

Paddling Force Profiles at Different Stroke Rates in Elite Sprint Kayaking

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In sprint kayaking the role that paddling technique plays in optimizing paddle forces and resultant kayak kinematics is still unclear. The aim of this study was to analyze the magnitude and shape of the paddle force–time curve at different stroke rates, and their implications for kayak performance. Ten elite kayak paddlers (5 males and 5 females) were analyzed while performing 2000-m on-water trials, at 4 different paces (60, 80, and 100 strokes per minute, and race pace). The paddle and kayak were instrumented with strain gauges and accelerometers, respectively. For both sexes, the force–time curves were characterized at training pace by having a bell shape and at race pace by a first small peak, followed by a small decrease in force and then followed by a main plateau. The force profile, represented by the mean force/peak force ratio, became more rectangular with increasing stroke rate ($F[3,40] = 7.87, P < .01$). To obtain a rectangular shape to maximize performance, kayak paddlers should seek a stronger water phase with a rapid increase in force immediately after blade entry, and a quick exit before the force dropping far below the maximum force. This pattern should be sought when training at race pace and in competition.

Keywords: biomechanics, kayak, force–time curve, stroke profile, acceleration

In sprint kayaking, due to changes in the magnitude of the force applied by the paddler, there is an intracyclic variation of the kayak's forward acceleration during each paddle stroke. To create forward acceleration, the paddler has to produce a force greater than the aerodynamic and hydrodynamic drag.¹ A kayaker's efficiency in generating propulsive forces is therefore a key determinant of success.² Therefore, in terms of biomechanical testing, the force applied to the blade should be the prime variable measured in elite kayaking, together with performance indicators such as boat speed.³

The magnitude and shape of paddle force–time curve variables determine the kayak acceleration and, consequently, the kayaking performance.^{1,4} Although the importance of these variables has not been investigated in studies of kayaking, the relationship between the shape of the force–time curve and performance has been recognized in rowing studies. Millward⁵ showed that maintaining a force close to the peak force (F_{peak}), from entry to paddle exit, is achieved by minimizing the speed variations of the kayak. Thus, the optimal force profile is rectangular rather than triangular. Further, for a given time of force application and maximum force achievable, given the constraints of the frontal area of the blade,⁶ the greatest impulse is achieved when the force is at its maximum throughout the period of force application (ie, a rectangular force profile).

Combined analyses of paddle force and kinematics have been conducted on a kayak ergometer,⁷ but conclusions were limited by the fact that the performance did not fully replicate on-water condi-

tions. Studies of on-water paddling kinetics have been performed,^{3,8} but were focused mainly on procedures and methods rather than on data analysis and discussion of force profiles.

The process of training involves competition simulation using high stroke rates (SRs), but also training at a variety of training paces that can go from 55 strokes per minute (spm) up to 140 spm or more.⁹ During sprint kayak races, the kayak paddler self-selects the SR according to the race distance (200 m, 500 m, or 1000 m). SR is a key determinant of kayak velocity,¹⁰ being considered one of the best biomechanical predictors of sprint kayak performance.^{11,12} For past years, coaches and athletes have used the SR as a variable that allows identification of training zones.⁹ The question of which shape of the force–time curve is adopted by elite paddlers at different SRs is still to be answered. It seems logical that if a rectangular pattern of force application is desirable to optimize performance in competition, then this pattern should be practiced in training. However, it is not known at present whether the pattern used at training paces does resemble those used by elite kayak paddlers at race pace.

The aim of this study was to analyze the magnitude and shape of paddle force–time curves of elite kayak paddlers (males and females) at different intensity conditions (different training paces and race pace), and their implications for performance and training. It was hypothesized that there would be differences in the paddling force profile between training paces and race pace, and that the best performances would be achieved with a force–time curve that tended toward a rectangular shape.

