ASSESSMENT OF A SPRINT KAYAKER'S KINETIC ASYMMETRIES AT INCREASING STROKE RATES

by

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Abstract

Kinetic movement asymmetries are known to affect factors of performance, increase the likelihood of injury, and to decrease with increased cadences. The two aims of this study were to characterize the forces and moments at the kayak ergometer paddle left and right footboard, and seat, and determine if stroke rate effects asymmetry indexes (ASI) in the kayak ergometer footboards and seat. A significant main effect of stroke rate was found on footboard mediolateral total stroke cycle impulse (TSI) ASI ($p<0.005$) where asymmetry index increased with stroke rate, footboard anteroposterior TSI ASI ($p<0.005$) where an inverted U-shaped relationship was found with stroke rate, and footboard roll total stroke cycle angular impulse (TSAI) ASI ($p<0.001$) where an inverted U-shaped relationship was found with stroke rate, and seat mediolateral TSI ASI ($p<0.05$) where it decreased with stroke rate. The results of this study show that footboard and seat lateral forces counteract each other.

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List of Abbreviations and Symbols Used

ANOVA -	analysis of variance	mph	miles per hour
ASI	asymmetry index	p	momentum
ax_x	x-axis center of pressure location	RM	repeated measures
ay_x	y-axis center of pressure location	SD	standard deviation
az0	distance from center of load cell to the top of the athlete contact point	s	second
cm	centimeter	spm	strokes per minute
CI	confidence interval	TSI	total stroke cycle impulse
COP	center of pressure	TSAI	total stroke cycle angular impulse
d	distance	v	velocity
dax_x	distance from origin, along the x-axis	vs.	versus
day_x	distance from origin, along the y-axis	W	work
F_x	Force	α	alpha
Hz	Hertz	$\Delta\ \theta$	angular distance
J	impulse	ΔJ	angular impulse
KE	kinetic energy	Δ	change
kg	kilogram	χ	chi
N	Newton	$^\circ$	degree
Nm	Newton meter	ε	epsilon
Ns	Newton second	η	eta
M	mean	•	multiply
m	meter	$\pm$	plus or minus
M_x	moment	*	significance
min	minute	τ	torque

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Chapter 1: Introduction

Sprint kayaking is an Olympic sport that requires high precision movements and time-specific force application. Coordinated movements from the upper and lower body are required when an athlete draws their paddle through the water and transfers force into their boat through the connection point at the footboard and seat (1,2). Kayak athlete performance has been measured and improved using kinematic (2–7) and kinetic (5,8–13) research, where small changes in technique make positive differences in performance. However, much of the present literature has exclusively measured movements in the upper body.

Cyclical force analysis is commonly used in kayaking to determine measures of performance. The ultimate goal of sprint kayaking is to have the highest average velocity in a race. Therefore, velocity is used as a performance measure. Average boat velocity is a resultant of the displacement per stroke and the stroke time (14), where the displacement per stroke can be affected by the propulsive forces generated by the kayaker. The measurement of these forces can be used by coaches and individuals working directly with athletes to help better their performances and prevent injuries.

In kayaking, ergometers are used for research, training, and performance testing. In a research setting, ergometers are commonly used to circumvent issues surrounding environment (i.e., waves, heat, and wind) and the limitations posed by technology (i.e., lack of wireless equipment). They can provide meaningful information that is otherwise hard to obtain in on-water settings. This information includes cyclical force and moment production and kinematic waveforms, in addition to physiological measures.

To date, the kayak paddle force profile has been studied, where the forces at the seat and footboard are not well understood. In sprint kayaking, the upper body is the main contributor to force production (1,15); however, mean kayak speed decreases by 16 % and mean paddle force decreases by 21 % when lower body movement is constrained (16). Therefore, the lower body forces should also be considered when assessing measures of performance.

To this authors knowledge, forces in the kayak footboard and seat have only been measured in the anteroposterior axis. In other sports (i.e., running), the proportion of horizontal force to the resultant force has been shown to be a predictor of running performance (17), which is likely applicable when assessing kayaking performance. As well, rotational motion (yaw) around the vertical axis is known to increase the drag factor in kayaking (9). The measurement of lateral and vertical forces and moments around the anteroposterior and vertical axis could provide new predictors of performance and, therefore, should be studied.

Kinetic asymmetries are not always perceivable by coaches and trainers. Understanding the presence and level of an asymmetry can assist in the improvement of performance and decrease the incidence of injury in athletes. Asymmetrical movements have been studied in sports, such as running, swimming, cycling, and rowing and are often used to improve performance and decrease the likelihood of injury (18–24). For example, the measurement of asymmetrical knee moments can be used to correct gait asymmetries (24).

In a performance analysis context, it is important to understand an athlete's level of asymmetry (i.e., the magnitude of difference between their left and right sides) to make corrections to their training program. The level of asymmetry is often measured by calculating an asymmetry index (ASI). The measurement of ASI can be used to educate coaches and trainers on an individual's predisposition to injuries, strength imbalances, and motor programs. The measurement of ASIs can be used to prevent injuries through strength training programs (25), and the quantification and identification of differences in strength (i.e., stronger side, percent difference between sides, etc.). As well, the measurement of asymmetries can be used to improve performance through the delivery of technical feedback to optimize performance.

Kayakers' lower body force and moment asymmetries have not yet been studied in any plane, where ASIs could possibly be influenced by the stroke rate. In rowing, it has been shown that higher stroke rates result in lower foot stretcher and handle force asymmetries (19,26,27). Runners and cyclists have also shown to be more symmetrical at higher velocities, which are often achieved by increasing cadence (24,28–30). Therefore, the purpose of this study is to determine if stroke rate influences the level of asymmetry on a kayak ergometer, by calculating ASI and to report kayaking footboard and seat forces and moments in three planes (x, y, & z). It is hypothesized that as kayaking stroke rate increases on an ergometer, the ASI between left and right paddle, footboard, and seat forces will decrease.

Chapter 2: Review of Kayaking

Kayaking is an Olympic level sport requiring athletes of high calibre to compete. The sport was formalized as an Olympic sport in 1936 for men, and for women in 1948 (31). The sport has since advanced through the introduction of new equipment and new paddling techniques (32). These changes were often implemented by small groups and then studied using kinetic, kinematic, and anthropometric methods to determine these measures' effects on kayaking performances (33). The introduction of a carbon fibre boat and a carbon fibre wing-shaped paddle were some of the greatest advancements in kayaking and have now been thoroughly studied (33,34). More recently, an emphasis on individual performance factors has been the focus of sport science (i.e., net paddle force production) (1,35–39).

Kayakers train at different intensities, depending on the focus of their workout. They train and race at stroke rates ranging from 60 spm to 140 spm or higher (40). Generally, athletes in single kayaks will paddle at 60 – 80 spm for a steady state pace and 110 - 140 spm or higher when racing. This is dependent on their age and level of competition. These athletes will spend varying amounts of time within 60 spm to 140 spm during their average week, depending on the coach and the specific training block.

Athletes spend most of the warmer season training on the water in racing kayaks, with a mix of cross training and strength training. However, in climates where the bodies of water freeze during cold seasons or if the weather becomes too cold to safely train outdoors, athletes will train on kayak and rowing ergometers. Anecdotally, athletes have discussed that kayak ergometers are a good substitute for on-water kayaking when the latter is not available, but that high stroke rates are harder to achieve due to the recoil of the rope not being fast enough.

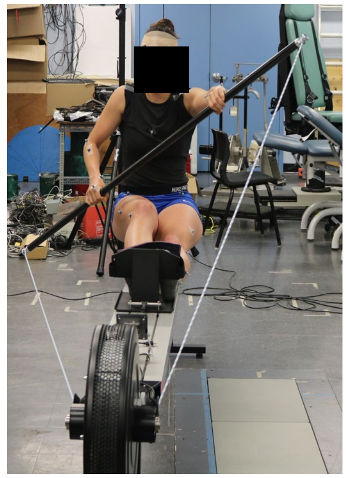

Figure 1. An example of an athlete on a kayak ergometer. The ergometer consists of a footboard, seat, and carbon fibre paddle shaft attached to a flywheel.

2.1 Kayak Ergometers

The intention of an ergometers are design is to mimic the physiological and mechanical stresses experienced in competitive settings (Figure 1) (41). A typical kayak ergometer consists of a footboard and a seat mounted in a fixed position, and a paddle shaft connected to a flywheel (Figure 2). The ergometer paddle is generally made of a carbon fibre shaft connected to a flywheel via a recoiling rope pulley system. Boat and ergometer footboards have foot straps that help the athletes secure their feet in place. The foot straps on ergometers and in boats are often made of a strong fabric, that allows the athlete to transfer forces directly from their lower body to the boat through both push and pull motions.

2.2 Stroke Cycle Kinematics

Traditionally, paddle movement is used to characterize a stroke cycle. A stroke cycle consists of two strokes, one left and one right. The kayak stroke cycle starts when the tip of the blade enters the water, called the catch phase/position (Figure 3) (1,42). The catch phase occurs when the paddler rotates their torso with an extended arm towards the bow (front of the boat). As the blade is pulled through the water, the ipsilateral knee is fully extended, while the foot pushes into the footboard. Conversely, the contralateral foot pulls on the footboard, while the contralateral knee bends to assist with the pulling motion. This pushing and pulling motion of the feet causes a moment along the vertical axis of the footboard.

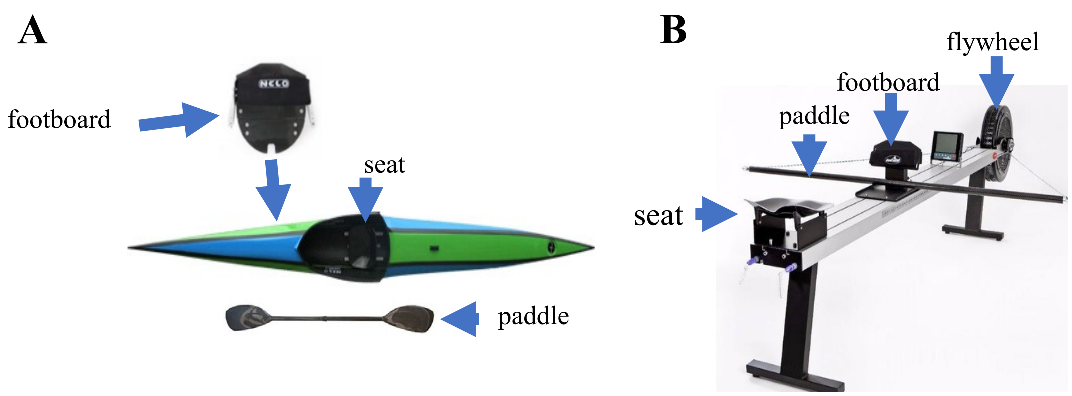

Figure 2. Components of a kayak boat and ergometer. Labeled A) kayak boat and paddle and B) kayak ergometer. There are some similarities between the two modalities, including a seat, footboard and paddle. There are also differences, such as the prescence of a flywheel.

The catch phase is followed by the draw phase. During this phase, on-water, one blade is pulled through the water and create propulsive forces (42). The footboard pushing motions stem from anterior hip rotations into the footplate. During the catch phase, the contralateral side of the torso to the pulling paddle blade, rotates posteriorly and downwards. As well, the hip on the ipsilateral side as the pulling paddle blade, moves anteriorly and inferiorly. Lastly, a pulling motion on the footboard is present on the contralateral side to the pulling paddle blade and is used to counter paddling pulling forces and to initiate the force production during this phase (2,43).

When the paddle reaches near vertical, the blade is removed from the water, called the exit phase (42). The exit phase is immediately followed by the aerial phase, where both blades are not in contact with the water and the opposite blade is moved anteriorly towards the bow of the boat to start the next stroke. During the aerial phase, the hips rotate, where peak vertical hip height is reached just prior to blade entry (44). On the ergometer, the aerial phase occurs when no intentional paddle pulling motions are present.

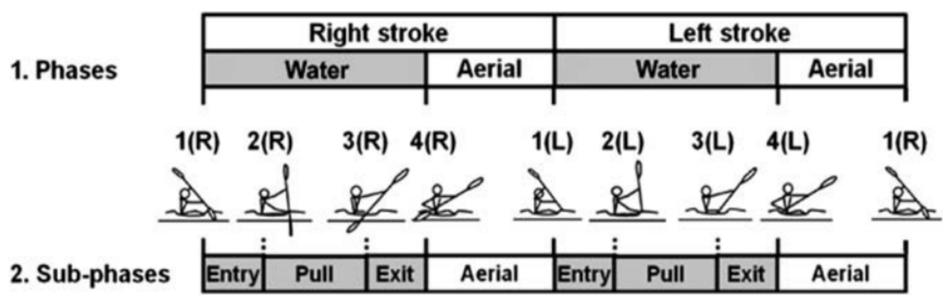

Figure 3. Phases of a sprint kayak stroke cycle. Two strokes, left and right side, constitute a stroke cycle. Adapted from McDonnell LK, Hume PA, Nolte V. An observational model for biomechanical assessment of sprint kayaking technique. Sport Biomech. 2012;11(4):507–23.

Stroke cycles can be characterized using lower body forces when paddle data is not present. Immediately prior to the paddle entering the water, the ipsilateral foot begins to push against the footboard (14). As such, it can be assumed that the initiation of footboard push forces starts at a similar time to the catch phase. Therefore, the stroke cycle can be defined using the footboard forces, by defining it as the initiation of one footboard push phase to the initiation of the following push phase of that same foot.

2.1 Kinematics' Effect on Kinetics

The kinematic stroke profile can directly relate to changes in velocity and force application (45). In kayaking, the limb positioning can have a gross effect on the force transfer between the athlete and the boat (1). This can be observed when comparing novice athletes (slower) to elite athletes (faster). Novice athletes tend to have more asymmetrical limb movements and shorter stroke lengths when compared with elite athletes, where novice athletes are known to produce lower forces (18). For example, boat velocity can be increased by increasing stroke length (a kinematic measure) and elite athletes are often characterized by higher velocities. As well, kinematics can be used to affect the length of the moment arm, relative to the center of rotation. This can change the magnitude of the forces required to create impactful moments. Therefore, it is fair to assume that kinematics can influence performance.

Due to the similarity in environment and use of cyclical movements, rowing mechanics can be compared to kayaking mechanics. Kinematic measures in rowing, such as spine angles and elbow angles, impact the force transfer through an athlete's body (46). The positioning of the athlete's limbs and body directly impact the length of the stroke, the orientation of the blade as it enters the water, and the effectiveness of force transfer from the blade of the oar through the athlete and into the boat. For example, in both rowing and kayaking, the more rigid an athlete is able to keep their body, the better the force transfer (1,46). This demonstrates the ability for kayaking kinematics to impact the force measured in the seat and footboard.

Velocities and propulsive forces are not necessarily achieved by using the same kinematics. For example, if two athletes competing in the same race had the same velocity, it is possible and likely that they are using two very different kinematic techniques. Ong et al. (47) changed elite athletes' kayaking kinematics (i.e., angular limb motions) by optimizing their boat set-up (i.e., grip width, footboard distance from seat and bottom of boat, paddle length, and blade length and width) in an attempt to increase their average velocity over a given distance. The new boat set-up resulted in speed decreases of approximately 0.15 m/s. In addition, they found higher velocities were correlated with higher measured paddle forces (i.e., impulse-momentum theorem), suggesting that force production can impact boat velocity. This could have been observed because athletes did not have enough time to adapt to the new boat set-up, or because more research needs to be performed on the methods of optimizing boat construction. This study demonstrates how kinematics are not the sole contributors to optimal kayaking performance.

Chapter 3: The Kinetics of Kayaking

It is important to understand the main contributing factors of forward propulsion to be able to improve kayaking performance. In kayaking, forward propulsion is the anterior displacement of a athlete-boat system through the water. Forward propulsion occurs when an athlete produces propulsive forces that exceed the opposing drag forces (43,48), and is dependent on the magnitude of the net propulsive force (49). Forward propulsion is achieved using high levels of muscular power that ultimately transfer force though the boat to create forward movement (1,43). The paddle, footboard, and seat contribute to kayak net propulsive force as they are the main points of athlete-boat contact the athlete has with the athlete-boat system (Figure 4) (1,16). Force produced in the paddle transfers through the athlete's arms, into their body, then legs and through the boat via the two points of contact between the athlete and the boat: the seat and the footboard (1,47).

3.1 Kinetic Contribution to Velocity

Understanding force applications throughout a kayak stroke cycle can help to optimize performances (11). A change in kayak boat velocity occurs when 1) distance travelled per stroke and/or 2) stroke time is changed (Figure 5) (14), which has also been noted in other sports, such as swimming (50). The distance travelled per stroke is the linear displacement of the boat within a singular stroke cycle and can be increased when

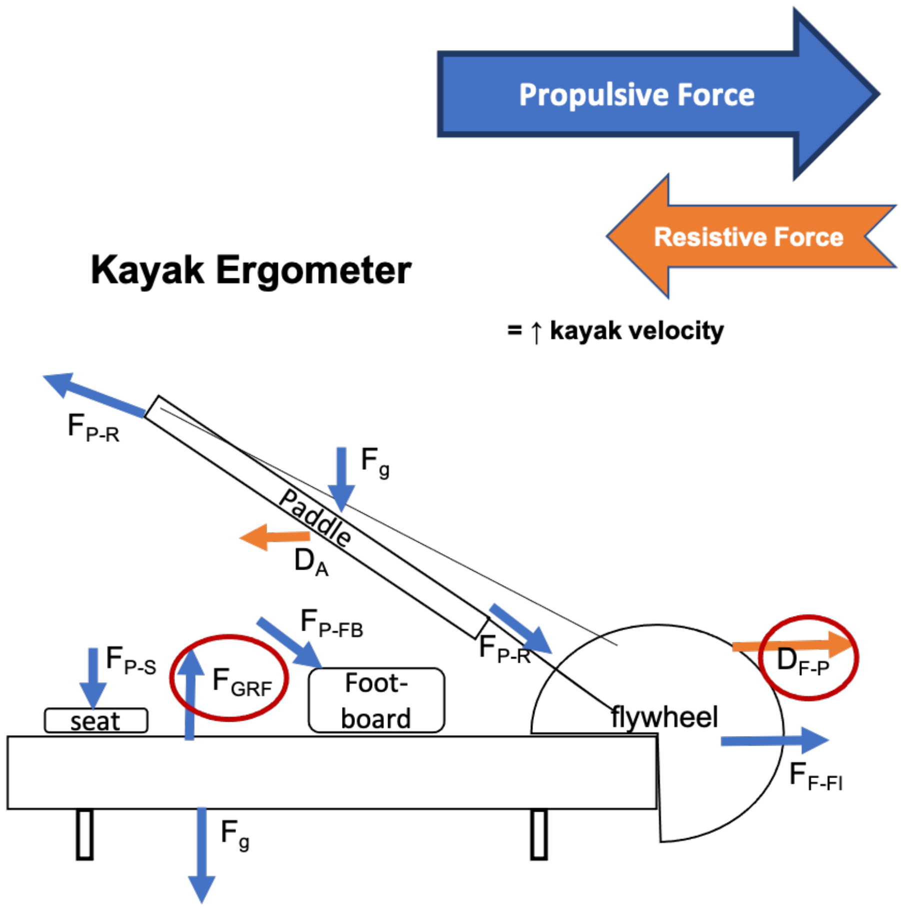

Figure 4. Free body diagram of a kayak ergometer. Note: force of the rope on the paddle, $F_{P\text{-}R}$, force of the person on the seat $F_{P\text{-}S}$, force of gravity, F_g, ground reaction force, F_{GRF}, force of the person on the footboard, $F_{P\text{-}FB}$, drag force of the flywheel on the person, $D_{F\text{-}P}$, drag force of the air on the paddle shaft, D_A

the propulsive forces at the paddle, footboard, and/or seat are increased. Displacement per stroke is the anterior distance travelled in a stroke cycle and can be influenced by the stroke length and the time a paddle's blade spends in the water. These can be increased by changing the entry displacement, pull displacement, and exit displacement.

Stroke time, the period of a stroke cycle, can be increased by lessening time spent in water phase by increasing the paddle impulse (36); however, the contributions of the footboard and seat to the stroke time have not yet been studied.

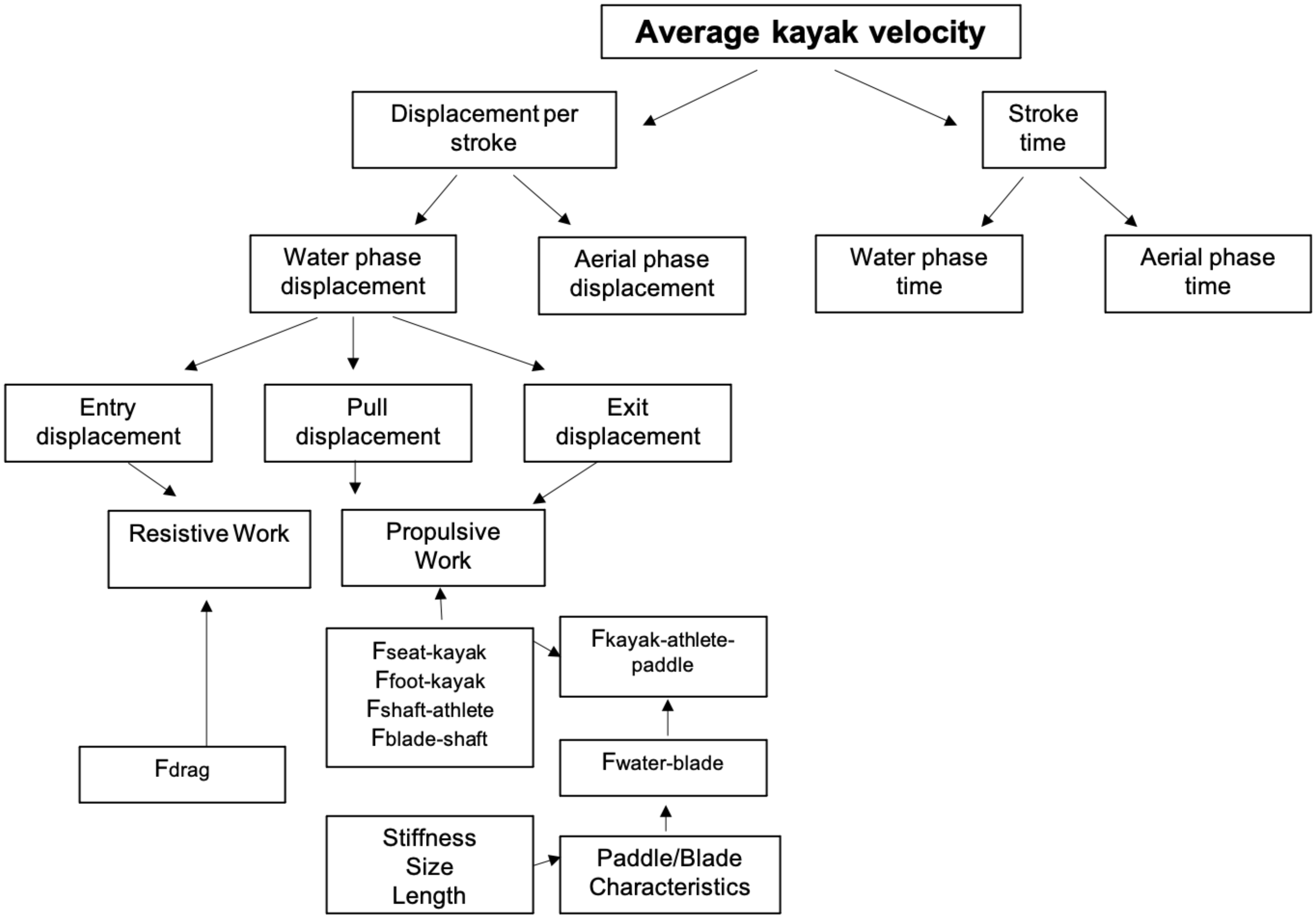

Figure 5. Deterministic model of sprint kayaking performance. This model shoes how a kayak athlete can change their average velocity throughout a race, where obtaining high average velocities is the goal of sprint kayaking. Concept based on McDonnell LK, Hume PA, Nolte V. A deterministic model based on evidence for the associations between kinematic variables and sprint kayak performance. Sport Biomech. 2013;12(3):205–20.

3.2 Kayaking Kinetics' Effects on Performance

Kayaking performance is a measure of average kayak velocity over a given race (Figure 5) and can be greatly impacted by the kinetic force production of the athlete and their environment (1).

3.2.1 Resistive Forces

There are two main types of drag forces that must be overcome to create forward movement: aerodynamic and hydrodynamic drag forces (1). Total drag can be calculated using the following equation: $F_T = F_H + F_A$, where F_T = total drag force, F_H = hydrodynamic drag, and F_A = aerodynamic drag force (1). Hydrodynamic drag is the main contributor to the net resistive force and acts on the boat as it propels through the water partially submerged (1,46). When on the water, aerodynamic drag is spread across the surface area of the paddler, their paddle, and the exposed boat, where the hydrodynamic forces are spread across the surface area of the boat and the blade as it passes through the water. The aerodynamic drag accounts for approximately 6 – 12 % of the total drag force depending on wind conditions and the athlete's weight (51).

Total hydrodynamic drag can be calculated as:

$$F_H = F_{Hf} + F_{Hp} + F_{Hw}$$

where F_{Hf} represents hydrodynamic friction drag force, F_{Hp} represents hydrodynamic pressure drag force, and F_{Hw} represents hydrodynamic wave drag force (1,52,53). Friction drag, also known as surface drag, occurs as water runs along the surface of the boat as it displaces through the water. Friction drag can be changed by manipulating the weight of the athlete and kayak, in addition to the materials used to make the paddle and boat. The weight of the kayak and athlete can change the amount of experienced friction drag as increasing the weight of the boat and or athlete can increase the amount of submerged area (wetted surface area), thus increasing the friction drag experienced (53). Form drag is experienced when the boat compresses the water particles as it glides through and separates the water, and is affected by the cross-sectional area of the object, the shape of the boat, and the smoothness of the surface (54). Wave drag is caused when the water accelerates in waves away from the hull of the boat (52). Friction drag is the greatest contributor to the total drag force (52). The angular rotations experienced in the boat increase the wetted surface area, thus increasing the magnitude of friction drag (52,53). The resistive forces can be reduced by decreasing the amount of drag forces, through methods such as decreasing the mass of the system and reducing the movements of the boat (pitch, roll, and yaw) (33).

Ergometers attempt to mimic drag forces imposed on the boat while kayaking on-water through the introduction of a flywheel. It is not well understood how accurately these forces are represented through the connection of the flywheel, the rope, and the attached paddle. However, some similarities are present between a flywheel and hydrodynamic drag. For example, the flywheel spins faster when more force is applied through the rope. The increase in rotational movement within the flywheel increases the amount of resistance experienced by the athlete, which is the same for on the water. As the athlete moves faster on the water, they experience more hydrodynamic forces. As previously mentioned, kayaker ergometers are commonly used for their ease in control of confounding variables and are sufficient when on-water collection is inaccessible.

3.2.2 Work and Angular Work

Work is a measure of force (F_{net}) over a distance (d). This can be applied in kayaking by measuring forward boat displacement, the amount of propulsive work, and the present drag forces (33). The net propulsive work in an athlete-boat system is a measurement of the contribution of work put into forward propulsion (i.e., footboard, seat, and paddle forces) and the magnitude of resistive forces (i.e., pressure, wave, and friction drag) over a given distance.

The Work-Energy theorem can be used to calculate the velocity of a boat, where boat velocity can be used to calculate displacement. The Work-Energy Theorem states that the magnitude of work (W_{net}) performed in a system comes from the change in kinetic energy (KE) of a moving object, where W_{net} can be calculated using the following equation:

$$W_{net} = d \cdot F_{net}$$

In kayaking, these forces can be measured through the paddle, footboard, and seat.

The Work-Energy Theorem can be used to determine the amount of translational kinetic energy and can be used to calculate the velocity of a boat. The amount of translational kinetic energy can be calculated using the equation:

$$KE = \frac{1}{2}mv^2$$

where m represents the mass of the kayak and person, and v represents the velocity of the boat. The net work is then calculated using the Work-Energy Theorem equation:

$$W_{net} = \frac{1}{2}mv_2^2 - \frac{1}{2}mv_1^2,$$

where v_2 represents the final velocity, and v_1 represents the initial velocity. The velocity of a moving kayak can be calculated using this equation:

$$v_2 = \sqrt{\frac{2W_{net}+mv_1^2}{m}}.$$

The net work can be calculated using the equation:

$$W_{net} = Fd,\ v_2 = \sqrt{\frac{2\bar{F}d+mv_1^2}{m}}.$$

The mass of the boat and the athlete stay constant throughout a trial, and therefore, the net work can be related to the magnitude of propulsive forces generated.

Angular work is a measure of the angular distance through which an object rotates when a magnitude of torque is applied against it, and can be measured as, *angular work* = $\tau\triangle\theta$, where τ represents torque and $\triangle\theta$ represents the angular distance. Angular work can be used to quantify the torque applied over an angular distance. It is important in a sports context as sports require both linear and angular movements. Rotational energy can be defined as the energy required to create angular work and the Work-Energy Theorem can be applied in the same way with angular work as it can with linear work, with the primary difference being the work and energy would be measured over an angular distance.

3.2.3 Impulse and Angular Impulse

Similar to rowing, higher impulses in kayaking have been related to higher average boat velocities (5,35,36,55). Weyand et al. (56) studied kinematic and kinetic contributions to running speed. They found that, at the upper range of a runner's velocity, higher cadences do not contribute to an increase in velocity. Instead, higher velocities in this range are achieved by increasing the ground reaction forces at foot contact, which is likely a result of a runner no longer being physically capable of increasing their cadence. This study also noted larger stride lengths in the upper running velocity ranges, which can be achieved through greater ground reaction forces. This suggests that stroke rate force production could possibly be a greater contributor than stroke rate or cadence when achieving maximal velocities.

The impulse-momentum theorem can also be used to model how force affects velocity, where momentum would be the boat and the athlete's resistance to moving and impulse would be the propulsive forces acting on the kayak-athlete system over time. The impulse-momentum theorem states that, $J = \triangle p$, where J represents impulse and $\triangle p$ represents a change in momentum. Impulse can be calculated using the equation:

$$J = F_{net} \cdot \triangle t$$

where $\triangle$ t represents the elapsed time. Momentum can be calculated using the equation $p = m \cdot v$, where p represents momentum. When using the impulse-momentum theorem to calculate the velocity of a moving kayak, the mass of the kayak can be assumed to be constant since the mass does not change as the boat moves through the water. As well, the difference in momentum needs to be calculated, therefore the equation:

$$F_{net} \cdot \triangle t = m(v_2 - v_1)$$

can be used to calculate velocity, where v_2 is the final velocity and v_1 is the initial velocity. When calculating the linear velocity of a moving kayak the equation:

$$v_2 = \frac{\overline{F} \cdot \triangle t}{m} + v_1$$

can be used. This equation shows that velocity is proportional to the net force and would theoretically increase as the propulsive impulses increase.

There are two impulses that have been researched in a kayak stroke cycle: the pull phase impulse and the total impulse (1,16,57). The total stroke cycle impulse (TSI) encompasses the impulse across one stoke, where the aerial phase impulse encompasses the impulse when the blade is in contact with the water during the propulsive phase of movement. Aerial phase impulse is also important to consider, as different paddle force waveforms have previously been found during this phase on an ergometer (57) and pulling forces occur during this phase in the footboard (16,58).

Angular impulse is the measure of the change in angular momentum over time, where angular momentum is a measure of the rotational inertia and motion an object has. This can be calculated algebraically using the following equation: $\Delta L = \tau \Delta t$, where ΔL represents angular impulse and Δt represents the period. The impulse-momentum theorem can be applied to angular impulse as well and can be used to describe how angular momentum changes over a period of time with the primary difference being that the measure would be over an angular distance.

To date, no studies have assessed the effects of angular impulse on kayaking performances. Angular impulse has been used to assess mechanisms of injury (59) and performance (60–62) in other sports. For example, the knee abduction angular impulse can be used to determine mechanical asymmetries between symptomatic and asymptomatic runners with patellofemoral syndrome (59). Angular impulse has also been used to provide guidance on equipment modifications, such as footwear (59). Therefore, the measurement of angular impulse has the potential to provide information on athlete's who are at a higher risk for specific injuries.

3.2.4 Lower Body's Kinetic Contribution

The lower body is an important contributor to the propulsive force production in an athlete-kayak system. When the lower body is constricted, 16 % of the mean kayak speed and 21% of the mean paddle force is lost (16). Based on these values, in races with durations ranging from 35 seconds to 4 minutes, restricting leg movement could possibly result in time differences of 5.7 - 30.1 seconds. It is, therefore, important to understand the contribution of all three points of contact (paddle, footboard, and seat) with the athlete-boat system when optimizing an athlete's performance.

Theoretically, the lower body's flexing and extending of the trunk and hips, relative to the seat, throughout the stroke cycle (i.e., rotational motions) increases the radius of rotation. This would change the athlete's mass distribution over its axis of rotation, affecting the moment of inertia in respect to their axis of rotation. If angular rotation was kept constant, or increases, the angular movements through the hips could increase the angular momentum of the kayak-athlete system, where the change in angular momentum would be a measure of impulse. Where change in angular momentum is proportional to the angular impulse, impulse is a measure of the force over a period of time, and higher impulses are correlated with higher velocities (47,63,64).

3.2.5 Center of Pressure

The center of pressure (COP) is used to determine the location of where the resultant force is being applied (65). The calculation of COP can provide information on individual or group patterns in force application throughout a stroke cycle. Determining patterns in COP location can be used to better understand the relationship between the location of the resultant force and performance measures. In the case of kayaking, COP can be analyzed to determine if an athlete favours their left or right sides.

Individual footboard COP has been measured using rowing ergometers. Elliot et al. (66) used a pressure sensor to determine the COP in athletes' forefeet and rear feet. However, the net COP has not yet been compared between both footboards and could be used to explain variability between resultant force locations in the left and right footboard. Further, asymmetrical motions have been identified in elite rowing athletes' seats while using a rowing ergometer (67), suggesting the possibility for seat asymmetries to be found in kayaking. In kayaking, it can be assumed that the COP will oscillate back and forth, in time with the push and pulling motions of the lower legs on the footboard. This would result from the altering pushing and pulling motions of the left and right sides of the lower body applying force against the footboard.

3.3 Kayak Force Profile

The stroke cycle can be studied using a force-time graph. The force-time graph allows researchers to assess the intra-stroke variability and asymmetries (36,68). In kayaking, the force-time graph has been used to characterize the paddle and footboard force waveforms (11,16,35,36,57,58), analyze discrete propulsive force measures (11,33,36,57,69), and calculate inter-stroke impulse (35,55). The majority of these measures have been used to characterize the paddle force profile (1,11,33,36,57,69–72), with some information on the footboard (16,58,73–75).

