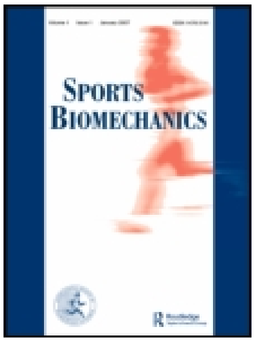

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Abstract
The aim of this study was to determine how the path chosen by elite slalom paddlers influences the time taken to negotiate an upstream gate. Six trials for international men's single kayak (MK1) ($n = 11$) and single canoe (C1) ($n = 6$) paddlers were digitized for a left-hand upstream gate. Results revealed that the absolute variability of paddlers increased as their total time increased ($r = 0.594$), but the coefficient of variation remained constant. There was a strong correlation ($r = 0.89$, each individual trial; $r = 0.93$, mean total time for each participant) between boat trajectory and the total time. The MK1 and C1 paddlers used similar strategies to negotiate an upstream gate. There were significant differences ($P < 0.05$) between the boat trajectory of the fastest and slowest paddlers (average distance between paddler's head and the inside pole). These results suggest that to achieve a faster upstream gate performance, paddlers should concentrate on the distance between their head and the inside pole. However, there would be an optimal distance beyond which any further reduction in the distance would impede technique and performance.

Keywords: *Biomechanics, kayak, paddler, performance, three-dimensional, whitewater*

Introduction

Elite canoe slalom competitions are won in about 90 s and top paddlers are often separated by less than half a second. Thus athletes search for strategies or techniques that provide them with an advantage over their competitors. However, the penalties for incorrect execution are severe, with paddlers incurring a 50-s penalty for incorrect negotiation of a gate and a 2-s penalty for contact with a gate. Scientific research of strategies and techniques that provide an advantage has been limited to time–motion analysis of canoe slalom paddlers (Hunter et al., 2007; 2008), with most research focusing on injuries (Fiore and Houston, 2001), officiating (Ritter, 1975; Miao and Bi, 2001), course design (Peters, 1987; Schmidt, 1993), mental state (Males et al., 1998), and discussions of possible future research (Knyora, 1976; Sperlich and Klauck, 1992).

Lapsed-time motion analysis of canoe slalom paddlers has been used to investigate the strategies of elite canoe slalom paddlers negotiating a course (Hunter et al., 2008). However,

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research based on lapsed-time motion analysis has limitations in terms of the information that can be collected without interference with the competition environment. Therefore, to attain a better understanding of strategies used in elite competition, more intrusive data collection methods are required.

The only researchers to analyse motion of an athlete and equipment through gates (snow-biking) used cinematography to determine the kinematic parameters, forces experienced and phases of the turn (Jelen and Jandová, 1999). To date, no research has investigated the kinematics of canoe slalom performance. A three-dimensional analysis of repeated runs and an investigation of how different biomechanical variables relate to the time taken to negotiate an upstream gate would provide coaches with critical information on technical characteristics that are beneficial to performance. Therefore, the aim of the present study was to determine how the path chosen by elite slalom paddlers influences the time taken to negotiate an upstream gate.

Methods

A six-gate canoe slalom course designed in consultation with elite canoe slalom coaches was set up on the top quarter of a whitewater course (Penrith, Australia) with five pumps generating whitewater flow at $14\,m^3/s$. The flow conditions were those used for the 2005 Canoe Slalom World Championships. The course involved four downstream gates and two upstream gates (Figure 1); the analysis in this investigation focuses on gate 2, which was a left-hand upstream gate.

