Relationship Between Strength, Technique, and Tactics with Canoe Slalom Performance

by

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Abstract

This research investigates the relationships between strength, technique, and tactics in canoe slalom. 15 C1 athletes paddled a white-water slalom course and a flat-water figure-8 course. Paddle forces, GPS data, and accelerations were collected to form a set of performance metrics. Relationships between performance metrics on flat-water or white-water with white-water race times were assessed through multiple regression. Additionally, the relationship between flat-water paddle force and flat-water lap time was modelled using a mixed effects model. White-water race times were successfully predicted using flat-water or white-water performance metrics (r^2 = 0.81 and 0.98 respectively). Flat-water lap time was significantly related to paddle force. Despite high correlations with white-water race time, the figure-8 test alone lacked predictive power. The figure-8 test could be a training tool for athletes and coaches to monitor improvements in paddling-specific strength. On white-water, athletes relied on high speeds, shorter distances and power to achieve fast times.

Keywords: canoe slalom; kayaking; performance analysis; strength; technique; tactics

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C1W	Single canoe women
C1M	Single canoe men
RFD	Rate of force development

Chapter 1.

General Introduction

Canoe slalom is an Olympic sport where athletes paddle down a white-water course through a set of suspended gates, trying to achieve the fastest time possible. The gates are placed in different currents, such that the athlete must navigate intelligently across waves, rolling water features that stop boat movement (called stoppers), and through upstream currents in eddies behind obstacles. According to international rules (International Canoe Federation or ICF), there must be six red upstream gates, which athletes navigate through in eddy currents against the main current, and up to 19 green downstream gates, with a maximum of 25 gates (ICF, 2022). The downstream gates are typically offset from one another, forcing the athletes to zig-zag across the water features. The line that an athlete takes through these gates is a major determinant of performance in canoe slalom, and a common source of added time is accidentally paddling low into the upstream eddies then having to attain up towards the gate. Success in slalom is largely determined by how well an athlete uses the features of the water—waves, eddies, and stoppers—to their advantage. Athletes must also be physically fit, using their powerful arms, core, and to some extent legs to propel the boat through the water. Slalom requires continuous power input, due to the many accelerations and changes of direction that occur in order to complete the gate sequence. Approximately 30 % of slalom strokes are intended to change the boat's direction (Hunter, 2010).

The races are held at different venues, and most of the international competitions are held throughout Europe. Each white-water venue has different water features and varies in the grades of water terrain difficulty. Although water features at the same venue typically remain unchanged between races, the sequence of gates across the features is altered for each race. Each race consists of two qualification runs, a semi-final, and a final. The qualification runs are completed on the same sequence of gates, which is a course specifically designed for that race which the athletes have never experienced before. The semi-final and finals run are completed on another brand-new set of gates, specifically designed to challenge the world-class athletes. The ways athletes navigate through the gates can differ, and some choices, such as a direct line between downstream offsets, are only possible by more experienced and stronger paddlers, or by the more agile kayak class. Other choices involve spinning backwards above a downstream gate, in order to slow the boat's movement in the fast current and have enough time to navigate properly throughout the gate without missing or touching it. The penalty for missing a gate is 50 seconds, which is substantial for a race that typically lasts between 90-110 seconds, depending on the venue and category. The penalty for touching a gate is two seconds, or approximately 2 % of race time. As medals can be decided with less than one second of separation between athletes, avoiding this penalty is also critical to success. If an athlete flips upside-down during the race, due to poor boat control against the powerful water features, they are allowed to roll back up and complete the race, though this is not common for experienced athletes. Canoe slalom is thus a physical, technical, tactical, and mental challenge.

There are two disciplines in canoe slalom, the single canoe class or "C1", and the single kayak class or "K1". The K1 class sit with their feet in front and use a double bladed paddle. The C1 class sit kneeling in the boat, and use a single bladed paddle. To take strokes on the other side of the boat the C1 paddlers either switch their hands, or simply cross the paddle to the other side to take a stroke with their body twisted. Both disciplines have men and women's categories. The men's kayak (K1M) is typically the fastest category, followed by the men's canoe (C1M), the women's kayak (K1W), and the women's canoe (C1W) typically have the longest times, although this gap is reducing over time (Hunter, 2010; Wells, 2018). The C1 class tends to be slower than the K1 class due to the single bladed paddle, which makes consistent propulsion more difficult, and reacting to events on the opposite side of the boat more difficult as well.

Little published research is applicable for canoe slalom (Messias et al., 2021). Thus, many paddlers rely on expert coaching knowledge, as well as general exercise research principles for their training programs. The potential for athletes to gain knowledge from anecdotal evidence (for example, copying the training plan of a single high-profile athlete) or from speculative physiological or biomechanical rationale without evidence for paddling is therefore high, and these weaker forms of knowledge are less likely to provide performance improvements. At the moment, many paddlers cannot rely on high quality evidence, such as scientific research, to inform their training (Rawlley-Singh and King, 2021). This may be because the available research in canoe slalom is not directly applicable to the athletes, or because many teams lack resources to have their own scientific support team working on proprietary research projects. Therefore, the relevance of published research in canoe slalom to the users—namely, athletes and coaches—needs to continue to improve, as this form of knowledge can be one of the strongest sources for improving performance in canoe slalom, along with expert coaching advice and individual athlete monitoring.

Technique and Tactics in Canoe Slalom

Technique and tactics are argued as the most important factor influencing performance in canoe slalom by expert coaches (Busta, 2020). Indeed, despite being a ninety second all-out race, many top athletes are between 30-40 years of age in canoe slalom which may indicate the importance of experience in developing technique and tactics. Tactics in canoe slalom include all decisions about navigation through a set of gates: the line and type of turn, boat angles, and speed. Technique in canoe slalom generally refers to the effectiveness of strokes and boat movements. Movements that waste energy towards undesired directions would show ‘worse’ technique, and movements that accomplish the goal with the least amount of energy would show ‘better’ technique. Technique is usually described qualitatively by an expert coach’s eye, rather than measured quantitatively.

Athletes must have good paddling technique, aiming to use the least amount of muscular effort in order to accomplish the task (Busta, 2020). Various coaching resources report aspects of the optimal stroke, such as trunk rotation, which relies on the strong muscles of the core (Busta, 2020; Ferrero and British Canoe Union., 2006). Work is underway in Australia to quantify effective and ineffective paddle strokes, though actual data appears exclusive to the Australian team (Lyons, 2005). There is currently no published research on the kinematics of a slalom stroke.

Athletes must also choose the best tactics for their paddling style to navigate a sequence of gates. Indeed, strategies such as a spin, where an athlete spins the boat backwards above a gate, versus a more direct strategy between gates, were proven to differentiate split times between paddlers by Hunter in his PhD working with the Australian slalom coaches and 17 slalom athletes (Hunter et al., 2008). Hunter also showed that the approach into an upstream gate can significantly impact the time it takes to negotiate the gate. Staying wide and then turning tight around the pole was proven much faster than trying to cut the line short and having to circle around wide below the pole (Hunter, 2009). Some countries, such as Britain and Germany, quantify the times of different lines between gates from qualifier one to two, or from semi-finals to finals, in order to help their athletes choose the fastest lines (Busta, 2020). Sometimes, however, the fastest lines have the greatest risk for incurring a penalty. Wells in her PhD work with British Canoeing showed the top semi-finalist time could be used to set a benchmark target for finals, and achieving this benchmark increases the chance of winning a medal. This could inform athletes what level of risk they should take when choosing lines for finals (Wells, 2018).

Strength and conditioning in canoe slalom

Physical fitness (strength, power, and aerobic fitness) in canoe slalom is also important, albeit less so than technique and tactics according to skilled coaches (Bílý et al., 2010; Busta et al., 2018). The majority of research in canoe slalom is centered around physical fitness.

High performing athletes tend to have higher general fitness than lower performing athletes in canoe slalom. General tests of upper-body power, such as the 30 second Wingate on arm-crank ergometer, show correlations of 0.6 with race time when looking across 18 C1M competing for spots on the Czech Junior, Under 23, or Senior National teams (Busta et al., 2018). However, among six C1M already on these National teams, correlations were only 0.3 (Bílý et al., 2010). It is likely that general tests of power cannot differentiate well between the top-performing athletes but are able to differentiate between top-performing and those ranked lower. Indeed, general strength tests such as handgrip strength were enough to differentiate top performers from lower ranking athletes (Busta et al., 2022). General tests of upper-body strength, such as the bench press one rep max, show correlations of 0.6 with performance among 18 athletes competing for spots on the Czech National team; while others such as the pull-up one rep max show insignificant correlations of only 0.2. (Busta et al., 2018). General aerobic fitness tests, such as the VO_2 peak while running, do not show relationships to athlete rankings (Busta et al., 2018).

Thus, more sport-specific tests of strength and power are needed to pin down the relationship between strength, power, and aerobic fitness with race performance. Indeed, pairing strength with the sense of water by properly ‘catching’ the water with the blade is an important factor that dictates whether an athlete can utilize their strength in canoe slalom performance (Busta, 2020). Some authors have attempted to quantify anaerobic capacity in flat-water performance through critical power or shuttle tests (Manchado-

Gobatto et al., 2014; Messias et al., 2015; Süss et al., 2008). But perhaps the most sport specific analysis of strength and power in canoe slalom comes from analyzing the kinetics of paddling. One research group attempted to do this by measuring the force applied to a tether on the boat as athletes paddled as hard as they could. The maximum force produced after several strokes during this anaerobic test showed correlations of -0.6 with race time for 12 Brazilian National Team members (Messias et al., 2015). Another researcher quantified paddle kinetics with an instrumented paddle (Macdermid et al., 2019). Macdermid observed paddle force gradually decline over the course of a flat-water slalom race for eight K1M, providing some indication of anaerobic capacity. However, despite the rate at which this decline occurred differing between athletes, it was not significantly related to race time. Unfortunately, the relationship between the actual peak forces and race time was not analyzed for these athletes. Instead, this relationship was investigated on easy white-water slalom, again where 12 K1M used an instrumented paddle (Macdermid and Olazabal, 2022). No relationship was found between average peak paddle force and ranking, with a correlation of only -0.11. However, the correlation between mean power and race time was -0.7.

Thus, the relationships between metrics of strength or power with canoe slalom performance can be large, and the highest correlations are around 0.5-0.7.

Variability in canoe slalom

Due to the nature of white-water features and the change in course designs for each race, canoe slalom is more variable than other sports (Nibali et al., 2011). Variation between runs on the same course can be large, with a coefficient of variation of 2.85 to 11.21 s reported by Vieira et. al for six Brazilian K1M (Vieira et al., 2015). For these men, the total number of strokes, total distance, and mean velocity also varied between runs, typically between 3-11 strokes, 10-40 meters, and 1-4 meters per second. Given such variation, the smallest worthwhile enhancement in slalom is larger than other sports (Nibali et al., 2011). Because the race times vary from course to course, absolute performance in canoe slalom is difficult to quantify. Ranking shows great variability in any given year, and the race times themselves become tighter or more spread out from the top racer depending on the year (Wells, 2018). However, trends in athlete performance over time are noted. There tends to be initial improvement in ICF ranking lasting approximately three to six years, followed by a plateau period with greater variation in ranking lasting approximately four years, followed by a gradual decline in performance after approximately six years (Wells, 2018).

In conclusion, canoe slalom is more variable than other sports, making performance across a season more difficult to track. Faster athletes have higher upper body power than slower athletes, on paddling-specific and non-paddling-specific tests. Tactics are a key part of performance as identified by expert coaches, but research into the tactics of canoe slalom is rare. Technique is also a key part of performance according to expert coaches but to date no published research has investigated the role technique plays in performance. The largest gaps in canoe slalom research therefore concern the importance of technique and tactics on performance.

Chapter 2. Paddling Study

Introduction

The motivation for this study is to examine how strength, technical, and tactical skills in canoe slalom relate to race time. In this thesis, the constitutive definition for strength is a general term that refers to muscular outputs such as force, velocity, power, and duration or rate of contraction. The constitutive definition of technique refers to the quality of boat movements and the relationship between strokes and boat movements. The constitutive definition of tactics refers to decision-making on the course, through choice of line, angle, and speed.

Previous research has compared flat-water paddling tests with sprints and turns to white-water performance (Baláš et al., 2020; Busta et al., 2018; Vajda and Piatrikova, 2021). These tests primarily incorporate physical and technical aspects of canoe slalom. Fast sprints require paddlers to have good strength as well as technique. Technique on sprints is especially relevant for the C1 class, as it is more difficult to paddle in a straight line. In order to paddle straight while taking strokes on only one side, many C1 paddlers engage the opposite edge of their boat as they take a stroke. This counters rotation due to the paddle stroke and helps the boat track straight. Fast turns also require paddlers to have good strength and technique. Controlling the edges in a turn ensures continuous rotational velocity without undue drag or slip. Both strength and technique ensure a fast exit from the turn, which is a critical skill in canoe slalom (Canoe Kayak Canada; Coaching Association of Canada, 2016).

Performance on flat-water tests with sprints and turns show correlations of 0.5-0.9 with white-water performance in all published studies thus far, to the best of my knowledge. In contrast, the results of some strength tests, such as bench press one rep max, show similar correlations of 0.6 with white-water performance, but others, such as bench pull one rep max, show only insignificant correlations of 0.2 (Busta et al., 2018). There were correlations of 0.6-0.86 between flat-water sprint and turn tests and white-water performance in 19 elite slalom athletes (Busta et al., 2018). These flat-water tests were also able to differentiate between nine elite and nine sub-elite slalom paddlers (Baláš et al., 2020). Shorter sprint and turn tests, with one to two turns and a duration of 11-19 seconds, have correlations of 0.5-0.91 (Busta et al., 2018; Vajda and Piatrikova, 2021).