Methods

Subjects

Ten elite kayak paddlers (5 females and 5 males) participated in the study (Table 1). All the kayak paddlers had a very high performance

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Table 1 Subjects' physical characteristics for each group, mean ± SD

Variables	Male Kayakers (n = 5)	Female Kayakers (n = 5)
Age (years)	24.17 ± 2.39	25.80 ± 3.81
Body mass (kg)**	86.42 ± 4.11	63.52 ± 3.46
Height (cm)**	183.10 ± 3.53	165.70 ± 3.66
Sitting height (cm)**	97.72 ± 2.84	88.75 ± 1.30

** $P < .01$, highly significant differences between sexes.

level. The criterion for subjects' inclusion in the current study was selection to compete internationally in the qualification races of the 2012 Olympic Games. Six of the 10 kayak paddlers (4 females and 2 males) participated at the London Olympic Games and then qualified for the finals. Subjects were fully informed of the nature of the investigation, and provided written informed consent before data acquisition. The study was approved by the local ethics committee and was performed according to the Declaration of Helsinki.

Procedures

The kayak paddlers performed 4 trials of 200 m at different paddling SRs: 60, 80, and 100 spm, and at race pace in which the athlete was free to select the SR, with 5 minutes recovery between trials. The SR represented different training zones (aerobic to race pace) as prescribed by the World Canoe Sprint Coaches Technical Group.⁹ The subjects were instructed to search for the best performance in each of the SR conditions. Each of the trials began with the kayak at a velocity of $2.78 \pm 0.04 \text{ m}\cdot\text{s}^{-1}$ (represents a very low intensity); at a signal, the athlete started the trial. The data were collected in calm water, with no influence of currents and with a wind velocity below $0.42 \text{ m}\cdot\text{s}^{-1}$ (corresponding to calm to light air on the Beaufort scale).¹³ Paddle forces generated by the paddler on the shaft and the kayak acceleration were collected continuously, recording at a sampling rate of 256 Hz. In the trials that had a specific SR to accomplish, the athlete used an audible metronome device (TempoTrainerPro, Finis, Livermore, CA) set to that SR. A GPS tracker (Forerunner 310XT, Garmin, Olathe, KS) allowed triggering at the start and the end of the each trial, and helped the athlete to control the velocity immediately before the start, since differences in start velocity would interfere with the time that the athlete took to perform the 200 m.

Data Analysis and Equipment

The individual equipment (paddle and kayak) of each kayak paddler was instrumented before the trials. The paddle was instrumented with the 'FPaddle' system and the kayak with a triaxial accelerometer (G-Link-mXRS, Microstrain, Williston, VT) placed inside the kayak and attached to the central rail for ballast in a level position (parallel to the kayak seat platform).

The 'FPaddle' system¹⁴ comprises deformation sensors, a force transducer, a transmitter and radio receiver, and signal processing software (Node Commander 2.4.0, Microstrain, Williston, VT). The paddle shaft was instrumented with 2 strain gauges for composite materials (HBM, Darmstadt, Germany) bonded directly onto the paddle shaft, thus decreasing possible erroneous sensing data.¹⁵ They were positioned in each side at the same longitudinal position from the tip of the blades (80 cm) to respond to the bending

of the shaft in one plane parallel to the larger surface of the blade. In addition, the strain gauges were connected to the voltage node V-Link-mXRS (Microstrain, Williston, VT) by wires. Gain and offset were set automatically by software.

The calibration of the system was performed statically by loading the paddle with calibrated masses (from 5 kg to 30 kg, in steps of 5 kg). The paddle was calibrated using the following procedures: (1) one support positioned on the right-hand grip position where the athlete grabbed the shaft (considering the third finger); (2) the other support positioned on the middle of the left blade (assuming that the force was acting upon the center of the blade—hypothetical center of hydrodynamic pressure);^{8,16} and (3) the different masses were suspended on the left-hand grip position (considering the third finger). The process was performed for both paddle sides. A strong linear relationship was found between the force on the paddle shaft hand grip (F_S) and the change in resistance within the quarter-bridge circuit (Wheatstone bridge) for both sides ($r = -1.00$, $P < .00$). Since force data were sampled at a high sampling rate frequency, at paddling frequencies from approximately 60 spm to 124 spm, it did not significantly influence the dynamic analysis.