Seventeen males participated in this study: 11 single kayak (K1) and six single canoe (C1) paddlers. Of the C1 paddlers, five were right-handed and one was left-handed. The data for the left-handed paddler were included with those of the right-handed paddlers because

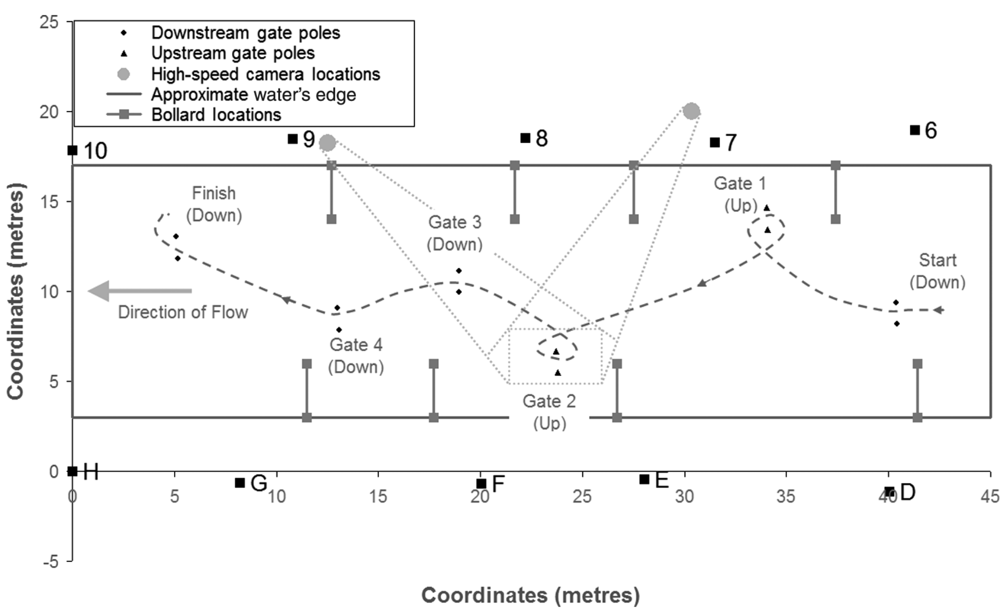

Figure 1. Scale diagram of course and equipment used for testing. The dashed line represents the approximate path of a paddler completing the course from right to left. Grey circles represent the location of the two high-speed cameras, which were focused on gate 2 (the dotted rectangle).

analysis revealed no differences between the strategies used with respect to the variables analysed. Each participant used their own craft and paddle conforming to the International Canoe Federation regulations. Kayakers have two paddle blades and are seated in their boat; canoeists have a single blade and kneel in their boat. All participants were ranked in the top 40 for a World Cup or the World Championships in 2005 for canoe slalom.

Paddlers performed six trials on the course, each of which took approximately 20 s. Paddlers had 5 min to perform their trial and walk back to the start to ensure full recovery between trials. Trials in which the paddler touched either of the gate poles were excluded from the analysis.

High-speed footage of gate 2 was captured using two high-speed cameras (Phantom V4.2 colour running firmware version 299; Vision Research Inc., New Jersey, USA) fitted with a 16–100 mm f/1.9 zoom lens. This footage was captured through a computer running the Phantom software V630. The cameras captured at 100 Hz with a resolution of 512 × 348 pixels and a shutter speed between 1/1000 and 1/500 of a second. The cameras were positioned 2.8 m above the water and oriented as defined in Figure 1.

A custom portable calibration rig consisting of two parts, a base frame that was levelled in the bed of the course when no water was running and a movable "T" section that was attached to each corner of the base frame and levelled (Figure 2). The volume calibrated for the high-speed cameras was 6 × 5 × 1.5 m. Twenty calibration points distributed throughout the volume were entered into the commercial software (Ariel Performance Analysis System, California, USA), which uses a three-dimensional direct linear transformation to convert digitized coordinates to real-world coordinates.

Soft, fluorescent orange hemispherical markers, 40 mm in diameter, were attached to the boats and helmet of each paddler to create visible landmarks on the boat and head that could be digitized easily. The locations of markers 5 and 6 were 0.05 m wider for C1 than K1 (Figure 3) because of the difference in boat width.

Results from a frequency analysis (fast Fourier transformation) on a trial revealed that the majority of the signal was below 1 Hz. To allow future analysis not considered in the current investigation, the video footage was manually digitized at 25 Hz using commercial software (Ariel Performance Analysis System, California, USA) to reconstruct three-dimensional kinematic information about the boat and paddler's head during the upstream gate.