Longer sprint and turn tests, with 4-12 turns and a mean duration closer to an actual race of 95-106 seconds, have correlations of 0.71-0.87 with canoe slalom performance (Busta et al., 2018; Vajda and Piatrikova, 2021).

It is not clear from a quantitative point of view why a simple flat-water sprint and turn test correlates so well with white-water performance. There seem to be physical and technical similarities between the test and a white-water course, but it is unclear to what extent these demands differ. Additionally, the tactics on a flat-water test are much simpler, with only one line into and out of each turn to navigate and without current. It is important to know which aspects of white-water performance these tests measure. Therefore, the first aim of this study is to examine the relationship between flat-water performance and white-water time.

Aim 1 and Hypothesis 1: I will investigate which aspects of performance on the flat-water sprint and turn test are linked to white-water race times. These may be physical, technical, or tactical. (1) I hypothesize that metrics of strength and technique, but not tactics, on the flat-water will be related to white-water performance.

Canoe slalom is more variable than other sports, with coefficient of variation between two simulated white-water race runs up to 11.21 s (roughly 11 %) on two runs of the same white-water course (Vieira et al., 2015). This variability makes slalom performance more difficult to summarize for a single athlete, as one mistake may push a paddler far off line. Additionally, it is difficult to summarize a single athlete's performance across the season because course designs change with each race. For example, the top C1 race time varied by 10.59 s across the world cups and world championships of 2022 (excluding the race at Tacen which was shorter due to low water; International Canoe Federation, 2022b). Additionally, different courses may favor different athlete styles, which introduces variability to the rankings between competitions. Thus, it is not as simple as other sports to evaluate the impact of recent training on a paddlers performance. A valid performance test would be useful to monitor progress among developing athletes and to monitor world-class athlete performance during different phases of their yearly training cycles—valid in the way that it can be used to approximate white-water performance as best as possible. Thus a second aim for this thesis is to determine how well a flat-water test with sprints and turns predicts white-water rankings (a), and if this test might be useful to track an individual athlete's improvement (b). Even if an athlete's rank cannot be accurately predicted by the flat-water sprint and turn tests, it may be useful to monitor improvements in specific skills, such as paddling-specific strength.

Aim 2a and Hypothesis 2a: I will determine how well the flat-water sprint and turn test predicts white-water race rankings, using flat-water race times and aspects of flat-water performance. I hypothesize there will be correlations of 0.5-0.9 between the flat-water sprint and turn test times and the white-water race times, but that ranking errors will make this test less valid to approximate white-water performance. (2a) Specifically, I hypothesize there will be errors in the top three placings.

Aim 2b and Hypothesis 2b: I will determine if an athlete's paddle force (representing paddling specific strength) is related to their flat-water sprint and turn lap time. Individual athletes may lose time on their laps due to decreased strength with fatigue, or they may lose time due to technical aspects of the test. Knowing how much time is gained due to a decrease in strength, or how much time could be lost without fatigue, would be useful for the athletes when planning training regimes. (2b) I hypothesize that lap time will decrease as paddle forces decline.

Importantly, despite flat-water sprint and turn tests having correlation coefficients with white-water performance from 0.6 to 0.9, there remains a component of performance that is not explained through flat-water tests. For example, as white-water difficulty increases, the relationship between canoe slalom white-water performance and flat-water performance decreases (Vajda and Piatrikova, 2021). Thus there is a unique element of the interaction between paddler and white-water feature, such as wave, eddy, or stopper, that also determines paddler performance.

Few studies focus on technique or tactics in canoe slalom, which is a persistent problem for the sport in the context of information available to less-experienced groups, as well as pushing performance forward with the most effective technical improvements. Attempts to quantify performance on white-water on a stroke-by-stroke basis certainly exist, but it is hard to draw more general conclusions for slalom training from these specific examples (Hunter, 2010). This study aims to understand if more general tactical principles related to the total distance travelled and boat heading direction (angle, Figure 5) are linked to race time. These tactics should represent one of the key difference between flat-water and white-water. Additionally, the exact physical demands of canoe slalom when more complex white-water technique and tactics are required are not yet researched. Therefore I will also examine how the physical demands of white-water differ from those of flat-water. Lastly, the balance of strength versus technique or tactics on a canoe slalom course is unknown. It is likely this balance changes throughout the course, depending on the gate sequence and white-water features at hand. This balance likely also changes for forward strokes versus turning strokes. The third aim of this thesis is to determine the importance of various aspects of strength, technical, and tactical skills to canoe slalom performance on white-water. I will do this by examining multiple metrics assumed to be associated with strength, technique, or tactics. If a metric is found to be associated with white-water race time, it could be of interest to track in training and in future research projects.

Aim 3 and Hypothesis 3: I will investigate which measurements of strength, technique, and tactics on the white-water are linked to white-water race times. (3) I hypothesize that the balance of these skills will shift across different split sections of the white-water course.

Methods

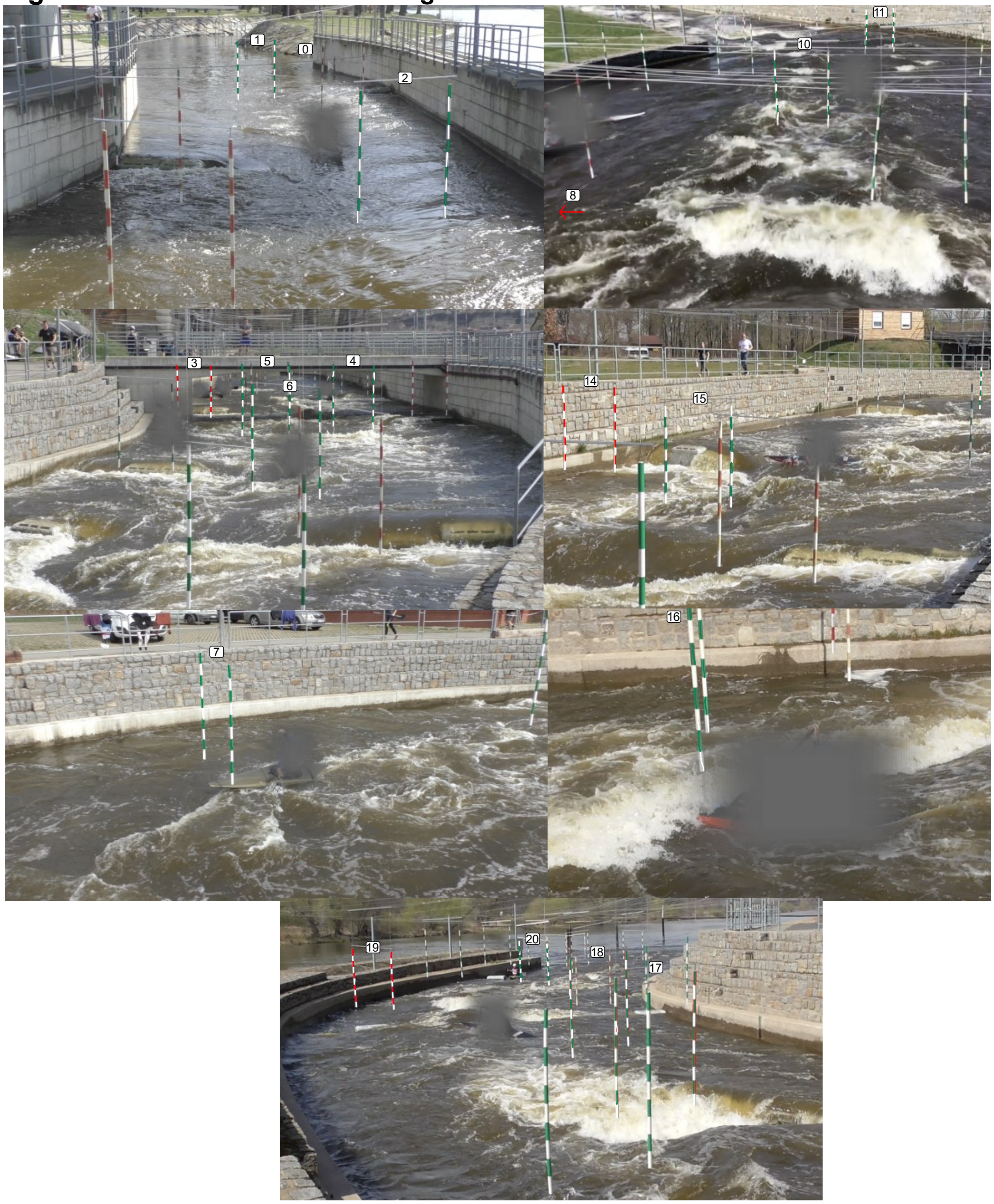
Participants

15 C1 athletes (10 male 5 female) participated in the study. Athletes were recruited from the Czech Republic Junior, U23, or Senior teams by Czech coach Dr. Jan Busta. Each participant gave informed consent and ethical approval was granted by the Institutional Ethics Review Boards at Simon Fraser University. The best previous results from our sample of athletes were Olympic silver, as well as World Cup podiums.

Study design

Data collection took place at the artificial white-water course in Roudnice in the Czech Republic. C1 athletes were asked to paddle a white-water slalom course. The course was set under ICF (ICF, 2022) rules, with 20 gates, six of which were upstream gates (Figure 1). There were equal left and right upstream gates. The course was designed to mimic an average canoe slalom competition course with no special moves. Athletes were asked to switch if they were able, switching the side of the boat and bottom hand that they paddled with. If they were not able, athletes relied on cross strokes to complete the course. The athletes performed their first run with their preferred technique (switching or not switching), and the second run with the other technique if they were able. Five athletes were analyzed for a second run of the white-water course (due to completing only one run due to time constraints or missing data), and athletes were given at least 15 minutes rest between runs. We captured video at four locations along the course, covering the entirety of the course. The white-water cameras were synced with an audible “Go” cue transmitted by radio. Penalties were confirmed by video (2 s if an athlete touches a gate, 50 s if an athlete misses a gate). The full race time was recorded by hand timer.

Figure 1: White-water course design



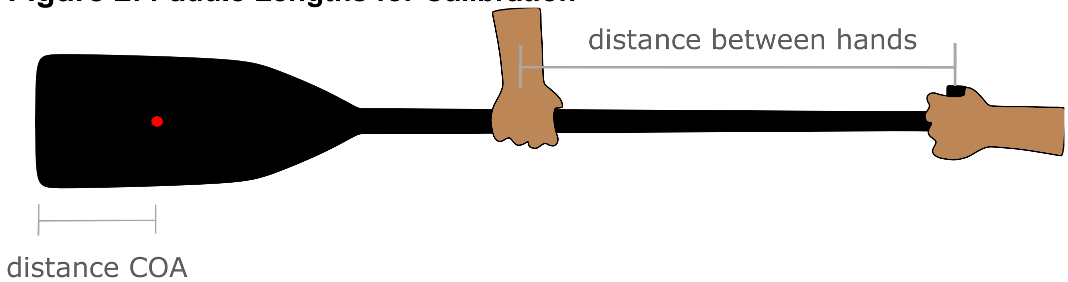
The white-water course included 14 downstream gates (green) and 6 upstream gates (red). Gates are numbered between the poles in the figure. Un-numbered gates were not used, and this format of multiple gates on the water is typical for the athlete's daily training. Gates 8 and 9 are off-screen, on either side of the top wave.

The athletes also paddled a figure-8 course around two gates on flat-water separated by 20 m at the flat-water section of the Roudnice course without flowing water. The course was an all-out test with nine repeats of straight paddling and eight turns, one from the left and one from the right. We collected race time and video of the performance. All but two athletes performed two flat-water runs. The athletes performed their first run with their preferred technique (switching or not switching), and the second run with the opposite technique if they were able.

Procedure

We placed an inertial measurement unit inside the boats in front of the athlete, just below the cockpit rim in order to collect linear accelerations and angular velocities (at 25 Hz) of the boats (MetamotionRL, MBIENTLAB, California, U.S.). The range of the accelerations and angular velocities ensured the full range of data was collected without clipping the signals. The IMU was aligned with the long axis of the boat. We attached a GPS unit to a helmet strap on the athlete's helmet to collect GPS coordinates and speed at 10 Hz (GLO 2, Garmin, Switzerland). Finally, we gave the paddlers a specific paddle that has force gauges embedded in the shaft to collect paddle forces (Canoe Power Meter 2^{nd} Gen, One Giant Leap, New Zealand). The paddle was adjusted to their preferred length. We also measured the point at which they gripped the paddle shaft in order to calibrate the paddles (Figure 2). The blade was the same for all paddlers (size M Revolution, G'Power, Poland), due to budget for only one power-meter equipped shaft, and the time constraints involved with switching blades. However, limiting smaller paddlers to use a blade too large, and larger paddlers to use a blade too small likely limited the athlete's power outputs. Athletes used their own canoes for data collection, and boat designs differed between athletes. This may have influenced the lines and turning styles between athletes.

Figure 2: Paddle Lengths for Calibration



Where COA is the centre of area of the paddle, represented by the red dot. We measured the total length and the spot the athlete gripped the paddle to obtain the distance between hands.

Paddle Calibration

The force-gauge equipped paddles were calibrated by hanging six different weights ranging from 7-41 kg, across six paddle lengths and two grip lengths. The highest value represents 402 N of force, around the highest force typically applied by canoe slalom athletes (Macdermid and Olazabal, 2022). Only one athlete on one stroke performed a force larger than this, at 424N. We devised an equation to calculate the paddle force, given a specific paddle length and grip length (Equation 1). The actual paddle force and the predicted paddle force using our equation had a correlation of 0.9998 across data from all weights and lengths, and root mean square error of 1.88 N, with the highest error of 4 N. As typical paddle strokes ranged from 100-300 N in our data, this is a relative error of 1-4 %. However there will also be error if the athlete gripped in a different position on the shaft while paddling than measured, though this is small at 6 N for a 5 cm difference. We used this same equation, ideal for static load calculation, in order to calculate paddle forces during dynamic paddling.