Based on equilibrium of moments, the F_S was used to determine the force applied on each blade (F_B) (Equation 1) by taking into consideration the distance between the center of the area of the blade and the near grip (d_A) and between grips (d_B).¹⁵

$$F_B = F_S \frac{d_B}{(d_A + d_B)} \tag{1}$$

Equation 1 assumes that the longitudinal instantaneous center of rotation of the paddle (pivot point on the paddle) is maintained stationary and positioned on the grip opposite to the propulsive side throughout the water phase (left and right). The shaft deformation measured by the 'FPaddle' system during the water phase of the stroke combined the force applied by both top and bottom hands, and was analyzed by the strain gauge closer to the bottom hand and parallel to the larger surface of the blade that was submerged.

Both items of equipment (G-Link and V-Link nodes) were working synchronously (node-to-node synchronization with a limit error of $\pm 32 \mu\text{sec}$) in a wireless communication system and transferring in real time to the WSDA-Base (Microstrain, Williston, VT). The force and acceleration data were exported to MatLab R2010a (The MathWorks Inc., Natick, MA) and analyzed using a routine specially developed for this application. A fourth-order low-pass Butterworth filter with a cut-off frequency of 20 Hz was used to smooth the data and remove the random error.¹⁷ The choice of cut-off frequency was based on residual analysis of the difference between filtered and unfiltered signals over a wide range of cut-off frequencies using the percentage variance accounted (VAF)¹⁸ to estimate the optimum cut-off frequency. For the applied cut-off frequency, the mean VAF was $98.87 \pm 1.03\%$, representing a difference between the filtered and unfiltered signals of less than 2%.

The paddling technique was analyzed considering the 2-phase model proposed by McDonnell et al,¹⁹ that divides a single stroke into the water phase (from entry to paddle blade exit from the water) and the aerial phase (from the paddle blade exit to the entry instant on the other side). For the current study, the definition of the entry and exit of the paddle on the water corresponded to the start and end of force application.²⁰ The software routine automatically detected the water phase of each stroke by identifying the onset and end of the force application. A visual inspection of the strokes was performed to ensure correct data selection. All the strokes performed during the 200 m were analyzed, from the moment the kayak paddler reached the requested SR.

The F_{peak} (highest point of force in each stroke), the time to reach the F_{peak} (time from the start of the water phase to the peak force), the F_{mean} (mean of the force values of the water phase by stroke), and the impulse (calculated as the integral of the water phase of the force–time curve) were calculated for each stroke. The $F_{\text{mean}}/F_{\text{peak}}$ ratio was calculated to reflect the force profile. This ratio, expressed as a percentage, is 100% if the force is rectangular (constant force) and 50% if it is triangular in shape.²¹ Since it is a ratio and independent of strength differences, the results of the male and female paddlers were pooled for statistical analysis. For graphical analysis of the force–time profile of male and female elite kayak paddlers at different SRs, the force–time curve data within each SR was time normalized to the median of the water phase duration. Since the duration of force application varied along the trial for each SR, time normalization to the median time enabled valid comparison of force profiles. The on-water force variables and shape of the force–time curve, indicated by the $F_{\text{mean}}/F_{\text{peak}}$ ratio in conjunction with inspection of the characteristics of the force–normalized time graphs, were analyzed for each of the different SR trials.

The mean kayak velocity was determined based on the time to travel the 200 m. The time variables analyzed based on the force–time curve were the duration of a single stroke and of the water and aerial phases (each as a percentage of the stroke duration). Mean SR for the entire trial was computed as the inverse of the mean stroke duration.

The kayak acceleration profile was analyzed, together with the synchronized force data, for the whole stroke to identify the times that corresponded to the start of positive acceleration and the instant the kayak started to decelerate, both as a percentage of the stroke duration.