Repeatability analysis revealed that the mean absolute difference of each data point from all markers across the three digitizing repetitions to the mean was 0.01 m, the maximum was 0.04 m, and the maximum absolute difference of every data point from all markers across the

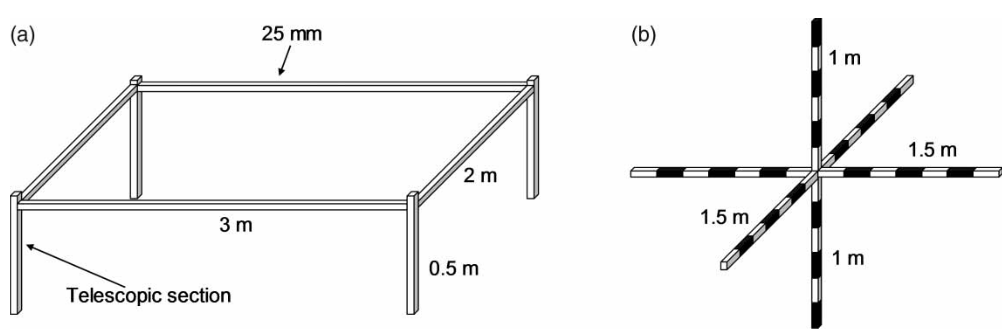

Figure 2. Calibration rig. The base frame (a) was placed in the bed of the course and levelled using the telescopic sections. To calibrate the volume, the movable "T" section (b) was attached to the base frame above each leg in turn and levelled.

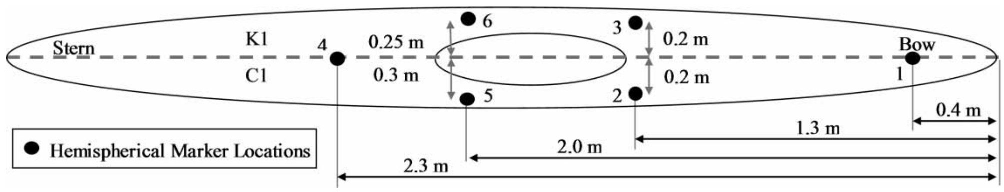

Figure 3. The locations of the hemispherical markers attached to each boat. The top half represents a single kayak (K1) and the bottom half a single canoe (C1).

three repetitions to the mean was 0.07 m. The raw x, y, z coordinates were then filtered using a fifth-order dual-pass Butterworth filter and a cut-off frequency of 2 Hz, which was selected from the results of the fast Fourier transformation and the Nyquist rate (twice the band width).

Total time was measured as the time taken for the head to travel from positions 1 to 4 and boat trajectory was defined as the mean distance between the paddler's head and the inside pole between positions 1 and 4 (Figure 4). Only data between positions 1 and 4 were analysed because this is where the majority of the turn occurs and reacceleration of the boat occurs after position 4. To compare the line taken around the gate by the two fastest and slowest K1 and two fastest and slowest C1 paddlers, the average of each data point was determined.

Comparison of C1 and K1 allows paddlers to optimize the strategies they employ not based solely on the best in their own category but the best over both categories. Although differences in boat and paddle design between kayaks and canoes may influence the extent to which strategies can be transferred between the categories, a better understanding of performance can be developed by comparing the effectiveness of strategies that different canoe slalom categories employ to negotiate obstacles.