Researchers have analyzed paddle force waveforms using force-time graphs to determine their effects on performance (11,16,33,35,36,55,57,58,69). Smoother force waveforms are related to greater impulses, as smooth waveforms have fewer dips in force (76). Having smooth force waveforms decreases the fluctuations in velocity, hence, increasing the average velocity over a given distance. Therefore, the ideal propulsive force stroke profile would be a smooth waveform that reaches peak force as soon as possible and remains close to the peak force for most of the propulsive phase. Michael et al. (1) suggested that the ideal paddle force profile would be rectangular, where the force hits peak force as the blade enters the water, then plateauing until the blade tip exits, as this would result in the greatest possible propulsive impulse.

3.3.1 Paddle Force

The kayak paddle force-time profile has been previously documented (1,11,33,36,57,69–72). Peak paddle forces have been measured to reach 274 - 375N for men and 153 – 290 N for women, while impulses of 109 N·s for men and 80 N·s for women at race pace, where the description of the equipment used was a telemetry system (33,70,77). Differences have been found when comparing the left and the right stroke impulses, where lateral impulse in the left (40.6 Ns) and right (37.2 Ns) sides of the paddle have been measured (33,70). Left (286.99 N) and right (303.35 N) intra-stroke peak forces were measured using two Sensix force sensors in a female world medalist (11), also suggesting the presence of an asymmetry in this athlete. Although, both studies did not characterize the observed asymmetries with an ASI, it is clear that kinetic asymmetries are present in paddling technique.

The shape and magnitude of the paddle force waveforms has been shown to be affected by stroke rate (1,14,69,71,72). The magnitude of the paddle force, during the draw phase, increases as the stroke rate increases (36). A large increase in anteroposterior force occurs when the stroke cycle is initiated as the athlete begins to draw their paddle posteriorly (57,58,78,79). The increase in net paddle force is followed by a momentary peak in force and then plateaus until the blade tip is removed from the water. Some studies have found a notable decrease in force following the momentary peak then preceded by a second peak, which is suggested to be a result of elastic recoil within the carbon fibre shaft (58,64,78,79); this has yet to be shown on the ergometer. The force decrease following peak force has only been observed at higher stroke rates of 100+ strokes per minute (spm) in both male and female kayakers (64).

3.3.2 Footboard Forces and Moments

The footboard forces are often measured individually, left and right foot measures, characterizing the push and pull forces (58,80). Nonetheless, moments in the footboard have not yet been measured. Kayaking footboard forces have only been collected in the anteroposterior plane, measuring the push and pulling forces collected on the ergometer (58,75,80) and on-water (16). This has limited our understanding of the lateral and vertical forces in the athlete-kayak system, which provides meaningful and interesting information on imbalances and stroke profile.

Footboard forces act as a counterforce to the contralateral paddle forces to keep the boat straight (80), and increases trunk rotation (33). The footboard forces originate from the hip's anterior rotation, which causes the opposing hip to create a posterior pulling force through the lower body (58,80,81). In addition, the footboard force is said to increase trunk rotation and paddle force production (33). The increase in trunk rotation creates a larger stroke length to optimize the distance travelled per stroke (14).

Some research has shown that footboard forces are greater than those measured in the paddle on the ergometer (58,80). Tornberg et al. (58) measured average footboard forces in novice to international level athletes (n = 3) on a kayak ergometer. Right (175 – 716 N) and left (106 – 667 N) pushing, and right (39 – 115 N) and left (7 – 186 N) pulling forces were measured. Nevertheless, not all studies have concluded that footboard forces have higher average anteroposterior forces than paddle forces.

The opposing push and pull forces likely create a coupled moment (a resultant moment, with no resultant force) in the footboard. The coupled moment would occur because of the feet creating resulting forces in equal and opposite directions on the left and right sides of the footboard. The coupled moment would momentarily cause a cessation of net force in the combined footboard system, and no COP would be present at this time. Unlike a normal system, where the coupled moment creates rotation, the footboard would not rotate due to the external force of the footboard stand holding the footboards' plates in a stationary position.

Measuring the footboard forces has the potential to contribute to the overall understanding of propulsive force in kayaking. If the footboard force profile was characterized, there is the potential to use sport science to optimize it through changes in technique. By characterizing footboard forces and comparing them to other known measures of performance (i.e., velocity), these understandings will contribute to the current body of literature and allow athletes, coaches, and performance analysts to better understand the role of the footboard in propulsive force and moment product.

3.3.3 Seat Forces and Moments

The seat is attached to the boat in the propulsive direction (i.e., forward linear displacement) and therefore, contributes to the propulsive forces (1). Begon et al.(80) measured wired uniaxial forces in the seat and footboard on a stationary kayak ergometer. Peak anteroposterior seat forces were found to be around 301 N in athletes with an average mass of 78.2 ± 9.4 kg. Where, Nilsson and Rosdahl (74) researched the validity of measuring forces from an on-water kayak seat but did not analyze the data outside of creating a calibration curve. No studies to date have characterized the contribution of seat forces throughout a stroke cycle and assessed their contribution to the net propulsive force. Further research on the contribution of seat forces and moments would increase the understanding of the seat's contribution to total kayak propulsive force production.

During the stroke cycle, the pelvis tilts as opposing feet thrust and draw against the footboards simultaneously. The tilting of the pelvis likely causes alternating mediolateral moments on the seat. Ergometers do not allow for trunk roll due to the stationary base (73); however, the athlete is likely alternately pressing through either hip as they go through the stroke cycle. On the kayak ergometer, ground reaction forces transfer through the platform onto the seat and then into the athlete. The ground reaction forces have not been measured during ergometer paddling but will likely change in response to the athlete's paddle and leg movements. By measuring seat forces in three dimensions, some of these assumptions will be tested and be able to contribute to the current body of work on kayaking propulsive forces and moments.

3.4 Current Methods of Kayak Force and Moment Data Acquisition

There is no standardized method of collecting paddle, footboard, or seat forces and moments. This section will outline the paddle, footboard, and seat methods currently used in the literature to collect force data.

3.4.1 Paddle Force Data Collection

Varying methods have been used to collect sprint kayak paddle forces. Paddle forces have been collected both on the ergometer (79,80,82) and on the water (11,35,36,57), where present research has only reported the resultant paddle force. Paddle forces have been measured through internal (83–88) and external (11,16,35,36,57,79,80) instrumentation of the paddle shaft.

Several studies have used a One Giant Leap® instrumented kayak force paddle, where load cells are placed inside the paddle shaft (83–88). In contrast, Begon et al. (80) is the only study to date to have collected solely anteroposterior paddle, footboard, and seat forces on a sliding kayak ergometer (an ergometer where the footboard and seat slide in the anteroposterior direction as the athlete paddles). They instrumented the connection points between the paddle blade tips and the ergometer's rope using 500 N range load cells, in addition to using potentiometers to measure the rope's orientations to identify the anteroposterior components of the paddle force. Similarly, others have instrumented the paddling ergometer with two strain gauge load cells using ball and sockets (79) and steel rings (58) between the paddle tip and the ergometer rope to measure the resultant paddle forces. Gomes et al. (36) used a custom system with two strain gauges bonded along the anteroposterior axis to the exterior of the paddle shaft. This group measured net paddle forces by placing one strain gauge 80 cm from either side of the individual athlete's blade tips to measure the bending forces in the paddle shaft. Further, Fleming et al. (57) instrumented both an ergometer and an on-water paddle shaft with two quad strain gauges located 20 cm from the center of the paddle shaft to measure the bending forces within the shaft.

3.4.2 Footboard Force Data Collection

The footboard forces have been measured by separating the left and right sides of the footboard (16,58,75,80). Begon et al. (80) used two separate uniaxial piezoelectric sensors in each footboard on a custom made sliding ergometer to measure the anteroposterior footboard forces. Similarly, Tornberg et al. (58) measured left and right anteroposterior pushing and pulling forces using strain gauges instrumented on top of a commercial ergometer's footrests. This group collected forces using strain gauges that were wired through data acquisition systems from National Instruments.

Sturm et al. (81) tested the feasibility of collecting only push footboard forces on an ergometer using four sensitive resistors (TekScan A201-100, Boston , USA) per foot. The sensitive resistors hosted microcontroller modules that acted as analog to digital signal converters and connected to a central system via Bluetooth radio that was close to the footboards. Nilsson and Rosdahl (16) instrumented two single-point aluminum force transducers to collect anteroposterior footboard forces. These transducers measured the left and right footboard forces, separately, and were connected to the rear plate in the footboard with two separate smaller footplates being placed on top of them. The load cells were wired to a portable, custom built data acquisition system that was mounted inside of the kayak.

3.4.3 Seat Force Data Collection

Presently, only one study has measured sprint kayak seat forces (80), and none have reported the moments in the seat. This group used two 2000 N range wired, uniaxial piezoelectric sensors, measuring the left and right forces in the anteroposterior plane. The seat was attached to the ergometer via near frictionless wheels, where the sensors were instrumented between this sliding component (sensor to sliding seat wheel platform) and the fixed component (sensor to seat) of the seat, where the physical seat was separated into left and right platforms.

3.5 Current Literature on Seat and Footboard Forces

Paddle forces are better understood than footboard and seat forces. The paddle and footboard, or paddle and seat, forces have been studied (16,58,75). However, few have assessed the paddle and footboard forces simultaneously on an ergometer (74,80), where only one study has simultaneously assessed the footboard, seat, and paddle forces, on an ergometer. All studies assessing footboard forces have exclusively measured uniaxial forces in the anteroposterior plane. This has left a gap in the understanding of propulsive forces contribution to overall boat velocity. In addition, no studies have measured the pitch, roll, and yaw moments experienced by the footboard or seat.

The legs are used in conjunction with the upper body to help propel the boat forward by allowing a platform for the athlete to generate additional forces that help an athlete maintain linear displacement (1). Previous research found that forces applied to the footboard are greater than those measured in the paddle (58). This is likely a result of the location of the force transducers compared to the applied force. Footboards are instrumented to allow force transducers to be located directly under the point of force application, while paddle forces are often measured within shaft between the hand and the blade position. The lower body also has larger muscles and a greater capacity to generate force (89), which likely contributes to larger forces being found at the ergometer footboard in comparison to the paddle. In addition, as the athletes pushes on their footboard, they rotate the ipsilateral side anteriorly towards the footboard, likely adding to the forces measured add this location.

The present literature on footboard and seat forces are limited in that they have only measured forces in the anteroposterior plane and have not yet measured moments. A better understanding of the forces in all planes of movement is needed due to the complexity of the kayaking movement. Having a better understanding of the forces in all three planes will provide a better understanding of the kayaking movement, especially when collecting kayaking on-water.

Chapter 4: Asymmetry

Most sports fall under one of two categories: symmetrical or asymmetrical movements. Symmetrical movements, in a sports context, are performed when motions are mirrored on the left and right side (i.e. butterfly strokes in swimming), while asymmetrical movements involve bilateral differences between the left and right sides (i.e. kayaking, running, sweep strokes in rowing, and free style in swimming) (90). Asymmetries can be quantified in several ways, right versus (vs.) left, dominant vs. non-dominant, stronger vs. weaker, etc. (91). For example, in running, the symmetry in the right and left ground reaction forces have been compared using ASIs (25,92,93) and, in cycling, the left and right asymmetrical power output has been compared in relation to pedaling cadences (94). These applications can be useful in the measurement and prevention of injury and in performance improvements (91).

The measurement of asymmetry in relation to injury is a two-fold problem; prolonged continuation of asymmetrical motions increases the chance of injury, which ultimately impacts athletic performance through the creation of muscular imbalances (90). In cyclical sports, such as kayaking, the potential for injury increases as the same asymmetrical motions are repeated with successive stroke cycles. The creation of muscular imbalances (i.e., the predominance of a muscle in a synergistic pairing of muscles (95)) further reduces an athlete’s ability to perform, as injuries lead to time taken away from training or, potentially, the cessation of all activity for an extended period of time (90). This epitomizes the importance of studying asymmetrical movements and methods for the measurement in athletic populations.

In kayaking, measuring asymmetrical movement is ideal for more than just injury prevention. Theoretically, having equal paddle forces from either blade would be optimal as it would allow for minimal deviations from linear boat displacement and ultimately would increase the displacement per stroke (1,14). Equal force application has the potential to decrease time lost to deviations off course. However, when asymmetries are present in the paddle, compensations in force are likely made in the seat and/or footboard to counteract them. Athletes can use a rudder to assist with steering but use of the rudder increases drag force depending on orientation and should be minimized.

Measuring the propulsive forces can be used to gauge athletic performance. This measure can be broken down into the contributions from the right and left sides and their ability to be symmetrical (96). Traditionally, lower levels of asymmetry are associated with more experienced athletes, and higher levels of asymmetry have been found in novice athletes when compared to elite athletes (96). Therefore, it is important to understand the levels of asymmetry when measuring factors of performance.

4.1 Motor Control of Symmetrical Movements

There are two types of asymmetries observed in the context of sport: skill dominance or lateralization, and force dominance or dynamic asymmetry (97). Skill dominance describes how humans tend to prefer the right or left side of their body when completing a physical skill (i.e., preferring to kick with the right leg during soccer), where force dominance describes when a limb can produce more force than the other side. Skill dominance can have an effect on force dominance, because of the conscious or subconscious preferential use of one side over the other (90,97). This often results in the increase in strength from the usage of the one side.

Higher levels of asymmetries are linked to decreased performances (21,25,91,98,99). For example, lower cycling performances in children compared to adults, can be attributed to an increased level in lower body asymmetry (98). This is likely a result of children having higher movement variability in combination with less exposure to cycling. The findings of Liu and Jensen (98) suggest that more control of movement is required at slower speeds, making it more challenging than pedaling at higher cadences. This resulted in less pronounced asymmetries when pedaling at higher cadences.

The level of asymmetry has been linked to the level of performance (18,96,100). For example, Mo et al. (100) studied asymmetries in novice, recreational, and competitive runners between 8 miles per hour (mph) – 12 mph. They found that novice runners had inconsistent asymmetries, recreational runners had their least asymmetric gait at their preferred speeds and presented a U-shaped pattern, while competitive runners' level of kinetic asymmetry was lowered with increasing speeds and were more symmetrical overall. The competitive runners have likely optimized their running technique to match the demands of performance. This is demonstrated through lower asymmetries at higher speeds, where at lower speeds they are efficient and strong enough that they do not need to be as completely symmetrical to perform well.

Muscle coordination of movement stems from motor programs ordering the timing of muscle contractions and the amount of force generated (i.e., the rate at which neurons fire) within muscles when they contract (101). While creating complex movements, a resultant force (i.e., the force of a foot pressing on a footboard) is produced through a coordinated group of muscles moving with an optimal contractile forces, then creating a resultant force in the intended line of movement (101).

When kayaking, inter-stroke variations in force production are expected. One of the explanations for this is that the central nervous system process that controls impulses converted into muscle motor units is ‘noisy’ (the standard deviation of force production within-subjects). This noise stems from varying signalling processes occurring simultaneously, such as several reflexes causing variability in the recruitment of muscles (101). The ‘noise’ results in slight deviations from the intended force of contraction in a muscle group and likely contributes to the asymmetrical inter-stroke variation in force production observed in kayaking athletes.

Changes in movement symmetry can occur at higher cadences in sport (19,24,26,28–30,94,100,102,103). One of the reasons for this can be described using Fitt’s Law of Speed-Accuracy trade off. When movement time (period of a physical movement) is decreased, the accuracy of the movement is also decreased (101). With shorter movement times, the amount of force a muscle must generate to move a bone increases, which causes higher stroke rates.

The exception to Fitt’s law occurs at the tails of maximal force production capabilities (i.e., the lower force requirements and requirements greater than 70% of maximal force production) when an inertial load is present (101). Increased movement accuracy is observed when force production is greater than 70% of maximal contraction force (101,104). This is a likely result of an increase in the ‘noise’ generated and a decrease in the coordination of muscle groups at these higher and lower force production ranges (101). In ergometer kayaking, an inertial load is present when the athlete pulls through the rope connected at the flywheel, while simultaneously pushing or pulling against a stationary footboard.

Differing movement patterns have been observed when individuals must use self-organization, where self-organization is the theory that movement patterns occur naturally through complex interactions with the environment, to complete a movement task (101). For example, at increasing movement speeds, performance would be threatened under Fitt's law; however, this is not always the case when completing complex tasks, such as kayaking at high stroke rates. Kelso et al. (105) suggest that, at higher movement speeds, the motor program seeks out more stable coordination patterns that are different from those at lower speeds. Under this theory, these alternate motor programs allow individuals to continue performing as well as and sometimes better than they would at slower speeds (101,105). In summary, there is evidence of both positive and negative effects of asymmetries and their changes on speed/force magnitudes.

4.2 Measuring Asymmetries

Asymmetrical differences can be measured through cyclic or acyclic capture methods. Cyclical methods include measures of consecutive repetitive movements (i.e. walking gait), while acyclic methods include unilateral movement (i.e. a vertical jump) (22). Few studies in sprint kayaking have evaluated the effect of asymmetries on acyclic kinetics (106), electromyography (107), and kinematics (18,108). To date, one study assessed cyclical sprint kayaking paddle force asymmetries (20), and no kayaking studies have assessed cyclical kinetic asymmetries in the lower body.

Lovell and Lauder (20) conducted the only study assessing sport-specific movement kinetic ASIs in kayakers. They measured the level of asymmetry in peak force and impulse production at maximal stroke rate in injured and non-injured kayakers on an ergometer. However, it is important to note that the measures of power and peak force were compared using the ergometer's output data, which to this authors knowledge, this method of data collection has not been validated in sprint kayaking.

Asymmetry levels are regularly calculated using an ASI (21,24,26,91,94,99,100,102,109–111), which is a measurement of the percentage of difference between left and right sides of the body. Robinson et al. (111)'s method of calculating ASI is commonly used:

$$ASI = \frac{|(X_{right} - X_{left})|}{(X_{right} + X_{left}) * 0.5} * 100$$

where ASI is the calculated ASI in percent, X_{left} is the measure of the left side of the body measure and X_{right} is the measure of the right side of the body measure. This method is best used for discrete measures, such as the maximum, average, and range of values (19).

ASIs have been quantified in several environments and under several contexts. However, it seems that ASIs of 15 % or greater are more likely to result in injury (91). For example, many studies have quantified the ASI surrounding knee injury and have been able to identify having an ASI score of 10 % or smaller on varying hop tests is an appropriate metric for reduced chance of injury (91). However, the application of an ASI in the context of sports performance, is not as well understood.

Some research has compared ASIs to measures of performance. For example, Rannama et al. (112) found that the presence of peak torque asymmetries in the knees extensors are correlated with reduced power during short maximal effort cycling tests (*r*

= -0.05; $p < 0.05$). It is known that reducing the asymmetry of movement increases performance, but the extent and thresholds of an acceptable ASI have not been established in kayaking. Setting appropriate ASI ranges and having standardized measures of testing in kayaking could provide a testing metric for team and crew boat selection and should be explored.

4.2.1 Calculating Center of Pressure to Determine Asymmetries

COP measures can be used to better understand asymmetrical movements, as it can provide a visual representation of the location of the resultant force relative to the origin of the system. It can also establish if the resultant force is favoured on the left or right side of the body through the calculation of the area of the COP covered. This measure can be used to determine asymmetries in application of the resultant force. Calculating COP can provide researchers insight on observed force and moment asymmetries.

COP is used to determine the asymmetries in many contexts. Shin et al. (113) have used measures of COP of the ground reaction force to calculate ASI during walking by calculating the average left and right COP values. In contrast, Chung et al. (114) studied the asymmetrical difference between feet to determine postural stability. Participants in this study stood with each foot on separate force plates so that they could calculate the net COP located between the two to determine the asymmetrical loading. These comparisons have proven to be important when assessing patterns of movement, and their concepts can be applied in kayaking research using COP to assess the level of asymmetry in the trajectory of the resultant force.

4.3 Asymmetry and Stroke Rate

Coaches often provide feedback on technique when athletes are paddling at stroke rates lower than their race pace, potentially limiting the applicability of the feedback for racing scenarios. The similarities in technique at varying stroke rates are not well understood in kayaking. To the author's knowledge, no research in kayaking has assessed the similarity of techniques between different stroke rates. Providing feedback at higher stroke rates has the potential to provide a greater benefit when working with athletes on their symmetry of movement. Research in rowing, running, and cycling have shown that the level of asymmetry decreases as stroke rates increase (19,24,26,28–30,102,103). The kayak paddle force waveforms change shapes as rate increase, as it stays near peak force for a greater portion of the pull phase and becomes more rounded near peak force as a result (36). Therefore, it is reasonable to assume that differences in asymmetries are present at different stroke rates in kayaking.

4.3.1 Rowing Asymmetries

Asymmetrical force application at the footboard is common in rowers (21,99,109). In highly trained athlete populations, it is suggested that this asymmetry can causes long term adaptations that go on to effect the athletes' activities of daily living, then increasing the chances injury in and out of sport because of muscular imbalances (19,21,109,115).

ASIs in rowing have been compared to performance factors. Fohanno et al. (19) presented different asymmetrical waveforms when comparing the left and right footboard forces in rowers. Foot force ASIs were calculated in eight university level rowers at 18 spm, 24 spm, 30 spm, and race spm, and it was found that the foot force ASI decreased as stroke rates increased (103). In addition, it has been shown that rowers present lower foot and handle force asymmetries at higher stroke rates on stationary rowing ergometers (19,26,102), with higher asymmetries in foot and handle force production in females compared to males (26).

The measurement of asymmetrical force and torque production can have great impacts both performance and movement patterns. Buckeridge et al. (99) measured the asymmetrical force production in rowing ergometer footboards and handles in relation to lumbar and lower body kinematics. They found that small changes in kinematics have meaningful impacts on footboard kinetics and that asymmetrical force production in the footboard is associated with changes in lower back and lumbar kinematics. In addition, they demonstrated that asymmetrical mediolateral force production can be a limiting factor in rowing performance (99). These measures demonstrate the impact asymmetry measures can have on athletic performance and injury prevention and show the potential implications this work can have in the sport of kayaking.

Lower body kinematic factors heavily influence symmetrical force production in rowers, which can likely be applied in kayaking. Rowers' hip and lumbar-pelvic kinematics are main determinants in predicting foot force output and reducing horizontal foot force, respectively (21). The effects of lower limb kinematics on force asymmetries have been studied in rowing. Differences in rower limb length can create asymmetrical motions on a rowing ergometer footboard forces (19,109). However, one study also found that bilateral anthropometric lower limb asymmetries did not have an effect on the rowing ergometer footboard kinetic measures (99). This could be the result of an adaptation in limb coordination to create symmetrical force outputs. This shows the possibility that anthropometrics may not influence kayak footboard kinetic asymmetries as athletes may learn to generate movement patterns that create symmetrical force production despite anthropomorphic asymmetries. However, more research in the area would be needed to confirm such information in kayaking.

These findings in rowing show the importance of researching asymmetrical movements in kayak athletes to determine the influence on measures of performance and injury. The rowing or kayaking lower body technique is similar in that both sports use a linear push and pull motion on the footboards, where the primary difference between sports is that kayakers' legs alternate bilaterally, where rowers' legs move simultaneously through the pushing and pulling motions. However, due to the similarities in the lower body's linear motions between rowing and kayaking, and the fact that the lower body is the main point of contact between the boat and the athlete, it is easy to justify the importance of researching the lower body kinetic asymmetries in kayakers.

4.3.2 Swimming Asymmetries

Asymmetry research has also been studied in swimming. Swimming and kayaking are comparable as they both require large ranges of forceful motion through the shoulder joint (115). Peak and mean front crawl force asymmetries were measured while swimmers were tethered with a strain gauge attached to the waist connection of the tether. In this group, faster swimmers demonstrated lower peak (13.32 ± 1.79 N) and mean force (7.01 ± 0.98 N) asymmetries when compared with slower swimmers' peak (18.28 ± 1.91 N) and mean (10.08 ± 1.03 N) forces (116), demonstrating the possibility for level of performance to affect ASI outcomes. In addition, a front crawl upper limb ASI range of 3 – 48.5 % and mean ASI of 19 % was found in a separate group of tethered swimmers using similar collection methods (117). This study found that 66.7 % of their 18 competitive swimmers presented upper body asymmetries. These results demonstrate the high level of variability in athletes' ASI and the presence of an asymmetry in cyclical movement.

4.3.3 Cycling Asymmetries

ASI have been heavily studied in cycling, comparing metrics such as knee angles, power outputs, and force outputs. Cyclists have shown to have lowered asymmetries at higher pedaling cadences (24,28–30). For example, González-Sánchez et al. (94) found that cyclists had higher power outputs and lower ASI at 120 rpm (12.6 ± 11 %) compared to 75 rpm (30.4 ± 39.2 %). In children and adults, lower asymmetries in cycling performance, measured by angular velocity at 90° and 270°, were found as pedaling cadences increased (98). These results suggest that slower speeds may require a higher level of control, as the slower speeds do not closely resemble the cadences individuals are accustomed to (91).

Chapter 5: Methods

5.1 Study Design

This study allowed the researcher to measure the resultant force in a kayak ergometer paddle, and three-dimensional forces and moments in individual footboards, and the seat, as well as calculate the force and moment asymmetries using an ASI. The study was a repeated measures (RM) design with stroke rate as the repeated factor (4 levels: 60, 80, 100, maximum rpm).

The purpose of this study was to determine changes in the kinetic asymmetries associated with stroke rate in sprint kayakers' paddle, seat, and individual footboards forces and moments. The first aim of this study was to characterize the forces and moments experienced by the paddle, footboards, and seat using a kayak ergometer at different stroke rates using qualitative measures. The second aim was to determine if the ASI of discrete force and moment measures changed for differing stroke rates.

To answer the first aim, grand ensemble averages of the paddle, footboard, and seat forces and moments were extracted to establish the kinetic patterns. In addition, eight discrete kinetic measures (maximum, minimum, mean, range, total stroke cycle impulse, push phase impulse, aerial phase impulse, and COP area) of each component (x-, y-, z-axis) of the recorded forces and moments were extracted. These data were analyzed by visual comparison of trends in the data.

To answer the second aim, the paddle's resultant force, the footboards' force, and moment components, in addition, the seat force and moment components were considered. ASIs were calculated using impulses and angular impulses, average forces and moments, and the area of the footboard and seat x-axis COP at each stroke rate condition. The effect of stroke rate on ASIs was then determined using statistical measures.

5.2 Participants

Informed consent was acquired prior to the initiation of the trials (Appendix A; Appendix B; Appendix C). The inclusion criterion for the participants in this study were: must be between 14 - 36 years old (coincides with the age of the majority of novice and international paddling athletes), a minimum of 1 year of paddling experience (18), and training a minimum of 5 sessions a week as part of their normal training regime. Participants were excluded if they answered ‘yes’ to any of the questions on the PAR-Q or indicated an injury within the Musculo-Skeletal Health Questionnaire (Appendix A).

Participants’ age, sex, self-reported preferred hand, and total years kayaking were recorded. Anthropometric measurements were performed using a stadiometer, a balance scale, and a Harpenden anthropometer (Holtain Ltd, Crosswell, UK). Anthropometric measurements included height, mass, shoulder circumference and width, waist circumference, forearm length and circumference, upper-arm length and circumference, hand length and width, trunk length, upper leg length and circumference, lower leg length and circumference, and foot length and width (Figure 6).

5.3 Kinetic Measurements

This study recorded the forces and moments acting on the paddle, footboard and seat while paddling on an ergometer. These recorded forces were then used to calculate the ASI for the components of the resultant forces and moments, as per Robinson et al. (111).

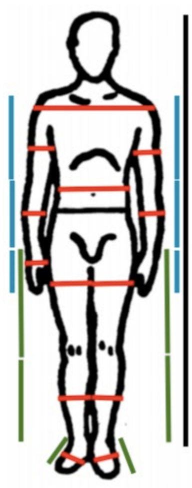

Figure 6. Anthropometric measures of the upper body, trunk, and lower body. The widths (red), upper body lengths (blue), lower body lengths (green), and height (black) were measured on each participant.

5.3.1 Ergometer Kinetics Measurement Set-Up

A Dansprint® ergometer (Dansprint, ApS, Denmark) was used to simulate the paddling motion (Figure 7). Before each trial, the paddle was adjusted to the participant's preferred paddle length and blade twist angle (i.e., the angle of the blade face relative to each other). The ergometer was raised to prevent the paddle's blades from hitting the ground and the ergometer rope was attached to the base of the blades using stiff steel D-rings. The ergometer's seat position was adjusted to each participant's preference and anthropometrics prior to the initial trial. The ergometer's footboard was kept in the same position for all participants, while the seat was adjusted to match the preferred distance from the footboard to seat. The length between the base of the footboard and the middle of the seat was measured for each participant.

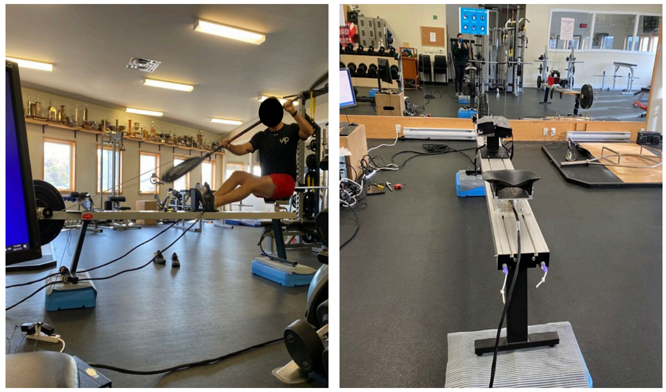

Figure 7. The kayak ergometer set-up and the instrumentation of the three AD2.5D load cells on the kayak ergometer. The ergometer was placed on two boosters to avoid the paddle's blades from hitting the floor.

5.3.1.1 Measurement of the forces and moments on the footboard and the seat

The forces and moments in the footboard and seat were measured using two AD2.5D-500 load cells placed at the left and right sides of the footboard and one AD2.5D-1000 load cell placed at the seat. The AD2.5D are tri-axial force transducers (6 degrees of freedom; x, y, z, pitch, roll, yaw; AMTI Force and Motion, Watertown, MA). Each load cell records the forces and moments in their own local coordinate system. Figure 8 shows the axis convention for each of the AD2.5D load cells as presented by AMTI.

The foot board load cells had an inclination of -64.65° in relation to the line of gravity (rotation around the x-axis). The seat load cell was aligned with the line of gravity (z-axis) and was level with the floor (x- and y- axes). This can be seen in Figure 9.

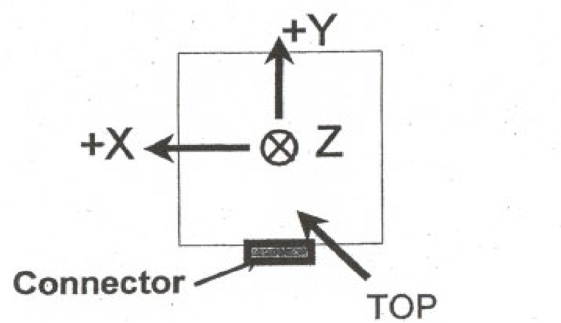

Figure 8. AMTI axis convention. Retrieved from: "TRANSDUCER INSTRUCTIONS: Single Element Multi-Component Transducer," by AMTI Force and Motion, 2013.

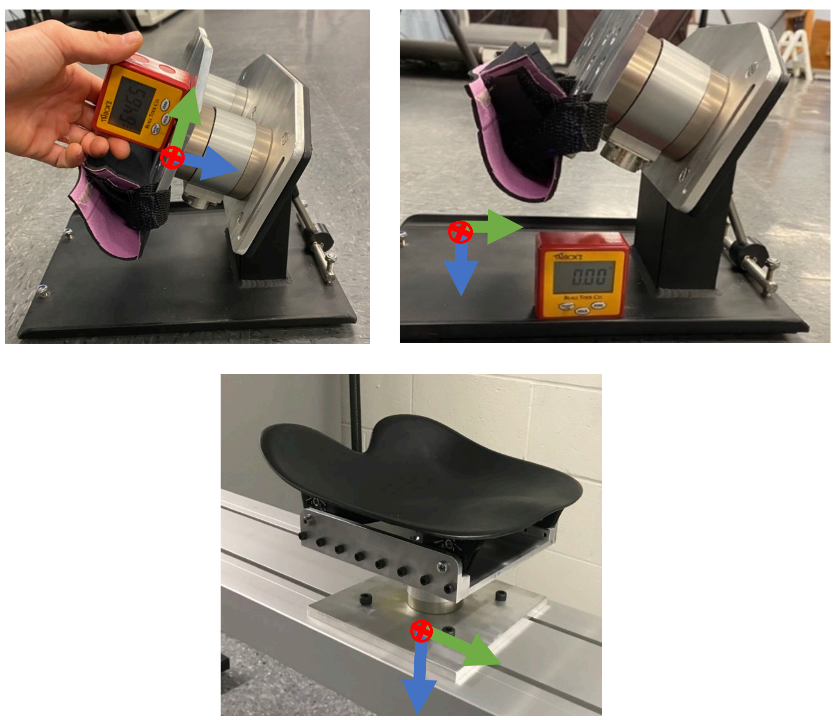

Figure 9. Local and global coordinate systems in the footboard and the seat. The footboard angle measured in the footboard's local coordinate system using an inclinometer (top left), and the global coordinate system shown on the footboard (top right) and the seat (bottom). The x-axis is demonstrated using red arrows, the y-axis is demonstrated using green arrows, and the z-axis is demonstrated using blue arrows.

A schematic of the load cell locations, the representation of the global coordinate system as well as the representations of the different local coordinate systems for the ergometer, the footboard load cells, and the seat load cell are shown in Figure 10.

The forces recorded in the footboard load cells were measured in their local coordinate systems. These forces were transformed with a coordinate system rotation (- 64.65° around the x-axis) to represent the forces and moments within the global coordinate system. As seen in Figure 10, in the global coordinate system, the longitudinal axis represents anteroposterior force and the roll moment in the footboard and seat. The lateral axis presents the mediolateral force when calculating asymmetries, otherwise it was referred to as the lateral axis, and pitch moments in the footboard and seat. The vertical axis presents the vertical forces and yaw moments in the footboard and seat.

When calculating the ASI, the right footboard underwent an additional axis rotation (+180° on the x-axis) to represent the right foot mediolateral (positive mediolateral axis towards the outside of the foot) appropriately (Figure 11).