Equation 1: Paddle force calibration

$$Paddle\ Force = (2.30592 + (2.18727 * distanceBWhands) - (2.85681 * distanceCOA)) * (strain - offset)$$

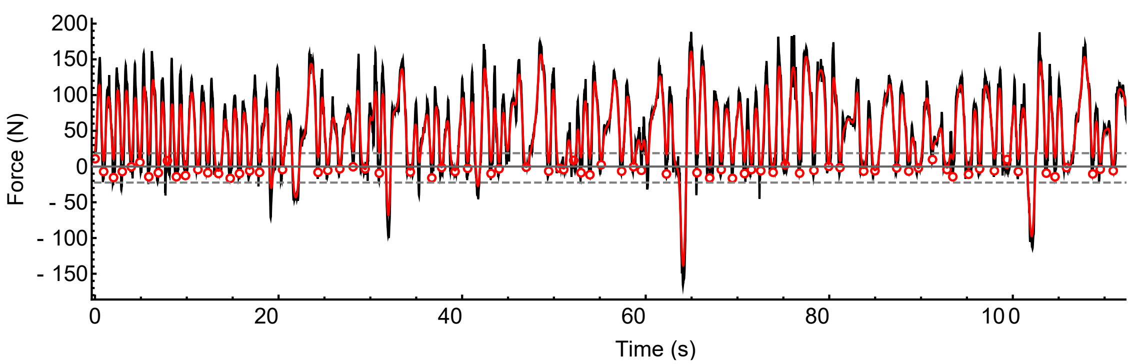
Where *Paddle Force* is the force in Newtons, the *distanceBWhands* is the distance from the middle of the top hand to the middle of the bottom hand (Figure 2), *distanceCOA* is the distance from the blade tip to the vertical centre of area of the blade (Figure 2), *strain* is the measured raw value from the paddles, and *offset* is the measured or calculated strain value when the paddle is at rest at the same temperature as data collection.

The strain gauges in the paddle responded to changing temperature during data collection. The possible root mean square error due to changing temperature was 8.7 N. This was obtained by using the time that the paddle was out of the water, before and after the run, to determine the offset and then taking the average of these two periods. This error is in addition to the 1.88 N error present in the calibration equation for the on-water trials. The orientation of the paddle may have also introduced some error, however, orientation of the paddle accounted for an error of only 0.5 N.

Paddle Data Processing

Paddle force data were split into paddle strokes. To split the paddle force data into strokes, a low-pass filter was applied (Mathematica LowpassFilter function, cut-off 7Hz), and the points at which the slope changed from negative to positive were identified as the start of a new stroke (Figure 3). Also identified was a positive and negative threshold, above or below which the stroke would not count as a new stroke. The threshold was 10 % of the maximum stroke force for each athlete. This allowed for turning strokes to have multiple peaks during their drive time. The low-pass filter was only used to split the strokes, and was not applied on the analyzed data. The separated strokes were then checked by eye.

Figure 3: Splitting force into strokes



In black is the raw force data, and overlayed in red is the filtered force data from which strokes were identified. The red circles represent points where the slope changed from negative to positive on the filtered red signal and indicate the start of new strokes, the magnitude of which has been aligned with the black raw force data. The gray dashed lines show the positive and negative thresholds, any fluctuations smaller than these could not count as new strokes. All strokes were confirmed by eye. Turning strokes are evident throughout: note the stroke at 20 s, 30 s, and 44 s for examples.

Strokes were then classified as forward strokes or turning strokes. This was determined by eye and manually adjusting the stroke classification points. Turning strokes also included combined turning strokes, such as a reverse sweep stroke into a draw stroke (both of which are turning strokes). The turning strokes were draw strokes (a turning stroke pulled into the boat), reverse sweep strokes (a turning stroke performed with the backside of the blade away from the boat) that led right into draw strokes, as well as draws or bow draws performed in the current. To operationally define turning strokes, all strokes with multiple peaks in force, longer strokes, and any strokes with negative peaks were said to be turning strokes. As the turning strokes were not confirmed by video, the classification was not perfect. However, any turning strokes that were shorter time and single peaked are expected to have minimal influence on the forward stroke data.

The flat-water paddle forces were also split into laps, including one straight section and one turn. These were split by first identifying the turning strokes. Turning stroke classification was perfect for the flat-water due to the simplicity of the figure-8 test. The recovery period between the end of the turning stroke and the start of the next forward stroke was identified as the start of the next lap. This exact time was chosen by using the filtered force data, as the point at which the slope changed from negative to positive. Thus lap one included a turn, while lap nine (the last straight section) did not.

The power-meter equipped paddles were unable to provide accurate power measurements for our protocol, which may be because they were designed for flat-water paddling. More than half the race had missing power data, and it did not appear synchronized with the force data. The specifics of the algorithm used to calculate power were proprietary and the raw IMU data included inside the paddles could not be accessed for modification. Therefore the metrics of power had to be estimated. Ideally, stroke power should represent the power produced by the athlete, which would include power to move the boat in the desired direction of travel and power wasted through unnecessary movements. Power is force times velocity, and while stroke force is relatively simple to obtain, stroke velocity was difficult to pin down on white-water. The velocity of the paddle, velocity of the current, and the effect of drag will all influence calculations of stroke velocity. If one uses the boat velocity (relative to the bank) in order to calculate stroke power, this calculation of stroke power will no longer only represent power produced by the athlete, but include any power gained from the current, and any power lost due to drag. For these reasons several calculations of stroke power were used.

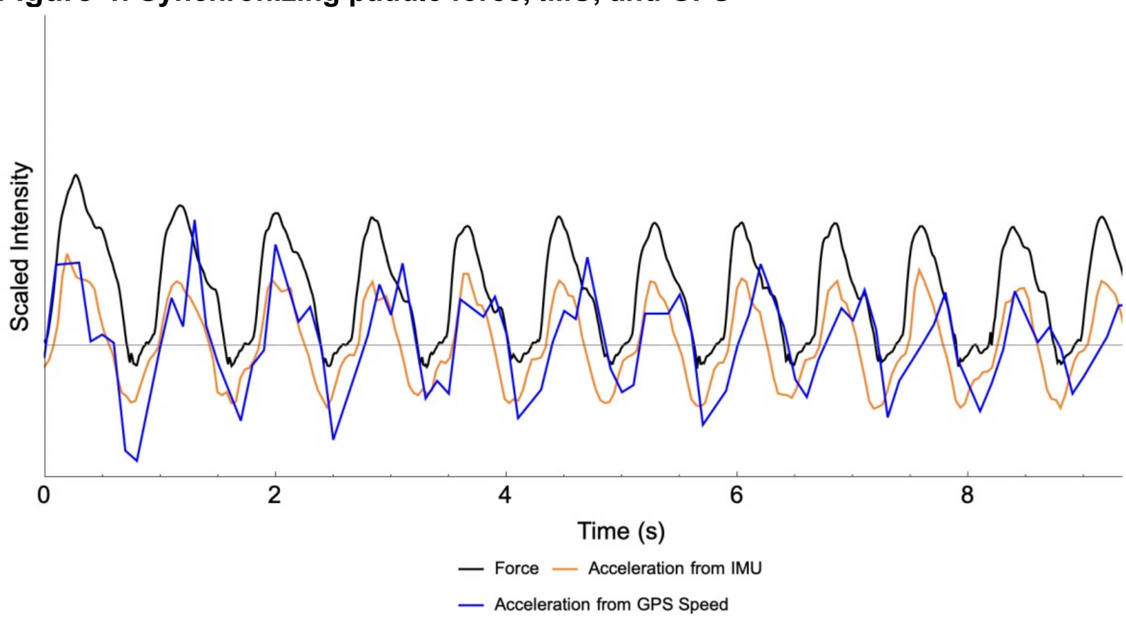
IMU Calibration

The accelerations were calibrated to have a zero offset by obtaining the mean value of acceleration from a point of stillness before the race and after the race and then subtracting this from the accelerations. This assumed that the net acceleration over this time was zero. The angles for each type of boat rotation were calculated by integrating the angular velocities obtained from the IMU. Despite filtering (Mathematica HighpassFilter function, cut-off 1Hz), drift remained in the angles from the gyroscope. Therefore, analyses of edging/roll and pitch were restricted to the straight sections of the flat-water figure-8 test.

Device Synchronization

The video and the paddles were synchronized by identifying the first frame that the paddle entered the water after the verbal “Go” signal. This was said to be the onset of paddle force. The IMU were then synchronized to the paddle forces by aligning the peaks that occur with each stroke in force and acceleration along the long axis of the boat (Figure 4). The GPS was synchronized to the paddle forces by first differentiating the GPS speed to obtain acceleration, and then aligning this with the peaks that occur with each stroke in acceleration along the long axis of the boat from the IMU (Figure 4).

Figure 4: Synchronizing paddle force, IMU, and GPS



Shown is an example of synchronization between the paddle, IMU, and GPS. The data was scaled to obtain similar magnitudes for each signal for synchronization purposes. Paddle forces were checked for a section at the beginning (shown here), middle, and end of the race to determine the best shift to align the two sources of acceleration within their given resolution (25 Hz for IMU, 10 Hz for GPS).

Splits

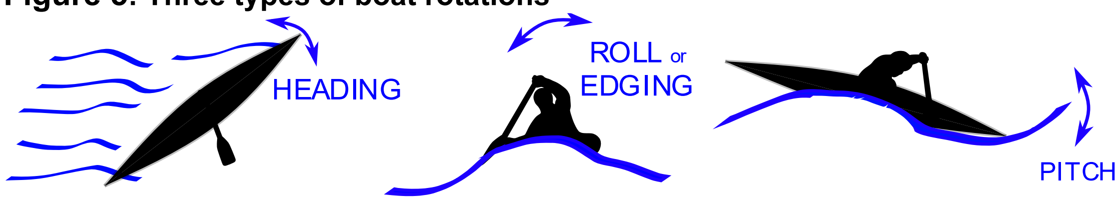
The entire race course was analyzed as a whole, as well as by eight splits (Figure 1). For the splits, the course was divided into downstream and upstream sections. Gates 0-2 were downstreams, had slow current but no waves, and were an easy offset combination (where gate 0 is the starting position for the race). Gates 2-4 were an upstream section, where gate three was a right upstream. Gates 4-7 were downstreams, a set of offsets through waves. In the upstream section gates 7-9, gates eight and nine were a set of double upstream gates, and the course was split once the paddler crossed upstream of the second upstream inside pole due to difficulties measuring the split on video. Gates 9-11 were a downstream section that include the exit from upstream 10, and were a set of offsets over waves. In the upstream section with gates 11-15, gate 13 and 14 were a set of double ups. This section includes the downstream gate 12 due to difficulties measuring the split on video. Gates 15-18 were a downstream section, a set of offsets through waves. And the final upstream section gates 18-20, Gate 19 was an upstream, and paddlers finished once they crossed the gate line of Gate 20. Analyzing the whole race as well the splits allow both the general skills important to slalom as a whole and the specific skills important to different water sections to be examined. Turning and forward strokes were analyzed together, however the effects of turning strokes alone are reported for each analysis. Split times were determined by video. Video was recorded between 25 to 60 Hz across the four cameras.

Performance Metrics

As the aspects of performance that are important to quantify for canoe slalom are not yet researched, 22 metrics were chosen that should represent some degree of an athlete’s strength, technique, tactics, or a combination; or else classify athletes by sex and mass. Age was not normally distributed, and logarithms, roots, nor inverse methods corrected age, so age was not included as a metric. All other metrics were normally distributed by a Shapiro-Wilks test and a p-value set at 0.05. The performance metrics were analyzed as a whole as well as by splits.

The metrics include: average peak stroke force, total impulse, overall power calculated from paddler and boat (overall $power_{pb}$), average stroke power calculated from stroke length and time (average stroke $power_{lt}$), overall mass specific $power_{pb}$, average rate of force development per stroke (RFD), total distance travelled, s.d. heading (boat left to right rotations; Figure 5), s.d. edging (boat side to side rotations; 'roll'; Figure 5), s.d. pitch (boat rocking up and down rotations; Figure 5), coherence between paddle force and edging, total stroke recovery time, average stroke drive time, average speed, acceleration, deceleration, total number of strokes, flat-water figure-8 race time, speed one stroke after the turns on the figure-8 test, speed six strokes after the turns on the figure-8 test, sex, and mass (Table 1).

Figure 5: Three types of boat rotations



Shown are the direction the boat is heading, the edging rotations side to side (called 'roll'), and the rotations that rock the boat (called pitch).