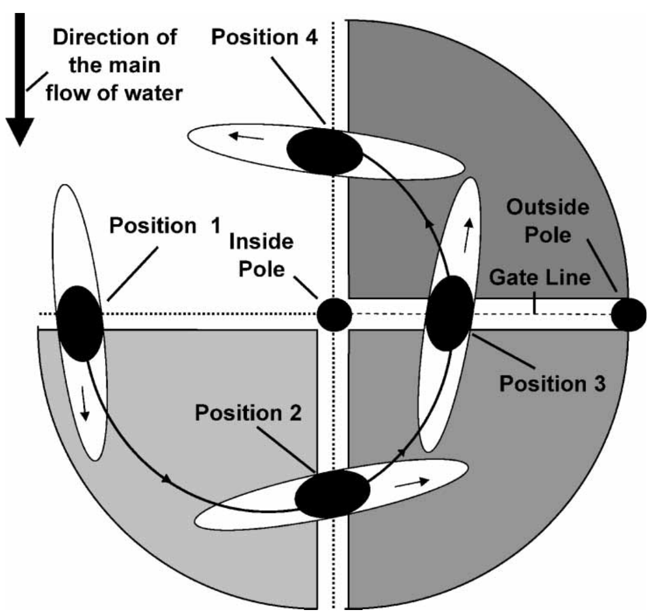

Figure 4. Section of the upstream turn analysed was from position 1 to position 4.

A Pearson's two-tailed correlation was used to determine the strength of the relationship between total time (independent variable) and boat trajectory (dependent variable). To determine if this relationship remained for each individual, a Pearson's two-tailed correlation was performed on each participant and the linear regression equations parameters calculated. The coefficient of variation and standard deviation of total time and boat trajectory across all analysed trials were correlated to total time to determine if trial variability increased as total time increased. A one-way analysis of variance (ANOVA) was performed on the four groups of paddlers (the two fastest vs. the two slowest paddlers in each class: K1 and C1) with total time and boat trajectory as dependent variables to determine if differences existed between the fastest and slowest strategies in this population. A *post-hoc* Scheffé test was used to assess differences between the groups.

Results

The largest difference in boat trajectory for both K1 and C1 was between the fastest two and the slowest two paddlers in each class (Figure 5). The two slowest paddlers in each category took a tighter line leading into the gate but after position 2 their

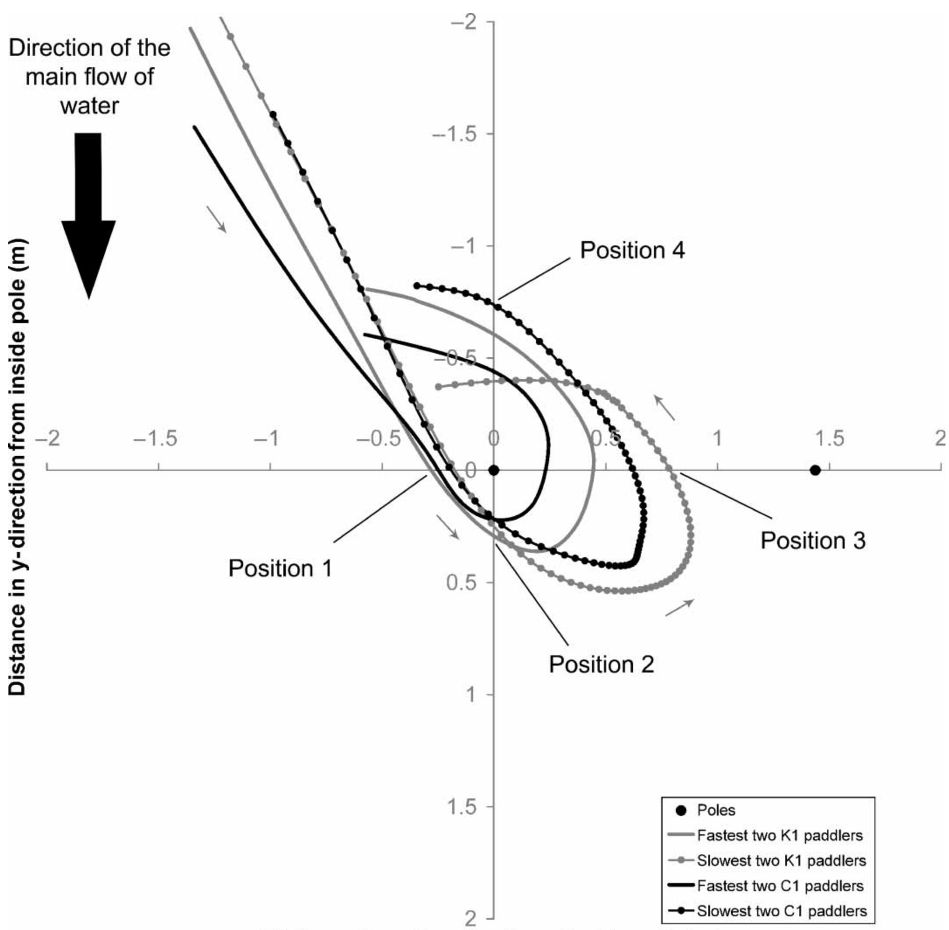

Figure 5. Mean boat trajectory in the x,y-plane for the fastest two and slowest two paddlers in K1 and C1.