One GEN 5: Advanced six-channel signal conditioner (AMTI Force and Motion, Watertown, MA) was connected to each load cell via a wired cable. The signal conditioners were connected to a data acquisition computer via USB ports. The gain in the footboard load cells was set to x1000 with an excitation of 10.0 V. The gain in the seat load cell was set to x500 with an excitation of 10.0 V. Force and moment data were collected through NetForce software (AMTI Force and Motion, Watertown, MA). Forces and moments were collected at 1000Hz. The data was then exported from NetForce (Watertown, MA) into MATLAB (version 9.8.0, R2020a; Nantick Massachusetts) as force and moment data in Newtons and Newton meters, respectively.

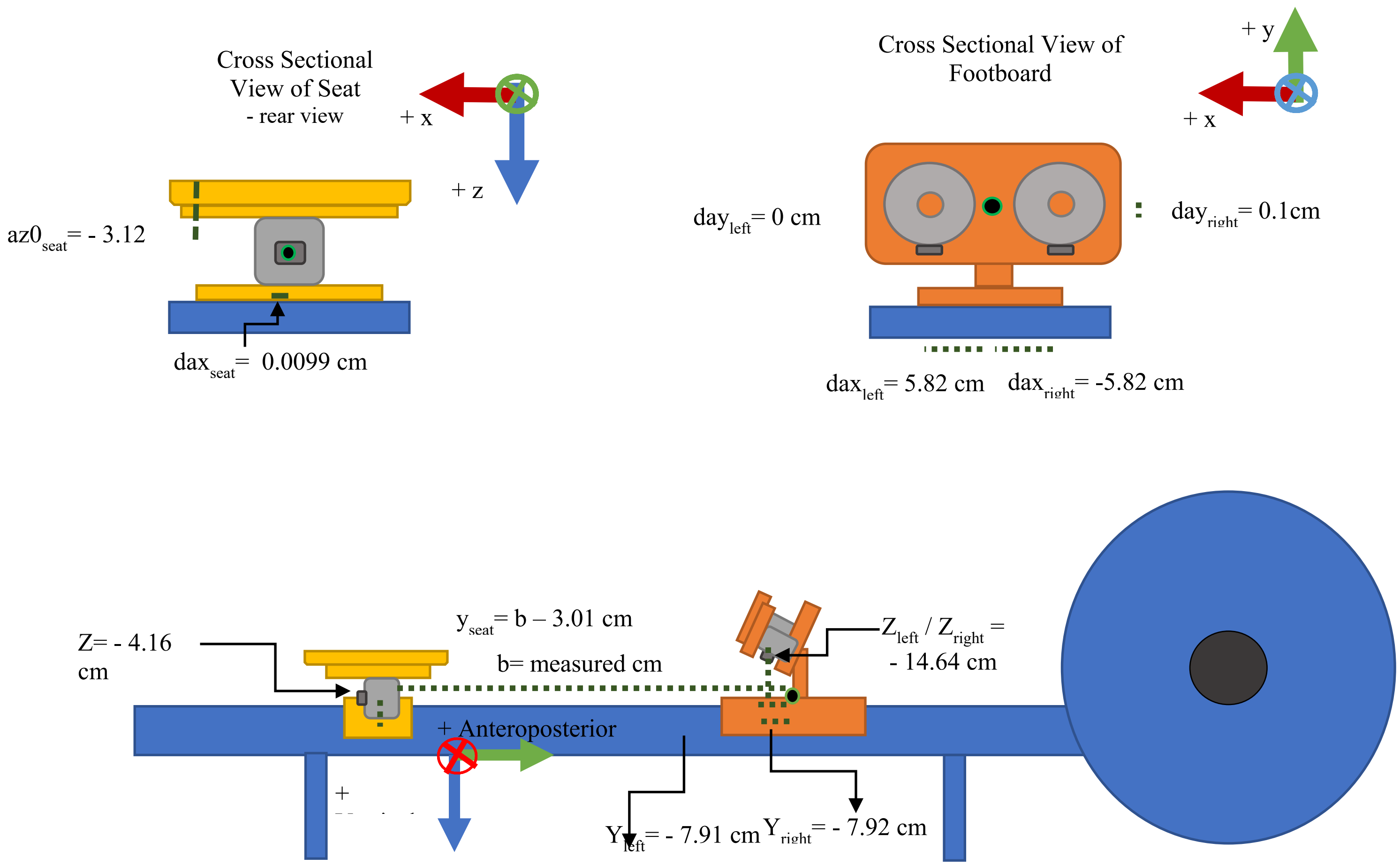

Figure 10. Local and global coordinate systems of the kayak ergometer with measurements. Combined footboard (top right) and seat (top left) local coordinate systems and measurements from the origin, represented by a black dot in the center of the footboard. The kayak ergometer (bottom) measurements from the global origin, black dot, and in the global coordinate system. Note. The red arrows represent the x-axis, the green arrows represent the y-axis, and the blue arrows represent the z-axis in the local coordinate systems. The red arrows represent the mediolateral axis, the green arrows represent the anteroposterior axis, and the blue arrows represent the vertical axis in the global coordinate systems.

Figure 11. Individual footboard local coordinate systems used when measuring asymmetries. This coordinate system was used to ensure that external rotation and lateral moments were both measured as positive values when comparing asymmetry indexes. Note: the red arrow represents the x-axis, the green arrow represents the y-axis, and the blue x represents the z-axis.

5.3.1.2 Center of Pressure Calculation

The COP was calculated using custom scripts in MATLAB (Natick, MA). Lateral and anteroposterior COP were calculated for the x-axis and y-axis, respectively. The Kistler equations were used for the calculation of COP (118). The COP was calculated in one local coordinate system for the load cells, where all axes pointed in the same direction (Figure 10). The z-force was used as a normal force, as it was measured perpendicular to the load cells in their local coordinate systems. The COP in the seat was calculated using the following equations (118):

$$Mx_{seat}' = Mx_{seat} + Fy_{seat} * az0_{seat} \ [1]$$

$$My_{seat}' = My_{seat} - Fx_{seat} * az0_{seat} \ [2]$$

$$ax_{seat} = \frac{-My_{seat}'}{Fz_{seat}} \ [3]$$

$$ay_{seat} = \frac{Mx_{seat}'}{Fz_{seat}} \ [4]$$

where Mx_{seat} and My_{seat} represent the moments around the x- and y-axis measured within the seat load cells, respectively. The Mx_{seat}' and My_{seat}' represent the calculated moments about the top of the seat's load cell around the x- and y-axis, respectively. The $az0_{seat}$ is the distance from the center of the load cell to the top of the seat. The ax_{seat} and ay_{seat} are the calculated lateral COP location and anteroposterior COP location, respectively. The Fx_{seat} is lateral force in the seat and Fy_{seat} is anteroposterior force in the seat. The Fz_{seat} is the normal force in the seat.

The individual COP of both footboard load cells were calculated using the following equations:

$$ax_{foot} = \frac{-(My_{foot} - Fx_{foot} * az0_{foot})}{Fz_{foot}} \quad [5]$$

$$ay_{foot} = \frac{Mx_{foot} + Fy_{foot} * az0_{foot}}{Fz_{foot}} \quad [6]$$

where ax_{foot} and ay_{foot} are the location of the lateral COP and the vertical COP, respectively. The Mx_{foot} and My_{foot} represent the moments around the x- and y-axis in the seat, respectively. The Fx_{foot} is the left or right x-force in the local coordinate systems of the footboard. The Fy_{foot} is the left or right y-forces in the local coordinate systems of the footboard. The Fz_{foot} is the left or right normal force in the footboard. The $az0_{foot}$ represents the distance from the center of the load cell to the top of the anterior footboard plate.

The individual foot load cell's COP was then used to calculate the combined footboard COP:

$$Mx_{feet} = (day_{left} + ay_{left}) * Fz_{left} + (day_{right} + ay_{right}) * Fz_{right} \quad [7]$$

$$My_{feet} = (dax_{left} + ax_{left}) * Fz_{left} - (dax_{right} + ax_{right}) * Fz_{right} \quad [8]$$

$$ax_{feet} = \frac{-(My_{feet} - az0_{left*}Fy_{left} - az0_{right*}Fy_{right})}{Fz_{left} + Fz_{right}} \quad [9]$$

$$ay_{feet} = \frac{Mx_{feet} + az0_{left*}Fx_{left} + az0_{right*}Fx_{right}}{Fz_{left} + Fz_{right}} \quad [10]$$

where Mx_{feet} and My_{feet} are the pitch and roll moments about the top of the combined footboard plate, respectively. day_{left} and day_{right} are the left and right distances from the center of the footboard load cell to the origin on the y-axis, respectively, while dax_{left} and dax_{right} are the left and right distance from the center of the load cell to the origin on the x-axis, respectively. The ay_{left} and ay_{right} represent the y-location of COP in the left and right individual footboards and ax_{left} and ax_{right} represent the x-location of COP in the left and right individual footboards. The Fz_{left} and Fz_{right} are the left and right normal forces, or in this case, the z-force in the footboard local coordinate system. The Fx_{left} and Fx_{right} are the left and right x-force in the local coordinate systems of the footboard. The Fy_{left} and Fy_{right} are the left and right y-forces in the local coordinate systems of the footboard. The $az0_{left}$ and $az0_{right}$ represents the distance from the center of the right and left load cells, respectively, to the top of the anterior footboard plate. The ax_{feet} and ay_{feet} are the COP location on the x-axis and y-axis in the combined footboard, respectively.

The origin in the seat was taken as the center of the seat load cell (Figure 10), while the origin of the combined footboard load cells was located at the center of the two load cells in both the lateral (x) and vertical (y) directions (Figure 10).

A threshold of 50 N was set for the combined Fz_{left} and Fz_{right}, as it was assumed that COP was negligible due to the presence of a coupled moment in the footboard when the normal force is under 50 N.

5.3.2 Paddle Kinetic Measurements

A One Giant Leap® (One Giant Leap Ltd, Port Nelson, Nelson) force paddle was used to measure ergometer paddle shaft forces. This paddle was instrumented with two pairs of strain gauges within the left and right paddle shafts and an inertial measurement unit (IMU). Forces were collected via the One Giant Leap® (Port Nelson, Nelson) proprietary app at a frequency of 100Hz. A long extra stiff force paddle was used for all participants.

Paddle force was excluded due to proportional bias and heteroscedasticity (Appendix D).

5.4 Experimental Procedures

Ergometer resistance was set according to the DanSprint Resistance Chart (Figure 12). Athletes were asked to complete a 10 - minute warm up to acclimatize to the

Athlete Weight (kg)	Flywheel Resistance Setting
<60	3
60-75	4
75-90	5
90-100	6
>100	7

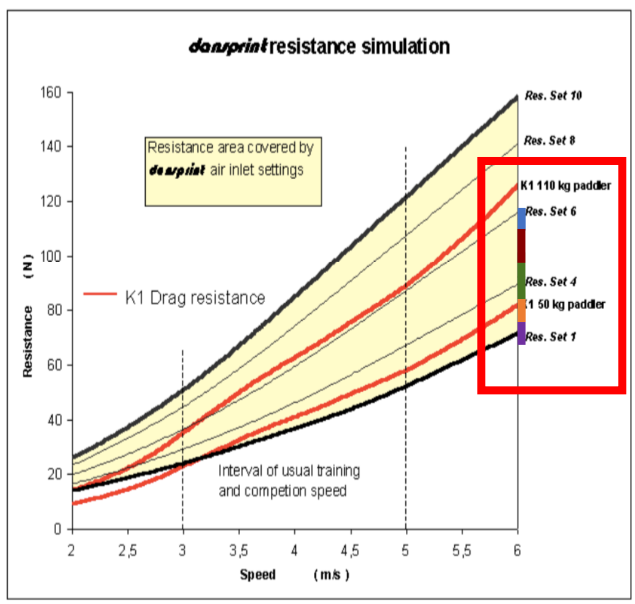

Figure 12. DanSprint® kayak ergometer resistance settings. Kayak ergometer resistance settings were selected using this Dansprint ergometer resistance simulation, reported in their technical report. Adapted from: Torp, O., "Technical Information.", n.d. (Report No. 1).

ergometer settings, to be prepared for the trials, and to avoid injury. Four 30-second ergometer trials at randomized stroke (60 spm, 80spm, 100 spm, & maximum spm), rates to remove order effects, were completed, as to mimic a 200 m sprint. Four stroke rates were used to measure differences in force and moment stroke cycle profiles at different stroke rates (64). Athletes were instructed to try and cover the ‘greatest distance possible’ without compromising or changing their technique (i.e., not over emphasizing the exit phase).

Once the ergometer characteristics were set up, load cells below the footboards and seat were tared with no participant sitting, or in contact with them. This was followed by collecting a five-second bias trial. The force and moment components in these trials were averaged and if a bias was present, it was removed from all data points within the trial it was found in (Appendix D).

The synchronization of the load cells was tested and confirmed by using a long stiff pole that was rested against the center of both footboard load cells, simultaneously. The middle of the stiff pole was hit, creating a spike in force in both load cells at the same time. It was confirmed, that both load cells were collecting within the same periods of each other. The load cell calibration was verified prior to data collection (Appendix F).

Each paddling trial began with the participant standing beside the ergometer. The paddle would be hit three times on the seat, to allow for synchronization between the three load cells and the paddle data. The athlete would then sit down on the ergometer and start the trial from a static position. The trial commenced when the researcher called out “1-2-3-Go!”. The trial ended at the completion of the 30-second trial when the researcher yelled “Stop!”. Athletes were given three-minutes rest between each trial to reduce the effects of fatigue. Athletes were provided with live feedback on their current stroke rate during each trial, so they could adjust their stroke rate. A stroke rate watch (Interval 2000 Split/Rate Watch, Nielsen-Kellerman Co., Boothwyn, PA) was used to inform the participant of their stroke rate in real time. All experimental conditions were completed in a randomized order.

Following the completion of each trial, the ergometer monitor was checked to determine if the athlete was within the target stroke rate (± 5 spm). If they were not, following the completion of the four trials, athletes were given a 3-minutes rest and asked to re-perform the trial(s) where the designated stroke rate was not met. If the athlete was not within ± 5 spm of the designated stroke rate for the trial, the trial was excluded, and the athletes were asked to re-do that trial. This only occurred once, where the athlete was provided with a three-minute rest following the completion of their fourth trial, and then repeated their faulty trial.

5.5 Data Analysis

The first aim of the study was fulfilled by:

1. Extracting and calculating eight discrete measures (maximum, minimum, mean, range, total stroke cycle impulse, push phase impulse, aerial phase impulse, and COP area) from the force time history.

2. Generating time normalized grand ensemble means for each kinetic measurement. The time history results were time normalized to the duration of a stroke cycle.

3. Visually analyzing the data for trends in the normalized waveforms, impulse, and average trends.

The second aim of the study was fulfilled by calculating an ASI for all the discrete measures. All the discrete measures, except for the COP on the footboard area, were included as the components of the forces and moments within the ergometer global coordinate system. The COP on the footboard area was presented in the footboard local coordinate system.

5.5.1 Stroke Cycle and Stroke Phase Identification

The stroke cycle was identified as the initiation of the left footboard anteroposterior force push phase to just before the initiation of the next left footboard anteroposterior force push phase. The push phase was identified as when the athlete was pushing on the footboard while the ipsilateral paddle shaft was being pulled against the ergometer rope, where the aerial phase was identified as the phase between push phases. The starts of the right and left stroke cycles were identified using custom MATLAB

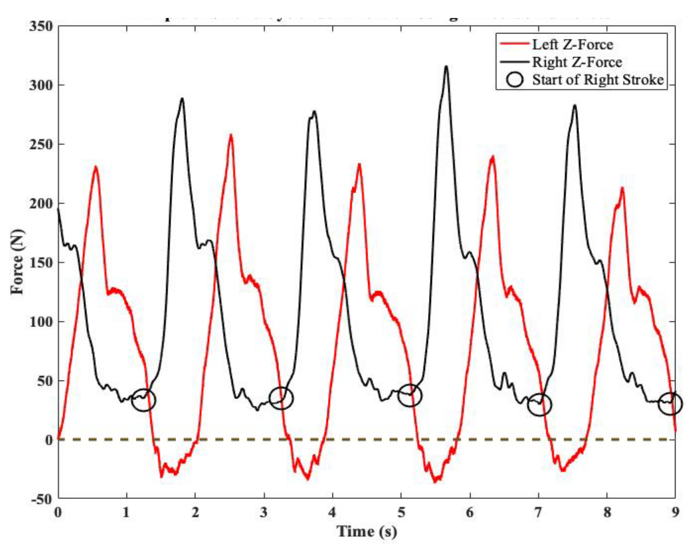

Figure 13. Illustration of stroke cycle identification methods used when an athlete did not pull on the footboard straps. This image shows unrotated data from the right footboard push z-forces (black) and left push and pull footboard forces for one athlete at 60 spm, and the points at which the right footboard forces have been identified to begin (black circle).

(Natick, MS) scripts that selected the sample at which a zero-crossing occurred. These points were manually confirmed by the researcher to ensure appropriate identification of thesis phases. When the participant did not push on the footboard, as demonstrated in the right footboard z-force in Figure 13, the initiation of the stroke cycle was manually identified. The initiation of the stroke cycle was manually selected based on the following characteristics: 1) just prior to a large increase in force towards peak force, and 2) was present in a minor dip in force.

Push phases were identified by using custom MATLAB (Natick, MS) scripts that identified when a zero-crossing was present in the normal footboard force (footboard local coordinate system z-force). This identified both the start and completion of the push phase, as this was a common characteristic of both the initiation and completion of the push phase. The start and completion of the push phases were then manually confirmed by researchers to ensure that the code identified the corrected push phase location. Aerial phases were identified as the time between push phases. When the normal footboard force did not have a zero crossing, the push phase initiation and completion were identified manually, as seen in the z-force recording of the appropriate load cell (Figure 13).

When generating the grand ensemble averages, the force and moment waveforms were normalized to percent stroke cycle (left push to left push event). Ten stroke cycles per participant were normalized to percent of stroke cycle (0 - 100 %) using the spline() function in MATLAB (Natick, MS). This same process was also performed for COP values calculated for each individual data point. These points were then normalized to percent of stroke cycle.

5.5.2 Discrete Measures Identification

Using the left stroke cycle duration, a rolling average was used to determine the average stroke rate of three stroke cycles. The ten consecutive stroke cycles closest to the experimental condition's designated stroke rate were selected for analysis. Each participant had 10 measurements per discrete measure, one from each stroke cycle. These 10 individual measures per participant were then averaged for each participant within each condition (60 spm, 80 spm, 100 spm, maximum spm).

Forces and moments were seperated into left- and right- side stroke cycle structured variable matricies for calculation of ASI. The footboard was divided into left and right sides by the individual left and right load cells (1 column x stroke cycle sample number). Right seat forces were denoted by a negative lateral force (x-force), whereas left seat forces were denoted by a positive lateral force in the seat (1 column x left/right side force sample numbers). Rightward seat roll moments were denoted by a positive moment along the y-axis and leftward roll moments were denoted by a negative moment (1 column x left/right side roll sample numbers). Rightward seat yaw moments were denoted by negative z-moments and leftward yaw moments were denoted by positive z-moments (1 column x left/right side yaw sample numbers).

The following discrete measures were identified using custom MATLAB (Natick, MS) scripts. The maximum, minimum, and average forces within a stoke cycle were identified using max(), min(), mean() functions, respectively, on the left- and right-side matrices. The range within a stroke cycle was found by adding the absolute maximum and minimum values together. The TSI was calculated as the integral of the total stroke cycle's force on the left- and right- side, separately, using the trapz() function, a trapezoidal numerical integration approach.

Push and aerial impulses were calculated as the integral of the force in the local footboard coordinate system for the left and right footboard, seperately. Push and aerial forces were seperated within the footboard, where push forces occurred when the athletes pushed on the left or right footboard (positive forces) and foot aerial phase forces occurred between footboard push phases, when the participant pulled on the footboard straps (i.e., negative anteroposterior footboard force), as seen in the left z-forces in Figure 13. The push and aerial footboard impulses were then calculated using the trapz() function in MATLAB (Natick, MA).

5.5.3 Asymmetry Index

The ASI was calculated by adapting the equation from Robinson et al. (111):

$$ASI(\%) = \frac{|(|X_{left}| - |X_{right}|)|}{(|X_{left}| + |X_{right}|) * 0.5} * 100 \ [11]$$

where X_{left} is the measure of the left side, X_{right} is the measure of the right side, and *ASI* is the calculated ASI. An ASI equal to zero, corresponds to complete symmetry. The ASI was calculated to have no direction to the value.

The asymmetry was calculated for all discrete measures of force and moments: TSI, TSAI, mean, and x-location COP area. The ASI was calculated for the lateral, anteroposterior, and vertical TSIs and forces, and the roll, and yaw TSAIs and moments in the footboard, in addition to the lateral forces, and roll, and yaw moments in the seat. When assessing the asymmetries in the seat values, the absolute value of the left and right side was compared, as the rightward lateral forces were defined with negative sign values and the leftward was defined with positive sign values. In addition, the rightward roll and pitch moments were defined with positive sign values, where the leftward were defined with negative. For example, if the left side had an average lateral force of 5 N and the right side has a mean lateral force of -5 N the ASI, void of taking absolute values, would not be able to be calculated, as the denominator would be equal to zero. When in reality, the left and right lateral forces in this example have the same magnitude of force, but in opposite directions. This is also why coordinate systems that were mirrored on the x-axis have been used in the footboards.

5.6 Statistics

Data was organized in 4 x 10 matrices (condition x participant average ASI) by force or moment. The independent variables were the four stroke rate conditions, and the dependent variable was the calculated individual's average ASI for 10 stroke cycles Table 1.

Statistical analyses were run with Prism 9 (Version 9.0.1, Graphpad, San Diego, CA) and SPSS (Version 26.0.0.2, IBM Corporation, Armonk, NY). A two-tailed paired t-test was used to determine if a significant difference between the left- and right-side anthropometric measures (forearm length and circumference, upper-arm length and circumference, hand length and width, trunk length, upper leg length and circumference, lower leg length and circumference, and foot length and width). The effect of the stroke rate on level of discrete measure ASIs impulse, average, and COP area were assessed using a one-way repeated measures (RM) analysis of variance (ANOVA) ($n = 18$) and confirmed with a Friedman's ANOVA when the data demonstrated a normal distribution. A Friedman's ANOVA was used to confirm the RM ANOVAs due to the small sample size in this work and was used to ensure that the results were not greatly impacted by the removal of outliers. These results were tested at α = 0.05.

Table 1. Asymmetry index outcome measures in the footboard and seat

Force Application Point	Axis	ASI Outcome Measures				
		Mean Force	COP	Mean Moment	TSI	TSAI
Footboard	Anteroposterior	✓		✓	✓	✓
	Lateral	✓			✓	
	Vertical	✓		✓	✓	✓
	x-axis		✓			
Seat	Anteroposterior			✓		✓
	Lateral	✓			✓	
	Vertical			✓		✓
	x-axis		✓			

Note. asymmetry index, ASI; center of pressure, COP; total stroke cycle impulse, TSI; total stroke cycle angular impulse, TSAI

The following assumptions were tested to determine if a critical parametric RM ANOVA was appropriate:

1) Continuous dependent variable. ASI was continuous.
2) Independent variable must be related groups or matched pairs. The independent variables consisted of related groups.
3) No outliers. Outlying data points were found using a robust regressions and outlier removal (ROUT) analysis, a non-linear regression analysis for identifying outliers (119). If an outlying data point was identified, the individual's data was excluded (Table 5).
4) Normality. The data was then assessed for normal distribution using a Shapiro-Wilk test, where normal data resulted in $p > 0.05$. If the data was found to be not normally distributed, all 10 participants' data were used in a

Friedman's ANOVA, as non-parametric rank tests are robust enough to handle outlying data points (120).

5) Sphericity. A Mauchly's test was run in SPSS (Armonk, NY) and used to determine if the data set violated the assumption of sphericity (121). The assumption of sphericity was not met when $p < 0.05$. If the assumption was violated, a Greenhouse-Geisser correction was used.

When a statistically significant result was found, a post hoc analysis was completed. Tukey's post hoc analyses were run when significant main effects were identified using the RM ANOVA, where a multiplicity adjusted p-value was reported. The multiplicity adjusted p-value determines the smallest significant familywise level, at which the comparison can be deemed statistically significant (122). When statistically significant results were present using a Friedman's ANOVA, a Dunn's multiple comparison test was used, where a multiplicity adjusted p-value was reported. Statistical significance of post hoc tests were tested at $p < 0.05$.

The partial eta-squared was used to determine the effect size of the RM ANOVAs and a Dunn's-Kendall's W test was used to determine the agreement between raters (left- and right-side values), or effect size, when a Friedman's ANOVAs was used.

Chapter 6: Results

6.1 Participant Characteristics and Experimental Conditions

Ten sprint kayak athletes from provincial and national teams that met the inclusion criterion participated in this study. The participants' descriptive characteristics (Table 2), and anthropometric data (Table 3) are presented below, where no significant differences between anthropometric measures and side were found for any measure (Table 3).

Table 2. Physical characteristics of participants.

Gender		Age (yrs)	Height (cm)	Mass (kg)	Hand Preference	Total Years Kayaking (yrs)
Males	*Females*	*M* ± *SD*	*M* ± *SD*	*M* ± *SD*	*Right Hand*	*M* ± *SD*
6	4	20.0 ± 6.2	174.7 ± 7.3	72.0 ± 8.8	10	11.8 ± 4.9

Note. Mean, *M*; standard deviation, *SD*; years, yrs; centimeters, cm; kilograms, kg,

Table 3. Group anthropometric measurements.

Anthropometric Measure	Measurement (cm)	
Shoulder Width	44.4 ± 3.3	
Trunk Length	45.3 ± 6.2	
Waist Circumference	85.7 ± 3.4	
Hip Width	30.3 ± 5.0	
	Right Measurement (cm)	Left Measurement (cm)
Upper Arm Circumference	32.4 ± 3.3	32.5 ± 3.4
Upper Arm Length	33.5 ± 2.2	33.1 ± 2.3
Forearm Circumference	26.8 ± 2.2	26.7 ± 2.1
Forearm Length	27.7 ± 1.9	27.6 ± 2.0
Hand Length	18.6 ± 1.5	18.8 ± 1.5
Thigh Circumference	54.3 ± 4.6	54.1 ± 4.5
Thigh Length	43.5 ± 4.5	43.5 ± 4.6
Lower Leg Circumference	36.5 ± 1.3	36.5 ± 1.1
Lower Leg Length	40.1 ± 7.4	39.9 ± 7.4
Foot Circumference	23.4 ± 1.5	23.5 ± 1.1
Foot Length	26.1 ± 1.3	26.3 ± 1.6

Note. *, $p < 0.05$; centimeter, cm
For all measures, except hip width ($n = 9$) and trunk length ($n = 6$), the average ± 1 standard deviation of ten participants is reported.

The stroke rates were kept within the required ranges for every condition. The maximum stroke rate condition did not have any constraints (Table 4).

Table 4. Average stroke rates during conditions.

Condition	Average Stroke Rate (spm)
60	62 ± 2
80	83 ± 3
100	102 ± 3
max	134 ± 11

Note. strokes per minute, spm
Measures reported in mean ± standard deviation.

6.2 Characterization of the forces and moments acting on the footboards and seats during ergometer paddling at different rates

This section will present the grand ensemble averages and discrete measure changes associated with different paddling stroke rates. The kinetic patterns occurring at the footboard will be presented first, followed by the kinetic patterns occurring at the seat. It is important to note that no statistics were performed on the footboards local coordinate data and that qualitative descriptors were used.

6.2.1 Forces and moments acting on the footboards

The following section will present the forces and moments acting on the footboard in the local footboard coordinate system and in the global ergometer coordinate system. Presenting the forces and moments in the footboard local coordinate system allows ease of comparison of the results to previous literature.

6.2.1.1 Footboard forces and moments in their local coordinate system.

The data in this section was separated into the x-, y-, and z-axis, as demonstrated in Figure 10.

Figure 14 illustrates the grand ensemble averages of the left and right footboard x-axis forces and moments. The footboard x-axis force increases as stroke rate increased, where no pattern was observed in the moments around the x-axis as stroke rate increased (Figure 14). The shape of the x-axis waveform also changed as stroke rate increased, where it became more rounded near peak and minimum force as stroke rate increased.

Figure 15 illustrates the grand ensemble averages of the left and right footboard forces and moments on and around the y-axis. The y-axis footboard force waveforms (Figure 15), were similarly shaped to the footboard z-axis forces (Figure 16). The footboard y-axis forces increased as stroke rate increased. No clear pattern was observed in the moments around the y-axis as a function of stroke rate (Figure 15).

Figure 16 illustrates the grand ensemble averages of the left and right footboard forces and moments on and around the z-axis. The average z-axis footboard force was also observed to slightly increase for the left foot but not for the right foot, as a function of stroke rate. The average z-axis force increases for the left footboard as a function of stroke rate but does not present a pattern for the right footboard (Figure 16). As well, the percent of the stroke cycle spent in the footboard push phase increased and the aerial phase decreased as stroke rate increased.

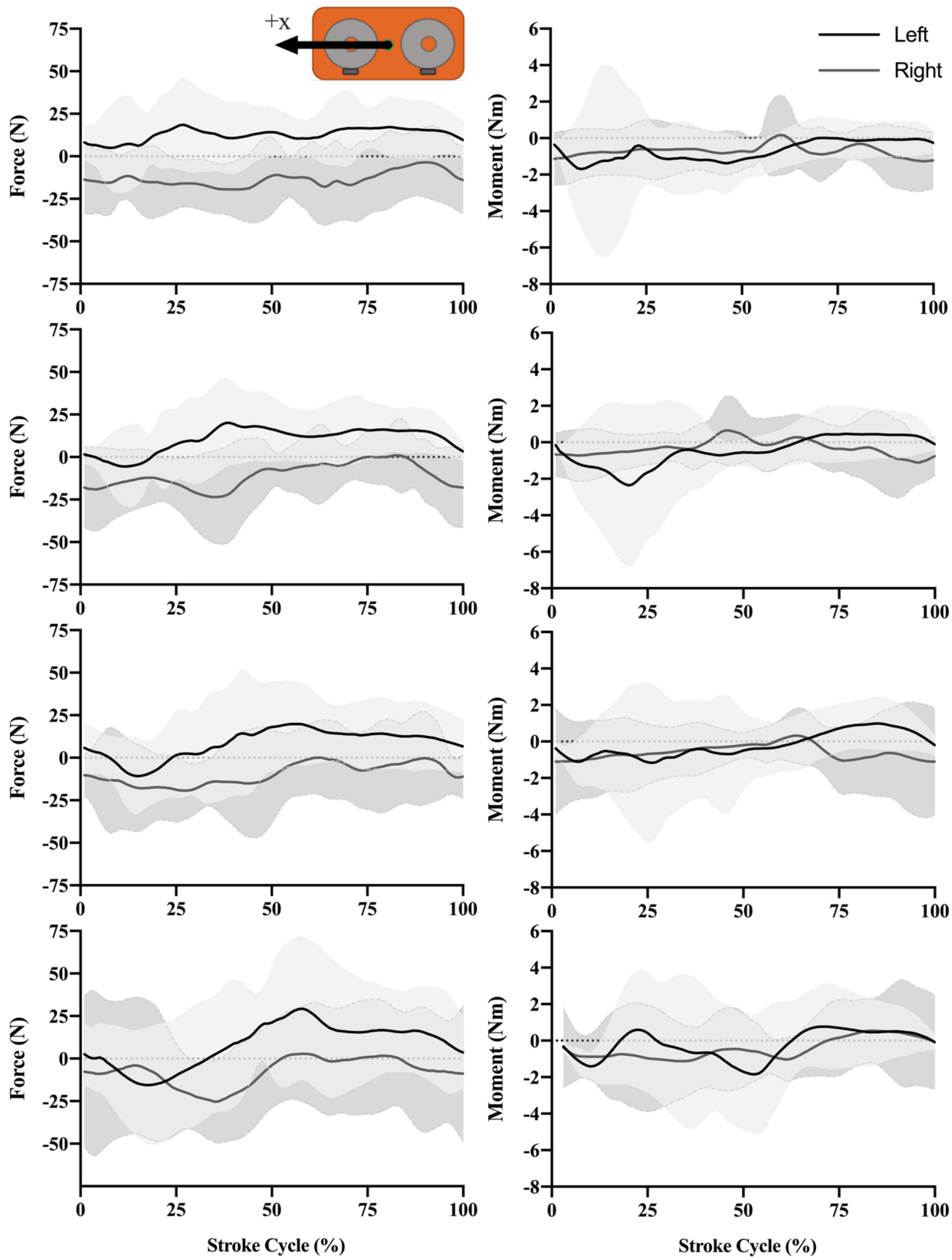

Figure 14. Grand ensemble averages of the footboards' x-axis forces and moments. Forces are presented on the left and moments are presented on the right at 60 strokes per minute (spm; A, B), 80 spm (C, D), 100 spm (E, F), and maximum spm (G, H) (Footboards' local coordinate systems).