Table 1: Performance metrics

Metrics that primarily represent strength	**Device**
Average peak stroke force (N)	Paddle
Total impulse over 89 s (N s)	Paddle
Overall power$_{pb}$ (W)	Paddle and GPS
Average stroke power$_{lt}$ (W)	Paddle
Overall mass specific power$_{pb}$ (W kg^{-1})	Paddle (and mass)
Average RFD per stroke (N s^{-1})	Paddle
Metrics that primarily represent technique	**Device**
s.d. edging (degrees) (boat side to side rotations, 'roll') (Figure 5)	IMU
s.d. pitch (degrees) (boat rocking up and down rotations) (Figure 5)	IMU
Coherence between paddle force and edging	IMU and paddle
Metrics that primarily represent tactics	**Device**
Total distance travelled (m)	GPS
s.d. heading (degrees) (boat left to right rotations) (Figure 5)	IMU
Metrics that represent strength, technique, and tactics	**Device**
Average stroke recovery time (s)	Paddle
Average stroke drive time (s)	Paddle
Total number of strokes	Paddle
Average speed (m s^{-1})	GPS
Acceleration (m s^{-2})	IMU
Deceleration (m s^{-2})	IMU
Speed one stroke after the turns (m s^{-1})	GPS and paddle
Speed six strokes after the turns (m s^{-1})	GPS and paddle
Figure-8 race time (s)	Hand timer
Metrics that classify athletes	
Sex	
Mass (kg)	

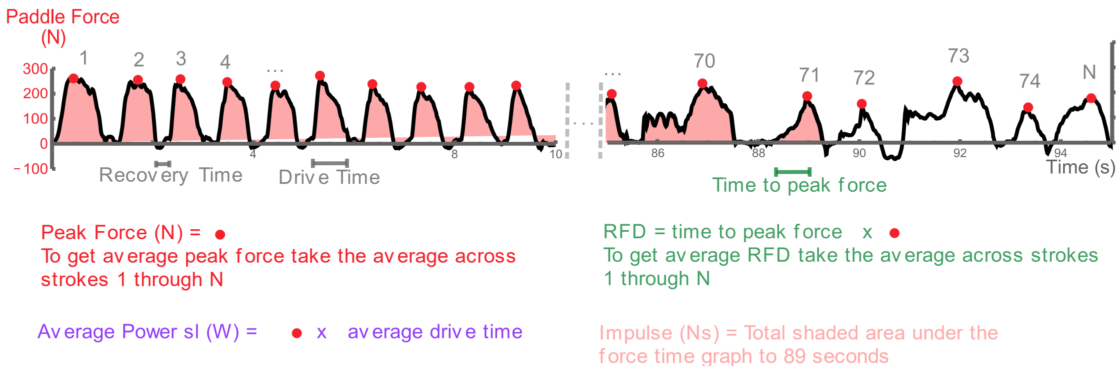
<u>Operationalizing Strength</u>

Metrics that primarily operationalize an athlete's strength are: average peak stroke force, total impulse, overall power$_{pb}$, average stroke power$_{lt}$, overall mass-specific power$_{pb}$, and average RFD.

Average peak stroke force: The maximum force for each stroke was obtained and then averaged across all strokes (or else forward strokes and turning strokes separately). (Figure 6). This measures an average 'peak strength' for each athlete.

Total impulse: This was calculated as the area under the force time curve. This was completed over the first 89 seconds of the race for each athlete in order to account for the fact that different athletes spent different amounts of time on the course and had greater

Figure 6: Calculation of Paddle Force Metrics



Shown is the paddle force for one athlete (black). These have been shaded in pink to illustrate the calculation of impulse as the area under the curve. The recovery time is the time between two strokes when the athlete applies little to no force. The drive time is the time during a stroke when the athlete is actively applying force. The time to peak force is the time from the start of the stroke to the maximum force in that stroke. Metrics shown: Average peak force, average stroke power$_{lt}$, average rate of force development per stroke, Impulse, Drive time, Recovery time.

chance to accumulate impulse (Figure 6). The inclusion of negative areas in the impulse was not found to impact the results, and there was no relationship between negative area and race time. This measures a total 'strength' across the whole paddle stroke.

Overall power$_{pb}$: This was the average peak stroke force multiplied by the average boat velocity (Figure 6). This approximates the average stroke power of the athlete. A better approximation would be to average the peak power across all strokes, but unfortunately we did not have instantaneous power measurements. One flaw in this estimate lies in the inability to separate power input of the athlete's muscles from power input due to the athlete's skill. The athlete may be skilled at utilizing power from the water, or unskilled at losing power to drag.

Average stroke power$_{lt}$: The mean peak stroke force was multiplied by the stroke length divided by average drive time. (Figure 6). As stroke length was unknown, all strokes were assumed to be one meter, across the whole course and between people. This assumption is incorrect, especially on white-water, but it allows for an estimate of stroke power that does not include the effects of the athlete's skill in utilizing power from the water.

Overall mass-specific power$_{pb}$: This was the overall power$_{pb}$ divided by athlete's mass.

Average rate of force development (RFD): The peak stroke force for each stroke was divided by the time it took to reach that force. The start of the stroke was defined as the point at which force became greater than 10% of each athlete's maximum force. Then the average across all strokes was obtained. The RFD is a correlate of power (Cormie et al., 2011), and allows for an estimate of explosive strength that does not include the effects of the athlete's skill in utilizing power from the water nor one that relies on a measurement of stroke length.

To evaluate the metrics of power or explosive strength, the standard error of the estimate (equation 2) between power$_{pb}$, power$_{lt}$, and RFD *with race time* (not with each other) in simple linear regression were compared, separately for the flat-water and white-water data. Low standard error of the estimate of race time should indicate the metrics are measuring some aspect of the same thing, here, an attempt to measure athlete power or explosive strength.

Equation 2: Standard error of the estimate

$$StandardErrorOfTheEstimate = \sqrt{\frac{(ActualTime - PredictedTime)^2}{N}}$$

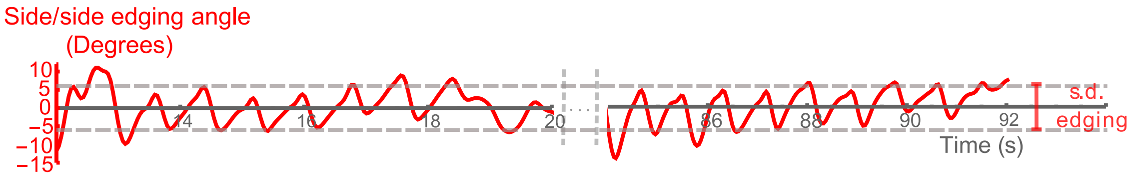
Where *ActualTime* is the measured race time, *PredictedTime* is the model predicted race time, and *N* is the number of athletes.

Operationalizing technique

Operationalizing technique and tactics is more challenging. Metrics were chosen that quantify aspects of paddling technique as well as metrics that represent how well athletes utilize the water. Some of these metrics included components of technique, tactics, and strength and will be described in turn. Metrics that primarily operationalize an athlete's technique are: s.d. edging, s.d. pitch, and coherence between paddle force and edging.

S.d. edging & s.d. pitch): To do this, the angles for each section were obtained, the mean angle for that section was subtracted, then all of the sections were pooled together to find the standard deviation (s.d.) (Figure 7). The standard deviation measures the angle change that occurred for each athlete over the section, which may be moderate or quite large. For example, paddlers use their edges to keep the boat tracking straight, help them turn, and to keep themselves stable. Additionally, extra rocking forward or backward (pitch) represents energy wasted due to rocking the boat during a stroke, and large rotations here are thought to indicate poor technique (Canoe Kayak Canada; Coaching Association of Canada, 2016).

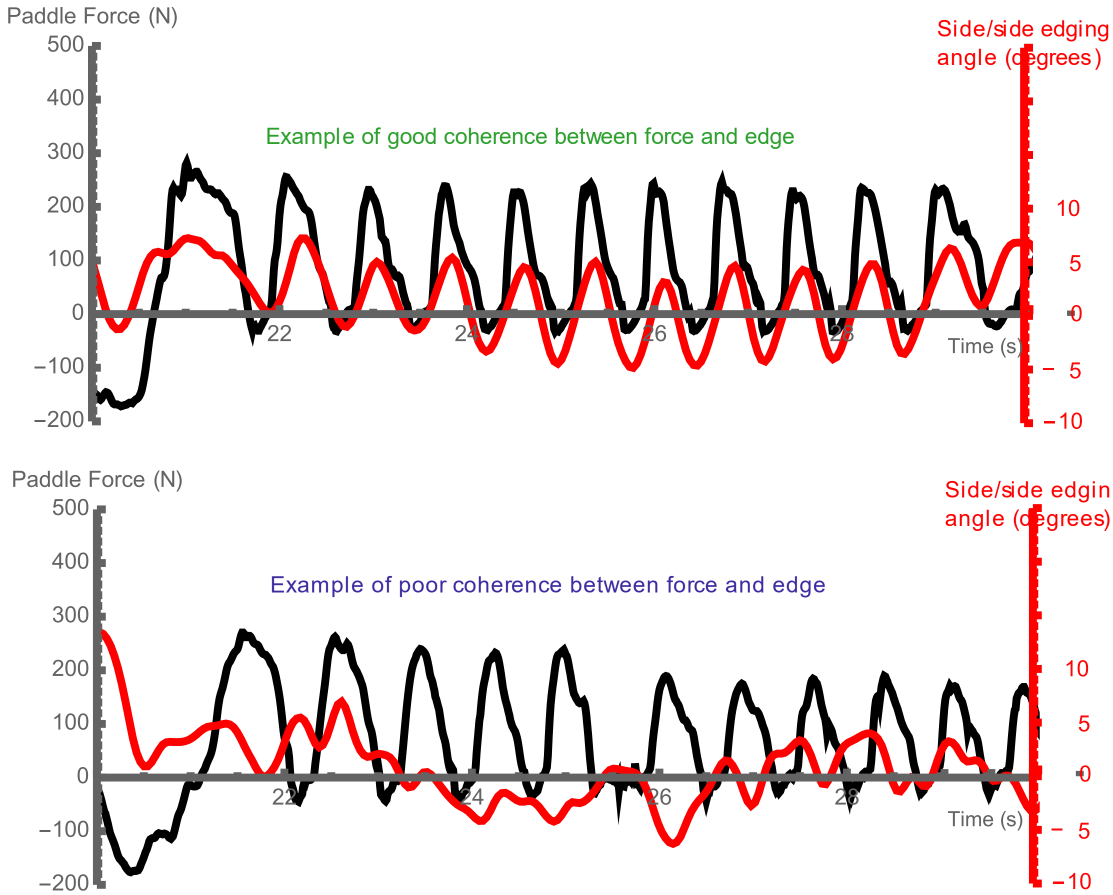
Figure 7: Calculation of boat rotation metrics



Filtered data from the gyroscope is shown, for the edging or roll angle, for two sections of the white-water course for one athlete. Each section is centred around 0 and the mean of that section is subtracted. The s.d. is indicated by the dashed lines. Metrics shown: s.d. edging. The other s.d. rotations were calculated similarly.

Coherence between paddle force and edging: Coherence between an athlete's edging (roll) and their stroke force was calculated around their dominant stroke rate (Figure 8). Coherence was calculated using the function cohere( ) in the package matplotlib (Hunter, 2007; Van Rossum and Drake Jr, 1995). This coherence should represent how well the athlete's changes in edge are synchronized to their stroke, which may help them paddle straight.

Figure 8: Calculation of coherence between force and edge



Shown are the paddle forces (black) and rotational data from the gyroscope for edging (red) for two athletes (top and bottom). The top athlete shows good synchronization between the two signals, which leads to good coherence. The bottom athlete shows poor synchronization and this leads to poor coherence. Metrics shown: Representation of coherence between force and edging

Average stroke recovery time: This was calculated as the time that the paddle force was below 10 % of the maximum paddle force (for a forward stroke) or above 10 % of the minimum paddle force (for a reverse stroke). The average recovery time was then determined across all strokes (Figure 6).

Average stroke drive time: This was the opposite of recovery time (i.e., the amount of time that the paddle force was above 10 % of the maximum paddle force or below 10 % of the minimum paddle force). The average drive time across all strokes was then determined (Figure 6).

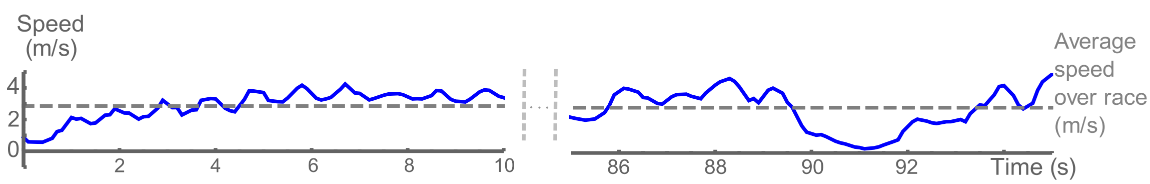
Total number of strokes: The total number of strokes was counted across the race, with combination turning strokes such as reverse sweeps into draws counted as one stroke

(Figure 6). In the split sections, partial strokes were counted by determining the percentage of the total length for that stroke that appeared in that split.

Average speed: Average boat speed across the entire race was obtained from the GPS (Figure 9).

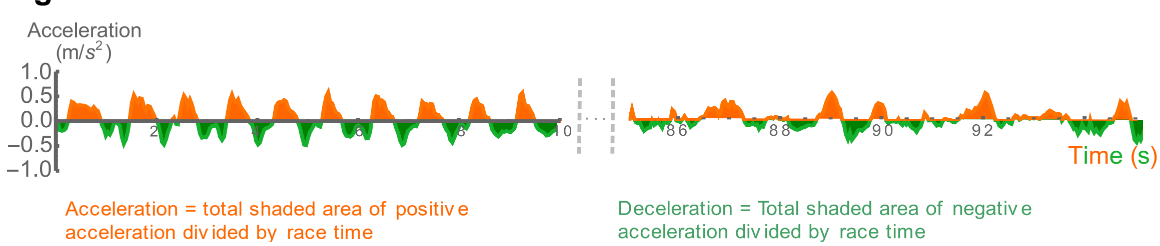
Acceleration & deceleration: The total positive or negative areas from the accelerations obtained from the boat IMU were divided by race time (Figure 10).

Figure 9: Calculation of average speed



Speed from the GPS is shown in blue for two sections of the white-water course for one athlete. The average speed is indicated by the dashed line. Metrics shown: Average speed

Figure 10: Calculation of acceleration and deceleration



Shown are the accelerations from the IMU. The positive accelerations are indicated by the orange line, and negative accelerations (decelerations) by the green. The area under the curve is shaded for each in orange or green respectively to indicate the calculation of total acceleration or total deceleration, which is then divided by race time. Metrics shown: Positive acceleration, deceleration

Speed one stroke after the turns on the figure-8 test & speed six strokes after the turns on the figure-8 test: A two second moving average was first applied to the GPS speeds to reduce fluctuations occurring with each paddle stroke. The maximum speed an athlete achieved after one and six strokes from the turn was then obtained from this filtered signal. Thus this represents an average of the speed a paddler achieves during the fastest point of their stroke and the slowest point when the paddle is not pulling through the water, as the stroke fluctuations are removed by the moving average.