line was wider than that of the fastest two paddlers. The faster paddlers had less distance between their head and the inside pole between positions 2 and 3 than the slower paddlers.

There was a strong correlation ($r = 0.89$) between boat trajectory and the total time taken to get from position 1 to position 4 (Figure 6, Table I). This relationship was stronger ($r = 0.93$) when the boat trajectory and the mean total time from position 1 to position 4 for each participant was used rather than each individual trial (Figure 7).

The correlation between boat trajectory and the total time for each paddler varied with all but one $r \geq 0.69$ (Table II). All produced a positive correlation, as seen in the gradients, which were all greater than zero.

otal time was moderately correlated with the standard deviation of total time ($r = 0.594$) and the standard deviation of the boat trajectory ($r = 0.657$) between trials. However, no correlation was observed between total time and the coefficient of variation of total time ($r = 0.228$), or the coefficient of variation of the boat trajectory ($r = 0.282$), between trials (Table I).

No significant difference was observed between the fastest two K1 and the fastest two C1 paddlers with respect to total time or boat trajectory. No significant difference was seen between total time ($P = 0.06$) taken by the fastest two C1 and the slowest two C1 paddlers, but the boat trajectory was significantly different ($P = 0.02$). The fastest two K1 paddlers were significantly different from the slowest two K1 paddlers with respect to total time ($P < 0.01$) and the boat trajectory ($P = 0.05$).

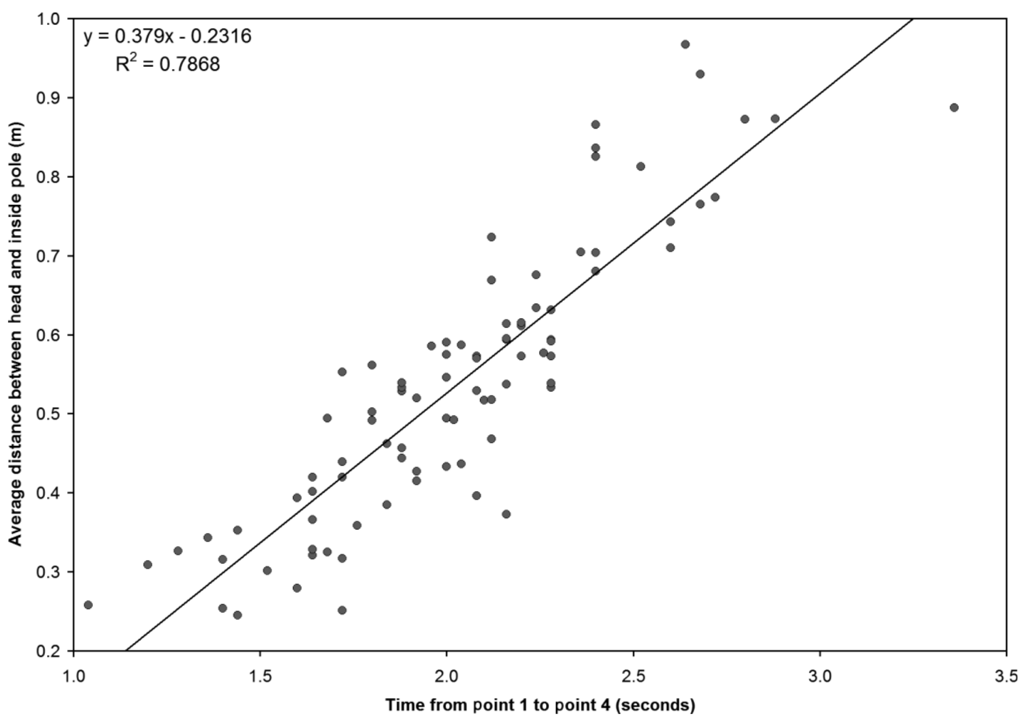

Figure 6. Correlation between total time and the boat trajectory for each trial.