Statistics

Statistical analyses of the effect of SR on $F_{\text{peak}}/F_{\text{mean}}$ ratio; duration of the water and aerial phases; and time to F_{peak} , F_{peak} , F_{mean} , and impulse were conducted using SPSS 12.0 for Macintosh (IBM, Inc., Chicago, IL). The data were checked for distribution normality and homoscedasticity with the Shapiro-Wilk and Levene tests, respectively. The intertrial comparison was performed using a repeated-measures one-way ANOVA (factor considered was SR with 4 levels: 60, 80, 100, and race pace frequency); pairwise comparisons were performed using a Bonferroni post hoc procedure. Correlations between variables were obtained using the Pearson moment correlation coefficient. For all tests, the level of significance was set at .05.

Results

The on-water force–time profiles for both groups changed in magnitude and shape with the increase in SR (Figure 1). The coefficient of variation of the force curve for females ranged from 19.55 at 60 spm to 42.78 at race pace, and for males from 25.08 at 60 spm to 44.90 at race pace. With increase in SR, the slope of the force–time curve at the beginning of the water phase increased (expressed by the decrease in the time to F_{peak}), and the time of force application decreased. For both groups, the force–time curves at race pace showed a first peak followed by a small drop before the main peak force. There was a significant intertrial correlation between the mean velocity and F_{peak} ($r = .663$, $P < .001$) and F_{mean} ($r = .804$, $P < .001$). The impulse values did not change significantly when performing an intertrial comparison ($F[3,40] = .09$, $P = .966$). However, the intratrial correlation showed that the higher mean

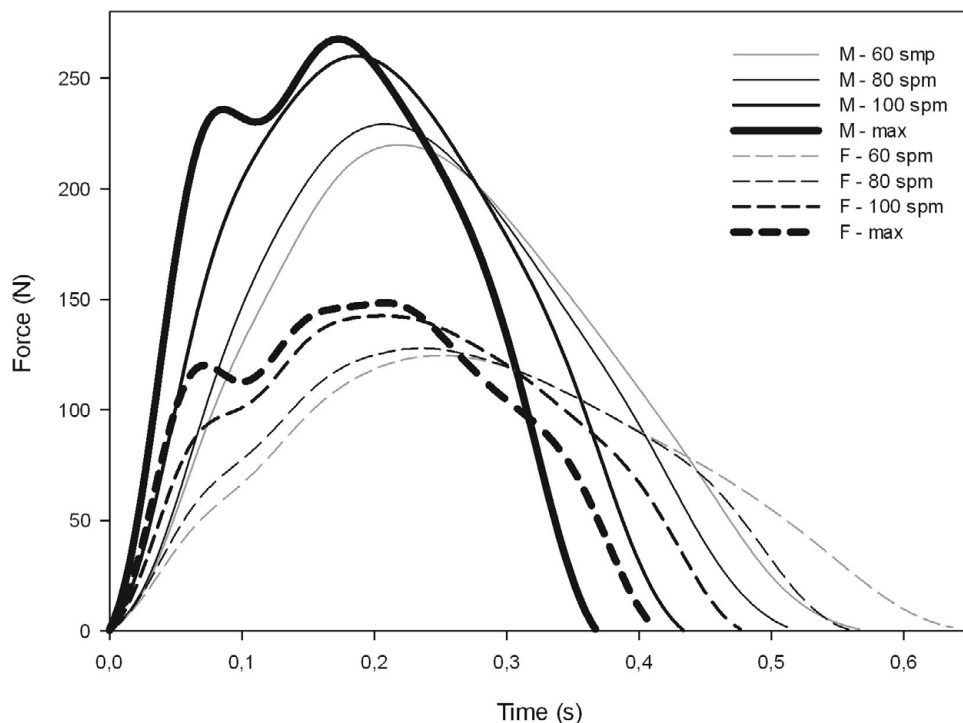


Figure 1 — Mean force–time curves for each sex and paddling stroke rate. Each data curve represents the mean normalized curve (270, 300, 330, and 360 strokes from both sides at 60, 80, and 100 strokes per minute [spm], and race pace [max], respectively). M = male; F = female.

velocities where obtained by the athletes who had higher mean impulses in each trial (60 spm, $r = .888, P < .01$; 80 spm, $r = .896, P < .001$; 100 spm, $r = .823, P > .01$; race pace, $r = .847, P < .01$).

