Cichowicz, J. (2011a). An experimental study of unsteady hydrodynamics of a single scull. *Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment*, 225(3), 282-294.

DeMerchant, Ch. (n.d.). Rowing and Rowboat Terminology. (https://www.christinedemerchant.com/terminology-rowing.html#:~:text=racing%20shells%20are%20very%20long,the%20hull%2C%20and%20sliding%20seats.&text=This%20makes%20the%20racing%20shell%20fast%20and%20very%20unstable.)

Dodd, C. (1987). *Henley Royal Regatta.* Trafalgar Square Publishing

Dodd, C. (1992). *The story of world rowing*. (S. Paul, Ed.) Random House UK.

Dubus, G. (2012). Evaluation of four models for the sonification of elite rowing. *Journal on Multimodal User Interfaces*, 5(3), 143-156.

Dudhia, A., (2000). Basic physics of rowing. http://eodg.atm.ox.ac.uk/user/dudhia/rowing/physics/basics.html

EDU, H. Harvard Natural Sciences Lecture Demonstrations.

Formaggia, L., Mola, A., Parolini, N., & Pischiutta, M. (2010). A three-dimensional model for the dynamics and hydrodynamics of rowing boats. *Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology,* 224(1), 51-61.

France, W. N., Levadou, M., Treakle, T. W., Paulling, J. R., Michel, R. K., & Moore, C. (2003). An investigation of head-sea parametric rolling and its influence on container lashing systems. *Marine Technology and SNAME news*, 40(01), 1-19.

Gayer, C. D. (1994). *Physiological discriminators of rowing performance in male, club rowers* (Doctoral dissertation, Washington State University).

Gladstone, B. (2021). *Advanced cruising & seamanship: The official manual for the American sailing association 106 advanced cruising course*. American Sailing Association.

Gravenhorst, F., Tessendorf, B., Arnrich, B., & Tröster, G. (2011, September). Analyzing rowing crews in different rowing boats based on angular velocity measurements with gyroscopes. In *International Symposium on Computer Science in Sport (IACSS 2011)*.

Groh, B. H., Reinfelder, S. J., Streicher, M. N., Taraben, A., & Eskofier, B. M. (2014, April). Movement prediction in rowing using a dynamic time warping based stroke detection. *Institute of Electrical and Electronics Engineers 2014 Ninth International Conference on Intelligent Sensors, Sensor Networks and Information Processing (ISSNIP)* (pp. 1-6).

Guisado, R. (2011). *Art of Surfing: A Training Manual for the Developing and Competitive Surfer*. Rowman & Littlefield.

Halladay, E. (1987). Of pride and prejudice: The amateur question in english nineteenth-century rowing. *The International Journal of the History of Sport*, 4(1), 39-55.

Hay, J. (1978). *The Biomechanics of Sports Techniques*. Prentice-Hall.

Hay, J. G. (1993). Track and field: running. *The Biomechanics of Sports Techniques. Fourth Edition.* (396-411). Upper Saddle River: Prentice Hall.

Heiman, S. E., Sanchez, D., & Tuleja, T. (1998). *The New Strategic Selling*. Nightingale-Conant Corporation.

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

Ibrahim, R. A., & Grace, I. M. (2010). Modeling of ship roll dynamics and its coupling with heave and pitch. *Mathematical Problems in Engineering*, 2010.

Kang, D., & Hasegawa, K. (2007). Prediction method of hydrodynamic forces acting on the hull of a blunt-body ship in the even keel condition. *Journal of Marine Science and Technology,* 12(1), 1-14.

Kleshnev, V. (2010). Boat acceleration, temporal structure of the stroke cycle, and effectiveness in rowing. *Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology*, 224(1), 63-74.

Kleshnev, V. (2020). *Biomechanics of Rowing: A unique insight into the technical and tactical aspects of elite rowing.* The Crowood Press.

Knudson, D. (1991). The tennis topspin forehand drive: Technique changes and critical elements. *Strategies,* 5(1), 19-22.

Knudson, D. (1993). Biomechanics of the basketball jump shot—Six key teaching points. *Journal of Physical Education, Recreation & Dance,* 64(2), 67-73.

Knudson, D. (2003). *Applying Biomechanics in Physical Education. In Fundamentals of Biomechanics* (pp. 213-223). Springer, Boston, MA.