Table I. Pearson's two-tailed correlations to total time

Variable	*r*-value
Boat trajectory (mean distance between head and inside pole)	0.93
Standard deviation for total time	0.59
Standard deviation for boat trajectory	0.66
Coefficient of variation for total time	0.23
Coefficient of variation for boat trajectory	0.23

Discussion and implications

The aim of this study was to determine how the path chosen by elite slalom paddlers influences the time taken to negotiate an upstream gate. The relationship between total time and the variability in paddler performance between trials, as determined by the standard deviation of both the total time and boat trajectory, indicated that quicker paddlers had less absolute variation compared with slower paddlers. However, there was only a weak relationship between total time and the coefficient of variation of total time and boat trajectory. This indicates that elite paddlers vary a similar percentage of their run time between runs, thus those with faster run times vary less in seconds. This suggests that the variation that paddlers possess is similar, but faster paddlers are able to use their variation in a positive sense to deal with the ever-changing environmental conditions and produce less absolute variation and therefore faster times.

The fastest two C1 and K1 paddlers used the same strategies to negotiate the upstream gate when the total time and the boat trajectory were considered. This indicates that

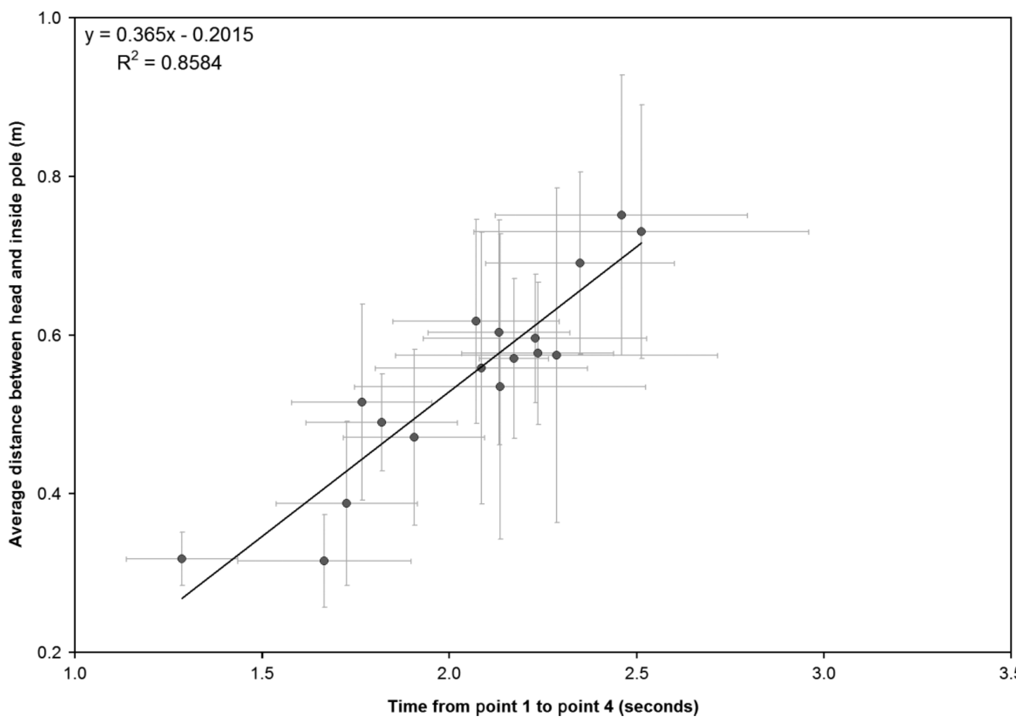

Figure 7. Correlation between mean total time and the boat trajectory for each paddler (± standard deviation).