Flat-water figure-8 time: Obtained by hand timer. Time was stopped when the athlete's body passed the last gate on lap nine.

Main Analyses

Aim 1: Aspects of performance on the flat-water sprint and turn test that are linked to white-water race times

&

Aim 2a: Using flat-water data to predict white-water times

This was accomplished by creating a flat-water multiple regression model to predict white-water race times. I first performed simple regression of all flat-water metrics against white-water race time to obtain r^2 values. The correlation coefficients, error, and p values from the simple regression are reported for each performance metric, as well as the impact of turning strokes. Flat-water performance metrics were then evaluated for their predictive power of white-water times through multiple regression analysis. The performance metric with the highest r^2 from simple regression was selected as the first parameter for the multiple regression model. All other metrics and their interactions were then added to this base model using forward selection in order of their r^2 values from simple regression. In the case of metrics that duplicate information (defined using some of the same data) and were correlated with each other, such as the metrics for power or explosive strength (which are all defined using average force), the metric with the highest r^2 from simple regression was chosen. Additionally, multicollinearity was tested for all of the included metrics. Selection stopped under the following circumstances: if the performance metric was not significant at $p<0.05$, if the residuals were not normally distributed (according to a Shapiro-Wilks test at $p<0.05$) or there was a recognizable pattern in the residuals, if the total ranking error no longer improved (by at least one placing), or if the sign of the variable's slope in multiple regression was opposite to that expected by simple regression (i.e. negative instead of positive, or vice versa). The athletes predicted times were ranked. Total ranking error is the sum of the number of placings that each athlete was off by in the predictions compared to their ranking in the real race. The p-value was not adjusted for multiple comparisons, as the high number of tests in the simple regression meant very few parameters may be significant for the multiple regression model. Specifically only one parameter could be used if the p-value was adjusted for multiple comparisons, which would restrict the analysis to simple regression. However, I wanted to determine the interplay between strength, technical, and tactical elements in canoe slalom, which requires an approach that accounts for the shared predictive power between these metrics. The regression was trained on the data from the best run of the flat-water figure-8 and white-water courses.

To evaluate the influence of the flat-water metrics on race time, I will first determine which metrics made the cut in the multiple regression model. These metrics measure aspects of white-water performance that are best captured by the figure-8 test. To evaluate the magnitude of this influence, several measures are reported. The increase in r^2 is the increase in the coefficient of determination when that metric was added last to the multiple regression model. Higher increases mean the metric had greater influence on the race times. Also reported are the *standardized* regression coefficients (slope, Equation 3), where larger coefficients have greater influence on race time. Lastly the influence of each metric on race time was evaluated by multiplying the slope (unstandardized) for each metric obtained from the regression model, by the maximum and minimum values of each metric, then obtaining the difference. This provides a number in seconds that evaluates how much potential race time was influenced by each metric. Metrics that did not make the cut into the multiple regression model can only be evaluated by the r^2 values from simple regression.

Equation 3: Standardized regression coefficients

$$StandardizedCoefficient_i = Coefficient_i \frac{StandardDeviation[x_i]}{StandardDeviation[y]}$$

Where *i* refers to the ith regression coefficient, x_i is the ith column of the design matrix from the regression model, and *y* is the response from the regression model.

To evaluate the predictive power of the flat-water test on white-water race times, the r^2, standard error of the estimates, total ranking error, ranking of the top three paddlers, and p values are reported for the multiple regression model.

Aim 2b: The relationship between paddle force and flat-water lap time

This was accomplished by creating a mixed effects model to predict flat-water lap time from paddle force, taking into account the individuality of the paddlers. A mixed-effects model was conducted with the function *lmer* in the package *lme4* in R (Bates et al., 2015; R Core Team, 2021). Lap time was predicted with average peak stroke force as a fixed effect and athlete as a random effect. The model was overfit when using both a random slope and intercept for the athletes (evident by an singular fit error from the lme4 package), so only a random intercept was used for the final model. The general estimate of intercept and slope from this analysis is reported, and the expected increase in race time that would result from a 10 % increase in force was determined. This can provide insight on how an individual athlete might improve their race by specifically targeting one of the metrics in training. The analysis here however is not causal, and a targeted training study would be required to properly evaluate how improvements in strength affect race time.

Aim 3: Strength, technical, or tactical demands of white-water slalom racing

This was accomplished by creating a white-water multiple regression model to predict white-water race times. I first performed simple regression of all white-water metrics against white-water race time. Then the performance metric with the highest r^2 from simple regression was selected as the first parameter for the multiple regression model, as in the flat-water model. Additional metrics were next selected from the highest ranking to lowest ranking r^2 until at least one metric from that primarily evaluated strength or primarily evaluated technique or tactics categories was obtained. For any metrics that were correlated with each other, the one with the higher r^2 was chosen. Multicollinearity was tested for the included metrics. Metrics were added to the model using backwards selection. Any metrics with a p-value less than 0.05 were removed from the model, as well as any metrics that showed the opposite signed slope as expected from simple regression. Additional metrics were then tested to confirm their influence on the model using similar exclusion circumstances as the flatwater model. If, when a metric was removed from the model, there was a decrease or no change to the total ranking error, that metric was excluded from the model. Metrics were also excluded if the resulting model had residuals that were not normally distributed or showed a clear pattern. The regression was trained on the data from the first run of the entire white-water course.

To evaluate the influence of strength, technique, and tactics on race time, I will first determine which metrics were selected for the final multiple regression model. These metrics measure aspects of white-water performance that are best captured by the figure-8 test. To evaluate the magnitude of this influence, the increase in r^2, the standardized regression coefficients, and the potential time in seconds influenced by each metric are reported, as in the flat-water model. Metrics that did not make the cut into the multiple regression model can then be evaluated through the correlation coefficients, error, and p values from simple regression, and the impact of turning strokes in simple regression is also noted.

The metrics influence across the split sections was first examined in simple regression. If the correlation coefficient r was stronger than 0.3 in the split section, the relationship was said to exist in the split, even if not statistically significant. The multiple regression model was then tested to see how well it could predict the split times for the athletes of run one and two (11 athletes for run 1 and 6 of these same athletes for run 2). Each of the split sections can be considered a different white-water course (though not independent), and it is likely that different skills and strengths are required to navigate them the fastest. Therefore, this test allows assessment of the validity of the relationships between these metrics and race times across different white-water courses, without explicitly having access to different white-water courses.

R^2, standard error of the estimate, total ranking error, and p values are reported to evaluate the white-water multiple regression model. The increase in r^2, the standardized regression coefficients, and the potential time in seconds influenced by each metric are also reported, as in the flat-water model. The model was also put to two further tests. One, it was tested by predicting race times of athletes who completed a second run of the white-water course. This population of athletes is drawn from the same as that used to construct the model, but the exact values of their metrics during run 2 were not used to construct the model. Standard error of the estimate and total ranking errors are reported. Two, the model was also tested to predict flat-water figure-8 times. Here too it is likely that different aspects of performance allow an athlete to succeed than on the white-water. Exact times would be difficult to predict based on the different currents in each section of the course and on the flat-water, so the errors in ranking are examined for the predicted athletes.

Also reported are race times and stroke characteristics related to force and stroke timing for both flat-water and white-water, split by sex. This will allow me to examine how the physical and technical demands differ between the flat-water figure-8 test and a white-water course. These values may be of use to those training in canoe slalom, especially those with access to a force gauge-equipped paddle who want to make comparisons of their own data to others in the same competitive category. However, caution is advised due to small sample sizes and the use of a single blade size for all athletes.

All analyses between the performance metrics and race times were completed on the raw race times, without penalties. Any changes due to the inclusion of penalty times are reported. The total number of athletes included in each analysis and their characteristics are in Table 3. All analyses and statistics except the mixed-effects model were completed in Wolfram Mathematica Version 12.1.1 (Wolfram Research Inc., 2020).

Statistics

P values were considered significant if they were less than 0.0011, which was adjusted for the large number of statistical tests (46 total). However, during multiple regression, p values were considered significant at p less than 0.05 to increase the number of metrics that could be analyzed concurrently. Due to the large number of statistical tests in this study, many p values were not statistically significant. To help evaluate whether these relationships really exist in canoe slalom, or whether they occurred by chance, several other sources of information can be used in conjunction with the correlations reported in simple regression. For the white-water metrics, the relationships were also evaluated for each split. Any relationship found across the whole race should also appear in at least one of the splits, otherwise it may have occurred by chance. Additionally, a second test is provided to evaluate whether these relationships may have occurred by chance, which is the percent by which the metric predicted race times better random chance. To sum up this test, a value of 0 % on this test means there was no difference between the true metric's relationship with race time and a completely random relationship with race time. A value of 100 % means the metric can perfectly predict race time. In more detail, the standard error of the estimate of the simple regression equation for each metric with race time was compared to the standard error of the estimate of the regression equation for a randomized version of each metric with race time. To randomize the relationship between each metric with race time, the function RandomSample in Mathematica (Wolfram

Research Inc., 2020) was used on each metric and race time, therefore pairing an athlete's metric with a random athlete's race time. Thus, any true relationship between the metric and race time was destroyed through randomization. The standard error of the estimate of the randomized metric was the average standard error of the estimate from 10,000 random simulations. To compare the two standard error of the estimates (one true to this dataset, and one completely random), the percent standard error of the estimate of the true metric was divided by the percent standard error of the estimate of the random metric (times 100 to obtain a percentage), where the percent standard error of the estimate is the standard error of the estimate divided by the mean race time (times 100). This was subtracted from 100 %, to obtain the percentage improvement in prediction accuracy, compared to a completely random metric.

Results

Race results

White-water race times for all age categories are in Table 2. Reported race times are the best of two runs. The best men's C1 time was 89.30 seconds, and the best women's C1 time was 98.67 seconds. The mean ± s.d. for the C1M was 97.05 ± 5.33 and for the C1W was 103.18 ± 4.67 (including penalties). On the white-water, all athletes performed their preferred technique (all women switched, three men switched, and three men did not switch and only used cross strokes). Flat-water race times are given in Table 2, again as the best of two runs. On the flat-water, all women used the switching technique, three men switched, four men did not switch, and three men performed one of each technique on their two runs. The flat-water figure-8 test (9x20 m) was highly correlated with white-water race time (Table 4).

Table 2: Race times and stroke characteristics by sex

	Men	Women
N	10 6	5 5
White-water Race (s) **Flat-water Race (s)**	89.30 to 103.03+4 89.71 to 101.23	97.23+2 to 107.47+2 93.07 to 102.15
Average Peak Stroke Force (N)	208 ± 35 213 ± 32	192 ± 25 182 ± 25
Rate of Force Development ($N\ s^{-1}$)	948 ± 235 1406 ± 572	685 ± 99 935 ± 203
Average Stroke Drive Time (s)	0.81 ± .06 0.69 ± .06	0.98 ± .12 0.76 ± .08
Average Stroke Recovery Time (s)	0.40 ± .05 0.41 ± .09	0.45 ± .06 0.43 ± .05

White-water results are on top, figure-8 flat-water results are below (20 m x 9), for each category. Race times are the raw time + penalty. Average peak stroke force, RFD, average stroke drive time, and average stroke recovery time are mean ± standard deviation.

Participants

Due to missing data from the GPS and IMU, the number of athletes included in each analysis varied. The characteristics of the athletes included in each analysis are presented in Table 3.

Table 3: Analyses and participants

		N	Ages (yrs)	Mass (kg)	Height (cm)
Aim 1 and 2a: Flat-water model to predict white-water times (Multiple Regression) and **Aim 2b: Flat-water model to predict lap time based on force** (Mixed Effects Model)	Female Male	5[1] 10[2]	20 ± 3 23 ± 7	64 ± 4 74 ± 7	171 ± 4 181 ± 5
Due to missing GPS data,some athletes were excluded from the white-water analysis					
Aim 3: White-water model to predict white-water times (Multiple Regression)	Female Male	5[1] 6[3]	20 ± 3 25 ± 9	64 ± 4 74 ± 6	171 ± 4 180 ± 6
Due to missing GPS data, some athletes were excluded from the IMU analysis					
Aim 3: Relationships between IMU parameters and white-water time (Simple Regression) (s.d. heading, positive and negative acceleration)	Female Male	5[1] 9[4]	20 ± 3 24 ± 7	64 ± 4 73 ± 7	171 ± 4 180 ± 5

N is the number of athletes included. Age, mass, and height are means ± standard deviation.
[1]: Three world cup podium finishes, two Jr/U23 world championships finalists
[2]: Two world championships podium finishes, five Jr/U23 world championships finalists
[3]: One world championships podium finish, three Jr/U23 world championships finalists
[4]: Two world championships podium finishes, three Jr/U23 world championships finalists

Aim 1: Aspects of performance on the flat-water sprint and turn test that are linked to white-water race times

The flat-water metric that had the strongest relationship with white-water race time during the preliminary simple regression was the flat-water figure-8 time, with a correlation coefficient of 0.84 (Table 4). The speed after six strokes from the turn also had a strong relationship with white-water race time, with a correlation of -0.83. These two metrics had a nearly perfect correlation with each other (r = -0.95), indicating the dependence of flat-water time on the speed achieved by six strokes after each turn. Each metric of power or explosive strength (overall $power_{pb}$, average $power_{sl}$, and average RFD) was also highly correlated with the others (r = 0.76-0.94), with standard error of the estimate from 7-26 %. However the best relationships were found between overall $power_{pb}$ and average $power_{sl}$. This indicates the metrics were measuring similar things, though the correlations were lower and standard errors higher for any relationships with RFD. Other flat-water metrics which had large or higher relationships with race time include: mass, total impulse, overall $power_{pb}$, average speed, and deceleration. The technical metrics s.d. edging and the coherence (synchrony) between paddle stroke and edge had correlations of 0.47 or -0.47. Full results from the preliminary simple regression are in Table 4. Turning and forward strokes tended to have similar relationships to white-water race time for the metrics that evaluated strength, and weaker relationships for the metrics that evaluated timing. However, the flat-water turning strokes had longer drive times than the flat-water forward strokes. After forward selection, the final flat-water model included: figure-8 race time and sex (Table 5).