Knudson, D., & Morrison, C. (1996). An integrated qualitative analysis of overarm throwing. *Journal of Physical Education, Recreation & Dance,* 67(6), 31-36.

Kok, M., Hol, J. D., & Schön, T. B. (2017). Using inertial sensors for position and orientation estimation. *arXiv preprint arXiv:1704.06053*.

Lewandowski, E. M. (2004). *The dynamics of marine craft: maneuvering and seakeeping* (Vol. 22). World Scientific.

Martin, T. P., & Bernfield, J. S. (1980). Effect of stroke rate on velocity of a rowing shell. *Medicine and science in sports and exercise*, 12(4), 250-256.

MathWorks, *MATLAB*. The Mathworks Inc., version R2021a.

McGinnis, P. M. (2013). *Biomechanics of sport and exercise*. Human Kinetics.

McNeely, E. (2009, February 19) *Balance and stability for rowing*. Peak centre. (https://peakcentre.wordpress.com/2009/02/03/balance-and-stability-for-rowing/#:~:text=Rowers%20require%20static%20balance%20when,quickly%20to%20accommodate%20the%20conditions.&text=Better%20body%20control%2C%20dynamic%20balance,potentially%20be%20involved%20in%20balance.)

Minorsky, N. (1922). Directional stability of automatically steered bodies. *Journal of the American Society for Naval Engineers,* 34(2), 280-309.

Misra, S. C. (2015). *Design principles of ships and marine structures*. CRC Press.

Newman, J. N. (2018). *Marine hydrodynamics* (p. 448). The MIT Press.

Nilsen, T. H., Notle, V., Armstrong. M. (2002). *Be a coach: Handbook.* FISA The International Rowing Federation.

Nolte, V. (2011). *Rowing Faster 2nd Edition.* Human Kinetics.

Nolte, V., & McLaughlin, S. (2005). The balance of crew rowing boats. *Malaysian Journal of Sport Science and Recreation,* 1(1), 51-64.

Perez, T. (2005). Control System Design for Autopilots with Rudder Roll Stabilisation. *Ship Motion Control: Course Keeping and Roll Stabilisation Using Rudder and Fins*, 221-250.

Perez, T., & Blanke, M. (2010, September). Ship roll motion control. *Proc. of 8th IFAC conference on control applications in marine systems* (pp. 1-12). *Elsevier*.

Perez, T., & Blanke, M. (2012). Ship roll damping control. *Annual Reviews in Control,* 36(1), 129-147.

Richer, S. D., Nolte, V. W., Bechard, D. J., & Belfry, G. R. (2016). Effects of novel supramaximal interval training versus continuous training on performance in preconditioned collegiate, national, and international class rowers. *Journal of strength and conditioning research*, 30(6), 1752-1762.

Sanderson, B. & Martindale, W. (1986). Towards optimizing rowing technique. *Medicine and Science in Sports and Exercise*, 18(4), 454-468.

Schneider, E., Hauser, M. (1981). Biomechanical analysis of performance in rowing. *Biomechanics VII-B*, 430–435.

Secher, N.H., (1975). Isometric rowing strength of experienced and inexperienced oarsmen. *Medicine and Science in Sports* 7(4), 280-283.

Senator, M., (1981). Why sliding seats and short stroke intervals are used for racing shells. *Journal of Biomedical Engineering* 103, 151-59.

Serveto, S., Barré, S., Kobus, J. M., & Mariot, J. P. (2009). A model of oar–boat–rower system to optimise rowing performance. *Computer Methods in Biomechanics and Biomedical Engineering,* 12(S1), 229-230.

Sforza, C., Casiraghi, E., Lovecchio, N., Galante, D., & Ferrario, V. F. (2012). A three-dimensional study of body motion during ergometer rowing. *Institutional Research Information System,* 22-28

Sliasas, A., & Tullis, S. (2011). Modelling the effect of oar shaft bending during the rowing stroke. *Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology*, 225(4), 265-270.

Smith, R. M., & Loschner, C. (2002). Biomechanics feedback for rowing. *Journal of sports sciences*, 20(10), 783-791.

Smith, R. M., & Spinks, W. L. (1995). Discriminant analysis of biomechanical differences between novice, good and elite rowers. *Journal of Sports Sciences*, 13(5), 377-385.