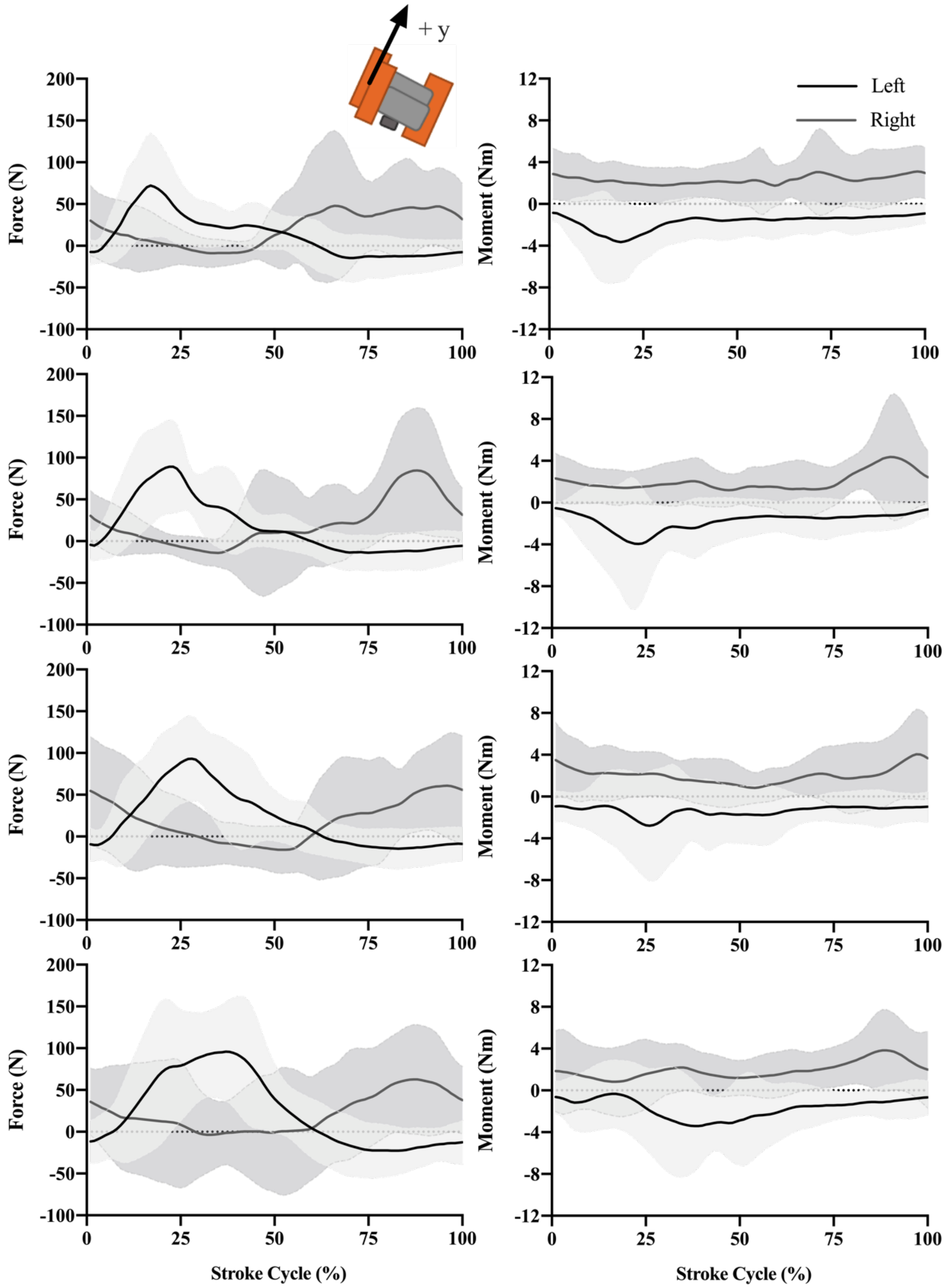

Figure 15. Grand ensemble averages of the footboards' y-axis forces and moments. Forces are presented on the left and moments are presented on the right at 60 strokes per minute (spm; A, B), 80 spm (C, D), 100 spm (E, F), and maximum spm (G, H) (Footboards' local coordinate systems).

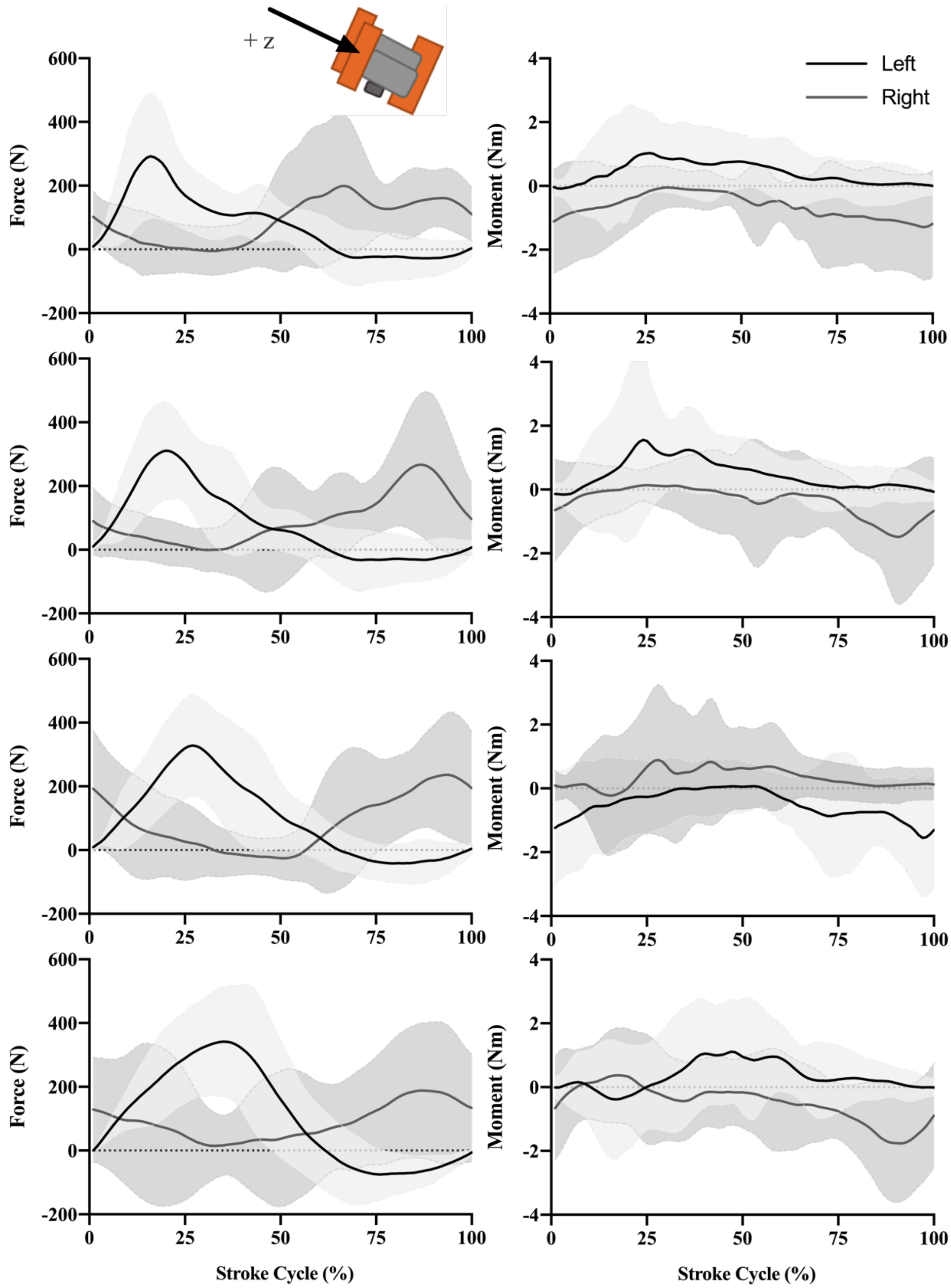

Figure 16. Grand ensemble averages of the footboards' z-axis forces and moments. Forces are presented on the left and moments are presented on the right at 60 strokes per minute (spm; A, B), 80 spm (C, D), 100 spm (E, F), and maximum spm (G, H) (Footboards' local coordinate systems).

6.2.1.2 Footboard forces and moments in the global ergometer coordinate system

Data presented in this section are the forces and moments acting onto the footboard but presented in the global ergometer coordinate system. The data was separated into the anteroposterior, lateral, and vertical axes, as demonstrated in Figure 10.

Footboard anteroposterior right and left TSIs decrease as stroke increases (Figure 17 – A). As well, the average footboard anteroposterior force was observed to slightly increase as a function of stroke rate in the left footboard but not in the right footboard (Figure 17 - C). The footboard roll moment in both the left and right footboards were observed to decrease as a function of stroke rate, with the highest roll moment being present at 60 spm for both footboards (Figure 17 – B).

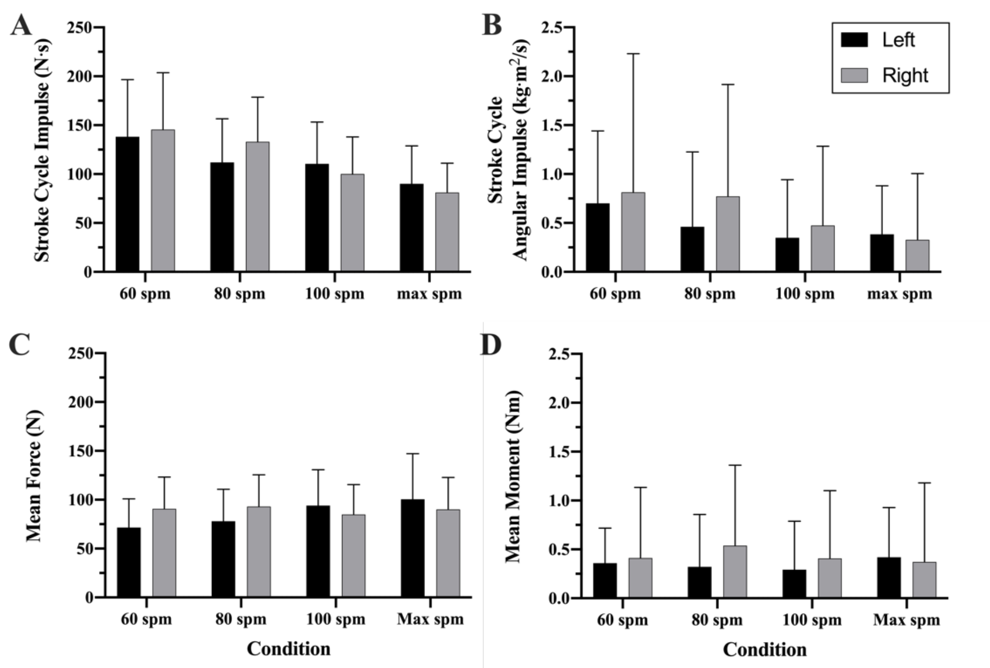

Figure 17. Left and right average footboard anteroposterior linear and angular impulse and forces and moments. (A) anteroposterior total stroke cycle impulse (B) roll total stroke cycle angular impulse, (C) average anteroposterior force, and (D) average roll moment on and around the anteroposterior axis (global coordinate system). These are demonstrated at the four stroke rate conditions. *Note:* strokes per minute, spm

The footboard lateral TSI was observed to decrease as stroke rate increased, while the right footboard TSIs were observed to be greater than the left footboard TSIs in the 60 spm and 80 spm conditions. The left footboard lateral TSI was observed to be slightly greater than the right footboard lateral TSI in the 100 spm and maximum spm conditions (Figure 18 - A). The magnitude of the footboard pitch TASIs were observed to decrease in the right foot as stroke rate increased, but in the left foot, the footboard pitch TASI was observed to decrease from 60 spm to 100 spm, followed by a slight increase from 100 spm to maximum spm (Figure 18 - B).

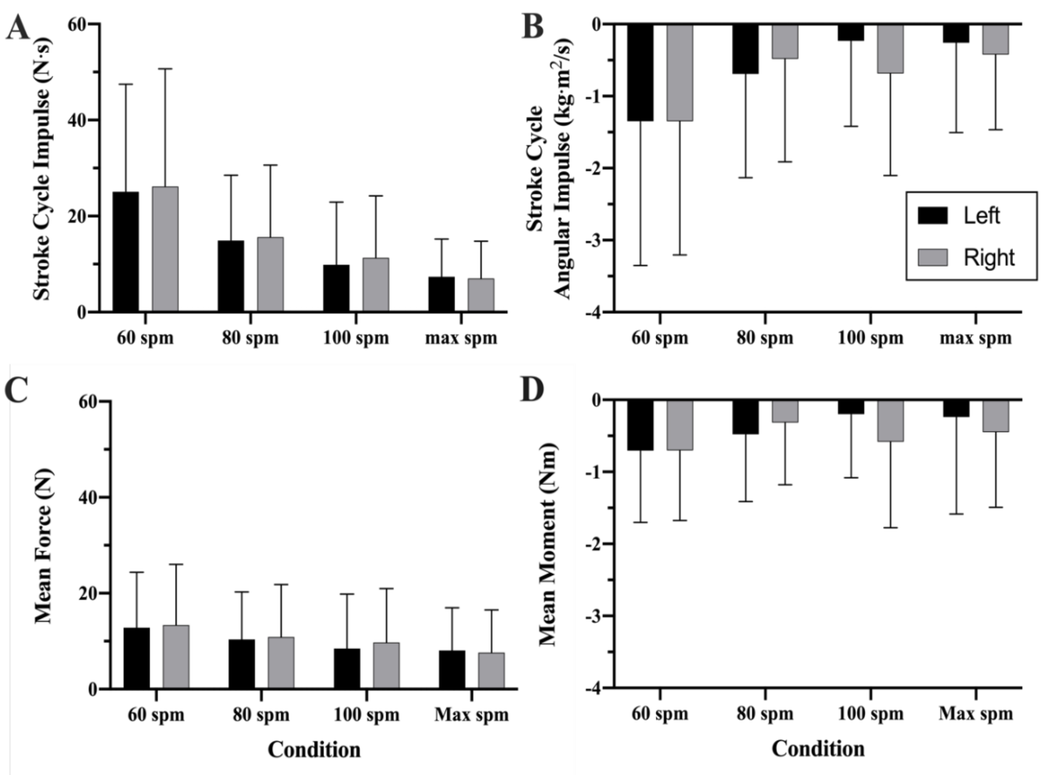

Figure 18. Left and right average footboard lateral linear and angular impulse and forces and moments. (A) lateral total stroke cycle impulse (B) pitch total stroke cycle angular impulse, (C) average lateral force, (D) average pitch moment (global coordinate system). These are demonstrated at the four stroke rate conditions. *Note.* strokes per minute, spm

The left and right footboard vertical TSI were observed to decrease with increasing stroke rate (Figure 19 – A). The left footboard yaw TSAI was observed to be greater in the right foot board than the left (Figure 19 – B). The right footboard yaw TSAI impulse was observed to decrease as the stoke rate increased. In contrast, the left averaged footboard yaw TSAI impulse decreased from the 60 spm to 100 spm, but slightly increased from 100 spm to maximum spm (Figure 19 – B). The average yaw moment in the footboard was observed to decrease as the stroke rate increased (Figure 19 - C).

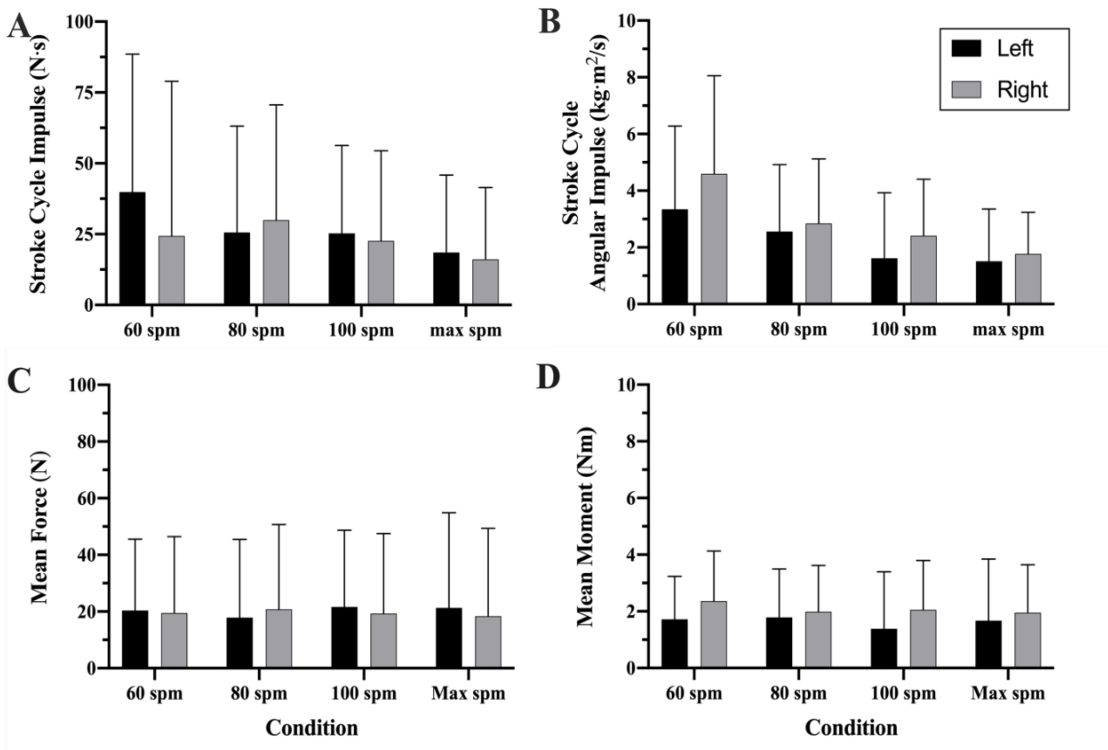

Figure 19. Left and right average footboard vertical linear and angular impulse and force and moments. (A) vertical total stroke cycle impulse (B) yaw total stroke cycle angular impulse, (C) average vertical force, (D) average yaw moment (global coordinate system). These are demonstrated at the four stroke rate conditions. *Note.* strokes per minute, spm

6.2.2 Forces and moments acting on the seat

The following section will present the forces and moments acting on the seat. As presented earlier, the seat load cell axes were aligned to the ergometer global coordinate system.

The seat roll moment was not observed to have a relationship with stroke rate (Figure 20). The seat lateral force was observed to become more round at peak and minimum force as stroke rate increase (Figure 21). The range of the seat yaw moment was observed to increase and the waveforms appeared to become more rounded as stroke rate increased (Figure 22). Appendix G contains the discrete measure values for the footboards and seat forces and moments on the anteroposterior axis (Table 1).

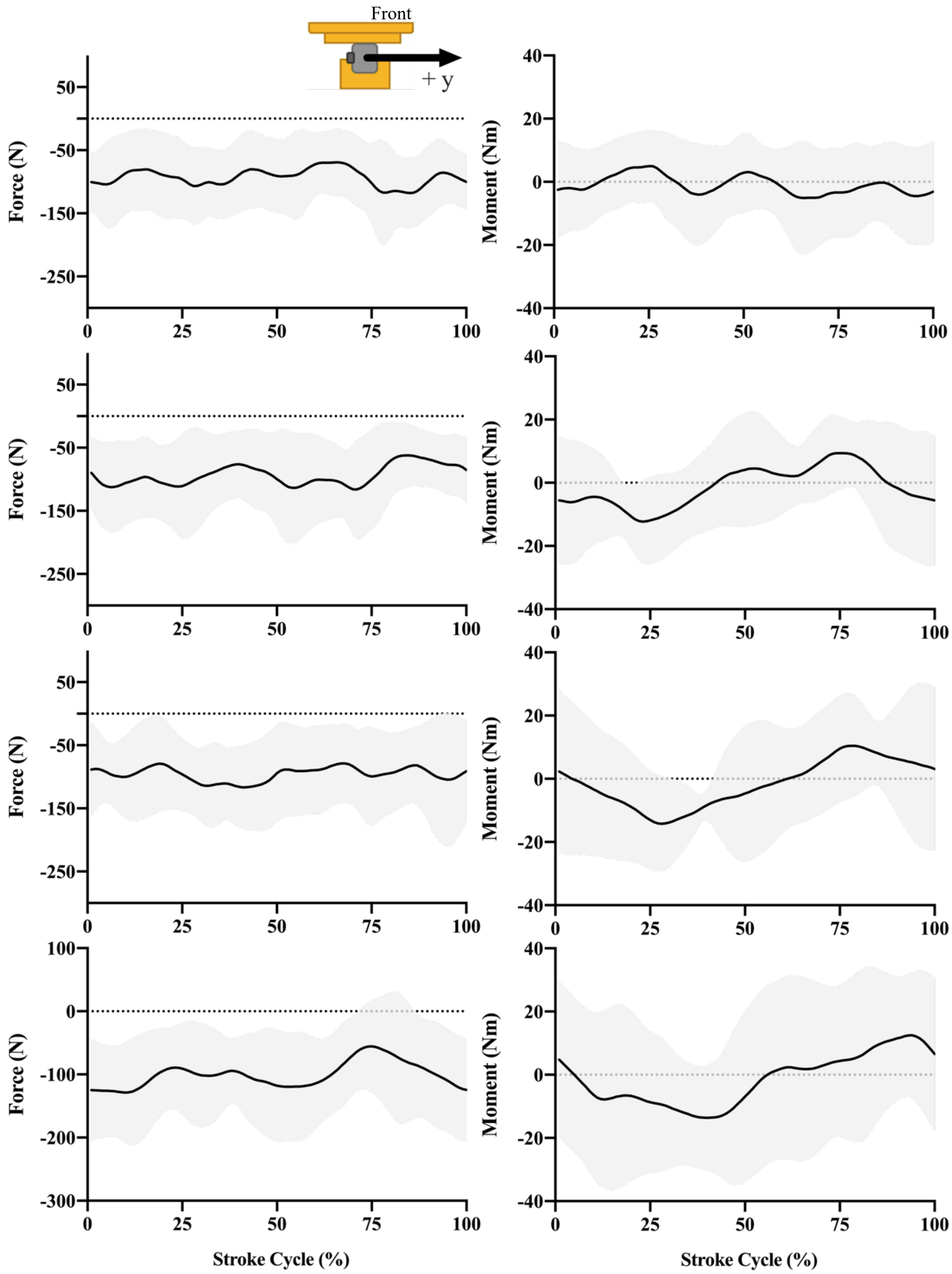

Figure 20. Grand ensemble averages of the seat's anteroposterior axis forces and moments. Forces are presented on the left and moments are presented on the right at 60 strokes per minute (spm; A, B), 80 spm (C, D), 100 spm (E, F), and maximum spm (G, H) in the ergometer global coordinate system.

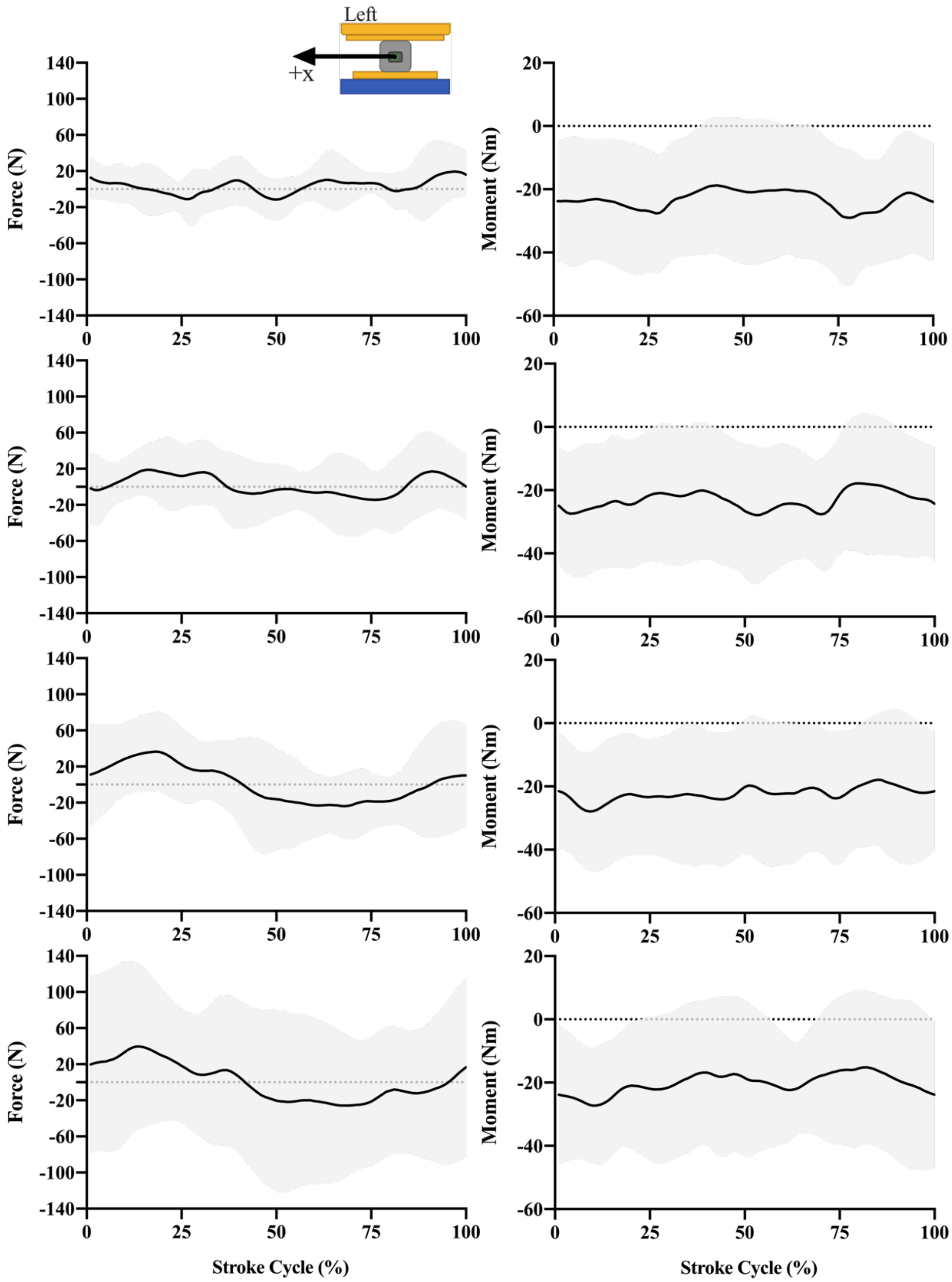

Figure 21. Grand ensemble averages of the seat's lateral axis forces and moments. Forces are presented on the left and moments are presented on the right at 60 strokes per minute (spm; A, B), 80 spm (C, D), 100 spm (E, F), and maximum spm (G, H) in the ergometer global coordinate system.

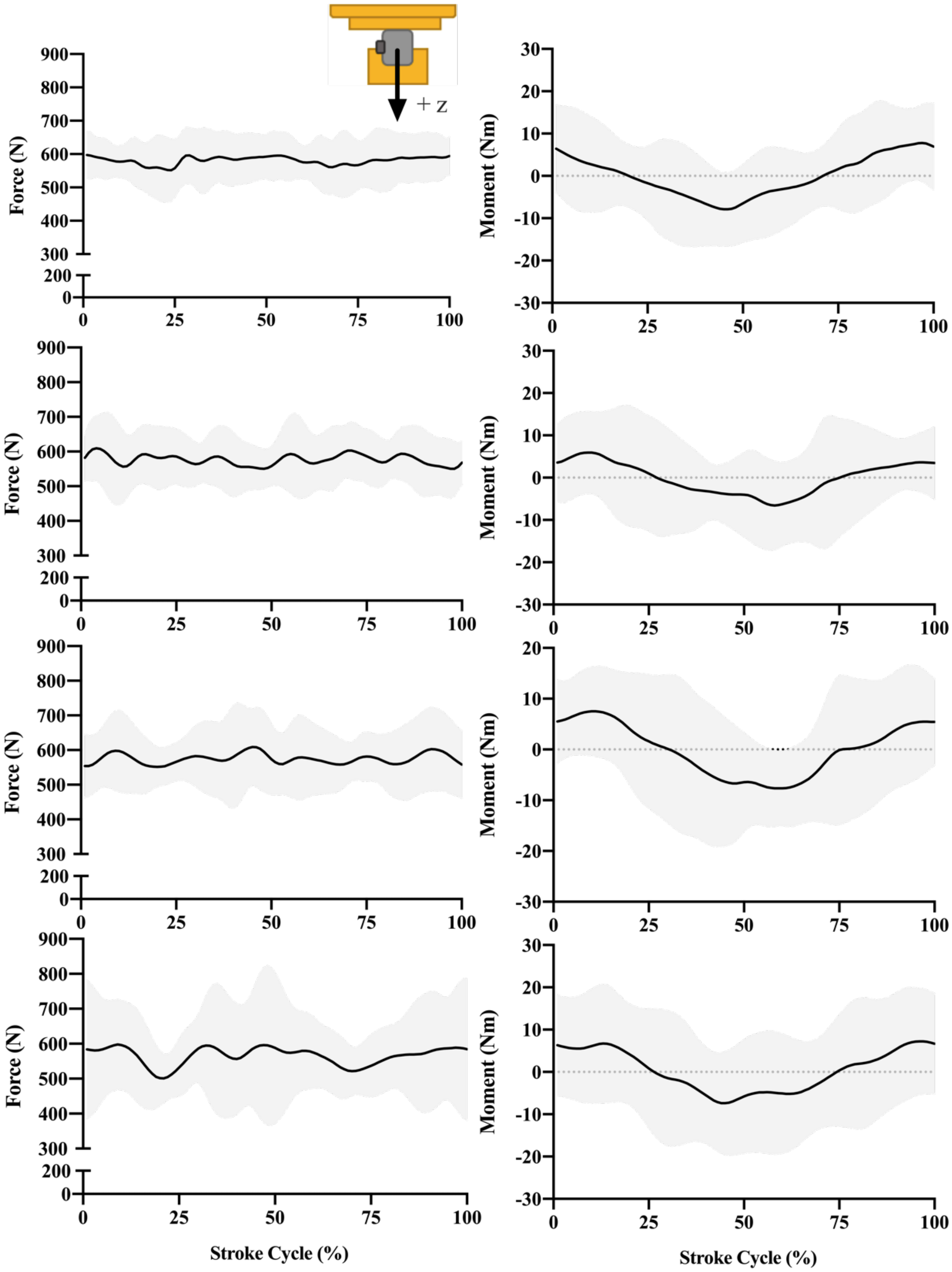

Figure 22. Grand ensemble averages of the seat's vertical axis forces and moments. Forces are presented on the left and moments are presented on the right at 60 strokes per minute (spm; A, B), 80 spm (C, D), 100 spm (E, F), and maximum spm (G, H) in the ergometer global coordinate system.

The magnitude of the seat roll moments decreased as the stroke rate increased (Figure 23 - B).

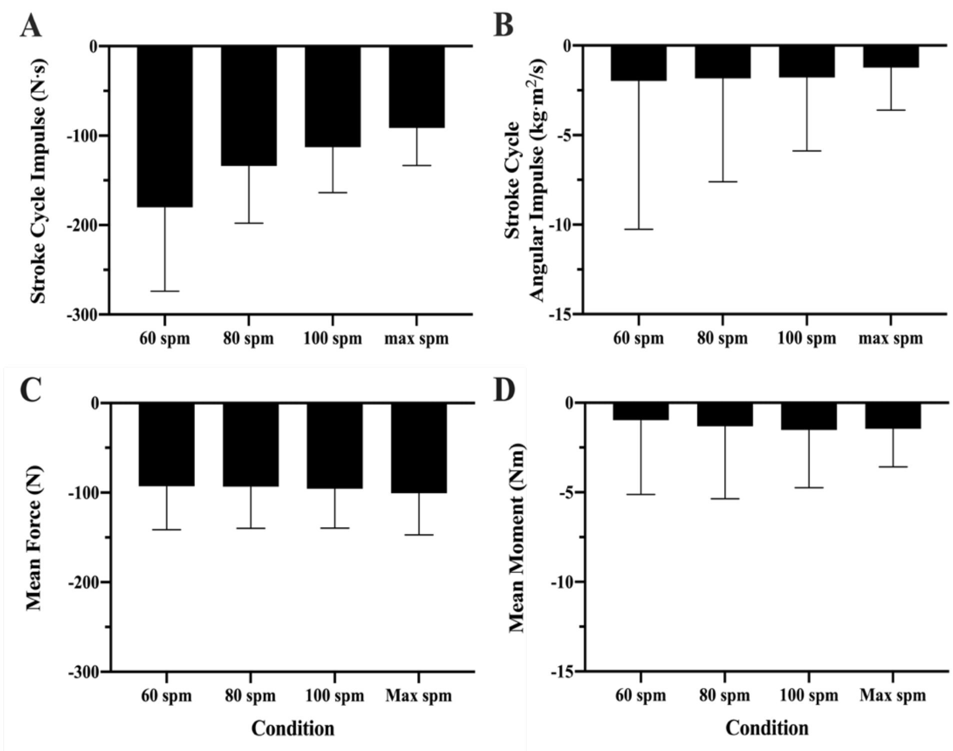

Figure 23. Average seat linear and angular impulse and force and moments on the anteroposterior axis. (A) anteroposterior total stroke cycle impulse, (B) pitch total stroke angular impulse, (C) average anteroposterior force, (D) average roll moment (ergometer global coordinate system). These are demonstrated at the four stroke rate conditions. *Note.* strokes per minute, spm

The seat lateral TSI was observed to decrease with stroke rate increases (Figure 24 - A). While the seat pitch TSAI was relatively constant between 60 spm to 100 spm, it was observed to be lowest at maximum spm (Figure 24 - B). The average footboard lateral forces were observed to decrease as stroke rate increased (Figure 18- C).

The seat lateral forces increased as stroke rate increased, while no pattern in the seat roll moment as a function of stroke rate was observed (Figure 24). Appendix G contains the discrete measure values for the footboard and seat forces and moments on the lateral axis (Table 9).

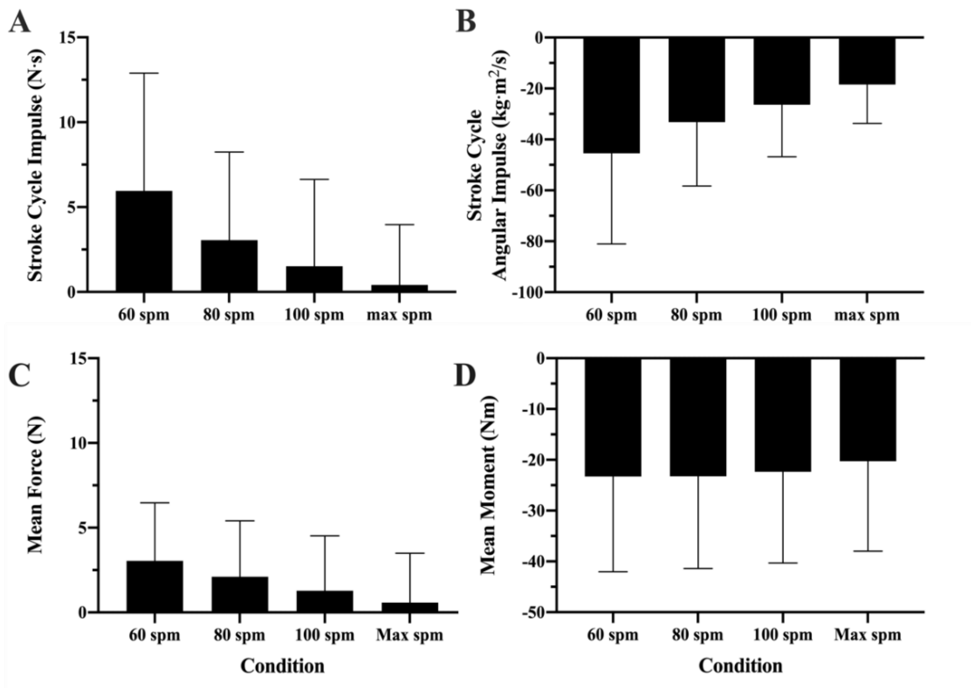

Figure 24. Average seat linear and angular impulse and force and moments on the horizontal. (A) horizontal total stroke cycle impulse, (B) roll total stroke cycle angular impulse, (C) average horizontal force, (D) average roll moment (ergometer global coordinate system). These are demonstrated at four stroke rate conditions. *Note.* strokes per minute, spm

The seat yaw moment TSAI increased as stroke rate increased, but these TSAIs measurements were small in magnitude (-0.0182 – 0.388 Ns; Figure 25- B).