The increase in r^2, p-value, standardized coefficient, and potential influence on race time for each metric is in Table 5. The most influential flat-water metric on white-water race time was the flat-water figure-8 time. Flat-water time had the greatest increase in r^2 when added last, had the largest standardized coefficient, and could explain 11.99 seconds of variability between the fastest and slowest athletes. In total, there were 18.17 s separating the true white-water times of the fastest and slowest athletes in this analysis. Sex had the next greatest r^2 when added last, and second largest standardized coefficient. Sex could explain up to 3.80 seconds of difference between the fastest and slowest athletes.

Table 4: Relationships between the white-water or flat-water metrics with white-water race time from simple regression

	r	% better than random error	p	Recognizable in splits? (|r| > 0.3)	Effect of including turning strokes
Average Peak Force	-0.50	9	0.12	2,4,6	Turns show the same relationship
	-0.43	6	0.11	–	Turns show slightly stronger relationship
Impulse	-0.51	9	0.11	No	–
	-0.55	13	0.03	–	Turns show similar relationship
Overall Power$_{pb}$	-0.66	20	0.03	2,4,6	–
	-0.55	13	0.03	–	Turns show the same relationship
Average Stroke Power$_{lt}$	-0.49	10	0.04	2,3,4,6,7	
	-0.35	3	0.19	–	Turns show similar relationship
Mass-Specific Power	-0.27	None	0.42	4,6	–
	-0.20	None	0.47	–	No change
Rate of Force Development	-0.55	12	0.08	2,3,7	Turns show weaker relationship
	-0.41	5	0.13	–	Turns show weaker relationship
Total Distance Travelled	0.34	None	0.3	1,2,4,6,7,8	–
	-0.13	None	0.64	–	–
Number of Strokes	-0.3	None	0.37	1,3,4,6,7,8	–
	-0.01	None	0.97	–	–
S.D. Heading	0.66	21	0.02	3,5,7	–
	0.32	2	0.24	–	Turns excluded
S.D. Edging	–	–	–	–	–
	0.47	8	0.08	–	Turns excluded
S.D. Pitch	–	–	–	–	–
	0.38	4	0.16	–	Turns excluded
Coherence between Force and Edge	–	–	–	–	–
	-0.47	8	0.08	–	Turns excluded
Average Recovery Time	0.61	16	0.05	2,3,4,7	Turns show slightly weaker relationship
	0.16	None	0.56	–	Turns show the same relationship
Average Drive Time	0.73	28	0.01	3,7	Turns show weaker relationship
	0.42	6	0.12	–	Stronger with both together
Average Speed	**-0.92**	**59**	**0.0001***	2,3,4,5,6,7	–
	-0.82	**40**	**0.0002***	–	Relationship is stronger with turns

Acceleration	-0.57	13	0.06	1,2,3,7,8	–
(along boat)	-0.47	8	0.07	–	Turns show opposite relationship
Deceleration	0.49	9	0.1	2,3,4,6,7	–
(along boat)	0.51	11	0.05	–	Turns show slightly stronger relationship
Figure-8 Test Times	**0.84**	**44**	**0.0001***	–	–
Speed One Stroke After Turn	-0.11	None	0.71	–	–
Speed Six Strokes After Turn	**-0.83**	**42**	**0.0001***	–	–
Age	–	–	–	–	–
	–	–	–	–	–
Sex	0.81	30	0.003	1,2,3,4,5,6,7,8	–
	0.67	23	0.01	–	–
Mass	-0.76	31	0.007	1,2,3,4,5,6	–
	-0.69	24	0.005	–	–

White-water results are on top in black, flat-water results are below in grey. * Indicates statistical significance.

Table 5: Flat-water predictors of white-water race time

	p-value	Increase in r^2	Standardized regression coefficient	Potential amount of race time due to metric
Figure-8 flat-water race time	>0.001*	0.35	0.677	11.99 seconds
Sex	0.03	0.09	0.346	3.80 seconds

* Indicates statistical significance

Aim 2a: Using flat-water data to predict white-water times

The final flat-water multiple regression model had an r^2 of 0.81, and predicted race times were within one second of actual race times for five of the fifteen athletes. However, the p-value was only significant for the figure-8 race time metric. The standard error of the estimate was 2.28 s. The test for multicollinearity resulted in a correlation less than 0.5 between sex and figure-8 flat-water race time. The total ranking error was 30 placings, including errors in the top three placings. The athlete who came in first place was predicted to come in third, the athlete who came in 2nd place was predicted to win, and the athlete who came in 3rd place was predicted to come in 5th.

The final flat-water model to predict white-water times is presented in Equation 4.

Equation 4: Flat-water prediction of white-water times

$$WWracetime = 3.3179 + 0.9636Fig8Time_{FW} + 3.7994Sex$$

Where WWracetime and $Fig8Time_{FW}$ are in seconds and Sex is 0 for male and 1 for female.

Nine athletes took 2 second penalties during their white-water race, with two additional athletes taking penalties of 4 or 6 seconds. The total ranking prediction error stayed the same when penalties were included, and the standard error of the estimate increased to 2.98 seconds.

Aim 2b: The relationship between paddle force and flat-water lap time

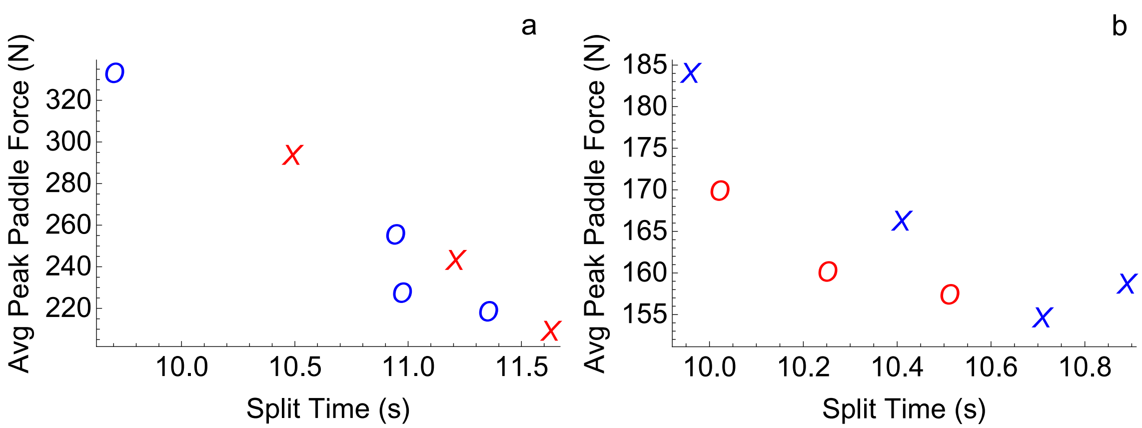
Although the overall relationship between average peak paddle force and race time was not significant amongst all athletes (Table 4), individual athletes exhibited significant relationships between peak force and lap time. An example of how lap time varied with average peak paddle forces is shown in Figure 11. The mixed-effects model revealed a significant effect for global intercept and slope at p<0.001. The estimate is provided in Equation 5:

Equation 5: Predicting lap time from paddle force

$$Laptime = 12.01 - 0.005976 AvgPeakForce$$

The lowest and highest average peak forces per lap were 158 and 265 N. Using the equation, if an athlete were to increase peak paddle force by 10 %, the average improvement in time they could expect on a straight-section lap is 0.9 to 1.5 %, depending on their initial paddle force and rate of fatigue. If an athlete capable of 200 N produced instead 220 N, they would see a total decrease of 0.65 seconds across laps 2-8 of the figure-8 test if they experienced a similar rate of fatigue. Alternatively, the equation can be used to predict the decrease in race time due to an improvement in fatigue-resistance. The average decrease in force from laps 2 to 7 was 20 %. Thus an athlete capable of 200 N would reduce their force to 160 N by lap 7, which is a reduction of 40 N. If an athlete were to improve their fatigue resistance by 10 %, and reduce force by only 36 N, they would see a total decrease of 0.07 s (assuming a linear decrease across laps 2 to 7). An athlete would need to improve fatigue resistance by 100 % to come close to decrease in race time resulting from a 10 % increase in paddle force.

Figure 11: Average peak paddle forces across figure-8 laps for two athletes



Blue markers are laps 2,4,6,8; and red markers are laps 3,5,7. a and b show two different athletes. These athletes did not switch, and used cross strokes and onside strokes on alternating laps. For athlete a, laps 2, 4, 6, and 8 were onside ('O'); while 3, 5, and 7 were cross ('X'). Athlete b chose the opposite, where laps 2, 4, 6, and 8 were cross ('X'), while 3, 5, and 7 were onside ('O'). Laps one and nine excluded.

Paddle force showed a steady decline with each lap, but the time achieved per lap had more variation. Paddlers tended to be fastest for the first lap, slow down over the course of the middle laps, and speed up again for the final lap. Some paddlers showed a preferred turning side, as seen for the athlete in Figure 11b, where the sections before an onside turn tended to have lower forces but shorter times, despite a steady declining paddle force for each lap.

Aim 3: Strength, technical, or tactical demands of white-water slalom racing

Fit and training data from the first run

The white-water metrics that had the strongest relationships with white-water race time during the preliminary simple regression, including at least one metric that primarily measured strength and one metric that primarily measured technique or tactics, were: average speed, sex, mass, average drive time, acceleration, overall $power_{pb}$, s.d. of heading on downstream sections, average stroke RFD, total impulse, and total distance travelled. Full results from the preliminary simple white-water regression are in Table 4.

Several of these parameters were highly correlated, insignificant, or resulted in unexpectedly signed slopes when used in multiple regression, thus after backwards selection and exclusion the final white-water model included: average speed, average RFD, and total distance travelled (Table 6). The test for multicollinearity resulted in correlations less than 0.4 for the included variables. The r^2 was 0.98, and predicted race times that were within one second of the actual race times for nine of the 11 athletes (and less than 1.59 s for all 11 athletes). However, the p-value for average RFD and total distance were not significant. All interactions were insignificant. Residuals were normally distributed and there were no clear patterns. The final model is presented in equation 6.

Table 6: White-water predictors of white-water race time

	p-value	Increase in r^2	Standardized regression coefficient	Potential amount of race time due to metric
Average Speed	>0.001*	0.65	-0.893	14.66 seconds
Total Distance Travelled	0.001	0.08	0.315	7.09 seconds
Average Rate of Force Development	0.009	0.01	-0.085	1.68 seconds

* Indicates statistical significance

Equation 6: White-water prediction of white-water times

$$Racetime = 138.6340 - 36.486AvgSpeed - 0.0024RFD + 0.2250TotalDistance$$

$$racetime = 138.6340 - 36.486AvgSpeed - 0.0024RFD + 0.2250TotalDistance$$

The metric with the greatest influence on race time was average speed (Table 6). It had the greatest increase in r^2 when added last, the largest standardized coefficient, and could explain 14.66 seconds of difference between the fastest and slowest athletes. The mean and s.d. of average speed was 2.8 ± 0.1 m s^{-1}, and the largest difference between athletes was 0.4 m s^{-1}. The next metric with greatest influence on race time was the total distance travelled, which could explain 7.09 seconds of difference between the fastest and slowest athletes. The mean and s.d. of total distance travelled was 286 ± 8 m, and the largest difference between athletes was 32 m. Average RFD could explain 1.68 s of difference between the fastest and slowest athletes. The mean and s.d. of the average RFD was 819 ± 214 N s^{-1}, and the largest difference between athletes was 712 N s^{-1}.

Seven of these athletes took 2 second penalties during their white-water race. Including these penalties in the predictions made the total ranking prediction error increase to 8, and the standard error of the estimate increased to 1.75 seconds.

Test Predictions: Split times, run two, and flat-water

The regression model had much larger errors when predicting the *split* times (Table 7). While the ranking of some athletes were predicted correctly, others were off by up to 11 placings. The model performed similarly on the athletes from run one and run two with average differences in error between the groups of less than a second.

When testing the model on six athletes with new data for *run two*, the standard error of the estimate was 0.78 seconds, and all rankings were correct (Table 7). Five of six predicted race times were within one second of the actual race, while the sixth was within 1.3 seconds. Thus, the model had good performance on new data from all six of the original athletes with new data for run two.

Predicted rankings for the *figure-8 flat-water test* with the multiple regression white-water model were better than the predicted rankings for the split sections. Rankings were accurate for two athletes (Table 7).

Table 7: Predicted race time from average speed, rate of force development, and total distance covered

	Standard error of the estimate (s)	Total error in ranking
Predictions for same white-water as model		
Run 1	0.84	4
Run 2	0.78	0
Predictions for white-water splits (mean) and flat-water		
Downstream Splits	22.75	47
Upstream Splits	33.78	44
Flat-water	13.68	18

Discussion

Flat-water figure-8 time and sex were the best predictors of white-water race time based off a flat-water figure-8 test. Metrics of paddling-specific strength and markers of good paddling technique on the flat-water also showed good relationships to white-water race time, with correlation coefficients of 0.5 or higher. Tactical metrics on the flat-water tended to show the lowest relationships to white-water race time, which is understandable considering the simpler tactics of a flat-water figure-8 test. While the correlation between the figure-8 test and the white-water race times was high at 0.84, using flat-water metrics as a tool to predict white-water time resulted in errors in the top three placings. Using the flat-water metric of average peak paddle force however led to successful prediction of flat-water lap times. This test could be used to predict decreases in race time due to an increase in paddling-specific strength. On the white-water, performance was best predicted by average speed, total distance, and the rate of force development. The extent to which athletes relied on these skills varied among different splits of the white-water course, evident by the difference in model prediction errors across upstream and downstream sections.