Smoljanović, T., Bohaček, I., Hannafin, J., Bay Nielsen, H., Hren, D., & Bojanić, I. (2018). Sport injuries in international masters rowers: a crosssectional study. *Croatian Medical Journal*, 59(5), 258-266.

Smoljanovic, T., Bojanic, I., Hannafin, J. A., Hren, D., Delimar, D., & Pecina, M. (2009). Traumatic and overuse injuries among international elite junior rowers. *The American Journal of Sports Medicine*, 37(6), 1193-1199.

Soper, C., & Hume, P. A. (2004). Towards an ideal rowing technique for performance. *Sports Medicine,* 34(12), 825-848.

Sponberg, E. W. (2011). The design ratios. *Sponberg Yacht Design Inc*.

Spyrou, K. J. (2000). The nonlinear dynamics of ships in broaching. *Marie Curie Fellowships Annals*, 1, 1-7.

Tessendorf, B., Gravenhorst, F., Arnrich, B., & Tröster, G. (2011, December). An imu-based sensor network to continuously monitor rowing technique on the water. *Institute of Electrical and Electronics Engineers, 2011 seventh international conference on intelligent sensors, sensor networks and information processing* (pp. 253-258). *Institute of Electrical and Electronics Engineers.*

Turner, A. (Ed.). (2018) *handbook of strength and conditioning: Sport-specific programing for high performance.* Routledge

Wagner, J., Bartmus, U. and de MarŠes, H. (1993). Three-axes gyro system quantifying the speciWc balance of rowing. *International Journal of Sports Medicine,* 14(S1), S35-S38

Webb, P. W. (2005). Stability and maneuverability. *Fish physiology*, 23, 281-332.

Wigglesworth, N. (2013). *The social history of English rowing.* Routledge.

Wilson, F., Gissane, C., Gormley, J., & Simms, C. (2010). A 12-month prospective cohort study of injury in international rowers. *British Journal of Sports Medicine*, 44(3), 207-214.

Zatsiorsky, V. M., & Yakunin, N. (1991). Mechanics and biomechanics of rowing: A review. *International Journal of Sport Biomechanics,* 7(3), 229–281

Appendix A: Pre-Approved Permission SAGE publications

SAGE Publishing

Disciplines Products Resources About

Search: keyword, title, author, ISBN

0

Due to global supply chain disruptions, we recommend ordering print titles early.

Rights and Permissions

- Books Permissions
- Journals Permissions
  - Process for Requesting Permission
  - Pre-Approved Permission Requests
  - Guidelines for SAGE Authors
  - Reusing Open Access and SAGE Choice Content
  - Posting to an Institutional Repository (Gold OA)
  - Posting to an Institutional Repository (Green OA)
  - License Information for CHORUS
- Accessibility
- Contact Us

Pre-Approved Permission Requests

SAGE provides gratis non-exclusive permission for limited re-uses of its content without the need for a formal request, as indicated below. This approval excludes any third-party content which requires permission from a separate copyright holder.

When re-using content under these terms, you must provide a full citation to the original source of the SAGE material wherever such material appears in your publication.

If you determine that your re-use does require permission, please see Process for Requesting Permission for further instruction.

Journals Exceptions

Information on this page does not apply to content sourced from the following journals:

- *Bulletin of the Atomic Scientists*
- *Contexts*
- *Diogenes*
- *Environment and Urbanization*
- *European Journal of Archaeology*
- *Journal of Asian and African Studies*
- *Journal of Fire Protection Engineering*
- *Journal of Perioperative Practice*
- *Language and Linguistics*
- *Index on Censorship*
- *International Journal of Comparative Sociology*
- *International Review of Administrative Sciences*
- *Medical Decision Making*
- *Race and Class*
- *Society and Mental Health*
- *Transcultural Psychiatry*

Gold Open Access and SAGE Choice

If you wish to reuse an Open Access article under a Creative Commons License (as indicated on the article), visit our page on Reusing Open Access and SAGE Choice Content for more information.

Article Sharing

SAGE Journals article access sharing lets you share a read-only version of an article with your friends and colleagues or on social media. For further information, see SAGE Journals Article Sharing.

Dissertation/Thesis Reuse

You may reuse up to three (3) figures/tables or a total of up to 400 words from a SAGE journal in your dissertation/thesis, provided the work will not be hosted on a commercial platform (such as ProQuest).

If your re-use exceeds this allowance, or if you will be posting your work on a commercial platform, you will need to request permission for the reuse.