The average seat vertical forces underwent little change as stroke rate increased (Figure 25 – C), and the seat pitch moments were greatest at maximum spm (Figure 25 - D). Appendix G contains the discrete measure values for the footboard and seat forces and moments on the vertical axis (Table 10).

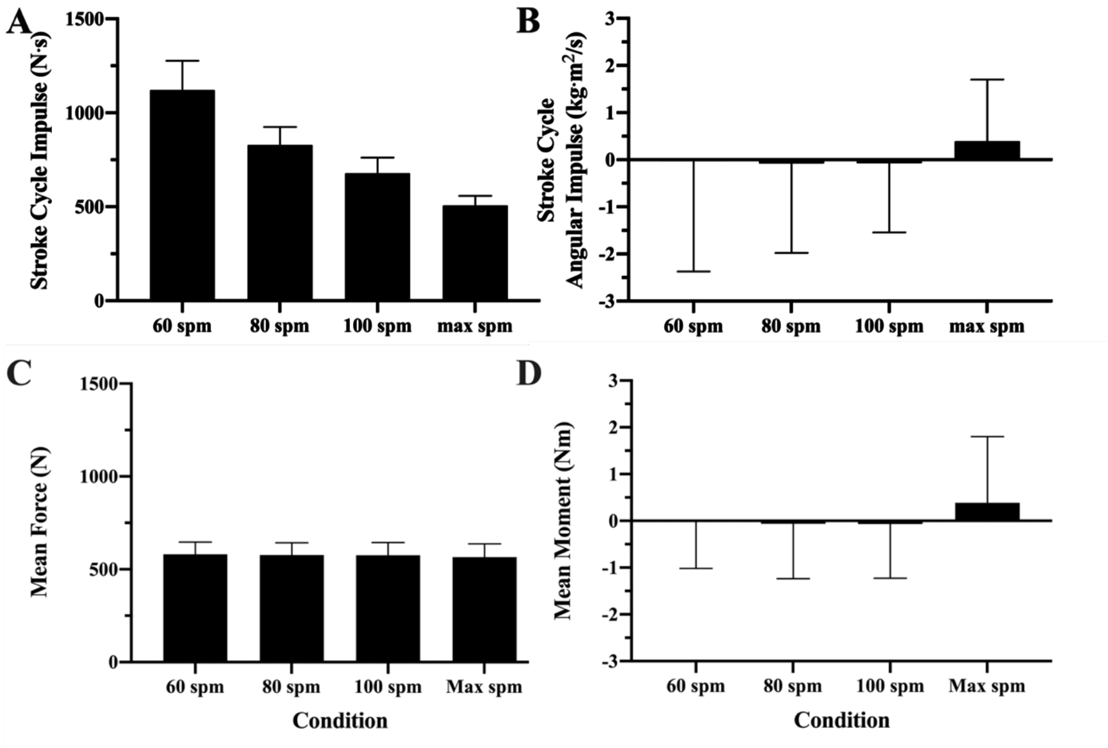

Figure 25, Average seat linear and angular impulse and force and moments on the vertical axis. (A) vertical total stroke cycle impulse, (B) pitch total stroke cycle angular impulse, (C) average vertical force, (D) average pitch moment (ergometer global coordinate system). These are demonstrated at the four stroke rate conditions. *Note.* strokes per minute, spm

6.3 Characterization of the footboard and seat Center of Pressure

The COP data is presented in the footboard and seat local coordinate systems. Participant’s 1, 4, and 8 average COP across a stroke cycle in the combined footboard and seat are illustrated in Figure 26. Participant’s 1, 2, and 9’s COP were observed to primarily stay on the left side of the combined footboard.

Participant 1, 4, and 8’s x- and y-axis COP locations in the combined footboard as a function of stroke cycle are shown in Figure 27 and Figure 28, respectively. Participants 4 and 8’s footboard x-axis COP was observed starting on the left side and oscillating to the right side (Figure 27). The participants range of seat x-axis COP values increased with stroke rate (Figure 28).

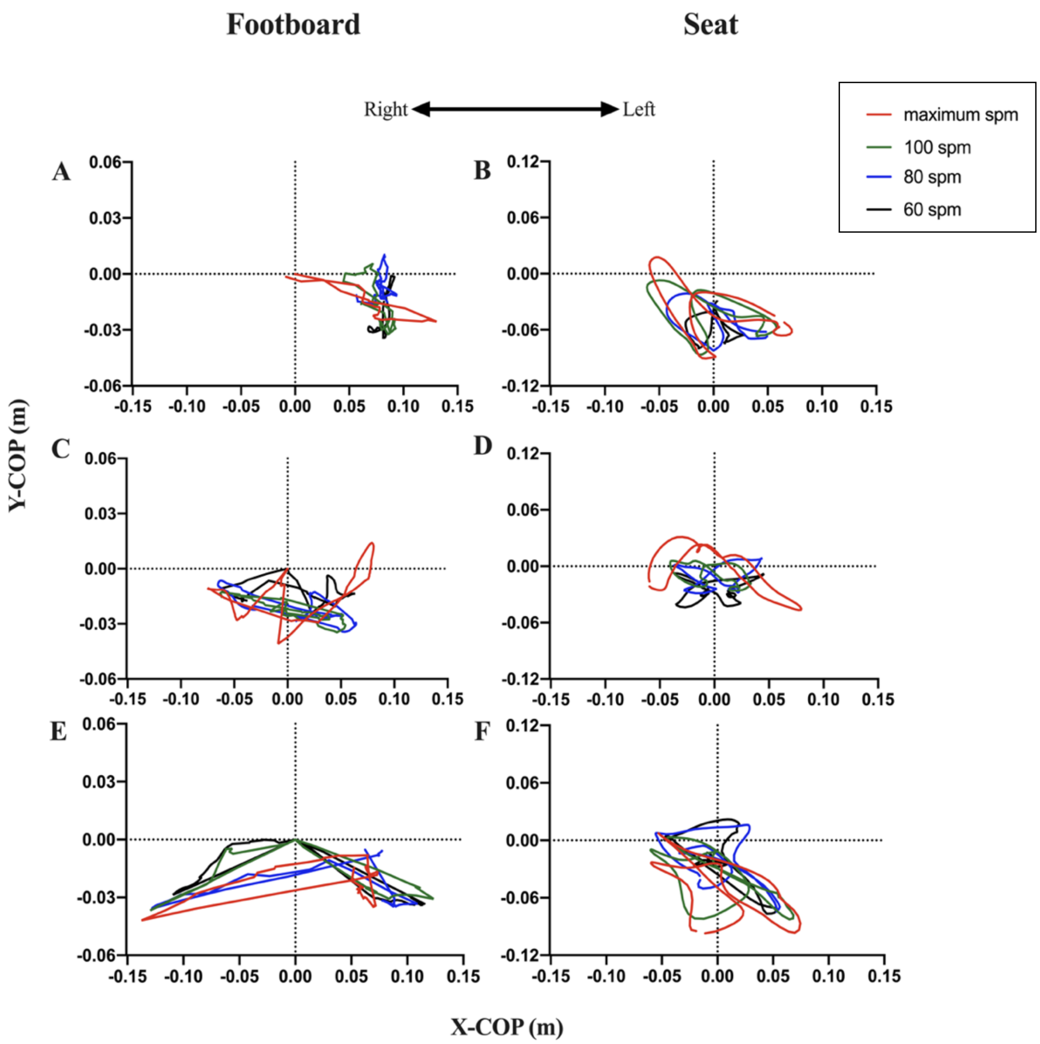

Figure 26. Footboard and seat center of pressure as a function of stroke cycle. Participant's 1 (A-B), 4 (C-D), and 8's (E-F) averaged center of pressure across 10 stroke cycles in the footboard (left) in the combined footboard coordinate system and in the seat (right) global coordinate system, respectively. Some participants favoured one side, where the others' center of pressure location oscillated between the left and right sides. Note: the axes are set within the parameters of the combined footboard and seat dimensions. On the footboard x-axis, positive is left and negative is right, where the y-axis, positive force is up, and negative is down. On the seat x-axis, positive is left and negative is right, where on the y-axis, positive is anterior and negative is posterior.

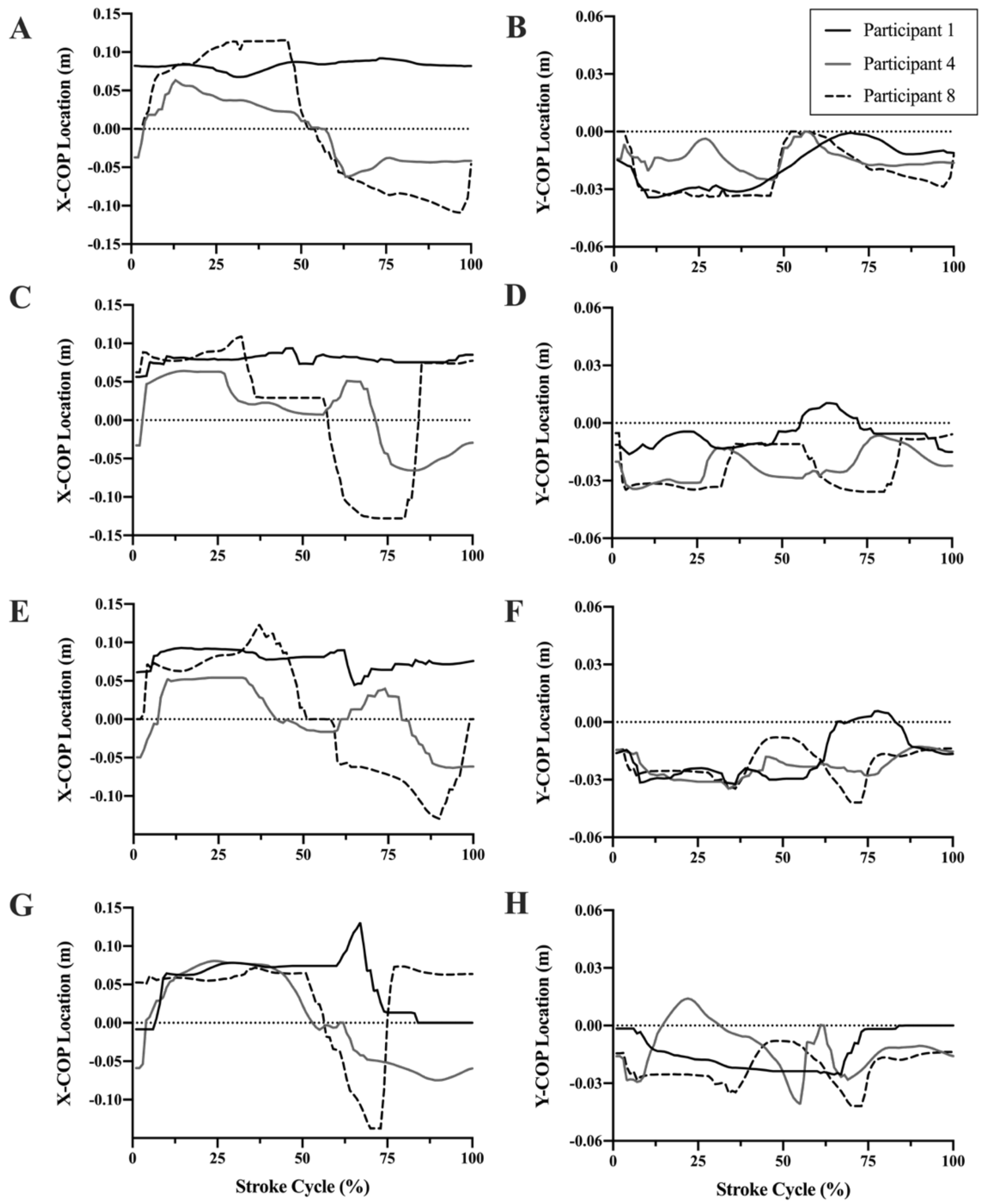

Figure 27. Combined footboard center of pressure x- and y- coordinates at different stroke rates. The center of pressure X- (left) and Y- (right) components are presented at 60 strokes per minute (spm) (A-B), 80 spm (C-D), 100 spm (E-F), and maximum spm (G-H). *Note:* for the x-axis, positive is left and negative is right, for the y-axis, positive force is up and negative is down.

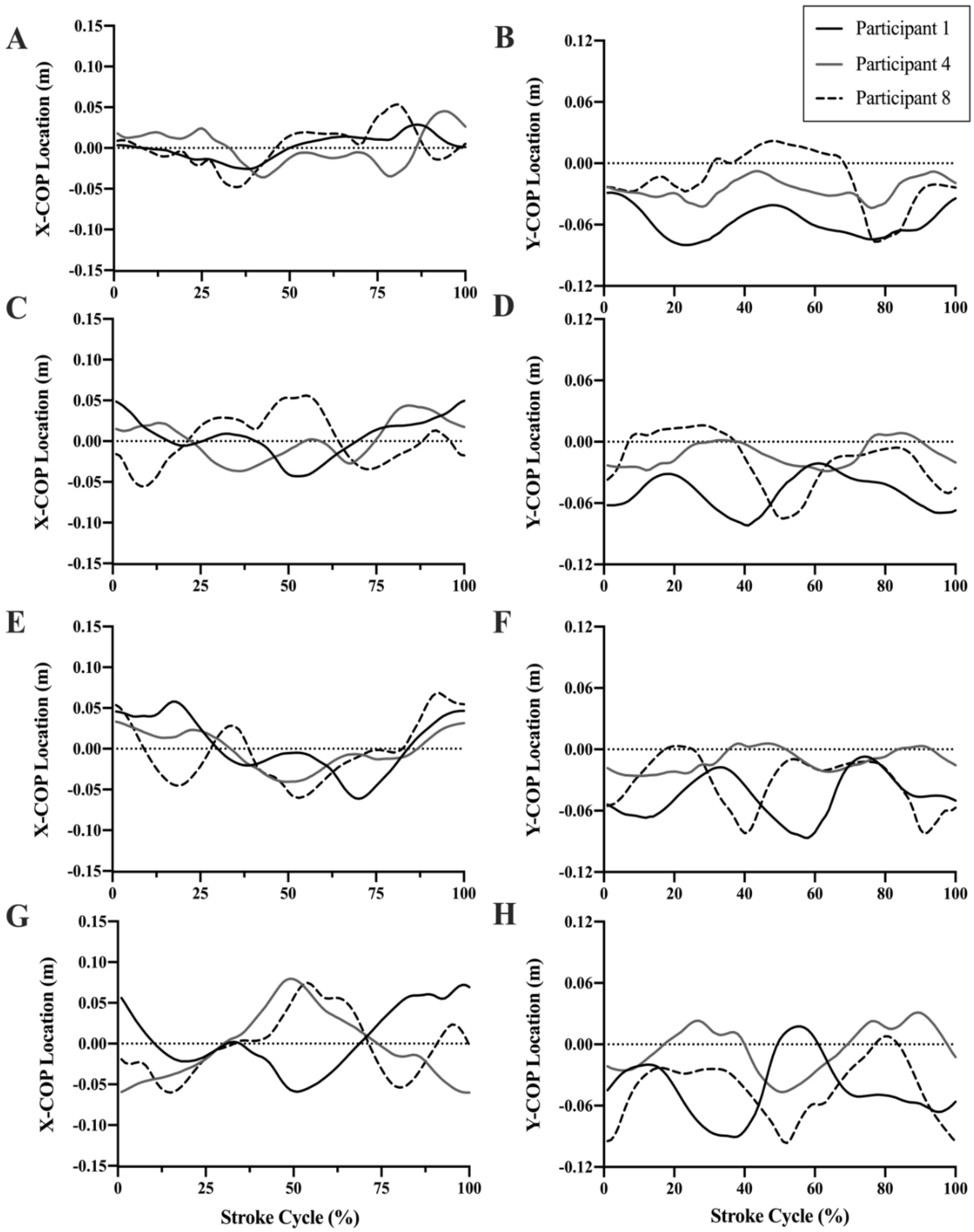

Figure 28. Seat center of pressure x- and y- coordinates at different stroke rates. The center of pressure X- (left) and Y- (right) components are presented at 60 strokes per minute (spm; A, B), 80 spm (C, D), 100 spm (E, F), and maximum spm (G, H) (Footboards' local coordinate systems). *Note.* On the x-axis, positive is left and negative is right, where the y-axis, positive is up, and negative is down.

6.4 Asymmetry Index

Table 5 presents the number of outliers removed from each ANOVA. The ASIs are presented in the ergometer global coordinate system, and are separated into the anteroposterior, lateral, and vertical axis. The longitudinal axis represents the anteroposterior axis, which characterizes the push and pull forces and the roll moment in the footboard and seat. The lateral axis presents the lateral force and pitch moments in the footboard and seat. The vertical axis presents the vertical forces and yaw moments in the footboard and seat.

Table 5. Number of identified outliers removed during repeated measures ANOVAs.

	Force			**Moment**	
	Total Stroke Cycle Impulse				
	Anteroposterior	*Lateral*	*Vertical*	*Roll*	*Yaw*
Feet	1	2	4	0	0
Seat		0		0	0
	Mean				
	Anteroposterior	*Lateral*	*Vertical*	*Roll*	*Yaw*
Feet	0	0	0	0	0
Seat		1		0	0
	Center of Pressure				
	x-axis location				
Feet	2				
Seat	3				

Note. Analysis of variance, ANOVA
In total stroke cycle impulse and mean in global ergometer system; center of pressure in local footboard and seat coordinate system.

6.4.1 Asymmetries Along the Mediolateral Axis

This section will summarize the effect of stroke rate on the ASI of variables related to the mediolateral axis: footboard force, footboard TSI, seat force, and seat TSI using statistical measures.

The effect of stroke rate on the ASI of the footboard average mediolateral force was tested. The data was normally distributed with the exception of the 100 spm condition (Shapiro-Wilk: 100 spm (W(3) = 0.824, $p = 0.0268$); no outliers were removed). A significant main effect of stroke rate was found (Friedman's: $\chi^2(3) = 15.60$, $p = 0.0014$, $r = 0.52$) with significantly higher ASI for the maximum spm in comparison to the 60 spm condition (Dunn's post hoc analysis: 77.6 ± 29.5 % vs 15.1 ± 4.2 %, respectively, $p = 0.0008$).

The effect of stroke rate on the ASI of the footboard mediolateral TSI is presented in Figure 29 - A. The data was normally distributed with the exception of the 100 spm condition (Shapiro-Wilk: 100 spm (W(3) = 0.822, $p = 0.0268$); no outliers were removed). A significant main effect of stroke rate was found (Friedman's: $\chi^2(3) = 15.60$, $p = 0.0014$, $W = 0.52$) with significantly higher ASI for the max spm compared to the 60 spm condition (Dunn's post hoc analysis: 77.6 ± 49.5 % vs 15.1 ± 4.2 %, respectively, $p = 0.0008$).

The effect of stroke rate on the ASI of the seat average mediolateral force was tested. The data was not normally distributed (Shapiro-Wilk: 80 spm (W(3) = 0.800, $p = 0.0202$) and 100 spm (W(3) = 0.814, $p = 0.0296$); no outliers were removed). A Friedman's ANOVA revealed that stroke rate did not have a significant main effect on the ASI of the seat average mediolateral force ($\chi^2(3) = 4.680$, $p = 0.1968$, $W = 0.16$).

The effect of stroke rate on the ASI of the seat mediolateral TSI is presented in Figure 29 -D. The data was normality distributed with the exception of the 60 spm condition (Shapiro-Wilk: 60 spm (W(3) = 0.812, $p = 0.0032$); no outliers were removed). A significant main effect of stroke rate on the ASI of the seat mediolateral TSI was found ($\chi^2(3) = 10.68$, $p = 0.0136$, $W = 0.36$). A Dunn's post hoc analysis revealed a significantly higher ASI at 80 spm (24.6 ± 10.9 %) when compared to maximum spm (10.5 ± 4.9 %; $p = 0.0194$).

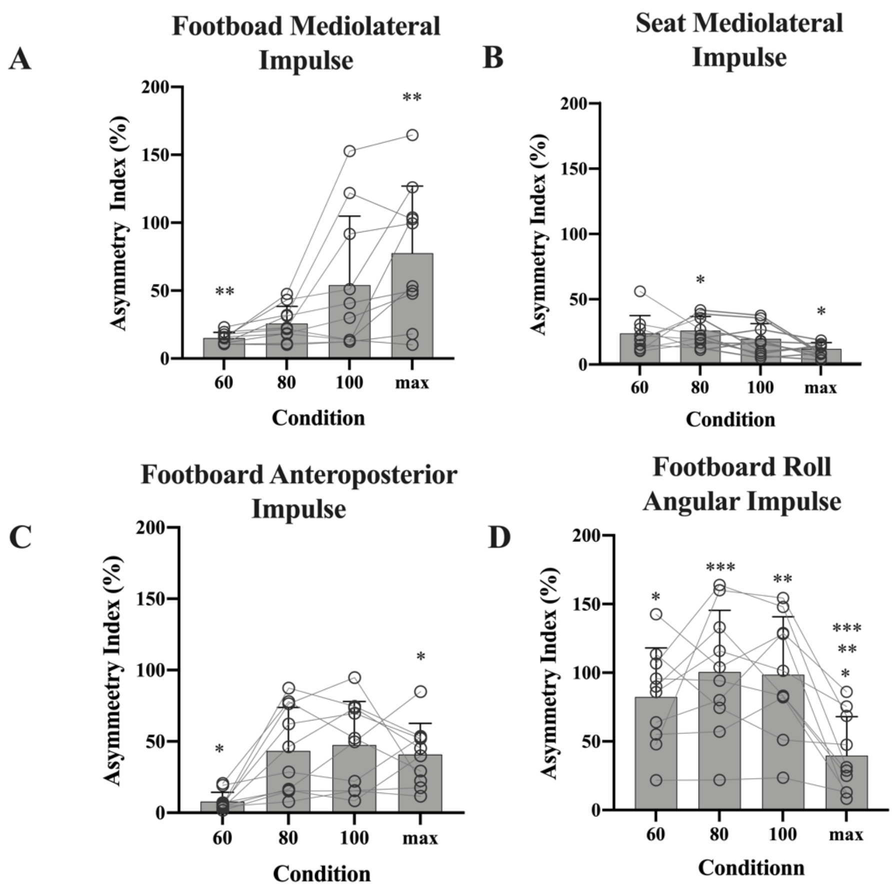

Figure 29. Stroke cycle had a significant effect on total stroke cycle impulse (TSI) and total stroke cycle angular impulse (TSAI). (global coordinate system) This graph represents individual participant TSI, and TSAI asymmetry indexes (ASI) (circles) compared to the group means and standard deviations (bars). (A) Stroke rate had a significant effect on mediolateral TSI ASI in the footboard, where ASI increased with stroke rate, (B) stroke rate had a significant effect on mediolateral TSI ASI in the seat, where 80 spm demonstrated the highest ASI of the four conditions, and the ASI decreased from 80 – maximum spm, (C) stroke rate had a significant effect on anteroposterior TSI ASI in the footboard, where ASI increased until 100 strokes per minute (spm) and then slightly decreased at maximum spm, (D) stroke rate had a significant effect on roll TSAI ASI in the footboard, where ASI was lowest at max spm. * $p < 0.05$, ** $p < 0.005$, *** $p < 0.0005$

6.4.2 Asymmetries Along the Anteroposterior Axis

This section will summarize the effect of stroke rate on the ASI of variables related to the anteroposterior axis: footboard force, footboard TSI, footboard roll moment, footboard roll TSAI, seat roll moment, and seat roll TSAI.

The effect of stroke rate on the ASI of the average footboard anteroposterior force was tested. The data was normally distributed (Shapiro-Wilk: 60 spm (W(3) = 0.9356, p = 0.508), 80 spm (W(3) = 0.876, p = 0.118; 100 spm (W(3) = 0.910, p = 0.278), max (W(3) = 0.946, p = 0.627); no outliers were removed), and it violated the assumption of sphericity (Mauchly's test: (χ2(5)= 0.132,1 p=0.009)), therefore, a Greenhouse-Geisser correction was applied (ε = 0.648). A RM ANOVA was used and found no main effect of stroke rate (F(1.95,17.51) = 0.34; p = 0.788, $\eta^2_{partial}$ = 0.025) was identified. This was confirmed using a Friedman's ANOVA (χ^2(3) = 2.760, p = 0.430, W = 0.092).

The effect of stroke rate on the ASI of the footboard anteroposterior TSI is presented in Figure 29 - B. The data was normally distributed (Shapiro-Wilk: 60 spm (W(3) = 0.950, p = 0.711), 80 spm (W(3) = 0.869, p = 0.148) 100 spm (W(3) = 0.8825, p = 0.199), max (W(3) = 0.941, p = 0.621); two outliers were removed), and the data did not violate the assumption of sphericity (Mauchly's test: (χ2(5)= 0.31,1 p =0.111)). A RM ANOVA was used and found a main effect of stroke rate (F(3,21) = 7.190; p = 0.0017, $\eta^2_{partial}$ = 0.51). A Tukey's post-hoc analysis showed a significant difference between the 60 spm cadence and all the other conditions (60 spm: 4.8 ± 1.7 %, 80 spm: 41.0 ± 31.4 %, 100 spm: 50.2 ± 33.0 %, max spm: 40.9 ± 23.9 %; 60-80 spm: p = 0.0129, 60-100 spm: p = 0.0017, 60-max: p = 0.0131). These results were confirmed with a Friedman's ANOVA, χ^2(3) = 18.480, p = 0.0004, W = 0.62 and a Dunn's multiple comparison (60-80 spm: p = 0.0032, 60-100 spm: p = 0.0008, 60-max spm p = 0.0109).

The effect of stroke rate on the ASI of the footboard average roll moment was tested. The data was normally distributed (Shapiro-Wilk: 60 spm (W(3) = 0.985, p = 0.995), 80 spm (W(3) = 0.975, p = 0.932), 100 spm (W(3) = 0.953, p = 0.708), max (W(3) = 0.981, p = 0.970); no outliers were removed) and did not violate the assumption of sphericity (Mauchly's: ($\chi 2(5)$= 0.395, p=0.211)). A RM ANOVA was performed, and no significant main effect of stroke rate was found (F(3,27) = 1.38; p = 0.271, $\eta^2_{partial}$ = 0.046). These results were confirmed using a Friedman's ANOVA ($\chi^2(3)$ = 1.800 p = 0.615, W = 0.06).

The effect of stroke rate on the ASI of the footboard roll TSAI is presented in Figure 29 - C. The data was normally distributed (Shapiro-Wilk: 60 spm (W(3) = 0.988, p = 0.993), 80 spm (W(3) = 0.974, p = 0.928), 100 spm (W(3) = 0.950, p = 0.668), max (W(3) = 0.894, p = 0.191)); no outliers were removed) and did not violate the assumption of sphericity (Mauchly's test: $\chi 2(5)$= 0.672, p=0.691). A RM ANOVA was performed, and a significant effect of stroke rate was found (F(3,27) = 8.58; p = 0.0004, $\eta^2_{partial}$ = 0.49). A Tukey's post-hoc analysis showed a significant difference between the max spm cadence and all the other conditions (60 spm: 82.3 ± 35.5 %, 80 spm: 100.5 ± 44.8 %, 100 spm: 98.4 ± 42.2 %, max spm: 39.6 ± 28.2 %; max-60 spm: p = 0.0204, max-80 spm: p = 0.0007, max-100: p = 0.0011). These results were confirmed with a Friedman's ANOVA ($\chi^2(3)$ = 13.1, p = 0.0045, W = 0.62). A Dunn's multiple comparison revealed a significant difference between the max spm condition and the two intermediate conditions (80- max: p = 0.0060; 100- max p = 0.0194). The lowest ASI of the footboard roll TSAI was observed at maximum stroke rate (39.6 ± 28.2 %) when compared with 60 spm (82.3 ± 35.5 %), 80 spm (100.5 ± 44.8 %), and 100 spm (98.4 ± 42.2 %).

There was no statistically significant effect of stroke rate on the ASI of the average seat roll moment. The data was normally distributed with the exception of the 60 spm condition (Shapiro-Wilk: 60 spm (W(3) = 0.826, p = 0.00304 and 80 spm (W(3) = 0.840, p = 0.0441); no outliers were removed). No significant main effect of stroke rate was found ($\chi^2(3) = 0.840$, p = 0.840, W = 0.028).

The effect of stroke rate on the ASI of the seat roll TSAI was tested. The data was normality distributed with the exception of the 60 spm condition (Shapiro-Wilk: 60 spm (W(3) = 0.779, p = 0.0081); no outliers were removed). No significant main effect of stroke rate on the ASI of the seat roll TSAI was found ($\chi^2(3) = 1.320$, p = 0.724, W = 0.044). The seat roll TSAI ASI was also lowest at maximum spm (24.7 ± 11.1%) when compared to 60 spm (49.5 ± 44.0 %), 80 spm (44.7 ± 33.8 %), and 100 spm (30.8 ± 13.41 %), but these values were not significantly different.

6.4.3 Asymmetries Along the Vertical Axis

This section will summarize the effect of stroke rate on the ASI of variables related to the vertical axis: footboard force, footboard TSI, footboard yaw moment, footboard yaw TSAI, seat yaw moment, and seat yaw TSAI.

The ASI of the footboard mean vertical force showed no effect from stroke rate. The data was normally distributed (Shapiro-Wilk: 60 spm (W(3) = 0.930, p = 0.449), 80 spm (W(3) = 0.908, p = 0.269), 100 spm (W(3) = 0.945, p = 0.615), max (W(3) = 0.960, p = 0.788); no outliers were removed) but violated the assumption of sphericity (Mauchly's test: χ2(5)= 0.251, p=0.060), therefore, a Greenhouse-Geisser correction was applied (ε = 0.698). A RM ANOVA found no significant main effect on the ASI

($F(2.095,18.85) = 0.240$; $p = 0.798$, $\eta^2_{partial} = 0.026$). This was confirmed using a Friedman's ANOVA ($\chi^2(3) = 2.040$, $p = 0.564$, $W = 0.068$).

The ASI of the footboard vertical TSI showed no effect from stroke rate. The data was normally distributed (Shapiro-Wilk: 60 spm ($W(3) = 0.970$, $p = 0.894$), 80 spm ($W(3) = 0.943$, $p = 0.683$), 100 spm ($W(3) = 0.893$, $p = 0.334$), max ($W(3) = 0.924$, $p = 0.532$); four outliers were removed) and did not violate the assumption of sphericity ($\chi2(5)= 0.703$, $p = 0.744$). A RM ANOVA was performed and found that stroke rate had no significant main effect on the ASI ($F(3,15) = 1.788$; $p = 0.1926$, $\eta^2_{partial} = 0.25$). A Friedman's ANOVA was completed and confirmed these results ($\chi^2(3) = 6.840$, $p = 0.0772$, $W = 0.23$).

The ASI of the average footboard yaw moment showed no effect from stroke rate. The data was normally distributed (Shapiro-Wilk: 60 spm ($W(3) = 0.855$, $p = 0.0663$), 80 spm ($W(3) = 0.853$, $p = 0.0635$), 100 spm ($W(3) = 0.894$, $p = 0.188$), max ($W(3) = 0.909$, $p = 0.275$); no outliers were removed) and did not violate the assumption of sphericity (Mauchly's test: $\chi2(5)= 0.412$, $p = 0.235$). A RM ANOVA found no significant main effect of stroke rate on the ASI ($F(3,27) = 0.589$ $p = 0.627$, $\eta^2_{partial} = 0061$). This was confirmed using a Friedman's ANOVA ($\chi^2(3) = 3.240$, $p = 0.356$, $W = 0.11$).

The ASI of the footboard yaw TSAI showed no effect from stroke rate. The data was normally distributed (Shapiro-Wilk: 60 spm ($W(3) = 0.8548$, $p = 0.0659$), 80 spm ($W(3) = 0.817$, $p = 0.0609$), 100 spm ($W(3) = 0.894$, $p = 0.191$), max ($W(3) = 0.910$, $p = 0.273$); no outliers were removed) and did not violate the assumption of sphericity (Mauchly's test: $\chi2(5)= 0.395$, $p = 0.212$). A RM ANOVA found no significant main effect of stroke rate on the ASI ($F(3,27) = 0.608$ $p = 0.616$, $\eta^2_{partial} = 0.062$). This was confirmed using a Friedman's ANOVA ($\chi^2(3) = 3.240$, $p = 0.356$, $W = 0.11$).

The ASI of the average seat yaw moment showed no effect from stroke rate. The data was normally distributed with the exception of 60 spm (Shapiro-Wilk: 60 spm ($W(3) = 0.812$, $p = 0.0203$); no outliers were removed). No significant main effect of stroke rate on the ASI of the average seat yaw moment was found using a Friedman's ANOVA ($\chi^2(3) = 0.360$, $p = 0.9484$, $W = 0.12$).

The ASI of the seat yaw TSAI showed no effect from stroke rate. The data was normally distributed with the exception of 60 spm (Shapiro-Wilk: 60 spm ($W(3) = 0.818$, $p = 0.00241$); no outliers were removed). No significant main effect of stroke rate on the ASI of the seat yaw TSAI was found using a Friedman's ANOVA ($\chi^2(3) = 2.52$, $p = 0.472$, $W = 0.084$).

6.4.4 Center of Pressure

The effect of stroke rate on the ASI of the combined footboard x-axis COP area was tested. The data not normally distributed at 60 spm and 80 spm (Shapiro-Wilk 60 spm ($W(3) = 0.748$, $p = 0.0077$) and 80 spm ($W(3) = 0.814$, $p = 0.0408$); no outliers were removed). A Friedman's ANOVA was used to test the ASI of the combined footboard x- axis COP area on ten participants and showed no main effect of stroke rate condition on ASI ($\chi^2(3) = 1.277$, $p = 0.7347$, $W = 0.043$).

The effect of stroke rate on the ASI of the seat x-axis COP area was tested. The data was found to be not normally distributed at 80 spm and 100 spm (Shapiro-Wilk 80 spm ($W(3) = 0.768$, $p = 0.0059$) and 100 spm ($W(3) = 0.868$, $p = 0.0944$); no outliers were removed). A Friedman's ANOVA found no significant effect of stroke rate on ASI ($\chi^2(3)$=2.010, p = 0.5641, W = 0.068).

A summary of the asymmetry analyses (calculated p-values) is presented in Table 6.

Table 6. The effect of stroke rate on the asymmetry index in the footboard and seat

Force Application Point	Axis	ASI Outcome Measures				
		Mean Force	COP	Mean Moment	TSI	TSAI
Footboard	Anteroposterior	0.788		0.271	0.0017*	0.0004*
	Lateral	0.0014*			0.0014*	
	Vertical	0.564		0.672	0.193	0.616
	x-axis		0.735			
Seat	Anteroposterior			0.840		0.724
	Lateral	0.197			0.0136*	
	Vertical			0.472		0.124
	x-axis		0.291			

Note. *, significant result; asymmetry index, ASI; center of pressure, COP; total stroke cycle impulse, TSI; total stroke cycle angular impulse, TSAI
If a RM ANOVA and Friedman's ANOVA were calculated then only the RM ANOVA p-value was presented, where if only a Friedman's ANOVA was calculated, then the p-value in this table was representative of the Friedman's ANOVA p-value.