Significant differences were observed between SRs for the $F_{\text{mean}}/F_{\text{peak}}$ ratio (highly significant between the 2 low SRs in analysis [60 and 80 spm] and the two higher SRs [100 spm and race pace]) (Table 2). The shape of the force–time profile, indicated by the $F_{\text{mean}}/F_{\text{peak}}$ ratio, became more rectangular with increasing SR ($F[3,40] = 7.87, P < .01$) and was positively correlated with mean velocity ($r = .416, P < .01$) (Table 2).

The time between the instant that the kayak started to decelerate and the end of the water phase expressed in percentage of the stroke duration decreased with increasing SR ($F[3,40] = 4.80, P = .008$). In addition, the observable characteristics of the force–time profile, together with the $F_{\text{mean}}/F_{\text{peak}}$ ratio, indicated a transition from a triangular to rectangular shape with increasing SR.

As the SR increased, there was a decrease in the duration of the water and aerial phases. When these phases were represented as a percentage of the stroke duration there was a tendency for the water phase to increase in relation to the aerial phase duration, for both sexes (Table 2; Figure 2). In addition, the duration of kayak acceleration increased as a percentage of the total stroke duration as SR increased.

There was a modest negative correlation between the $F_{\text{mean}}/F_{\text{peak}}$ ratio and the delay between the start of force application and the beginning of kayak acceleration ($r = -.453, P = .008$).

Discussion

The aim of this study was to analyze the paddling force profile and force–time curve variables at different SRs, and their implications for kayak performance. Although few studies have focused on paddle force analysis in kayaking, many authors have analyzed oar force in relation to technique in rowing, considering its importance in analyzing rowing technique.^{1,22–24} Variables related to the shape of the force profile, such as the area under the force curve (impulse) and the $F_{\text{mean}}/F_{\text{peak}}$ ratio, have been studied in rowing.^{5,21,22} Similarly, this type of analysis in kayaking has the potential to help kayak paddlers and coaches work toward successful performances.

The deformation of the paddle shaft was correlated with the force and its calculation considered that the pivot point of the paddle had been maintained in a position on the top hand (Equation 1). Although this assumption can overestimate the force produced during some part(s) of the water phase, it has been reported that elite kayak paddlers tend to maintain a high paddle pivot resulting

Table 2 The mean \pm SD for the paddling force–time curve variables for each sex and $F_{\text{mean}}/F_{\text{peak}}$ for the total sample

	Sex	Stroke Rate (spm)			
		60	80	100	Race Pace
Stroke rate (spm)	Male	63 \pm 5	81 \pm 3	99 \pm 6	124 \pm 7
	Female	60 \pm 3	79 \pm 6	100 \pm 6	112 \pm 3
Time to perform 200 m (s)	Male	54.35 \pm 2.29	47.85 \pm 2.00	43.67 \pm 1.88	38.68 \pm 0.83
	Female	61.35 \pm 0.95	53.76 \pm 1.73	48.08 \pm 2.36	44.94 \pm 1.21
Mean velocity 200 m (m·s ⁻¹)	Male	3.68 \pm 0.15	4.18 \pm 0.18	4.58 \pm 0.20	5.17 \pm 0.11
	Female	3.26 \pm 0.05	3.72 \pm 0.12	4.16 \pm 0.16	4.45 \pm 0.12
Water phase duration (s)	Male	0.56 \pm 0.03	0.50 \pm 0.04	0.43 \pm 0.03	0.37 \pm 0.03
	Female	0.64 \pm 0.03	0.55 \pm 0.02	0.48 \pm 0.01	0.43 \pm 0.02
Aerial phase duration (s)	Male	0.40 \pm 0.05	0.24 \pm 0.03	0.18 \pm 0.04	0.14 \pm 0.03
	Female	0.35 \pm 0.01	0.23 \pm 0.05	0.17 \pm 0.05	0.12 \pm 0.02
Time to F_{peak} (s)	Male	0.22 \pm 0.03	0.21 \pm 0.02	0.19 \pm 0.02	0.16 \pm 0.02
	Female	0.26 \pm 0.03	0.24 \pm 0.03	0.21 \pm 0.02	0.20 \pm 0.01
F_{peak} (N)	Male	225 \pm 31	234 \pm 32	266 \pm 33	274 \pm 35
	Female	126 \pm 11	130 \pm 8	146 \pm 7	153 \pm 11
F_{mean} (N)	Male	118 \pm 16	128 \pm 18	157 \pm 18 ^a	171 \pm 18
	Female	72 \pm 6	80 \pm 9	92 \pm 13 ^a	99 \pm 15
Impulse (N·s)	Male	66.3 \pm 7.3	63.9 \pm 7.3	67.7 \pm 9.5	63.2 \pm 8.4
	Female	46.5 \pm 5.9	44.1 \pm 5.5	44.2 \pm 6.3	42.3 \pm 6.6
$F_{\text{mean}}/F_{\text{peak}}$ ratio (%)	Total sample	53.3 \pm 3.3 ^{b,c,d}	57.2 \pm 3.9 ^{a,c,d}	61.0 \pm 3.8 ^{a,b,d}	64.8 \pm 3.7 ^{a,b,c}