Race results

In our study, the top C1W time was 1.10 times that of the top C1M time (including penalties). This is similar to the 1.11 times difference seen between the top C1W and C1M in the 2022 World Championship Finals. In our study, the slowest C1 paddler, male or female, was 1.23 times that of the top C1 paddler. Again, this is similar to the spread seen in the 2022 World Championship Finals (excluding 50-second penalties), where the difference between the slowest C1W and fastest C1M was 1.24 times. Thus, the spread in race times for our C1 paddlers was similar to that seen between World Championship finalists this year. As our sample included several World Cup podium athletes, the level of skill among our sample was on-par with world championship finalists.

Aim 1: Aspects of performance on the flat-water sprint and turn test that are linked to white-water race times

Despite the fact that canoe slalom is a sport of many accelerations and decelerations, the aspect of flat-water performance that showed the highest relationship to white-water time was the speed achieved after six strokes from the turns of the figure-8 test. In preliminary tests, the relationship between speed and white-water time increased as the athletes took additional strokes away from the turn: it was lowest at only one stroke out of the turn and increased to a maximum around six strokes out of the turn. Thus, it is top speed in canoe slalom that seems most influential on performance. For example, an athlete who consistently had one of the lowest speeds directly out of their turns was able to gain large amounts of speed as they paddled on the straight sections, and as a result finished second in the flat-water test.

No tactical metrics were included in the flat-water multiple regression model to predict white-water times. The tactical metric total distance travelled had a small, negative, insignificant relationship with white-water race time. The other tactical metric, the s.d. heading, had one of the lowest correlations with white-water race time. Thus hypothesis 1, that the tactical measures chosen in this study would not be well reflected by the figure-8 test, was accepted. It is likely that the tactics were simple enough for this test to cause very little differentiation between athletes. Instead, the figure-8 test focuses on aspects of strength and technique. However, it should be noted that athletes could choose different tactics for the type of turn they executed, though this was not evaluated as in this study nearly all athletes chose the same type of turn (back sweeps).

Flat-water metrics of strength and power were associated with white-water times. Two of the relationships between flat-water strength and white-water race time had correlations of -0.55 (impulse and overall $power_{pb}$), although these were not significant when considering the large number of statistical tests conducted in this study. Messias et al. also found flat-water metrics of strength associated with white-water race times—namely the peak force achieved during a 30 s all out test (Messias et al., 2015). Of the metrics that more directly quantified athlete strength (remember, a general term that refers to muscular outputs such as force, velocity, power, and duration or rate of contraction), the total impulse had the strongest relationship with white-water time. Athletes who could generate large paddle force for a long amount of time tended to be more successful than those who could generate less. In this study, impulse was evaluated as the total impulse across an equal amount of time for all athletes. In contrast, a study by Macdermid evaluated the average impulse per paddle stroke, and this was not found associated with race time (Macdermid and Olazabal, 2022).

There were correlations of 0.6 and 0.7 between average recovery or drive time with race time, though insignificant. Some authors have suggested strategies aimed at reducing total recovery time, such as reducing switching, to improve performance (Wakeling et al., 2022). Indeed, the correlation of 0.6 between recovery time and race time in this study may appear to support such a strategy, but caution is advised. As switching accounts for only a small portion of recovery transitions (7.2 %) (for C1W; Tilden et al., 2021), the results for average recovery time reported here are primarily based on the recovery time of other stroke transitions where the paddler has not switched hands. Additionally in preliminary analyses, the *total* recovery time (normalized to race time) was instead calculated and this showed a trivial insignificant relationship with race time. Thus, it seems unlikely that shortening the total recovery time will lead to performance enhancements for C1 paddlers. Instead, the impact of switching as a tactic to navigate specific sections of white-water should be investigated in future research.

Technical flat-water metrics were also associated with white-water race times. There were many examples where an athlete with lower power achieved faster race times than a more powerful athlete, even after adjusting for mass. This is similar to that seen in the study by

Macdermid, where nearly half the athletes completed the course with large differences in power output yet achieved similar race times (Macdermid and Olazabal, 2022). The fastest athletes on the figure-8 test carried speed much better than their competitors without simply relying on paddle power. Of the metrics that more directly quantified athlete technique, the s.d. edging and coherence between paddle strokes and edge showed the strongest relationships to white-water race time. This is likely due to the technique of the C1 forward stroke. In the C1 boat, it is more difficult to paddle fast in a straight line compared to the K1 boat. To paddle fast it is best to take strokes on only one side of the boat, as each cross or switch transition tends to be slower (Tilden et al., 2021). However, taking strokes on only one side of the boat requires skilled edging to go straight. Poor control over the line or wobbly edge control may have led the slower athletes to experience greater s.d. edging. Additionally, one strategy C1 paddlers use to paddle in a straight line is to engage the opposite edge of the boat into the water during the stroke. Due to the boat's shape, engaging the opposite edge seems to provide a turning force to counter the turning force resulting from the stroke. During recovery, paddlers return the boat to flat to ensure they achieve full rotation and forward reach for a good forward stroke. Thus, this technique requires paddlers to synchronize their strokes with their edges. In the figure-8 test, paddlers with greater synchrony between their strokes and edges had significantly faster race times. The balance of strength and technique exhibited by the figure-8 test could differ for K1 athletes, as the influence of edging on straight sections will be much less prominent than for the C1 athletes, due to the greater ease in maintaining a straight line.

Including turning strokes in the analysis often produced similar results to including only forward strokes (Table 4). Turning strokes tended to have similar force and $power_{lt}$, yet larger impulse, though their relationships with white-water race time were similar to those from forward strokes. Understandably, the turning strokes had more variable rates of force development, and their inclusion thus weakened the relationship between RFD and white-water race time. Turning strokes also had longer recovery times (nearly double), and this provided a slightly stronger relationship with race time. It is likely that athletes who began their next stroke faster after the turn were able to gain more speed after their first stroke, which was deemed important in the multiple regression analysis. Turning strokes also tended to have lower accelerations along the line of the boat, and lower accelerations here were associated with better white-water race times, which is opposite to the relationship for forward strokes. This also makes sense, as during a turn on the figure-8 test the boat ideally will not continue to accelerate away from the gate.

Aim 2a: Using flat-water data to predict white-water times

The flat-water figure-8 time had a very large correlation (r = 0.84) with white-water race time. Despite the lack of white-water features and narrowed line options, top-ranked athletes on the white-water also ranked highest on flat-water. This is similar to associations found by other researchers where correlations are of similar magnitude (Busta et al., 2018; Vajda and Piatrikova, 2021). Using flat-water time *alone* as a predictive tool for white-water performance, however, led to small ranking errors for nearly every athlete, including those in the top three. Indeed, in the results the 1st, 2nd, and 3rd in white-water placed 3rd, 1st, and 6th on flat-water, respectively. Therefore hypothesis 2a, that there will be errors in the top three placings, was accepted. Busta et al. also relied on multiple regression of flat-water tests to predict race ranking (Busta et al., 2018). They had a typical ranking error of 2.74 placings by using the results of three separate flat-water tests. The typical ranking error in our model was similar at 2.53 placings. The slight increased accuracy in our model may be due to the longer flat-water test we used, as longer sprint and turn tests had greater correlations with white-water race performance in a study by Vajda and Piatrikova (Vajda and Piatrikova, 2021). We used a 9x20 m figure-8 test with nine sprints and eight turns, while Busta et al. relied on two 2x20 m sprints with one turn and one 5x40 m sprint with four turns. That said, in preliminary analyses, we found very similar correlations with white-water race time for only one lap of the figure-8 test. It may be that a short test is sufficient to capture the relationship to white-water performance, which would make it easier to employ for regular athlete testing. It should also be noted that actual performance times were used in regression for this study, while Busta et al. appear to use rankings for regression. It seems the use of the flat-water figure-8 test as a tool to differentiate athletes is most helpful when multiple metrics of the flat-water performance are included, and when there are larger differences in race times between the athletes of interest (>2.53 s).

Aim 2b: The relationship between paddle force and flat-water lap time

The flat-water figure-8 test revealed differences in lap time as an athlete's peak stroke force decreased due to fatigue. Hypothesis 2b, that lap time will decrease as paddle forces decline, was accepted. Therefore, the figure-8 test could be a training tool for athletes and coaches to monitor improvements in paddling-specific strength, with minimal set-up and equipment beyond the original construction of a simple regression model. Indeed, performance on flat-water tests shifts throughout the year with the training load cycle, showing that these tests can monitor athlete progress (Süss et al., 2008). This is quite useful, because absolute performance in canoe slalom is difficult to monitor as race times change from course to course. Based on the initial results of a figure-8 test, a coach could predict the increase in figure-8 time for an athlete based on a 10 % improvement in their stroke force. If an athlete who has achieved a 10 % improvement in the gym underperforms from this estimate on the flat-water, it would quantify for the athlete how challenging they find it to transfer these improvements to their paddling stroke. Other athletes may match or overperform the predictions, and these athletes could be more confident that their gains in the gym were transferring to their paddling performance. If a coach did not have access to a paddle strain-gauge to create an individualized model for their athlete, they could rely on the general model presented in Equation 5, albeit this is a weaker approach.

Though not large, with a 10 % increase in peak stroke force, most paddlers are expected to improve their race times by 0.8-1.5 %, depending on their initial race time. Because this relationship was modelled off of a decrease in force due to fatigue, and not an increase in force due to training, it is likely that the effects of fatigue concurrently reduced both force and skill. That said, most metrics of technique measured in this study did not show strong increases or decreases as the flat-water test progressed. Instead, relationships with the left or right turn were found. Many paddlers had a preferred turning side, on which they tended to have shorter lap times. This was often accompanied by a difference in the number of strokes per lap depending on the side of turning. Still, the expected decrease in race time due to improvement in paddler force is actually expected to be larger than that reported here, if the athlete were able to maintain good technique. The best prediction for race time improvement due to increased force may come from a model that instead relies on several non-fatiguing flat-water tests, or a direct test after training intervention.

Surprisingly, although general conditioning and resistance to fatigue should benefit canoe slalom performance, differences in this aspect of physical fitness were not large between athletes. Additionally, the effect on race time by improving fatigue resistance by 10% using the model was very small. In preliminary analyses, the first sprint and turn of the figure-8 test had the same relationship to white-water time as the entire figure-8 test did. This is because most athletes fatigued at a similar rate. This similar rate of fatigue is evident from the mixed-effects model, where athletes showed similar negative slopes between paddle force and lap time. Macdermid (2019) also observed paddle force gradually decline over the course of a flat-water slalom race, indicating the effect of fatigue on performance. However, despite the rate at which this decline occurred differing between athletes, it was not significantly related to flat-water slalom race time (Macdermid et al., 2019). Likewise, Messias et al. found that fatigue during a 30 s all out sprint was not related to white-water race time (Messias et al., 2015). In our test, there are of course examples where an athlete was keeping up with the race winner for the first half of the test and began to lose the race as they fatigued at a faster rate. But in general, it seems differences in fatigue-resistance are smaller than differences in strength or power between slalom athletes.

Aim 3: Strength, technical, or tactical demands of white-water slalom racing

The aspects of strength evaluated in this study that were best linked to white-water race times include the average RFD, overall $power_{pb}$, and average peak force. Although these relationships were insignificant in simple regression, they had correlations of -0.5 or stronger, were visible in several of the white-water splits, and their relationship with white-water time was different than random. Thus these metrics may be useful to investigate in future white-water studies.

The aspects of technique evaluated in this study unfortunately could not be linked to white-water race times. S.d. edging, s.d. pitch, and coherence between paddle force and edging were too variable over the full white-water course and the white-water splits to make sense of. Therefore, to evaluate the technical aspects of white-water, it is suggested that a more specific approach that isolates a particular type of white-water move is utilized. For example, the use of edge while crossing stoppers could be examined to investigate how much faster the time can be with a flat boat.

The aspects of tactics evaluated in this study that were best linked to white-water race times include the total distance travelled and the s.d. heading. These relationships were visible in nearly all of the evaluated splits, and correlations of 0.34 and 0.66 respectively (although insignificant) with white-water race times. Thus these simple tactical metrics may be useful in future white-water studies as they can be summarized over a course or sections of a course. In this study, we were restricted to using the total distance travelled and heading angle, instead of the exact path the boats took through the water. This was due to inaccuracy in the absolute GPS coordinates. With more accurate GPS systems (such as RTK) or 3D video analysis, future work could investigate in more detail the fastest lines between a sequence of gates. For example, this was successfully done by Hunter, who found wide lines into upstream gates were faster than tight lines (Hunter, 2009). Incorporating the influence of the water features into these analyses would best capture the tactical choices of canoe slalom.

The metrics that were deemed most influential, with a strength, technical, or tactical influence, were the average speed, total distance, and rate of force development. Naturally, average speed and total distance were strongly linked to race time. Of the included metrics, an athlete's average speed had the strongest relationship to race time in the white-water multiple regression analysis, out of all the metrics measuring strength and skill. With 16.72 seconds separating the slowest and fastest included athletes in the whitewater analysis, 14.66 seconds of separation could come from differences between average speeds of the athletes. The average speed is a metric that contains aspects of both strength and skill—namely—how much power an athlete puts in as well as their ability to transfer that power to the boat and utilize features of the water to their advantage. Additionally, seven seconds of separation between the athletes could come from differences in the length of their lines, which varied by up to 32 m. The total distance an athlete travels reflects their line choice and ability to stay on the intended line. Although it could be said that higher strength may allow one to choose more difficult, shorter lines, the total distance travelled is primarily a metric of skill. Accounting for both average speed and total distance travelled predicted white-water times better than either alone, evident by the higher r^2 value for the two together (Table 4 and 6, where r^2 for both combined is 0.97). A further 1.68 seconds of separation could come from differences in the rate of force development between the athletes, which indicates the explosive power of the athletes. The smaller time explained by differences in athlete RFD is a result of the lack of relationship seen between stroke force and race time, as stroke force ultimately muddied the relationship of velocity with race time.