6.5 Individual Differences

Participants 4, 5, 7, and 10s' ASI in the seat mediolateral TSI increased as stroke rate increased, where this was not observed with the rest of the participants (Figure 29– A). This can also be observed in seat average roll moments for participants 2, 3, and 6 (Figure 30), Two ASI patterns as a function of stroke rate were present in the ASI of the average seat roll moment. Participants 2, 3, 6, and 10 were observed to start at higher ASIs relative to the others and then their ASIs decreased as stroke rate increased.

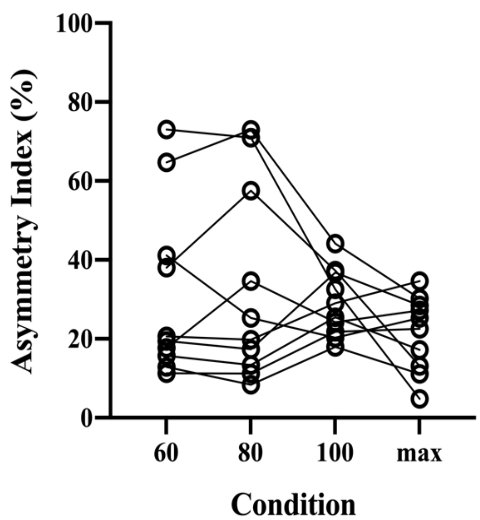

Figure 30. Individual's average roll moments in the seat across a stroke cycle during four stroke rate conditions. There are two patterns of asymmetry presented throughout this condition. Participants who start with a higher asymmetry index and decrease as stroke rate increases and participants who show no consistent pattern with stroke rate.

Chapter 7: Discussion

The purpose of this work was to determine if stroke rate influences paddle, footboard, and seat kinetic asymmetries on a sprint kayak ergometer. The first aim of this work was to characterize the paddle, footboard, and seat kinetic patterns while paddling on an instrumented kayak ergometer at different stroke rates using qualitative measures. The second aim of this work was to establish if paddling at different rates changes the asymmetries of selected discrete kinetic variables acting on the paddle, footboard, and seat.

The first aim was met through the acquisition of paddle, footboard, and seat forces and moments. A One Giant Leap (Port Nelson, Nelson) force paddle was used to measure forces and three AD2.5D load cells (Watertown, MA) to measure three-dimensional forces and moments from individual footboards and the seat. However, due to fixed and proportional bias, the paddle force data was excluded from data analysis (Appendix D). The footboard forces and moments have been reported in their local coordinate system, as well as in the ergometer global coordinate system. Lastly, the seat forces and moments were reported in the ergometer global coordinate system.

The second aim was met by comparing the ASI of selected discrete kinetic measurements in the footboard and seat at four stroke rate conditions (60 spm, 80 spm, 100 spm, and maximum spm). Stroke rate had a significant effect on ASIs on the mediolateral ($p < 0.005$, increases with stroke rate) and anteroposterior TSI in the footboard ($p < 0.01$, increases with stroke rate), roll TSAI in the footboard ($p < 0.0005$, inverted U-relationship with stroke rate), and mediolateral TSI in the footboard ($p < 0.05$, decreases with stroke rate; Figure 29), as well as on average lateral footboard force ASI ($p < 0.005$, increase with stroke rate).

This work adds to the current literature by characterizing the footboard and seat lateral and vertical forces, in addition to the pitch, roll, and yaw moments over different stroke rates. It provides guidance on expected footboard and seat forces and moments in sprint kayakers and their kinetic asymmetries. To date, few studies have measured the footboard and seat forces in the anteroposterior plane (16,58,74,80), and no studies have reported kinetic asymmetries in the kayak footboard and seat.

7.1 Footboard and Seat Force and Moment Acquisition

A novel acquisition system was used for the purposes of this study. Previous work has only measured footboard and seat forces in the anteroposterior direction (16,58,75,80), while the present work was able to measure three-dimensional forces and moments. Three AMTI AD2.5D (Watertown, MA) load cells were used, including one 1000 lbs range load cell and two 500 lbs range load cells. The calibration of the load cell was tested using known weights prior to data acquisition (Appendix F), and the base tare of the load cells was tested following data acquisition (Appendix E). These methods demonstrated the system's ability to measure in stationary environments and that hysteresis following data collections was not present, respectively.

The 1000 lbs load cell was used to measure seat forces and instrumented so that the vertical axis was perpendicular to the kayak ergometer platform (Figure 9; Figure 10). The group maximum magnitude of the reported forces in the seat were measured at 844.6 ± 163.36.1 N in the vertical direction, -240.3 ± 71.2 N in the anteroposterior direction, and 134.7 ± 41.9 N in the lateral direction in the load cell's local coordinate system, which were within the capability of the system used.

The 500 lbs load cells were used to measure foot forces and instrumented so that the vertical axis was perpendicular to the kayak ergometer footboard platform (Figure 9; Figure 10). The maximum reported forces in the left footboard were measured at 443.02 ± 151.78 N on the z-axis, 150.22 ± 59.75 N on the y-axis, and 57.87 ± 24.05 N in the x-axis on the lateral direction in the load cells' local coordinate system, which were within the capability of the system used. The maximum reported forces in the left footboard were measured at 434.58 ± 151.78 N on the z-axis, 148.43 ± 42.37 N on the y-axis, and 51.53 ± 16.16 N in the lateral direction on the x-axis in the load cells' local coordinate system, which were within the capability of the system used.

During this study we were able to collect data on a wide variety of athletes, including elite male kayakers and young female kayakers, demonstrating the capability of this system to acquire on various skill levels. The results collected in this study show the feasibility of this system to collect in a controlled environment on a kayak ergometer but suggest the capability to collect on water. In this case, certain modifications would need to be made to the system to better waterproof the load cells and stretch the wires between the kayak boat and a secondary boat holding the data acquisition system.

7.2 Force and Moment Characteristics

The first aim of this work was to characterize the forces and moments acting at different points on the kayak ergometer by using grand ensemble averages, in addition to discrete measures (maximum, minimum, mean, range, total stroke cycle impulse, push phase impulse, aerial phase impulse, and COP area) in the kayaking footboard and seat

(Appendix G). This work observed that kayak mean anteroposterior footboard force increases and its stroke cycle waveform changes shape as stroke rate increases, mean roll moment decreases as stroke rate increases, and that small differences in force production can be found between genders (see discussion below). In addition, kayak average footboard z-force was observed to increase (Figure 16), while average roll moment decreased as stroke rate increased (Figure 16).

7.2.1 Anteroposterior Forces

In this work, the anteroposterior forces (the push and pull force) in the footboard contributed the greatest amount of force to the resultant footboard forces. This was expected because the anteroposterior footboard forces are in the direction of movement. Average anteroposterior footboard forces were observed to slightly increase as stroke rate increased. This is a result greater peak forces (Appendix G; Table 8) and the forces staying closer to peak force for longer periods at higher stroke rates (Figure 16). Rowing ergometer handle and footboard forces (46,123) and kayaking paddle net forces (35,36) have been found to increase as stroke rate increases, so it was surprising to see such a small change in anteroposterior footboard force as stroke rate increased as one would assume greater forces are produced at higher stroke rates.

Specifically, the shape of the anteroposterior force-time curve became more rounded near peak force and covered a greater percentage of the stroke cycle with an increase in stroke rate (Figure 16), which is also consistent with other paddle and oar force waveform findings (1,19,26,28–30,35,36,46,103,123). This has been observed in two other studies measuring kayaking paddle force-time profiles (35,36). The optimal kayak paddle force profile is suggested to be rectangular, where the force immediately spikes to peak force and continues at this rate until the exit phase, where the force drops (decreases) (1) as this maximizes the possible impulse per stroke. It could be expected that a more rectangular force-time profile in the footboard would coincide with a more rectangular paddle force profile. The findings in this work suggest that athlete's footboard forces become closer to a rectangular shape at higher stroke rates. It is likely that the athletes use footboard forces to create greater pulling forces at the paddle and to assist in the stabilization of the boat when on-water. Athletes would benefit from learning to increase the anteroposterior impulse in the footboard at higher stroke rates by applying greater forces at the initiation and completion of the footboard push phase in order to enhance performance.

As stroke rate increases, a greater overlap between left and right anteroposterior footboard forces was observed (Figure 16). This indicates that athletes push with both the left and right forces simultaneously during specific phases of the stroke cycle. The simultaneous pushing forces could be used to counteract an imbalance in paddle forces or may be a result of the athlete not being strong enough to counter the contralateral paddle forces with solely one lower limb. This pattern was particularly prominent at maximum stroke rate and is likely why the left footboard anteroposterior forces increased with stroke rate, while no observable relationship between the right footboard mean anteroposterior forces and stroke rate was present.

The increase in anteroposterior forces with stroke rate could also result from the athlete rotating their pelvis more anteriorly to increase footboard force production with increasing stroke rates. The average (Figure 18) and peak (Appendix G) pitch moments with increasing stroke rates suggest that the athlete presses on the footboard with a more anteriorly rotating moment, and decreasingly posteriorly rotating moments in the seat, where at maximum spm, the average posteriorly rotating moment is a positive value (Figure 25). The anteriorly rotating average pitch moments in the footboard are unsurprising due to the anteriorly rotated angle of the footboard relative to the direction the athlete presses on it. In addition, with an anteriorly rotating average pitch moment in the seat at maximum, it suggests that the athlete could be either more anteriorly seated on their seat or that they are rotating further forward in their hips to increase the force produced using the lower body.

Anteroposterior left and right footboard forces were observed to have different magnitudes but have similar waveform shapes (Figure 16) when compared with the vertical left and right footboard forces, when measured in the footboard local coordinate system (Figures 1; Figure 5, respectively). This is likely a result of the angle of the footboard, which is -64.65° compared to the ergometer platform. As the athlete pushes and pulls along the anteroposterior axis in the global coordinate system, some of the pushing and pulling forces the athletes exerted on the footboard are translated into the vertical forces. Therefore, it could be predicted that the anteroposterior and vertical footboard waveforms were similarly shaped.

The magnitude of anteroposterior seat forces in this study were found to range between -240 N and -0.2 N, which is different from the anteroposterior minimum and peak seat forces (-94 - 301 N) reported by Begon et al. (80), where anterior force in both studies was denoted by a positive force. The differences in measures stem from this group using a sliding ergometer, an ergometer that's footboard and seat slide in the anteroposterior direction on near frictionless rollers. The quick changes of direction of the footboard and seat in the anteroposterior plane during the catch and exit phase would cause additional forces, as the inertia of the athlete (opposing the direction of movement of the footboard and seat) would cause a momentary spike in force. The results found in this study likely differ as a static ergometer was used in the present work.

7.2.2 Footboard and Seat Moments

The moments in the footboard and seat have not yet been quantified in sprint kayaking. This work was able to measure three-dimensional moments on a kayak ergometer and show them at different stroke rates. The average pitch, roll, and yaw moments in the footboard and seat have been reported, along with other discrete measures in Appendix G.

Peak and minimum roll and yaw moments were found to be close in magnitude. Peak seat roll moments were found between 21.3 Nm and 38.2 Nm in the seat during the four stroke rate conditions, while minimum roll moments were found between -24.6 Nm to -37.2 Nm at different stroke rates, which are similar in magnitudes. The same relationship between peak and minimum yaw moments was also observed. The differences in the value's sign denote the direction of the moment. A positive roll moment denotes a rightward roll moment, and negative value a leftward roll moment, while a positive yaw moment denotes a rightward moment, and a negative denotes a rightward moment. During the kayak stroke cycle, the hips rotate both on the anteroposterior and lateral plane simultaneously, and symmetry in movement between the left and right sides in the lower body is desirable. Therefore, it was expected that the values of the peak and minimum roll moments would be close in magnitude.

The peak pitch moments did not demonstrate the same relationships between the peak (-8.9 to 4.3 Nm) and minimum (-39.8 – -42.2 Nm) in magnitude at different stroke rates when compared with the roll and yaw moments peak and minimum magnitude relationships. Anteriorly rotating pitch moments were measured as positive signs, while posteriorly rotating pitch moments were measured as negative signs. These results imply that kayak athletes sit slightly posterior to the center of the seat when on a kayak ergometer during stroke rate conditions, apart from maximum stroke rate. Sitting posterior to the center of the seat throughout the entirety of the stroke cycle would cause negative peak and minimum pitch moments to be measured.

It was noteworthy that the peak pitch moment during the maximum stroke rate condition was anteriorly rotating, while the peak and minimum pitch values were measured as posterior moments at all other stroke rate conditions. This suggests that athletes either adjust their seating position when paddling at a maximum stroke rate by sitting more anteriorly on the seat, or they possibly flex further through their hips, shifting their center of mass forward. The additional flexion in their hips would create a greater radius of rotation. At higher stroke rates, having a greater radius of rotation in combination with the greater limb movement velocities would increase the angular momentum. In addition, the anteriorly rotated pitch moment during the maximum stroke rate condition could also be a result of the athlete reaching further during the catch phase, increasing the pitch moment arm.

Conversely, more negative minimum pitch moments were found at maximum stroke rate when compared with all other stroke rate conditions. This implies that athletes draw the paddle and rotate their shoulder past the center of the seat and lean further backwards at maximum stroke rates. The increase in posterior trunk and arm movements would create a larger moment arm in the posterior direction, then creating a more negative pitch moment. The posterior shoulder and arm movement is more likely the cause of the negative pitch moments than an increase in force, as the average lateral force that contributes to the pitch moment was observed to decrease at highs stroke rates.

7.3 Gender Differences in Forces and Moments

The men were observed to create greater forces than women; for example, their average anteroposterior footboard forces were greater than those of the women in this study (Figure 31). However, it was interesting to note that women were observed having greater average combined footboard roll moments when compared with the men (Figure 31). As well, greater average lateral combined footboard forces were observed in the women from 80 to maximum spm when compared to the men (Figure 32).

Differences in gender mean force and moment production were observed in this work, both men and women were observed to follow similar trends with stroke rate, but

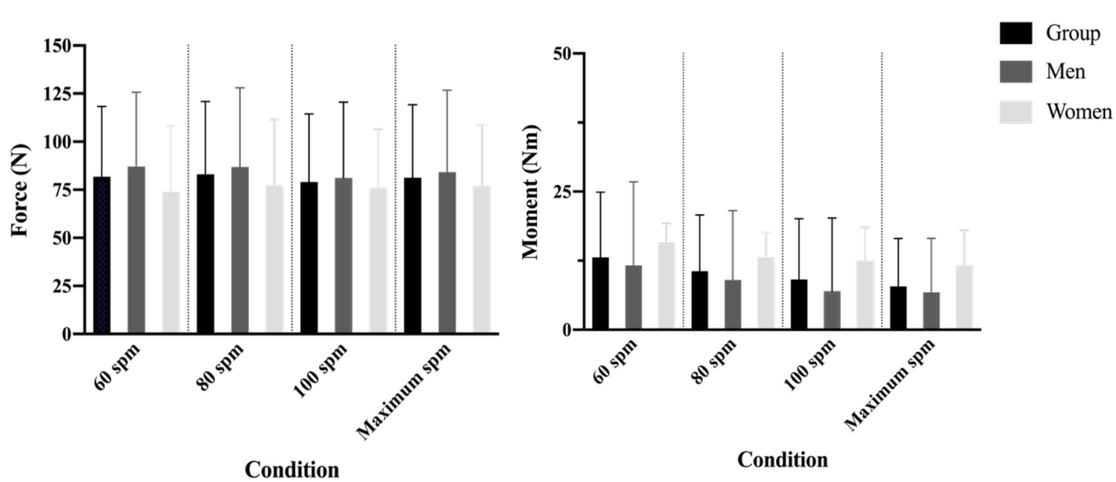

Figure 31. Group, men's, and women's average stroke cycle anteroposterior forces (left) and roll moments (right) across four stroke conditions.

differences in the absolute output of force and moments. For example, men were noted to achieve higher average lateral and anteroposterior footboard forces, where women often achieved higher roll moments (Figure 31).

It was anticipated that the men would produce higher forces when compared with the women, as the men in this study were taller and weighed more on average, suggesting a greater muscle mass, given the athletic population sampled in this work. As well, men are known to have higher maximum force and impulse production capabilities than women (124–126). Therefore, differences in force production between men and women are unsurprising. However, it was interesting to note that higher roll moments were observed for the women when compared to the men. This might be a result of the lower experience level of the women in this study. Roll moments would increase the drag forces as a result of increasing the amount of boat orientation roll while on the water (52). These results could also show a gender-specific difference in technique that has not yet been identified due to no previous studies having measured this metric yet.

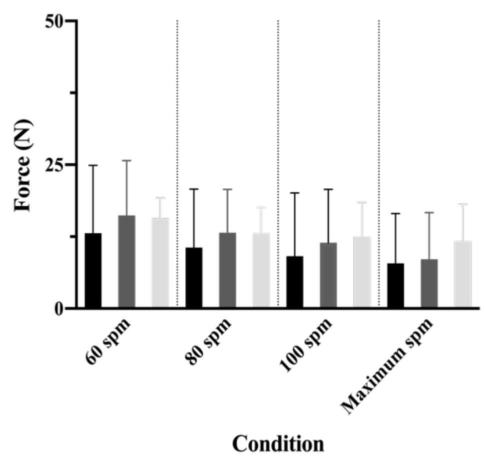

Figure 32. Group, men's, and women's average stroke cycle lateral forces across four conditions.

7.4 Asymmetry Index

It was hypothesized that kayaking ASIs would decrease as stroke rate increased since this has been found in other sports (19,24,26,28–30,102,103). This hypothesis was found to be too broad and should have focused on forces and moments that have a large impact on the performance of kayaking athletes (i.e., anteroposterior forces, roll moments, and yaw moments). For example, roll and yaw have a greater impact on the drag forces experienced while kayaking on the water (9), and would be more important to focus on than the pitch moment. The findings of this work show that the average lateral TSI and average force in the footboard ASI increase as stroke rate increases (Figure 29), where the seat mediolateral TSI in the footboard ASI decreases as stroke rate increases (Figure 29). As well, the anteroposterior TSI in the footboard ASI increases as the stroke rate increases.

This work found that stroke rate influences average, impulse, and angular impulse ASIs, specifically, the ASIs in the mediolateral and anteroposterior footboard impulse, roll angular footboard impulse, mediolateral seat impulse, and average mediolateral force and roll moment in the footboard. In addition, it was surprising to see that anteroposterior TSI ASI increased as stroke rate increased, as previous studies have shown the opposite trend (100).

7.4.1 Anthropometric Measures and Asymmetry Indexes

The present work did not find anthropomorphic asymmetries within the sample population. Contrasting results have been found on the effect of anthropomorphic asymmetries on force production (97,127). Longman et al. (127) suggest that anthropometric asymmetries result in movement adaptations to account for output inefficiencies. They suggest this this inefficiency would require an additional amount of effort on the inefficient side, then requiring more effort when completing a race. If these adaptations are developed over a lifetime, there is a possibility that the individual has adapted to optimize their movements based on their own anthropology, as suggested by the concept of self-organization (101). In addition, these asymmetries have been suggested to be a part of the developmental stability of an organism, the ability of an organism to adapt based on environmental and/or genetic disturbances (97). Furthering that there is a possibility anthropomorphic asymmetry may not result in force asymmetries.

7.4.2 Asymmetries on Mediolateral Forces

The mediolateral left and right footboard forces were measured to have lateral forces on both the left and right sides, suggesting that the lateral forces are used to counter the paddle forces. On the ergometer, the paddle is attached to the flywheel via a rope connection. At this connection point, there would be a singular force vector in the direction of the rope, where the pulley system attempts to maintain constant tension between the paddle and the flywheel, and the rope is angled towards the center of the ergometer during the aerial phase. In addition, the ergometer is suggested to apply tension through all aerial phases of the stroke cycle (57), which is not present in on-water kayaking (8,35). As stroke rate increases, the rate at which the flywheel spins, increases. This causes an increased anterior-medial pulling force between the paddle and the ergometer via the rope. This force would need to be counteracted elsewhere in the boat athlete system.

The footboard is likely being used to compensate for asymmetrical forces in the paddle. It was found that stroke rate had a significant effect on the mediolateral footboard TSI ASI ($p < 0.005$), where the ASI increases as the stroke rate increases (Figure 29 - A). The stroke rate also had a significant effect on the ASIs of the average mediolateral seat forces, but in contrast, the ASI decreased with increases in stroke rate ($p < 0.0005$; Figure 29 - D). Larger footboard lateral forces (7.4 – 26.2 N; Figure 18) were observed when compared with the seat lateral forces (0.5 – 6.9 N; Figure 24 - C). With small seat force asymmetries at high stroke rates, it is likely that the footboard is used to counteract the opposing paddle forces as no other propulsive or drag forces are present in the athlete-boat system.

7.4.3 Roll and Yaw Moment Asymmetry and Stroke Rate

On the water, the footboard force application is often used to keep the boat displacing linearly through the water (80). Athletes have a greater control over the linear and angular displacements of the boat through the footboard, when compared with the seat. On ergometers, the athletes' feet are directly connected to the footboard via thick cloth straps, while the athlete has no direct connection to the seat. As well, the individual foot locations on the footboard have a greater radius of gyration when compared with the seat, as they are located further from the center of rotation in both the anteroposterior and lateral planes. Having a larger radius of gyration in the footboard allows the athlete to create a greater moment with the use of less force than would be needed to create the same moment about the seat. As a result, athletes will likely have consciously or subconsciously developed a pattern of controlling the boat's linear and angular movements through the footboard while on water. This learned pattern of movement and force application is likely transferred into ergometer kayaking and can be observed in the lateral forces and moments observed in this work and their ASIs at different stroke rates.

In this work, the average roll moment ASI was observed to have an inverted U-relationship with stroke rate ($p < 0.01$; Figure 29 - C), where the ASI was the smallest at maximum stroke rate ($p < 0.0005$). In kayaking, a sport in which athletes must keep their center of gravity over a narrow boat shell, the roll and yaw moments have a greater effect on the hydrodynamic drag force than the pitch moment (1,9). This is because roll and yaw moments greatly increase the amount of the boat's wetted surface area, which increases drag forces (9). The finding that the average roll moment ASI reduced is at high stroke rates supports the idea that the athletes consciously or subconsciously decrease the roll moment to optimize their movements by decreasing the drag forces.

Athletes tend to be more efficient as they approach their racing speeds, so it is foreseeable that athletes have a more efficient stroke at their maximum stroke rate in this work. Mo et al. (100) demonstrated how competitive runners' asymmetry was lowered with increasing speeds and their form became more symmetrical than that of novice and recreational athletes. The competitive runners have likely optimized their running technique at higher speeds and cadences to be able to improve performance. This demonstrates the ability for elite athletes to adapt their technique to be more efficient at higher speeds. This has also been demonstrated in rowing, where athletes produced lower handle force asymmetries at higher stroke rates (19,26,102,103), and in cycling where higher cadences have been associated with lower ASIs (24,28–30).

Stroke rate did not have a significant effect on yaw TSAI in the footboard ($p = 0.8685$) or seat ($p = 0.8399$) ASI and the average footboard yaw moment ($p = 0.3651$).

However, the observable waveforms suggest the potential presence of a relationship muted by large standard deviations. Athletes were observed decreasing their footboard and seat roll and yaw TSAI as stroke rate increased (footboard: Figure 18, Figure 19; seat: Figure 24, Figure 25, respectively). However, large standard deviations were present, suggesting a decreased the significance of the effect of stroke rate on yaw TSAI ASI. This may be corrected if larger samples sizes or more focused (i.e., only elite athletes) samples sizes were used.

The standard deviation between participants in the seat roll TSAI ASI was observed to be lowest at maximum spm and that the standard deviation of the footboard roll TSAI ASI was lowest at maximum spm. This work tested on a wide breadth of experience levels; therefore, this could suggest that at higher stroke rates, athletes at a provincial level or higher are more likely to decrease their roll moment regardless of skill level.

7.4.4 Impulse Asymmetry Index Reduction as a Result of High Stroke Rates

Impulse and angular impulse were primarily compared between stroke rate conditions as the measures account for the differences in stroke cycle period that cannot be shown when calculating the average stroke cycle measures. The results in this work show that several TSI, and subsequently TSAIs, decrease as stroke rate increases. Previous literature has shown that as stroke rate increases, the overall impulse in a singular stroke cycle decreases (35,36,128,129). However, creating higher average impulses at a given stroke rate result in higher boat velocities (35,36). Impulse is a product of the force over a given time and, therefore, stroke rate inversely affects impulse

(35). Since the propulsive phase and the aerial phase periods are shorted at higher stroke rates (1,35,36), this result was foreseeable.

Greater intra-cycle forces must be produced throughout the stroke cycle in order to maintain greater impulses (35). Elite athletes regularly spend a small period of their paddle pull phase producing forces smaller than the drag forces (36). Athletes unknowingly do this as an attempt to increase impulse through increasing the time spent in the water phase. However, this becomes an inefficient use of energy as the boat decelerates when the drag forces are greater than the propulsive forces. It has previously been suggested that athletes are better to shorten the time spent in the water phase when the alternative is spending energy creating propulsive forces smaller than those of the drag forces (35).

The results in this work and previous studies demonstrate the importance of measuring net impulse over prolonged periods, rather than force over a specific stroke cycle. The use of force-time curves has been recommended for performance analytics (35). They are useful tools when making technical corrections focused on the maintenance of space under a force-time curve at high stroke rates. Force-time curves are still important when it comes to improving kayaking performance; however, this work suggests the significance of analyzing stroke cycles successively as opposed to individually.

Higher stroke rates have the potential to increase the net impulse. For example, the average impulse during a single stroke cycle in this work was ~138 Ns at 60 spm and ~110 Ns at 100 spm. If one were to calculate the net impulse over a minute, assuming an athlete stayed perfectly at these given stroke rates and TSI, then net impulse over a minute would be 8280 N*min at 60 spm and 11,000 N*min at 100 spm. Athletes should be encouraged to create higher inter-cycle average forces when at higher strokes rates, rather than using higher stroke rates to produce lower forces. Future studies may benefit from analyzing the impulse over a given period (i.e., impulse per minute) to analyze the effect of impulse at certain stroke rates on performance.

Gomes et al. (35) calculated on-water kayak paddle stroke cycle impulses and multiplied it by the stroke rate in 10 elite kayakers paddling. Impulses multiplied by stroke rate were highly correlated with velocity. In addition, athletes were observed to increase their stroke rate to compensate for a decreased TSI. This was performed by creating greater average and peak paddle forces. A similar pattern was observed in this work in the footboard anteroposterior forces. The kayakers in this work were observed decreasing anteroposterior footboard TSI as stroke rate increased while their mean anteroposterior footboard forces slightly increased and their peak anteroposterior footboard forces increased (Figure 29; Appendix G).

7.4.5 Individual Differences

Individual differences were observed in ASI patterns across stroke rates. Some individuals' ASIs were affected by stroke rate and others were not. As seen in Figure 30, data from participants 2, 3, 6, and 10 followed with this work's hypothesis as their average roll moment ASI decreased as stroke rate increased, while the other participants' ASIs showed little change across all four stroke rate conditions. Individual differences in ASI while performing the same task have been observed in several other studies (26,62,91,99,130). Mattes and Wolff (26) suggested that factors such as gender, stroke rate, and physical fatigue affect ASI, where gender and physical fatigue are parameters that affect people individually. In addition, Buckeridge et al. (99) found asymmetries in footboard forces and lower limb kinematics on a rowing ergometer in novice, intermediate, and elite rowers; however, they did find a large inter-subject variability in asymmetry. These results suggest that large variabilities between subjects at all levels of sport exist.

Bini and Hume (62) suggest that ASIs can be present regardless of individual performance level. For example, participants with the fourth and the eighth fastest cycling distance completion times had over a 25 % difference in pedal force ASI, despite the small differences in performances. The present work observed a large variance in experience level between those that followed the typical and atypical ASI stroke rate patterns. Specifically, participants 2 and 10 were both experienced national team members, while participants 3 and 6 were younger provincial team athletes. This suggests that individual differences in ASI can be present regardless of experience.

7.4.6 Footboard Pull Forces

Large differences in pull forces were found both between individuals and within certain individuals' stroke rate conditions. This work has found that some individuals do not pull on the foot straps with one or both feet (Figure 33) and some individuals pulled with one or both feet in some conditions and did not pull in other conditions. The differences in pushing and pulling forces between feet can be observed in the group left and right anteroposterior minimum footboard forces, where minimum anteroposterior forces would be considered the equivalent to peak pulling forces. The differences ranged from 3.7 N to 20.8 N.

The footboard pulling forces are in the direction of the paddle movement and possibly contribute the propulsive forces in the athlete-boat system. It is known that the paddle forces translate through the body and into the boat to create forward propulsion (1), so it is not unreasonable to assume that forces exerted in the footboard can assist with the production of paddle forces. Therefore, it is surprising to see that not all athletes pull on the footboard straps. The lack of pull force by some athletes may be a result of a change in technique used when on the ergometer or that some athletes do not effectively use the footboard straps. Future studies would benefit from measuring the pulling force on water and determining the relationship between pull force and boat velocity.

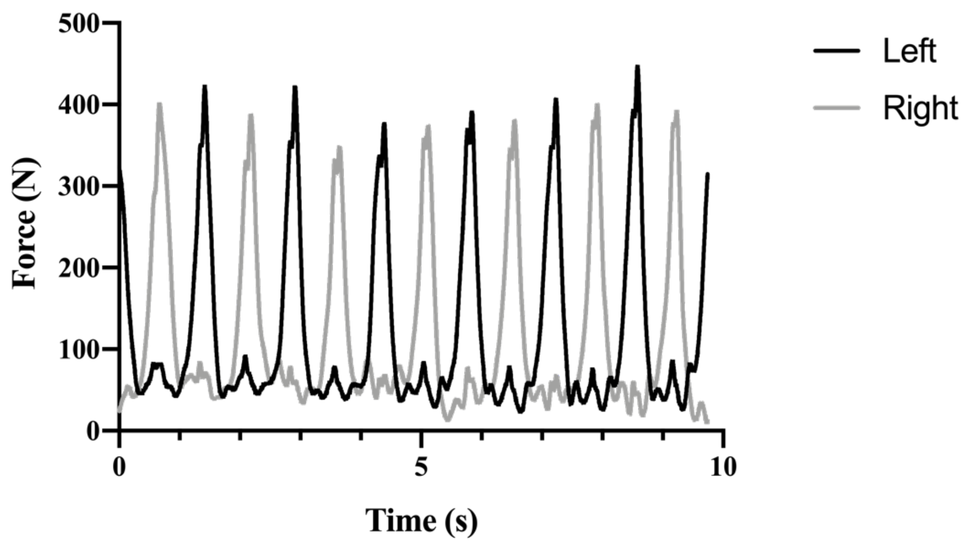

Figure 33. An example of participant 1's anteroposterior footboard forces in the right and left footboards. This athlete did not pull on the footboard, since the footboard forces do not have zero crossings.

7.4.7 Center of Pressure

To date, COP has only been used to characterize the start of a stroke cycle in rowing (66) and has not yet been measured in the kayak footboard or seat. This work calculated the COP to determine if athletes preferentially used one side of the footboard when applying forces, to better understand the relationship between the path of the resultant force and stroke rate. It was found that some individuals favour a certain footboard side, and that the COP is not affected by stroke rate. When individuals favour a side, they could possibly be constantly applying force and not pulling on the opposite side to the favoured one.

Individual differences were also observed in the COP, where participant 1, 2, and 9s' COPs were located entirely on the left side of the footboard, and that participant 10's COPs were predominantly on the left side compared to the right. This is demonstrated in Figure 26 - panel C, where the COP was located entirely on one side in the footboard. When looking at these individuals' normal force asymmetries, participants 1, 2 and 10 had lower asymmetries in the anteroposterior force in the footboard compared to the rest of the group, and participants 2, 9 and 10 had large roll moment asymmetries. These likely played a part in contributing to the one-sided COP.

COP was calculated using a threshold of ± 50 N of normal force and presented as a function of stroke rate, because with the absence of normal force, there is no COP. In this study, there were several times throughout the stroke cycle that no COP location was calculated as the normal force was measured to be within the threshold of ± 50 N. It is possible that, at brief moments in time, the pushing and pulling are equal, creating a couple-moment. This has not yet been reported in the kayaking literature.

7.5 Assumptions and Limitations

The low sample size in this work resulted in lower calculated effect sizes in the post hoc analyses. For example, the small effect sizes calculated by the RM ANOVAs for ASI of the roll TSAI ($\eta^2_{partial} = 0.06$) and moderate effect size from the Friedman's ANOVA for ASI of the mediolateral seat impulse ($r = 0.356$) make the magnitude of the stroke rate relationship on these measures less impactful. The small sample size also created a large standard deviation, due to the large variation in experience level and the differences in gender. This group was comprised of two national team, three junior national team, and five junior provincial team athletes, creating large variations in technique and maximal force production capabilities. In addition, women have been shown to have higher asymmetry levels then men in both adults and juniors (26,131,132), thus possibly contributing to the size of the standard deviation in this study.

This study assumes that ergometers are similar to on-water kayaking. However, the mechanical ecological validity of ergometers is not fully understood. This has the potential to present differences in results when compared to on-water kayaking and should be considered when analyzing them.

For three trials across 10 individual and four stroke rate conditions, the seat was moved and not tared prior to initiation. The data from these trials were post-processed to remove any existing bias by determining the noise within these trials when the athlete was not sitting on the seat (Appendix E).

The paddle forces were not reported in this study due to both proportional bias and heteroscedasticity that could not be corrected using a log transformation of the raw data. This limits the findings, as some assumptions have been made about the effect of the paddle kinetics on the footboard and seat kinetics. As well, the ergometer paddle had blades on it for all trials as the One Giant Leap® (Port Nelson, Nelson) was used for testing. This could have caused small changes in the athlete's kinematics as this is not the normal set-up of an ergometer.

This study presents a unique situation, in that those who identified as men were more experienced than those who identified as women. Two of the six men were national team paddlers and one of the six was on the junior national team, where two of the four women had been on the Junior Pan-American team. The differences in experience between the two genders could possibly affect the results when comparing genders.

A non-directional ASIs was calculated. By using a non-directional ASI calculation, the limb dominance is ignored by removing the identity of the dominant limb. This limits the present work's ability to identify patterns between specific side imbalances and performance and reduces the clinical relevance.