Table II. Pearson's two-tailed correlations and linear regression equations for each participant between total time and boat trajectory

Participant	Category	Trials	*r*-value	Gradient	y-intercept
1	C1 (R)	6	0.99	0.440	−0.407
2	K1	6	0.94	0.462	−0.482
3	K1	6	0.97	0.589	−0.670
4	K1	6	0.78	0.583	−0.640
5	K1	6	0.95	0.627	−0.593
6	K1	6	0.91	0.534	−0.547
7	C1 (L)	6	0.69	0.175	0.022
8	C1 (R)	6	0.90	0.204	0.055
9	K1	5	0.94	0.544	−0.510
10	C1 (R)	4	0.76	0.228	0.074
11	K1	6	0.79	0.436	−0.366
12	C1 (R)	4	0.82	0.223	0.099
13	C1 (R)	4	0.71	0.325	−0.073
14	K1	4	0.96	0.501	−0.481
15	K1	3	0.03	0.028	0.508
16	K1	5	0.96	0.474	−0.478
17	K1	6	0.76	0.272	0.045

although the two categories have different limitations resulting from kayakers having two blades and being seated versus canoeists having a single blade and kneeling, the methods used to negotiate the upstream gate are similar (Figure 5). Therefore, the teaching points for both groups of paddlers would be the same. Also, due to the rules of canoe slalom, paddlers generally only get to watch a few demonstration runs of the course. Therefore, based on the results of this study, it would indicate that paddlers should pay attention to all categories and not just their own during demonstrations.

The fastest two K1 paddlers were significantly quicker around the gate than the slowest two K1 paddlers and also took a significantly different line, demonstrating that even within an elite population differences exist in the way the fastest and slowest athletes negotiate an upstream gate. This information is beneficial to coaches and athletes in determining the best line to take through gates and how this line will relate to time and performance. In C1, there was a difference in the line taken and the total time around the gate of the fastest two and the slowest two paddlers, although the difference in total time was not significant. This is probably due to the small number of participants in this category, their similar ability or the short comparison time. Further insight into upstream gate technique could be attained through comparison of left- and right-handed C1 paddlers performing onside and offside gates.

This research found that minimizing the distance between the paddler's head and the inside pole is an important consideration when negotiating an upstream gate, as it has significant implications for performance. A relationship between total time and boat trajectory existed when the average of multiple trials for each individual was considered and if each trial was considered. Thus, when considering individual paddlers, their fastest times were achieved in those trials when their head was closest to the inside pole. In addition, when comparing paddlers, the fastest times were achieved by those who minimized this distance. These results are supported by the graphical representation of the boat trajectory demonstrating the wider lines taken around the gate by the slowest two paddlers in each category compared with the fastest two (Figure 5). This relationship was not perfect and thus additional factors must be considered such as differences in paddler mass, boat design, paddle propulsion, variations in water flow between trials, as well as tactics for completing the upstream gate in relation to completing the whole six-gate section. Due to the rules of slalom canoeing, it is anticipated that there is an optimal distance beyond which any further reduction in this distance would impede performance due to the increased risk of touching the gate. The positioning of the gate before and after the upstream gate as well as the water conditions and relative location of the upstream gate to course and water obstacles differs for every course and upstream gate within a course. Therefore, it is important to consider these when looking at the path the paddler takes around the gate. However, the relationship of boat trajectory and total time should remain regardless of individual gate characteristics.

Conclusion

In determining how elite slalom paddlers negotiate upstream gates, it was found that the absolute variability of a paddler decreases as their level of skill increases (as determined by total time taken), but the percentile variation remains constant. Men's K1 ($n = 11$) and C1 ($n = 6$) paddlers did not appear to use different strategies to negotiate an upstream gate. In addition, even within this elite population the lines of the two fastest paddlers compared with those of the two slowest K1 and C1 paddlers, as measured by the average distance between a paddler's head and the inside pole, were significantly different. Paddlers seeking faster upstream gate performance could improve by focusing on minimizing the distance between their head and the inside pole. However, it is anticipated that there is an optimal distance beyond which any further reduction in the distance would impede technique and performance due to the increased risk of touching the gate.

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