Note. Male n = 5 and female n = 5. All analyzed for each stroke rate, mean \pm SD. spm = strokes per minute.

^a $P < .05$, significantly different to 60 spm.

^b $P < .05$, significantly different to 80 spm.

^c $P < .05$, significantly different to 100 spm.

^d $P < .05$, significantly different to race pace.

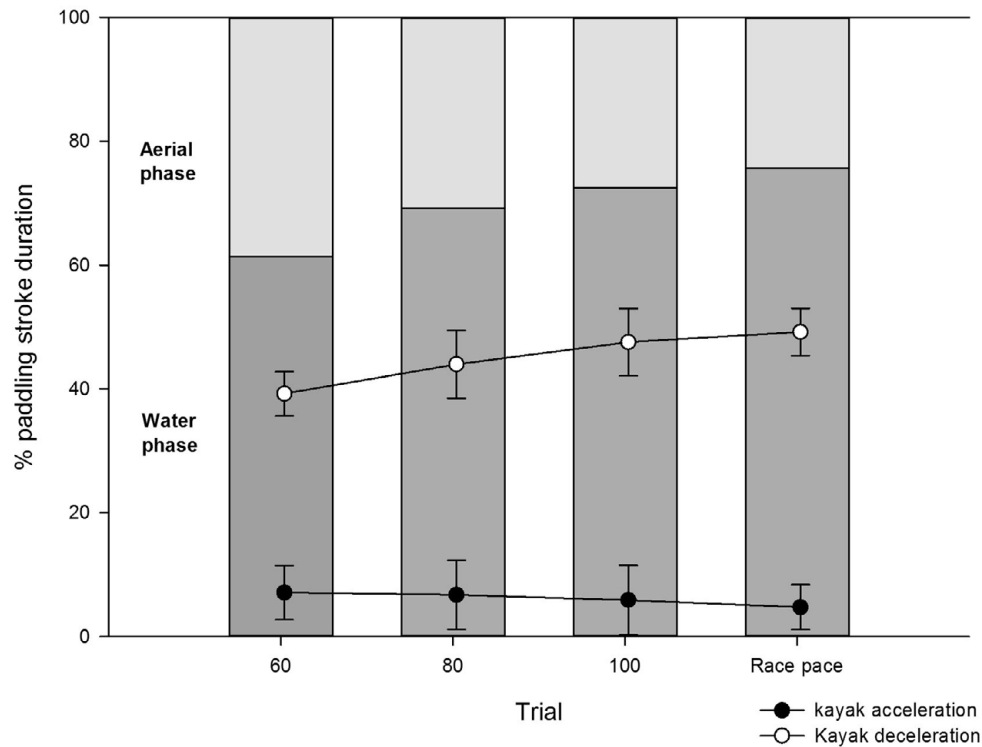


Figure 2 — Water and aerial phase durations, and the moment during the water phase when the kayak started to accelerate and decelerate. All are expressed as a percentage of the duration of a single stroke (means \pm SD).