7.6 Future Direction of Research

This research showed that stroke rate affects ASIs in the footboard mediolateral and anteroposterior TSI, footboard roll TSAI, and seat mediolateral TSI. These results suggest that, as stroke rate increases, paddle force asymmetries increase, and the footboard forces are used to counter them. As well, the paddle, footboard, and seat forces and moments have also not been measured simultaneously while kayaking on the water. The next step would be to instrument a paddle to measure paddle forces and moments in combination with the footboard and seat forces and moments to confirm these findings and to determine how they apply while kayaking on the water. The seat and footboard forces and moments are not well understood in kayaking, especially not in the lateral and vertical plane. It would greatly benefit the current body of literature on kayaking if these forces and moments were related to measures of performance, such as boat velocity and power.

The low statistical power in the RM ANOVA on roll TSAI requires further investigation to determine if stroke rate affects this measure. Future studies should focus on investigating paddle, footboard, and seat forces and moments for larger sample sizes to ensure a strong statistical power. It would also be beneficial to sample from a large sample size with different experience levels to determine if asymmetry in paddling is related to level of sport, or if the correction of asymmetries can lead to improvement in performance in high-level athletes. If not a larger sample size, it might be beneficial to normalize forces and moments to body weight. For example, the two individuals with the largest mass in this study had the greatest vertical forces and some of the largest roll forces. By normalizing measures to weight, it would allow for a more standardized comparison between the participants to better understand if these measures are a result of their force production or their individual anthropometrics.

Future studies should include kinematic data collection to be able to identify the stroke cycles using the paddle. Kinematic would also assist in the understanding of body and limb positionings' effect on stroke kinetics.

As well, the similarities between on-water and ergometer kayaking are not well understood. Studies in rowing (129,133,134) have shown that kinetic differences between ergometer and on-water sport are different. In kayaking, Fleming et al. (57) measured differences in the paddle forces during the recovery phase, but little research has been done comparing the paddle, footboard, and seat kinetics similarities between on-water and ergometer kayaking.

This work found that some athletes pull on the footboard, while others do not. It would be interesting to determine if athletes who do not create pull forces on the footboard ergometer do the same on the water to better understand how the pull forces contribute to on water and ergometer performance measures.

7.7 Conclusions

It can be concluded that the mediolateral and anteroposterior footboard total stroke cycle impulse asymmetry indices increase as stroke rate increases, the roll angular impulse ASI has an inverted U-relationship with stroke rate, and that mediolateral seat impulse ASI decreases with increased stroke rate. Due to these results, and the difference in the magnitude of footboard and seat forces and moments counteract each other to maintain the athletes on their seat while on the ergometer.

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Appendix A Informed Consent Process

Informed Consent Process

Using the email script template (Appendix B), an Information Letter with Consent/Assent Form document (Appendix A), a PAR-Q (Appendix C) and a Musculo-Skeletal Health History Questionnaire (Appendix C) will be e-mailed to anyone who contacted a study investigator for review. A child (14-18 years) and adult (19+ years) assent section is included in Appendix C.

The participants (and parents if potential participant is 18 years old or younger) will be encouraged to read all materials beforehand to ensure they meet the inclusion and exclusion criteria. When the participants arrive at the testing site on the testing day, they will be introduced to the investigators who will explain the study design and they will be provided an opportunity to address any questions or concerns they may have. Participants will be reminded of the rationale, purpose and methodology involved with the study, familiarized with all study procedures, the equipment involved, the anticipated time commitments and any risks and discomforts associated with the study. The PAR-Q (Appendix C), and the Musculo-Skeletal Health Questionnaire (Appendix C) will be reviewed without the participants stating overtly their answers. For participants over 18 years of age the consent form will be reviewed and signed before any other actions are taken. For participants aged between 14 and 18 years old, the assent script will be reviewed with parental permission while the parent reviews the consent form (Appendix C).

Steps for when a potential participant aged 18 years and younger enters the testing site are as follows:

- The researcher will ask the parent if they consent for their child to participate in the study.
- If yes, the researcher will read the potential participant the assent script (Appendix C) to the minor while the parent reads the consent form (Appendix C). The assent section highlights the study's purpose, what the participant will be asked to do, what they can expect, and what to do if they decide they no longer want to participate.
- The researcher will ask the potential participant if they have any questions about the study, or if they are confused about what they are expected to do. The researcher will answer any questions the participant or their parent ask.
- If there are no questions, the researcher will ask the potential participant if they still want to participate in the study. If yes, the researcher will ask the participant to sign the line "Participant's Assent Signature" in the informed consent form. If no, the parent and participant will leave the laboratory.
- If the participant has agreed to take part in the study, the remaining signatures will be completed in the informed consent form.

The parent/guardian will be reminded that they are required to attend the data acquisition sessions and stay with their child at all times during the study.

Following this step, the participants will be prepared for, and perform through, the experimental protocol. Throughout this process participants will be encouraged to voice any concerns or questions they may have, and they will be informed of the option to have their data removed from the study up to one month following testing.

Oral consent is not required. Waiver of informed consent is not sought.

Appendix B Recruitment Email

Recruitment Email Template – Approved by Dalhousie University's Ethics Board

Dear __________________________,

Thank you for your interest in our study entitled: "Comparing the mechanics of kayaking on-water to kayaking on an ergometer", which is being conducted by Ms. Kayla Bugeya Miller, a master's student in the MSc in Kinesiology program, and Mr. Josh Goreham, a doctoral student in the PhD in Health program at Dalhousie University. Participation in the study is voluntary and you may withdraw at any time. This is a fun and engaging opportunity for you to participate in a university research study, and experience biomechanics firsthand.

In this study, we apply the engineering principles of motion to the human body to understand the similarities between kayak ergometers and on-water kayaking movement patterns. We use state of the art equipment that allow us to track your movement with a new piece of biomechanics equipment, inertial measurement units, while you paddle on an ergometer and on-water kayaking trials. More specifically, we are attempting to determine the similarities between the two methods for future laboratory research and better understanding kayaking performance between skill levels. As well, this information will help us develop tools for understanding human movement better.

To be eligible for this study you need the following:

- Be between the ages of 14 and 35
- Have answered 'No' to all the following questions (PAR-Q and Musculo-Skeletal Health).
- Have more than 1 year of experience.
- Have not capsized in the previous year.
- Be able to swim for 75m continuously and tread water comfortably for 2 minutes.
- Have answered 'No' to all of the questions below.

Please read the following questions and answer them without sharing your answers with us:

1. Has your doctor ever said that you have a heart condition and that you should only do physical activity recommended by a doctor?
2. Do you feel pain in your chest when you do physical activity?
3. In the past month, have you had chest pain when you were not doing physical activity?
4. Do you lose your balance because of dizziness or do you ever lose consciousness?
5. Do you have a bone or joint problem (for example, back, knee or hip) that could be made worse by a change in your physical activity?
6. Is your doctor currently prescribing drugs (for example, water pills) for your blood pressure or heart condition?
7. Do you know of any other reason why you should not do physical activity?

8. Have you had surgery to either of your upper extremity in the past 12 months and has your physician restrained you from returning to doing sport activities?
9. Have you had an injury to either of your upper extremity in the past 12 months?
10. Do you have any history of heart disease?
11. Do you have any prior history of stroke?
12. Do you have any lung or breathing problems that interfere with your ability to perform daily activities?
13. Do you have any form of arthritis (i.e., rheumatic, psoriatic) or gout?
14. Do you have any history of neurological disease?
15. Have you had back pain in the past 12 months that has prevented you from doing activities of daily living?
16. Do you have any history of bone disease? (i.e., osteoporosis)

If you are eligible, agree to participate, and your age category needs more participants, you will be asked to visit the Canoe Kayak Canada Training Center in the Canoe Kayak Atlantic Division building (34 Boathouse Ln, Dartmouth) for one testing session and Dalhousie University's Dalplex in the BEN Lab (6260 South St, Halifax, Room 216).

On your first visit, we will review the study with you, review the eligibility and the exclusion criteria, and will ask you to sign the Informed Consent/Assent form. These documents are provided to you as an attachment to this email. Please review the Par-Q and Musculo-Skeletal Health Questionnaire. If you determine that you are ineligible to participate in the study, please destroy these forms (i.e., shred hard copies, delete electronic copies). The consent/assent form only needs to be read prior to coming to Canoe Kayak Atlantic Division. The consent/assent form will be completed and signed in on the day of testing. If the participant is between the ages of 14-18, a parent/guardian is required to stay on-site during the testing period.

We will measure your force production in your footboard, seat and paddle on the ergometer and on-water. Both testing times will take approximately 1.5 hours, separately. You will need to bring proper attire for typical exercise (t-shirt, shorts, sports bra, running shoes, etc.) and a change of clothing for if you capsize.

Thank you for considering participating in this study. This is a unique opportunity to be involved in cutting edge research. Please talk to your family (if you are under the age of 19). If you are interested in participating, contact the BEN lab (902-494-2066 or biodynamics.dalhousie@gmail.com) directly to make an appointment. We will contact you within the next couple of weeks.
If you have questions or need more information about this study, please do not hesitate to contact us using the information listed below.
Sincerely,

Kayla Bugeya Miller, MSc student (Principal Investigator)
BEN Laboratory: Phone: 902.494.2066 Email: biodynamics.dalhousie@gmail.com

Appendix C Health Questionnaires and Informed Consent

PAR-Q & You

Physical Activity Readiness
Questionnaire - PAR-Q
(revised 2002)

PAR-Q & YOU

(A Questionnaire for People Aged 15 to 69)

Regular physical activity is fun and healthy, and increasingly more people are starting to become more active every day. Being more active is very safe for most people. However, some people should check with their doctor before they start becoming much more physically active.

If you are planning to become much more physically active than you are now, start by answering the seven questions in the box below. If you are between the ages of 15 and 69, the PAR-Q will tell you if you should check with your doctor before you start. If you are over 69 years of age, and you are not used to being very active, check with your doctor.

Common sense is your best guide when you answer these questions. Please read the questions carefully and answer each one honestly: check YES or NO.

YES	NO	
☐	☐	**1. Has your doctor ever said that you have a heart condition and that you should only do physical activity recommended by a doctor?**
☐	☐	**2. Do you feel pain in your chest when you do physical activity?**
☐	☐	**3. In the past month, have you had chest pain when you were not doing physical activity?**
☐	☐	**4. Do you lose your balance because of dizziness or do you ever lose consciousness?**
☐	☐	**5. Do you have a bone or joint problem (for example, back, knee or hip) that could be made worse by a change in your physical activity?**
☐	☐	**6. Is your doctor currently prescribing drugs (for example, water pills) for your blood pressure or heart condition?**
☐	☐	**7. Do you know of any other reason why you should not do physical activity?**

If you answered

YES to one or more questions

Talk with your doctor by phone or in person BEFORE you start becoming much more physically active or BEFORE you have a fitness appraisal. Tell your doctor about the PAR-Q and which questions you answered YES.

- You may be able to do any activity you want — as long as you start slowly and build up gradually. Or, you may need to restrict your activities to those which are safe for you. Talk with your doctor about the kinds of activities you wish to participate in and follow his/her advice.
- Find out which community programs are safe and helpful for you.

NO to all questions

If you answered NO honestly to all PAR-Q questions, you can be reasonably sure that you can:

- start becoming much more physically active – begin slowly and build up gradually. This is the safest and easiest way to go.
- take part in a fitness appraisal – this is an excellent way to determine your basic fitness so that you can plan the best way for you to live actively. It is also highly recommended that you have your blood pressure evaluated. If your reading is over 144/94, talk with your doctor before you start becoming much more physically active.

DELAY BECOMING MUCH MORE ACTIVE:

- if you are not feeling well because of a temporary illness such as a cold or a fever – wait until you feel better; or
- if you are or may be pregnant – talk to your doctor before you start becoming more active.

PLEASE NOTE: If your health changes so that you then answer YES to any of the above questions, tell your fitness or health professional. Ask whether you should change your physical activity plan.

Informed Use of the PAR-Q: The Canadian Society for Exercise Physiology, Health Canada, and their agents assume no liability for persons who undertake physical activity, and if in doubt after completing this questionnaire, consult your doctor prior to physical activity.

No changes permitted. You are encouraged to photocopy the PAR-Q but only if you use the entire form.

NOTE: If the PAR-Q is being given to a person before he or she participates in a physical activity program or a fitness appraisal, this section may be used for legal or administrative purposes.

"I have read, understood and completed this questionnaire. Any questions I had were answered to my full satisfaction."

Musculo-Skeletal Health Screening Questionnaire

Question
Have you had prior surgery to either upper extremity? How long ago?
Have you had an injury to either upper extremity? How long ago?
Do you have any form of arthritis (i.e., rheumatic, psoriatic) or gout?
Do you have any history of bone disease? (i.e., osteoporosis)
Have you had back pain in the past year that has prevented you from doing activities of daily living?
Do you have any history of neurological disease?
Do you have any history of heart disease?
Do you have any prior history of stroke?
Do you have any lung or breathing problems that interfere with your ability to perform daily activities?

Biodynamics
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DALHOUSIE UNIVERSITY

Kinetic differences between on-water and ergometer kayaking.

Non-Interventional Study
Informed Consent/Assent Form; Ages: 19 and over

STUDY TITLE: Kinetic differences between on-water and ergometer kayaking.

PRINCIPAL OR QUALIFIED INVESTIGATOR
Kayla M. Bugeya Miller, MSc student
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Faculty of Health Profession
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Mitacs

Biodynamics
Ergonomics
Neuroscience
LAB

You have been invited to take part in a research study being conducted by Ms. Kayla Bugeya Miller (Master of Science in Kinesiology student) and Mr. Josh Goreham (PhD in Health student) from the Faculty of Health at Dalhousie University. Your participation in this study is voluntary and you may withdraw from the study at any time. There will be no impact on your studies, employment, performance evaluation or the services you receive if you decide not to participate in the research. The information below tells you about what you will be asked to do and about any benefit, risk, or discomfort that you might experience.

Who will be conducting the research?

Investigators for this project are: Ms. Kayla Bugeya Miller, Mr. Josh Goreham and, Dr. Michel Ladouceur. All three investigators are from the Kinesiology division within the School of Health and Human Performance at Dalhousie University. Ms. Bugeya Miller conducts this research as part of her MSc thesis. Mr. Josh Goreham conducts this research as part of his PhD thesis.

Should you have any questions or concerns about the study, Ms. Bugeya Miller can be contacted via email (kaylabmiller@dal.com) and Mr. Goreham can be contacted via email (josh.goreham@dal.ca) or both can be contacted by telephone at (902) 494-2066. Dr. Ladouceur can also be contacted via email (michel.ladouceur@dal.ca) or telephone at (902) 494-2754.

The researchers will:

- Discuss the study with you
- Answer your questions
- Keep confidential any information which could identify you personally
- Be available during the study to deal with problems and answer questions

Please ask as many questions as you like. If you have any questions later, please contact the lead researcher.

Purpose and Outline of the Research Study

This study is being conducted to determine the similarities between a kayak ergometer and on-water kayaking in novice and elite athletes.

Our long-term goal with this research is to eventually create a method to measure movements on the water, but to do this we must start in a laboratory. In addition, this research will allow us to better understand how athletes paddle on a kayak ergometer. We are trying to develop a series of models to help us understand how these patterns change with age and paddling experience. Using these models, a better understanding of kayaking technique can be developed to enhance performance in Canadian kayaking for years to come.

Who Can Participate in the Research Study?

You may participate in this study if you are between 14 and 35 years old and are a healthy individual who kayaks.

You may not participate for this study if you:

- Have answered 'Yes' to any questions on the Physical Activity Readiness-Questionnaire.
- Suffer from joint problems or other physical limitations that will not permit you to perform upper arm movements.
- Less than 1-year experience and train less than 5 times a week.
- Have capsized in the previous year.
- Cannot swim 75m continuously and tread water comfortably for 2 minutes.

It is anticipated that twenty people (male and female) will participate in this study throughout the Halifax metro region of Nova Scotia.

What You Will Be Asked to Do?
You will visit the Canoe Kayak Atlantic Division one time and the Dalplex one time. We will measure your upper-body and lower-body limb sizes, conduct a kayaking trial on an ergometer, and conduct a kayaking trial on the water. The visit to Canoe Kayak Atlantic Division will require approximately 1.5 hours of your time and the visit to the Dalplex will require 1.5 hours of your time. When you arrive a on your testing day, the research team (usually 2 persons) will explain all the equipment and procedures used for the study, review this form with you and your and answer any questions. The team will review the PAR-Q and Musculo-Skeletal Health Questionnaire with you without asking you to state your answers. You will then be asked to sign this Informed Consent/Assent document. Once the Informed Consent/Assent is signed, you will be asked to change into the appropriate clothing for the study – tight fitting exercise shorts or tights, tight-fitting exercise shirt, sneakers, and a water bottle. Please consider the weather on the day of testing and bring the appropriate clothing for both indoor and outdoor activity, along with a change of clothing for if you capsize. If you do not have any of these items, they will be provided for you.

We will measure your: (1) height, (2) body mass, (3) shoulder circumference and width, (4) trunk length and waist circumference and width, (5) forearm length and circumference, (6) upper-arm length and circumference, (7) hand length and width, (8) upper leg length and width, (9) lower leg length and circumference, and (10) foot length and width.

We will record the force you produce in their footboard, seat and handle while kayaking.

You will be asked to perform two tasks in a random order, over two visits.
Task 1: You will be asked to paddle on an ergometer for seven different 30 second trials. You will paddle at different stroke rates and intensities. The stroke rates will range from 60 to 120 strokes per minute (spm), with 20 spm increments. You will then perform a maximum 30 second trial at your own chosen stroke rate as if you would be racing.
Task 2: You will be asked to paddle on-water for another seven different 30 second trials. You will paddle at different stroke rates and intensities. The stroke rates will range from 60 to 120 spm with 20 spm increments. You will then perform a maximum 30 second trial at your own chosen stroke rate.

At the time of testing, it is important that you tell the investigators or research assistants if anything unusual is happening with your health. An example of this would be if you were experiencing shortness of breath, chest pain, etc.

You are free to withdraw from the study at any point during the protocol. When the study is finished or if you decide to stop participating, you will not be required to do anything further.

Possible Benefits, Risks and Discomforts?

You will not receive any direct benefits for participating in this study. Participants are sometimes interested in learning about their movements, so we can provide you information upon request. The information found in this study will be presented at scientific conferences and will be published in scientific and clinical journals.

Time inconvenience: Your visit to the testing site will take approximately 3 hours of your time.

Sudden Cardiac Death: 1:300000 high school athletes die of sudden cardiac death when performing maximal exercise, where in competitive athletes aged 10-39 years old, the incidence of sudden death during exercise was found to be 1 in 100000.

Breach of confidentiality**:** As with all research, there is a chance that confidentiality could be compromised; however, we are taking all precautions to minimize this risk.

Risk of Capsizing: There is a minor risk that you may capsize during testing procedures due to loss of balance in the boat.

Risk of Drowning: Due to the nature of water sports, there is a minor risk of drowning if you were to capsize your boat or fall off the docks.

Heat Exhaustion: If testing is conducted on a hot day, there is a risk of getting heat exhaustion during testing. However, tests will not be conducted in weather hotter than 29° C to mitigate this.

Exerting and over-stretching muscles: Due to the nature of the testing, there is a chance that you may over-stretch or exert one or more muscles during testing.

Colliding, contacting, or falling with/onto other objects or people: Lake Banook and Lake MicMac are used both recreationally and for training purposes. As well, there are floating docks, buoys, and objects that naturally occur on the lake. These all provide minor risks for collision, contact, and falling. These occurrences could result in abrasions, broken bones, blunt force trauma, spinal cord injuries, or soft tissue injuries.

Compensation / Reimbursement

There is no compensation for being part of this research study. We will reimburse you for out-of-pocket transportation-related expenses you incur because of participating in this study (e.g., city transportation or parking). These expenses will be reimbursed following completion of the testing site visit. The maximum amount of reimbursement is $20.

Research Related Injury: If you become ill or injured as a direct result of participating in this study, necessary medical treatment will be available at no additional cost to you. Your signature on this form only indicates that you have understood to your satisfaction the information regarding your participation in the study and agree to participate as a subject.

In no way does this waive your legal rights nor release investigators, the research staff, the study sponsor or involved institutions from their legal and professional responsibilities.

Privacy and Confidentiality

The people who work with your information have special training and have an obligation to keep all research information private. Only the research team at Dalhousie University will have access to this information. We will describe and share our findings in progress reports, class presentations and written thesis. We may also submit our findings for publication to an academic journal. We will be very careful to only talk about group results so that no one will be identified. This means that ***you will not be identified in any way in our reports***.

Use of your Personal Information: If you decide to participate in this study, the investigator(s) and study staff will look at your personal information and collect only the information they need for this study. "Personal information" is information about you that could identify you because it includes information such as your name.

- Name,
- Address,
- Telephone number,
- Email address,
- Age on day of testing
- Information from the study interviews and questionnaires;

When you sign this form, you give us permission to:

- Collect information from you
- Share information with the people conducting the study
- Share information with the people responsible for protecting your safety while participating in this research

Use of Your Study Information: The research team will collect and use only the information they need to complete this research study. "Study data" is information about you that is collected for the study, but that does not directly identify you.

Even though the risk of identifying you from the study data is very small, it can never be eliminated.

You have the right to be informed of the results of this study once the entire study is complete. If you would like to be informed of the results of this study, please provide your name, address, and telephone number.

Your access to records: You may ask the Principal Investigator to see the information that has been collected about you. You may ask to make corrections to this information by talking with a member of the research team.

If You Decide to Stop Participating

You are free to leave the study at any time. If you wish to withdraw your consent, please inform the Principal Investigator.
If you decide to stop participating at any point in the study, you can also decide whether you want any of the information that you have contributed up to that point to be removed. You may decide to have your information removed up to one month after your final testing day. After that time, it will become impossible for us to remove it because it will already be analyzed.
The Dalhousie University Research Ethics Board or the Principal Investigator has the right to stop participant recruitment or cancel the study at any time.
Lastly, the principal investigator may decide to remove you from this study without your consent for any of the following reasons:

- You do not follow the directions of the Principal Investigator;
- In the opinion of the Principal Investigator you are experiencing side effects that are harmful to your health or well-being;
- There is new information that shows that being in this study is not in your best interests;

If you are withdrawn from this study, a member of the study team/principal investigator will discuss the reasons with you.

How to Obtain Results?
You can obtain either group results or your individual results by including your contact information at the end of the signature page and we will send them to you via your preferred method.
The findings of this project will be used to help us understand how movement patterns during paddling change with experience. This will provide important information for the understanding of paddling technique and its relationship with experience.

What Are My Responsibilities?

As a study participant you will be expected to:

- Follow the directions of the Principal Investigator
- Report if there are any changes in your health that could affect your performance to the Principal Investigator prior to or during the data collection.
- Report any problems that you experience that you think might be related to participating in the study

<u>Declaration of Financial Interest</u>
Mitacs is reimbursing the Principal Investigator's institution to conduct this study. The amount of payment is sufficient only to cover the costs of conducting the study.

<u>What About Questions or Problems?</u>
We are happy to talk with you about any questions or concerns you may have about your participation in this research study. Please contact Ms. Kayla Buegya Miller at kaylabmiller@dal.ca or Mr. Josh Goreham at josh.goreham@dal.ca or (902) 494-2066, at

any time. We will also tell you if any new information comes up that could affect your decision to participate.
If you have any ethical concerns about your participation in this research, you may also contact Director, Research Ethics, Dalhousie University at (902) 494-1462, or email: ethics@dal.ca

What Are My Rights?
You have the right to receive all information that could help you make a decision about participating in this study. You also have the right to ask questions about this study and your rights as a research participant, and to have them answered to your satisfaction before you make any decision. You also have the right to ask questions and to receive answers throughout this study.

In the next part, you will be asked if you agree (consent) to join this study. If the answer is "yes", you will need to sign the form.

CONSENT FOR STUDY PARTICIPATION (For Participants 19 years and older)

Project Title: Comparing the mechanics of on-water and ergometer kayaking.

I, ______________________________ have read the explanation about this study. I have been given the opportunity to discuss it and my questions have been answered to my satisfaction. I agree to take part in this study. I realize that my participation is voluntary and that I am free to withdraw from the study at any time.

 (initial above)	I have read and answered “NO” to all questions in the PAR-Q and Musculo-Skeletal Health Screening Questionnaire.

Please fill in the dates personally

________________________________ ________________________________

Print Name of Participant DATE (Year.Month.Day)

I confirm that I have explained the nature and purpose of the study to the participant named above and have answered all questions. In my judgment, the participant is voluntarily and knowingly giving informed consent to participate in this research study.

________________________________ ________________________________

Name of Person Obtaining Consent Signature

Please send me (please circle):

GROUP RESULTS INDIVIDUAL RESULTS BOTH NEITHER

Please contact me at (please list a phone number, e-mail address, or mailing address):

Mailing Address or Phone Number	E-mail Address

Biodynamics
Ergonomics
Neuroscience
LAB

DALHOUSIE UNIVERSITY

Kinetic differences between on-water and ergometer kayaking.

Non-Interventional Study
Informed Consent/Assent Form; Ages: 14 to 18

STUDY TITLE: Kinetic differences between on-water and ergometer kayaking.

PRINCIPAL OR QUALIFIED INVESTIGATOR	Kayla M. Bugeya Miller, MSc student BEN Lab, Room 217, Dalplex Faculty of Health Profession Dalhousie University 6260 South St., Halifax, NS B3H 4R2 kaylabmiller@dal.ca, (902) 499-0172

FUNDING AGENCY: This work is supported by Mitacs and Own The Podium through the Mitacs Accelerate Program.

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The researchers will:

- Discuss the study with you and your child
- Answer you or your child's questions
- Keep confidential any information which could identify you personally
- Be available during the study to deal with problems and answer questions

Please ask as many questions as you like. If you or your child has any questions later, please contact the lead researcher.

Purpose and Outline of the Research Study
This study is being conducted to determine the similarities between a kayak ergometer and on-water kayaking in novice and elite athletes. Our long-term goal with this research is to eventually create a method to measure movements on the water, but to do this we must start in a laboratory. In addition, this research will allow us to better understand how athletes paddle on a kayak ergometer. We are trying to develop a series of models to help us understand how these patterns change with age and paddling experience. Using these models, a better understanding of kayaking technique can be developed to enhance performance in Canadian kayaking for years to come.

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Your child may participate in this study if they are between 14 and 18 years old and are a healthy individual.
Your child may not participate for this study if they:

- Have answered 'Yes' to any questions on the Physical Activity Readiness-Questionnaire.
- Suffer from joint problems or other physical limitations that will not permit your child to perform upper arm movements.
- Less than 1-year experience and train 5 or less times a week.
- Have capsized in the last year.
- Cannot swim 75m continuously and tread water comfortably for 2 minutes.

It is anticipated that twenty people (male and female) will participate in this study throughout the Halifax metro region of Nova Scotia.

What You Will Be Asked to Do? – (For Participant and Parent/Guardian)
You will visit the Canoe Kayak Atlantic Division one time and the Dalplex one time. We will measure their upper-body and lower-body limb sizes, conduct a kayaking trial on an ergometer, and conduct a kayaking trial on the water. The visit to Canoe Kayak Atlantic Division will require approximately 1.5 hours of you and your parent/guardian's time and the visit to the Dalplex will require 1.5 hours of both your time. Your parent/guardian will be asked to stay on site for the duration of the testing. When you and your parent/guardian arrive on your testing days, the research team (usually 2 persons) will explain all the equipment and procedures used for the study, review this form with you and your parent/guardian and answer any questions. The team will review the PAR-Q and Musculo-Skeletal Health Questionnaire with you without asking you to state your answers. You and your parent/guardian will then be asked to sign this Informed Consent/Assent document. Once the Informed Consent/Assent is signed, you will be asked to change into the appropriate clothing for the study – tight fitting exercise shorts or tights, tight-fitting athletic shirt, sneakers, and water bottle. Please consider the weather on the day of and bring clothing for both indoor and outdoor activity. As well, we do not expect it to happen but please bring a change of clothing in case you capsize. If you do not have any of these items they will be provided.

We will measure your: (1) height, (2) body mass, (3) shoulder circumference and width, (4) trunk length and waist circumference and width, (5) forearm length and circumference, (6) upper-arm length and circumference, (7) hand length and width, (8) upper leg length and width, (9) lower leg length and circumference, and (10) foot length and width.

We will record the force you produce in your footboard, seat and handle while kayaking.

You will be asked to perform two tasks in a random order over two sessions.

Task 1: You will be asked to paddle on an ergometer for seven different 30 second trials. You will paddle at different stroke rates and intensities. The stroke rates will range from 60 to 120 strokes per minute (spm), with 20 spm increments. You will then perform a maximum 30 second trial at your own chosen stroke rate as if you were racing.
Task 2: You will be asked to paddle on-water for another seven different 30 second trials. You will paddle at different stroke rates and intensities. The stroke rates will range from

60 to 120 spm with 20 spm increments. You will then perform a maximum 30 second trial at your own chosen stroke rate.

At the time of testing, it is important that you or your parent/guardian tell the investigators or research assistants if anything unusual is happening with your health. An example of this would be if they were experiencing shortness of breath, chest pain, etc.
You are free to withdraw from the study at any point during the protocol. When the study is finished or if you decide to stop participating, you will not be required to do anything further.

Possible Benefits, Risks and Discomforts?
Your child will not receive any direct benefits for participating in this study. Participants are sometimes interested in learning about their movements, so we can provide your child with information upon request. The information found in this study will be presented at scientific conferences and will be published in scientific and clinical journals.

Time inconvenience: Your child's visit to the testing site will take approximately 3 hours of your time.
Sudden Cardiac Death: 1:300000 high school athletes die of sudden cardiac death when performing maximal exercise, where in competitive athletes aged 10-39 years old, the incidence of sudden death during exercise was found to be 1 in 100000.
Breach of confidentiality**:** As with all research, there is a chance that confidentiality could be compromised; however, we are taking all precautions to minimize this risk.
Risk of Capsizing: There is a minor risk that your child may capsize during testing procedures due to loss of balance in the boat.
Risk of Drowning: Due to the nature of water sports, there is a minor risk of drowning if your child were to capsize their boat or fall off the docks.
Heat Exhaustion: If testing is conducted on a hot day, there is a risk of getting heat exhaustion during testing. However, tests will not be conducted in weather hotter than 29° C to mitigate this.
Exerting and over-stretching muscles: Due to the nature of the testing, there is a chance that your child may over-stretch or exert one or more muscles during testing.
Colliding, contacting, or falling with/onto other objects or people: Lake Banook and Lake MicMac are used both recreationally and for training purposes. As well, there are floating docks, buoys, and objects that naturally occur on the lake. These all provide minor risks for collision, contact, and falling. These occurrences could result in abrasions, broken bones, blunt force trauma, spinal cord injuries, or soft tissue injuries.

Compensation / Reimbursement
There is no compensation for being part of this research study. We will reimburse you and your child for out-of-pocket transportation-related expenses incurred because of participating in this study (e.g. city transportation or parking). These expenses will be reimbursed following completion of the testing site visit. The maximum amount of reimbursement is $20.

Research Related Injury: If your child becomes ill or injured as a direct result of participating in this study, necessary medical treatment will be available at no additional cost to you or your child. You and your child's signatures on this form only indicates that you have both understood to both your satisfaction the information regarding your child's participation in the study and agree to participate as a subject. In no way does this waive your child's legal rights nor release investigators, the research staff, the study `sponsor or involved institutions from their legal and professional responsibilities.

Privacy and Confidentiality

The people who work with your child's information have special training and have an obligation to keep all research information private. Only the research team at Dalhousie University will have access to this information. We will describe and share our findings in progress reports, class presentations and written thesis. We may also submit our findings for publication to an academic journal. We will be very careful to only talk about group results so that no one will be identified. This means that ***your child will not be identified in any way in our reports***.

Use of your child's Personal Information: If your child decides to participate in this study, the investigator(s) and study staff will look at your child's personal information and collect only the information they need for this study. "Personal information" is information about you that could identify you because it includes information such as your;

- Name,
- Address,
- Telephone number,
- Email address,
- Age on day of participation
- Information from the study interviews and questionnaires;

When you and your child sign this form, you give us permission to:

- Collect information from your child
- Share information with the people conducting the study
- Share information with the people responsible for protecting your child's safety while participating in this research

Use of Your Child's Study Information: The research team will collect and use only the information they need to complete this research study. "Study data" is information about your child that is collected for the study, but that does not directly identify your child.
Even though the risk of identifying your child from the study data is very small, it can never be eliminated.
Your child has the right to be informed of the results of this study once the entire study is complete. If your child would like to be informed of the results of this study, please provide your name, address, and telephone number.

Access to records: You or your child may ask the Principal Investigator to see the information that has been collected about you. You or your child may ask to make corrections to this information by talking with a member of the research team.

If Your Child Decides to Stop Participating

Your child is free to leave the study at any time. If your child wishes to withdraw their consent, please inform the Principal Investigator.

If your child decides to stop participating at any point in the study, you or your child can also decide whether they want any of the information that they have contributed up to that point to be removed. You or your child may decide to have their information removed up to one month after your final testing day. After that time, it will become impossible for us to remove it because it will already be analyzed.

The Dalhousie University Research Ethics Board or the Principal Investigator has the right to stop participant recruitment or cancel the study at any time.

Lastly, the principal investigator may decide to remove your child from this study without you or their consent for any of the following reasons:

- You or your child do not follow the directions of the Principal Investigator;
- In the opinion of the Principal Investigator your child is experiencing side effects that are harmful to their health or well-being;
- There is new information that shows that being in this study is not in their best interests;

If they are withdrawn from this study, a member of the study team/principal investigator will discuss the reasons with you and your child.

How to Obtain Results?

You and your child can obtain either group results or their individual results by including your contact information at the end of the signature page and we will send them to you via your preferred method.

The findings of this project will be used to help us understand the differences in mechanics between a kayak ergometer and on-water kayaking in novice and elite athletes. This will provide important information for the understanding of paddling technique and its relationship with experience.

What Are Your Child's Responsibilities?

As a study participant they will be expected to:

- Follow the directions of the Principal Investigator
- Report if there are any changes in their health that could affect their performance to the Principal Investigator before or during the study.
- Report any problems that they experience that you think might be related to participating in the study

<u>Declaration of Financial Interest</u>

Mitacs is reimbursing the Principal Investigator's institution to conduct this study. The amount of payment is sufficient only to cover the costs of conducting the testing.

<u>What About Questions or Problems?</u>

We are happy to talk with you and/or your child about any questions or concerns you or your child may have about your participation in this research study. Please contact Ms. Kayla Buegya Miller at kaylabmiller@dal.ca or Mr. Josh Goreham at josh.goreham@dal.ca or (902) 494-2066, at any time. We will also tell you and your child if any new information comes up that could affect your decision to participate. If you or your child have any ethical concerns about their participation in this research, you or your child may also contact Director, Research Ethics, Dalhousie University at (902) 494-1462, or email: ethics@dal.ca

What Are My Child's Rights?