The model did not predict split times well. This is likely due to the different balance of strength and skill seen across different sections of white-water. For example, although a large relationship with split RFD and split time is evident in downstream gates 15-18 (Table

4), in the upstream section gates 2-4 this relationship is hardly different from a random association. As the influence of turning strokes tended to dull the relationship between RFD and race time, this makes sense due to the greater influence of turns in the upstream section. The lower associations with split RFD in split 2-4 may also have been due to the slower current with more similarity to flat-water than the rest of the course, as the RFD also tended to have less influence on the flat-water.

In contrast, the relationship with overall split $power_{pb}$ and split time was more prominent for the upstream section gates 2-4, and less prominent for the downstream section gates 15-18. In many cases, the upstream splits in gates 2-4, 7-9, and 11-15 showed strong relationships with split force and power. In upstream sections, athletes experience the greatest decelerations as they come into the eddies for their turns. Thus, in order to regain speed fast, force and power must be generated. This is likely in contrast to the downstream split in gates 15-18, where the athletes already had large speed from the faster current and needed to maintain this speed to have a short split time. Thus greater power may be needed for the upstream sections.

Average split speed showed the strongest relationships with split time in gates 0-2, 4-7, and 11-15, the first two being downstream sections. In contrast, the relationship between total distance in each split and race time was strongest in gates 2-4, 7-9, and 11-15, which are all upstream sections. Thus on the upstream splits, racers may not have differed as much in speed but achieved faster times by travelling less distance in total. This did not mean they cut their entry lines into the gates short, but rather, achieved tighter turns around the poles without needing to take extra strokes in the eddy around the pole and saving themselves distance. Indeed, a wide approach line was proven faster than a tight entry line by Hunter (Hunter, 2009). As gates 11-15 included double upstream gates, the potential for athletes to enter the eddy low twice was high. This likely produced the majority of difference in race time for this section. In contrast, the line through gates 15-18 was shorter overall, and if an athlete veered too far off course they likely would have incurred a penalty here. Indeed, although the maximum variation in distance travelled on the splits ranged from 2.7 to 6.9 m depending on the split, the average of this variation was higher for the upstreams, once the difference in total section length was accounted for by dividing by the mean distance of each split. Though speed played a larger role, in downstream sections the faster athletes still tended to travel shorter distances. Here, shorter distance is likely achieved by taking tighter lines between the offsets. The faster speeds in the downstreams may have been achieved by positioning their boats at an angle that created less drag in their intended direction of travel on the downstream sections. This would more of the athletes path would be aligned with the direction of the current, producing greater resultant speed on the boat. Indeed, faster athletes made more moderate changes in angle left-to-right as they travelled the downstream sections (Table 4). Thus on downstream sections, the same strategy (tighter lines) leads to faster race times through both a shorter distance and faster speed.

The balance of strength, technique, and tactics thus shifted across the different splits, and hypothesis 3 was accepted. This suggests that the metrics found to be most important in this study—speed, distance travelled, and power—may have different importance on another white-water course or at another white-water venue. It is critical to take into account the importance of this variability when evaluating performance in canoe slalom. To achieve fast race times, top athletes likely adjust their strength, technique, and tactics to the moves at hand—which likely makes skill hard to quantify across too disparate of white-water sections, as seen for the technical metrics in this study. Instead of producing maximum power for the full course, they likely utilize power only on moves where it is required. Instead of using maximum edge, there is likely an optimal edge for the move at hand. Instead of taking lines which gain maximum speed from the water or cutting lines to the shortest distance, they likely choose optimal lines that strike a balance between speed and distance to achieve the shortest time.

Indeed, despite the associations shown in this work, there were many examples where athletes used different strategies to achieve similar race times. For example, in the upstream section in gates 7-9, two athletes achieved split times of 12.99 and 12.77 seconds. These two athletes had identical mass and distance travelled in the split, and achieved similar speeds. However, the first athlete achieved their time with a mean peak force and impulse 1.4 times greater than the other athlete. And in the downstream section in gates 9-11, two athletes achieved similar times of 8.65 and 8.64 seconds. The first athlete had slower average speed but had travelled one meter less than the second athlete, who travelled at a higher average speed. In slalom, there are many different strategies that paddlers can use to achieve fast times, which makes linking performance characteristics to race times in general quite difficult. However, shying away from this variability in scientific research may not push performance forward as much as accepting the nature of our sport and finding better ways to honor it

Surprisingly, the whitewater model predicted flatwater rankings better than the split rankings. In preliminary analyses, athlete rankings in the splits were much different than their final rankings. For example, the race winner placed first in only three splits. The metrics selected here—average speed, total distance, and RFD—may represent performance best when averaged across an entire performance, such as that for whitewater and flatwater. However, these metrics appear to have different importance when investigated over a small section of whitewater. Breaking down whitewater performance to these split sections and learning more about what makes specific sections of whitewater fast is critical for pushing performance in canoe slalom forward. Even the top athlete in this study had room to improve their race time by improving their split times to match the fastest athlete in each split.

Predictions of race time based on average speed, total distance travelled, and overall $power_{pb}$ were within one second for the majority of athletes in both runs one and two. Even though the data from run 2 was not included in construction of the original model, rankings were accurate. This demonstrates the general importance of speed, distance, and power for race times on *this* white-water course, across high performing C1 athletes.

Stroke characteristics

This is the first time that stroke characteristics are reported for C1 athletes in the literature. The peak paddle forces for these athletes are higher than those reported for K1 athletes. For example, development level K1M (up to and including semi-finals at a World Cup) produced peak forces of 184 N on average (Macdermid et al., 2019). This number refers to bottom hand force, and it differs from the paddle force reported in our study. In our study, average peak paddle force was between 130-257 N, and if converted to bottom hand force with distance from T-grip to blade centre of area of 1.212 m and distance between hands of 0.763 m (Equation 7), is 207-408 N. Individual stroke peak paddle forces were higher and reached up to 424 N, which is a bottom hand force of 673 N. This is over twice that reported for one male kayaker of 300 N (Macdermid and Olazabal, 2022). Indeed, canoe athletes are thought to produce greater forces than kayak athletes due to the larger blade.

Equation 7: Paddle blade force to bottom hand force

$$BottomHandForce = \frac{PaddleBladeForce * DistanceTgripToCOA}{DistanceBwHands}$$

Where *BottomHandForce* is the force in Newtons, PaddleBladeForce is the force reported in this study which refers to the force at the blade, *DistanceTgripToCOA is the total length of the paddle minus the distance to the blade COA, and DistanceBwHands is the distance between the middle of the two hands (Figure 2).*

The relationship between flat-water strength and white-water performance found in Aim 2a may result from similar task demands between the water types. For example, average peak stroke forces were very similar between the flat-water figure-8 test and white-water of moderate to difficult level (Class II-III) in this study. However, it is likely that power and explosive strength demands on the two types of water differ. Higher rates of force development were seen for flat-water, even among only forward strokes. The relationship between average white-water RFD and white-water race time was slightly stronger than that for average flat-water RFD. This relationship was higher than that found by Macdermid (Macdermid and Olazabal, 2022).

Unfortunately, due to the differences in current, estimates of overall $power_{pb}$ from white-water and flat-water cannot be directly compared. Comparing the average stroke $power_{lt}$ is also not possible because the assumption that all strokes have the same length of 1 m is especially incorrect for white-water. For example, assuming peak paddle force was 300 N and drive time was 0.88 seconds, then a 20 cm adjustment in stroke length leads to a difference in power of 67 W. On the flat-water in our study, average stroke $power_{st}$ ranged from 230 – 450 W for the men, and overall $power_{pb}$ ranged from 330 – 532 W for the men. These estimates of power are higher than those reported in the literature for male slalom kayakers and on a kayaking ergometer, of 220 W for flat-water kayaking and 240 W on a kayak ergometer (Bielik et al., 2019; Macdermid et al., 2019). On the flat-water, athletes likely take more similar strokes making the average stroke $power_{st}$ more accurate than on the whitewater, however this assumption cannot be tested from our video as the camera panned between gates, making the horizontal displacement of the paddle not align with the horizontal axis of the camera. Future work may want to tape a calibration strip to the side of the boat, as this could be used to determine stroke length.

Mass effect

There was a strong effect of mass on race times on white-water, flat-water, and in the white-water splits. As mass increased, race time decreased. Given the range of ages in the athletes of this study, it is likely that a large component of the mass effect was due to differences in experience (and therefore skill) based on age. As age was not normally distributed this is difficult to evaluate. However, taking the paddlers aged 17-20, there was a very large correlation between mass and age of r = 0.85. This may also explain why mass-specific $power_{pb}$ was not related to race time in this study, unlike that reported for general power and paddling specific power in other studies (Busta et al., 2022; Messias et al., 2015). Normalizing power by mass may have actually normalized power by both mass and experience, muddying any effect that would normally be present with race time.

Sex effect

Although the sample sizes by sex are small, this is the first time that paddle force characteristics are reported for female slalom paddlers. There was a tendency for female C1 paddlers to produce lower forces and rates of force development than male C1 paddlers, although both sexes were similar when normalized for mass. This likely contributed to the sex difference in race time, where a difference between males and females was evident in every split. The association between race times and sex had one of the lower standard error of the estimates on white-water. The expected reason for a sex effect in sport is that there ought to be differences in muscular output that help contribute to better performance. However, although a sex difference was evident in every split, an association between overall $power_{pb}$ and split time was only evident in three of the upstream sections. As well, there were no significant relationships between average peak force and race time in either the white-water course or the figure-8 flat-water test. Although higher paddle forces should propel the boat forward with greater acceleration for a given mass, leading to faster velocities and shorter race times, conflicting factors dulled this relationship in our study of C1 paddlers, even when force was normalized for mass.

Limitations

Restricting smaller paddlers to use a blade too large and larger paddlers to use a blade too small likely limited the power outputs for our athletes. Despite the useful coaching advice that ideal paddle strokes appear to 'stick' in one place in the water while the boat moves forward, the paddle must experience some movement or slip through the water in order to change its momentum (where momentum equals mass times velocity). Even in the hypothetical situation where a paddler grabs a post fixed to the riverbed in order to pull themselves forward, the momentum of the post/riverbed system will change. Since the post is fixed to the riverbed (and ignoring bending), it has the mass of the entire earth to contend with, so the change in velocity is imperceptibly small. But during regular paddling, the mass of concern is much smaller (that of the small amount of water around the blade), and the change in velocity to this water around the blade will be measurable. The momentum of the water, boat, and paddle will be conserved, and the momentum of the paddle blade and water will impart an equal but opposite momentum onto the boat, pushing it forward. Unfortunately, we did not have access to this paddle velocity in our study.

If paddlers picked a blade that was too large, they would not be able to pull the blade very fast through the water, and thus the momentum imparted to the boat may be lower than a properly sized blade. Given the large blade area, the paddler must reduce the speed at which they pull the paddle through the water in order to produce a force that they are capable of maintaining throughout the race. Thus, this paddler would have lower paddle power than what they are used to and must lower their stroke rate to accommodate the larger blade. If instead paddlers picked a blade that was too small, they would be able to pull the blade very fast through the water. The paddle force would be reduced, as paddle force is proportional to the area of the blade and the squared speed of the paddle relative to the water (Sprigings et al., 2006). Thus, this paddler must increase their stroke rate by decreasing the drive time to accommodate the smaller blade. The too small blade would also make paddling less efficient, as a greater change in velocity to the water results in more kinetic energy being lost to the water. An improper blade size will also have repercussions for muscular power, which will be affected by the relative velocity between the boat and paddle. Optimizing muscular power requires a moderate level of force and velocity due to the nature of their opposing relationship in muscle tissue. If a paddler were faced with too large a blade, they could have higher muscular force, but lower muscular velocity, and thus lower muscular power. If a paddler were faced with too small a blade, they could have higher muscular velocity, but lower muscular force, and thus lower muscular power. Indeed, the concept of matching blade size to paddler power is not foreign in the sprint community (Sprigings et al., 2006). Although slalom paddlers may not undertake such a formal procedure to determine their blade size, they may choose a blade size based on feel that inadvertently allows optimal power for their paddling style. Thus, the effect of power on race time may have been stronger under the paddler's own blade size and shape, as well as with an appropriate calculation of power based on paddle velocity.

While other limitations have largely been discussed in the methods and have been greatly reduced as factors influencing these results, they are also noted here for completeness. There was error in the calculations of force due to calibration, drift from temperature changes, and athlete hand positions, these are expected to be 11 N or less. There was also error in the s.d. rotations due to drift in the gyroscope, thus only the straight or downstream sections were chosen for analyses or else excluded for the whitewater. Absolute error in the GPS coordinates is up to 2 m, thus, this study relied only on relative measurements which largely cancel out this error for short time periods due to autocorrelations in the errors. Lastly, the accelerations may have offset error between athletes due to drift, although this was minimized by subtracting the mean acceleration over the course of the race including still periods at the beginning and end. Split times may also have inaccuracies of up to 0.2 s, as these were determined by video. It is expected these were inaccurate by up to 5 frames, or 0.2 s for the cameras with the lowest frame rates.

Conclusion

As a coaching tool, the figure-8 test may be best utilized to assess individual improvements within athletes over time. Although flat-water figure-8 performance was highly associated with white-water performance, the figure-8 test alone lacked predictive power and could not differentiate between athletes with narrow separations in race time. Instead, using multiple performance metrics is recommended to differentiate between athletes of similar level. The most influential aspect of flat-water performance was the top speed obtained during this test, as opposed to the maximum acceleration. C1 paddlers also relied on their edging technique to achieve fast figure-8 times. On white-water, athletes relied on high speeds and to a lesser extent shorter distances to achieve the fastest times. High speeds were achieved through a combination of technique, tactics, and power.

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