You and your child have the right to receive all information that could help them make a decision about participating in this study. You and your child also have the right to ask questions about this study and their rights as a research participant, and to have them answered to you and your child's satisfaction before making any decision. You and your child also have the right to ask questions and to receive answers throughout this study.

In the next part, you and your child will be asked if you agree (consent) to join this study. If the answer is "yes", you and your child will need to sign the form.

MINOR ASSENT AND PARENTAL PERMISSION FOR STUDY PARTICIPATION
(For Participants Between 14 and 18 years old)

Project Title: Comparing the mechanics of on-water and ergometer kayaking.

I, ______________________________ (Parent/Guardian) have read the explanation about this study. I have been given the opportunity to discuss it and my questions have been answered to my satisfaction. I agree to allow my child to take part in this study. I realize that my child's participation is voluntary and that I am free to withdraw them from the study at any time.

I, ______________________________ (Participant) have read the explanation about this study. I have been given the opportunity to discuss it and our questions have been answered to my satisfaction. I give my permission to take part in this study. I realize that my participation is voluntary and that I am free to withdraw from the study at any time.

	I have read and answered "NO" to all questions in the PAR-Q and Musculo-Skeletal Health Screening Questionnaire.
(initial above)	

Please fill in the dates personally

______________________________ ______________________________
Participant's Assent Signature Parental Permission Signature

______________________________ ______________________________
Print Name of Participant DATE (Year.Month.Day)

I confirm that I have explained the nature and purpose of the study to the participant named above and have answered all questions. In my judgment, the participant is voluntarily and knowingly giving informed assent to participate in this research study.

______________________________ ______________________________
Name of Person Obtaining Assent/Permission Signature

Please send me (please circle):
GROUP RESULTS INDIVIDUAL RESULTS BOTH NEITHER
Please contact me at (please list a phone number, e-mail address, or mailing address):

Mailing Address or Phone Number	E-mail Address

Minor Assent Script

To be reviewed with minor upon parental consent.

Thank you for your interest in our study.

Taking part in this study is up to you, and you may choose to stop at any time. Taking part in the study might not benefit you directly but may be used to develop tools for understanding human movement.

The purpose of this study is to understand the similarities between kayak ergometers and on-water kayaking in novice and elite athletes' movement patterns.

We will measure your force production at your footboard, seat and paddle while you kayak on an ergometer and on-water, separately.

Testing will be completed over two sessions of approximately 1.5 hours each. The testing will take place at Canoe Kayak Canada Training Center in the Canoe Kayak Atlantic Division building and the Dalplex. Lastly, Dalhousie University's Research Ethics Board has reviewed this research study. You will be asked to perform two separate tasks: paddling on an ergometer and paddling on-water. During the ergometer task you will perform seven separate 30 second paddling trials at varying stroke rates. These rates are: 60, 80, 100, 120 spm, and one maximal sprint trial. During the on-water task, you will also be asked to perform the same seven separate 30 second paddling trials at the same varying stroke rates.

The testing should cause the same minor discomforts experienced during higher intensity workouts you have during a sprint practice. Due to kayaking being an on-water sport, there are minor risks of flipping your kayaking and becoming distressed well in the water, just as there are when you go out with your coaches.

If at any time before or during the testing, you experience any discomfort or unusual pain you may stop participation immediately. If any of this occurs, please let the research team know immediately. Stopping participation in this study at any point will not negatively impact you or your standings.

At this point, do you have any questions?
Answer more specific questions from minor.

Are you still interested in participating in the study?
If no: Thank the minor and parent for coming in.
If yes: Ok. There are some questions that I need to ask in order to make sure that you are eligible to participate in the study.

Have you competed for one or more years?
If yes: Continue to next question

If no: Thank the minor and parent and tell them that they are not eligible to participate.

Have you capsized or flipped your kayak in the previous year?
If no: Continue to next question
If yes: Thank the minor and parent and tell them that they are not eligible to participate.

Can you swim 75m continuously and tread water comfortably for 2 minutes?
If yes: Continue to next question
If no: Thank the minor and parent and tell them that they are not eligible to participate.

Are you between the ages of 14 and 18 years old?
If no: Thanks, them and their parent/guardian for their time.
If yes: continue to ask questions.

A screening tool we use to make sure people are eligible for our study is called the Physical Activity Readiness Questionnaire (PAR-Q). We also use a Musculo-skeletal Health Questionnaire. I am going to read 16 questions from the Physical Activity Readiness Questionnaire and Musculo-Skeletal Health Questionnaire. Please do not answer the questions aloud, but do make a note yourself if you answer "yes" to any of the questions.

1. Has your doctor ever said that you have a heart condition and that you should only do physical activity recommended by a doctor?
2. Do you feel pain in your chest when you do physical activity?
3. In the past month, have you had chest pain when you were not doing physical activity?
4. Do you lose your balance because of dizziness or do you ever lose consciousness?
5. Do you have a bone or joint problem (for example back, knee or hip) that could be made worse by a change in your physical activity?
6. Is your doctor currently prescribing drugs (for example, water pills) for your blood pressure or heart condition?
7. Do you know of any other reason you should not do physical activity?
8. Have you had surgery to either of your upper extremity in the past 12 months and has your physician restrained you from returning to doing sport activities?
9. Have you had an injury to either of your upper extremity in the past 12 months?
10. Do you have any history of heart disease?
11. Do you have any prior history of stroke?
12. Do you have any lung or breathing problems that interfere with your ability to perform daily activities?
13. Do you have any form of arthritis (i.e. rheumatic, psoriatic) or gout?
14. Do you have any history of neurological disease?
15. Have you had back pain in the past 12 months that has prevented you from doing activities of daily living?
16. Do you have any history of bone disease? (i.e. osteoporosis)

Did you answer "yes" to any of the previous 16 questions?

If yes: If you answer, "Yes" to any question on the PAR-Q or Musculo-Skeletal Health Questionnaire, you are ineligible to participate. PAR-Q guidelines show that you are not ready for physical activity if you answer yes to a question.
Thank the minor and parent for their time.
If no: Ok. Thank you for answering these questions, you are eligible to participate in the study.

Do you have any further questions for us?
If yes: *answer questions*.
Do you still wish to participate in this study?
If yes: If you and your parent have decided that you are still interested in participating in this study, please sign the participant assent box on the last page of the consent form.
If no: Thank minor and parent for their time.

Appendix D Validation of the One Giant Leap® Force Paddle

Introduction

The measurement of sprint kayak paddle force provides an opportunity to assess factors of performance and kinetic asymmetries. Previous studies have used the kayak force paddles to measure the contribution of paddle force to the propulsive kayaking forces (135), where some have used the One Giant Leap® (One Giant Leap Ltd, Port Nelson, Nelson) kayak force paddle to do so (83–88). The validation of the One Giant Leap® kayak paddle has previously been performed on a single Slalom kayaker (86), but has yet to be tested on sprint kayakers. Therefore, the aim of this technical note was to validate the use of a One Giant Leap kayak force paddle for measurement of ASIs by comparing the ratings of measurement between the left and right paddles.

Methods

Six female elite sprint kayak athletes (21 ± 4.6 years) completed four 30 second trials at different stroke rates (60 strokes per minute (spm), 80 spm, 100 spm, and maximum spm). The top hand (hand away from the water) and bottom hand (hand closest to the water) force measures as outputted by the One Giant Leap® (One Giant Leap Ltd, Port Nelson, Nelson) software were compared for data analysis. Ludbrook (136)'s method for determining proportional bias and confirming systematic bias was used.

Results

The mean difference of the two measures was -59.96 N, with a 95% confidence interval of -78.91 N to -41.00 N. The Bland-Altman limits of agreement were -88.77 to 208.7 (Figure 34). A proportional bias with heteroscedasticity was found (r = 0.3959, β = -29.37, F(1,62) = 38.12, p < 0.0001; Figure 34), and therefore, no systematic bias could be found.

Due to the presence of heteroscedasticity and proportional bias, the raw data was log transformed and plotted on a difference compared to average value plot (Figure 35). The heteroscedasticity and proportional bias (r = 0.2034, β = 0.3699, F(1,62) = 15.94, p = 0.0002) were not removed, and therefore, Figure 34 was used to represent the difference between measures.

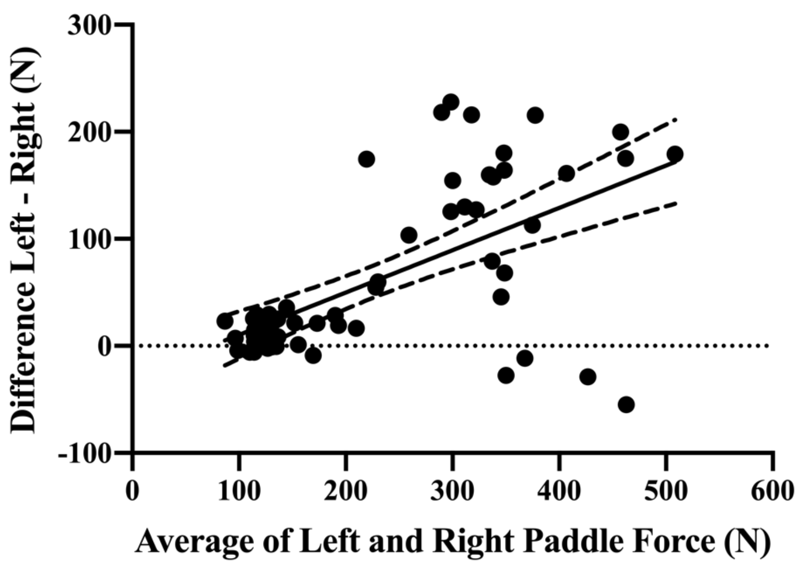

Figure 34. A Bland-Altman plot demonstrating the magnitude of differences between the right and left paddle force measures. Note. Solid line, mean; dashed lines, hyperbolic confidence interval (i.e., 95% Confidence Intervals). Newtons, N

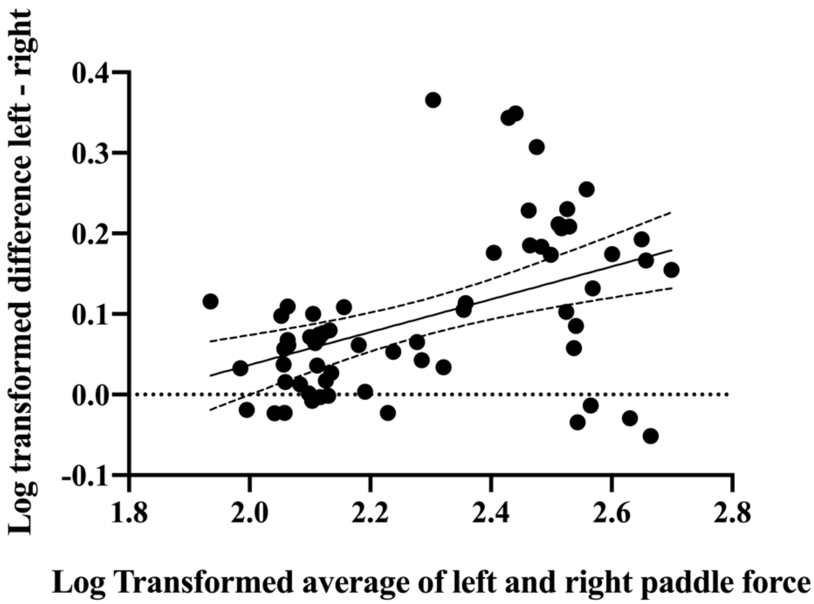

Figure 35. Log transformed difference compared to average plot demonstrating the magnitude of differences between the right and left paddle force measures. Note. Solid line, mean; dashed lines, hyperbolic confidence interval (i.e., 95% Confidence Intervals). Newtons, N

Conclusions

Heteroscedasticity and proportional bias were found, where the errors increased at larger force values. Therefore, the One Giant Leap Paddle® was deemed unacceptable for use in this study.

Appendix E Evaluation of the Drift and Bias in AMTI Load Cell Measurements

Introduction

Confirming the presence of biased data and load cell drift is an important part of analyzing force and moment data. This allows researchers to appropriately correct the force and moment waveforms, ensuring they are analyzing the true force and moment values. Large differences between load cell calibrations and drift cannot be present when calculating asymmetry indexes as this would provide uncertainty in the accuracy of the data. Therefore, the purpose of this technical note was to determine the difference of drift and bias in the left and right footboard load cells.

Methods

A kayak ergometer was instrumented with three AMTI AD2.5D load cells (6 degrees of freedom; x, y, z, pitch, roll, yaw; AMTI Force and Motion, Watertown, MA) in the footboard (2) and seat (1). Data was collected at 1000Hz.

Five provincial and national team kayakers (2 females; 18.6 ± 3.8 years) completed four 30 second trials at different stroke rates (60 strokes per minute (spm), 80 spm, 100 spm, and maximum spm) in a randomized order. The data collection started with participants off of the ergometer. The ergometer paddle was then hit three times on the seat as a means to synchronize the paddle forces with the AMTI load cells forces, for a different study. The participants mounted the ergometer when instructed to do so by the researcher and completed a 30 second trial. Following the 30 seconds of data collection, the participant dismounted the ergometer and five or more seconds of data was obtained before the termination of data collection.

Three seconds of anteroposterior force data from before the initiation (pre-trial) and after the completion of the trial (post-trial) were clipped and averaged, separately, for each stroke rate condition using custom MATLAB scripts (*version* 9.8.0, R2020a, Nantick Massachusetts). In three cases the seat was moved following the taring of the load cells. In these cases, the tare was checked during the data analysis phase. If the data had an offset from zero, the averaged bias across the three seconds was removed (Figure 36; Figure 37, respectively). Values were then sorted into the pre-trial average force values in the left and right footboard, separately, post-trial average force values in the left and right footboard, separately, and all average force values in the left and right footboard, separately.

The data was compared using three t-tests: 1) left footboard pre-trial compared to post-trial, 2) right footboard pre-trial compared to post-trial, 3) left footboard pre-trial and post-trial compared to right footboard pre-trial and post-trial. This data was analyzed in Prism 9 (Version 9.0.1, Graphpad, San Diego, CA).

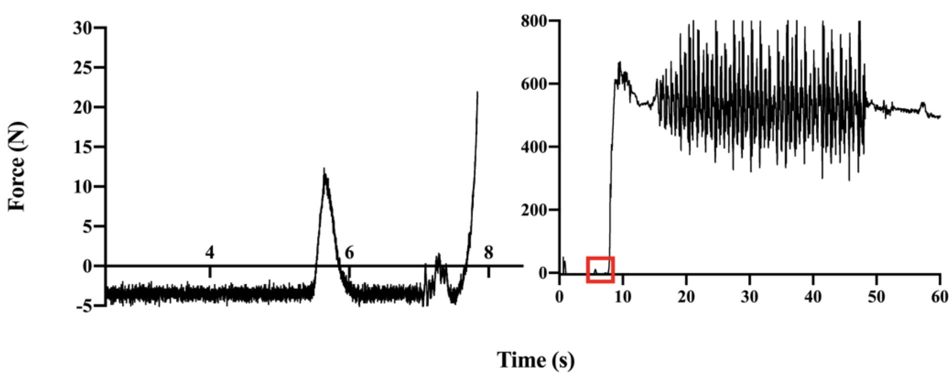

Figure 36, An example of bias present in the data before processing. Forces and moments were not tared (left) and 60 seconds of the same vertical seat force (right) with a red box to denote where the data on the left was clipped from.

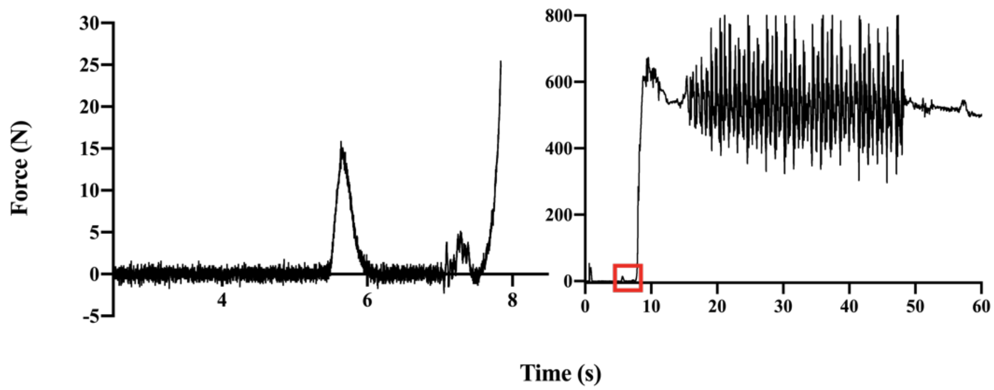

Figure 37. An example of bias corrected force. Forces and moments after the removal of the bias (left) and a 60 second of the same corrected vertical seat force (right) with a red box to denote where the data on the left was clipped from.

Results

Pre-trial and Post-trial average force values have been presented by stroke rate condition in Table 7. A significant different was found between left footboard pre-trial and post-trial data (p = 0.0246), with a mean difference of 0.1259 ± 0.2307 N. A significant difference was found between right footboard pre-trial and post-trial data (p = 0.0357), with a mean difference of 0.09484 ± 0.1876 N. A significant difference was found between left and right footboard data (p <0.001), with a mean difference of 0.5084 ± 0.4779 N.

An example of a full participant's raw trial is provided (Figure 38). At the start of the trial, three spikes in the vertical seat force represents when the paddle was hit on the seat for synchronization of the One Giant Leap® (One Giant Leap Ltd, Port Nelson, Nelson) force paddle and the three AD2.5D load cells (AMTI Force and Motion, Watertown, MA). Following this, it is demonstrated that the data is tarred at zero Newtons of force and zero Newton meters of moments. The participant then mounts the ergometer at 12 seconds, starts their trial at 22 seconds, finishes their trial at 54 seconds, and then continues to sit on the seat until 91 seconds, where they then proceed to dismount the ergometer. Following the participant dismounting the ergometer, it is demonstrated that the tare of the force and moments still remains at zero Newtons.

Table 7. Average anteroposterior pre-trial and post-trial force values in the left and right footboard.

Condition (spm)	Left Footboard (N) Pre-Trial	Post-Trial	Right Footboard (N) Pre-Trial	Post-Trial
60	-0.25582	-0.12542	0.14186	0.24378
80	-0.26382	-0.2508	0.34688	0.40968
100	-0.35066	-0.1474	0.17338	0.31214
Maximum	-0.37926	-0.22222	0.18392	0.25978

Note. spm, strokes per minute; N, Newtons

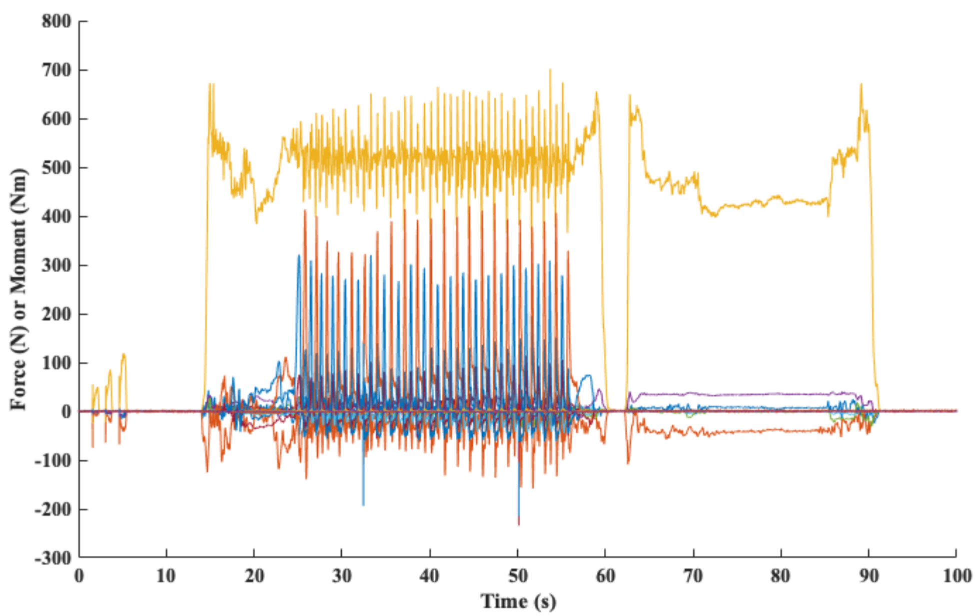

Figure 38. An example of participant 5's raw 80 stroke per minute trial data. The left and right footboard and seat's three-dimensional force and moment component data has been provided. A total of 18 force and moment waveforms have been plotted. Three notable waveforms on this graph are the seat vertical force (yellow), the left anteroposterior footboard force (orange), and the right anteroposterior footboard force (blue).

Conclusion

Despite significant differences found between left and right footboard load cells, the average difference between the two measures (0.5084 ± 0.4779 N) was deemed small enough to not have an impact on calculated asymmetry indexes as the footboard forces being compared have magnitudes of several hundred Newtons. As well, despite significant differences the average differences between the pre-trial and post-trial values in the left (0.1259 ± 0.2307 N) and right (0.09484 ± 0.1876 N) footboards were deemed to be small enough to not affect calculated asymmetry indexes.

Appendix F A Vertical Calibration of AMTI Load Cells.

Introduction

Calibrating load cells is an important step in data analysis. The calibration ensures that the interpretation of the load cell output accurately represents the true force output being measured and controls the level of error by minimizing the level of uncertainty within the data.

Methods

Three AMTI AD2.5D load cells (two 500 lbs capacity, and one 1000 lbs capacity) (6 degrees of freedom; x, y, z, pitch, roll, yaw; AMTI Force and Motion, Watertown, MA) were calibrated using known weights. The weights placed on the 500 lbs load cells were 44.5 N, 111.2 N, 222.4 N, 355.8 N, and 444.8 N. The weights placed on the 1000 lbs load cell were 44.5 N, 111.2 N, 222.4 N, 355.8 N, 533.8 N, 734.0 N, and 867.4 N. The placement of the weights was randomized for all load cells.

The load cells were placed on a flat surface, which was verified using a level. The weights were then placed on the load cell before the initiation of the trial. Each weight was recorded for five seconds as it sat stationary on top of the load cell. The measured vertical forces were averaged across the five second trials and compared to the known weights.

Results

No biases were found, as demonstrated in (Figure 39), where the measured force output, in Newtons, was compared to the known weights.

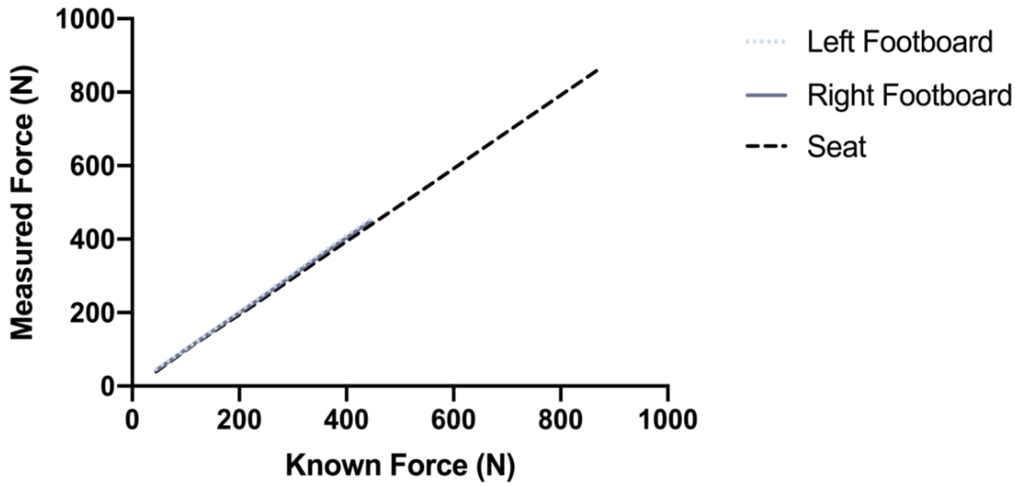

Figure 39. Calibration of three AD2.5D load cells. The calibrations in the three AD2.5D load cells were verified. This graph shows known masses converted into Newtons compared with the measured forces.

Conclusion

The AMTI AD2.5D load cells used in this study were determined to be appropriately calibrated.

Appendix G Discrete Force and Moment Measures in the Footboards and Seat

Table 8. Anteroposterior axis force and moment discrete measures (ergometer global coordinate system).

Condition (spm)	Forces (N)				Moment (Nm)			
	60 spm	80 spm	100 spm	Max spm	60 spm	80 spm	100 spm	Max spm
Left Footboard								
Peak	419.8 ± 138.9	428.1 ± 112.4	448.8 ± 124.6	461.1 ± 153.6	0.7 ± 0.5	0.9 ± 0.8	1.1 ± 0.9	1.0 ± 0.8
Minimum	-61.8 ± 68.9	-69.4 ± 78.0	-74.9 ± 58.0	-112.6 ± 63.1	-1.9 ± 1.0	-1.7 ± 1.1	-1.7 ± 0.9	-1.9 ± 1.0
Range	487.5 ± 181.2	500.6 ± 164.9	525.6 ± 161.8	573.7 ± 184.4	2.6 ± 1.3	2.6 ± 1.5	2.8 ± 1.2	2.9 ± 1.0
Push Impulse	33.1 ± 21.9	28.7 ± 17.6	30.3 ± 15.9	28.1 ± 18.3	-2.4 ± 2.2	-1.4 ± 1.9	-0.9 ± 2.0	-1.0 ± 1.7
Aerial Impulse	-9.8 ± 14.7	-5.9 ± 9.2	-5.8 ± 9.9	-5.7 ± 4.6	-0.9 ± 1.0	-0.8 ± 1.0	-0.4 ± 0.6	-0.3 ± 0.3
Right Footboard								
Peak	459.2 ± 162.1	464.6 ± 124.0	464.9 ± 119.3	451.0 ± 105.9	1.7 ± 1.2	2.1 ± 1.6	1.8 ± 1.2	1.8 ±1.4
Minimum	-41.6 ±72.0	-48.6 ± 70.6	-78.6 ± 75.7	-123.3 ± 89.2	-0.8 ± 0.5	-0.9 ± 1.0	-1.2 ± 1.0	-1.2 ± 0.7
Range	526.7 ± 190.0	526.9 ± 159.8	550.5 ± 167.2	576.6 ± 170.3	2.5 ± 1.1	3.0 ± 1.8	3.1 ± 1.6	3.1 ± 1.4
Push Impulse	-2.4 ± 2.2	-1.4 ± 1.9	-0.9 ± 2.0	-1.0 ± 1.7	3.0 ± 2.7	1.7 ± 1.9	1.7 ± 1.6	1.1 ± 1.3
Aerial Impulse	-9.2 ± 11.0	-4.2 ± 9.4	-8.6 ± 7.4	-4.5 ± 17.0	1.3 ± 1.1	1.0 ± 0.98	0.6 ± 0.62	0.7 ± 0.68
Seat								
Peak	-31.0 ± 56.0	-25.0 ± 50.8	-15.2 ± 57.1	-0.2 ± 58.9	21.3 ± 5.7	25.4 ± 5.4	29.3 ± 6.5	38.2 ± 7.0
Minimum	-189.5 ± 72.2	-205.1 ± 82.8	-220.7 ± 77.5	-240.3 ± 71.2	-24.6 ± 10.7	-27.4 ± 10.9	-30.9 ± 10.8	-37.2 ± 9.1
Range	240.3 ± 91.4	249.8 ± 99.9	270.9 ± 88.1	291.1 ± 78.0	-2.0 ± 8.3	-1.84 ± 5.8	-1.8 ± 4.1	-1.23 ± 2.4

Note. strokes per minute, spm; Newton, N; Newton meter, Nm

mean ± 1 standard deviation; the push impulse and aerial impulse are the only values reported in the local footboard coordinate system

Table 9. Lateral axis force and moment discrete measures (ergometer global coordinate system).

Condition (spm)	Forces (N)				Moment (Nm)			
	60 spm	80 spm	100 spm	Max spm	60 spm	80 spm	100 spm	Max spm
Left Footboard								
Peak	40.5 ± 14.0	44.7 ± 16.8	48.2 ± 19.3	57.9 ± 24.1	2.0 ± 2.4	2.3 ± 1.8	2.9 ± 1.6	3.1 ± 2.1
Minimum	-25.9 ± 15.3	-28.5 ± 16.7	-36.9 ± 20.1	-44.7 ± 18.0	-4.9 ± 4.1	-4.8 ± 4.1	-4.5 ± 4.0	-4.6 ± 3.4
Range	66.7 ± 23.7	73.2 ± 25.5	85.1 ± 30.3	102.5 ± 37.1	7.1 ± 1.3	7.1 ± 1.5	7.4 ± 1.2	7.8 ± 1.0
Push Impulse	16.0 ± 15.3	6.7 ± 8.3	3.2 ± 6.7	2.6 ± 7.8	-1.3 ± 1.6	-0.9 ± 1.2	-0.5 ± 1.0	-0.5 ± 1.1
Aerial Impulse	9.7 ± 11.8	7.4 ± 8.4	4.9 ± 7.7	3.5 ± 8.6	-0.2 ± 0.6	0.1 ± 0.6	0.2 ± 0.5	0.2 ± 0.5
Right Footboard								
Peak	29.2 ± 13.1	36.1 ± 13.3	36.2 ± 16.7	49.8 ± 19.1	1.4 ± 2.0	2.2 ± 1.7	2.1 ± 2.3	3.0 ± 2.8
Minimum	-40.3 ± 16.3	-43.2 ± 14.7	-47.3 ± 16.9	-55.5 ± 22.1	-3.0 ± 1.7	-2.8 ± 1.4	-3.7 ± 1.6	-3.5 ± 1.3
Range	69.75 ± 13.4	79.3 ± 14.5	83.5 ± 21.6	105.3 ± 34.7	4.5 ± 2.0	5.2 ± 1.8	6.1 ± 2.5	6.7 ± 3.5
Push Impulse	-1.3 ± 1.6	-0.9 ± 1.2	-0.5 ± 1.0	-0.5 ± 1.1	-0.8 ± 1.2	-0.4 ± 0.8	-0.6 ± 1.2	-0.4 ± 0.8
Aerial Impulse	-15.0 ± 12.0	-8.0 ± 8.2	-7.1 ±7.3	-6.5 ± 7.0	-0.5 ± 0.8	-0.2 ± 0.8	-0.2 ± 0.6	-0.2 ± 0.5
Seat								
Peak	55.2 ± 19.9	74.9 ± 24.3	93.7 ± 32.4	134.7 ± 41.9	-8.9 ± 19.6	-8.3 ± 20.6	-4.5 ± 20.0	-8.9 ± 19.6
Minimum	-52.5 ± 24.4	-66.8 ± 25.9	-83.0 ± 32.0	-124.4 ± 44.2	-39.8 ± 16.5	-40.6 ± 17.3	-41.2 ± 16.9	-39.8 ± 16.5
Range	107.7 ± 42.3	141.7 ± 49.1	176.7 ± 62.6	107.7 ± 42.3	-45.4 ± 35.6	-33.2 ± 25.03	-26.4 ± 20.38	-45.4 ± 35.6

Note. strokes per minute, spm; Newton, N; Newton meter, Nm

mean ± 1 standard deviation; the push impulse and aerial impulse are the only values reported in the local footboard coordinate system

Table 10. Vertical axis force and moment discrete measures (ergometer global coordinate system).

Condition (spm)	Forces (N)				Moment (Nm)			
	60 spm	80 spm	100 spm	Max spm	60 spm	80 spm	100 spm	Max spm
Left Footboard								
Peak	91.1 ± 42.1	83.2 ± 35.4	87.5 ± 40.0	84.2 ± 49.8	6.1 ± 4.5	7.1 ± 5.5	6.6 ± 4.4	6.5 ± 3.2
Minimum	-10.1 ± 31.0	-18.1 ± 32.6	-18.6 ± 33.6	-27.5 ± 30.8	-0.7 ± 1.8	-1.3 ± 2.4	-2.6 ± 4.4	-2.6 ± 4.4
Range	118.6 ± 54.5	114.6 ± 44.1	121.1 ± 48.2	121.1 ± 52.0	7.4 ± 3.8	8.9 ± 4.3	9.7 ± 3.1	9.7 ± 2.5
Push Impulse	164.3 ± 49.3	125.9 ± 44.7	125.2 ± 41.4	113.7 ± 40.8	0.7 ± 1.0	0.5 ± 0.8	0.1 ± 0.9	0.2 ± 0.7
Aerial Impulse	-17.0 ± 47.9	-12.0 ± 38.8	-11.7 ± 24.9	-24.5 ± 17.6	0.04 ± 0.4	0.06 ± 0.4	0.07 ± 0.2	0.06 ± 0.1
Right Footboard								
Peak	80.3 ± 43.7	81.2 ± 36.5	87.2 ± 37.7	85.8 ± 36.1	0.1 ± 1.7	0.9 ± 2.5	1.2 ± 2.9	1.8 ± 2.8
Minimum	-10.2 ± 31.6	-11.9 ± 35.9	-17.1 ± 36.6	-29.2 ± 37.2	-7.1 ± 4.0	-7.6 ± 5.5	-7.5 ± 3.7	-7.2 ± 2.4
Range	107.0 ± 55.5	110.2 ± 43.6	121.0 ± 46.6	126.2 ± 44.6	8.3 ± 3.7	9.3 ± 4.7	9.4 ± 3.1	9.4 ± 2.3
Push Impulse	170 ± 70.0	121.5 ± 61.9	111.3 ± 36.8	85.7 ± 44.4	-1.2 ± 1.2	-0.4 ± 0.8	0.6 ± 0.7	-0.4 ± 0.5
Aerial Impulse	-5.8 ± 62.5	1.4 ± 53.7	-18.7 ± 36.1	-11.1 ± 58.7	0.08 ± 0.4	0.07 ±0.4	0.07 ± 0.2	-0.04 ± 0.4
Seat								
Peak	702.4 ± 92.9	730.4 ± 92.7	759.9 ± 99.7	844.6 ± 163.4	17.9 ± 4.6	19.5 ± 6.0	21.3 ± 5.5	25.5 ± 5.3
Minimum	466.2 ± 73.3	444.8 ± 70.1	440.8 ± 65.6	385.7 ± 57.4	-16.4 ± 3.5	-18.4 ± 3.9	-20.6 ± 4.6	4.6 ± 5.6
Range	1168.6 ±146.7	1175.2 ±141.5	1200.6±140.3	1230.3 ±170.5	0.00 ±2.3	-0.08 ± 1.9	-0.07 ± 1.5	0.4 ± 1.31

Note. strokes per minute, spm; Newton, N; Newton meter, Nm

mean ± 1 standard deviation; the push impulse and aerial impulse are the only values reported in the local footboard coordinate system