from a restricted horizontal movement of the top hand and much of the bottom hand.²⁵

In this study, the $F_{\text{mean}}/F_{\text{peak}}$ ratio values increased with the increase in SR and mean velocity, indicating a change toward a rectangular force profile. This rectangular shape should be more efficient since it maximizes the area under the force–time curve for a given achievable F_{peak} , while minimizing the period of force application to enable a high SR. A high SR is known to be related to good performances in kayaking.^{10,25,26}

It was also observed that as the $F_{\text{mean}}/F_{\text{peak}}$ ratio values increased with the increase in SR, the delay between the start of force application and the beginning of the kayak acceleration decreased. This fact indicated a tendency for a vertical slope at the beginning of the water phase and a rapid achievement of the F_{peak} , considered to be an indicator of stroke efficiency.¹

Near the end of the water phase, the delay between the beginning of the kayak deceleration and the end of force application decreased with increasing SR. This result suggests that, at low SR, maintaining the blade on the water at the end of the water phase may slow down the kayak. The amount of force that is being produced in this section of the stroke seems that it is insufficient to overcome the increase in drag produced by the blade on the water.

For both sexes in the first 3 trials, the force–time curve had a bell shape. In the race pace trial, with the increased rate of force application, the athletes sought to increase the force rapidly and achieve a plateau early in the water phase. Creating a plateau on the top of the force–time curve maximizes the impulse for a given attainable F_{peak} and duration of water phase, and reflects the ten-

dency toward a rectangular profile of the force–time curve as a way to improve performances.²²

The force–time curve shape on the race pace trial was characterized by a first small peak, followed by a small decrease in force, and then followed by the main plateau. The decrease in force immediately after the initial rise may be, in part, explained by the elastic response of the paddle shaft due to its degree of stiffness, a response that probably starts when the kayak paddlers try to diminish the aerial phase duration, accelerating the paddle to reach the water as fast as possible. Increasing the stiffness of the paddle shaft may allow a more rapid force rise to the plateau and reduce the force ‘bounce’, so that a high force is maintained more constant without the small drop in force before the main plateau. Nowadays, paddle manufacturers provide paddle shafts with different degrees of stiffness and the athlete is responsible for choosing the one he/she thinks can get better performances. Paddling with different shaft stiffness should be investigated to understand the influence on paddling force shape. Even if it is found that an increase in shaft stiffness decreases the force ‘bounce’, further study will be required to determine the influence of stiffness on power development, muscle coordination, and injury risk.

The correlation between impulse and mean velocity in each SR trial was highly significant, expressing that, if the area under the force–time curve is increased and the SR maintained, the kayak velocity would increase. The mean velocity was strongly correlated with F_{mean} , more than F_{peak} . Different authors^{5,7} have suggested that the maintenance of force near the F_{peak} throughout the water phase is of greater importance to performance than the F_{peak} itself, since

the force pattern can vary from almost triangular to rectangular²² with the same F_{peak} .

Also contributing to the rectangular force profile was the fact that, with the increase in SR (representing a decrease in stroke duration), the slope at the beginning of the stroke increased even though the time to peak in percentage of the water phase duration increased due to the decrease in the water phase duration percentage after the F_{peak} . Therefore, as the SR increased and the kayak paddlers searched for higher performances, there was a decrease in the time spent in an ineffective part of the water stroke. A similar finding was observed by Kendal and Sanders¹¹ when analyzing the paddling technique of elite kayakers. Since the F_{peak} occurs near the time when the paddle is vertical,^{11,25} prolonging the water phase beyond that point is only valuable if the force can be maintained near the level of the peak force. Kendal and Sanders¹¹ found that a long paddle backward reach, although it contributes to longer water phases, does not result in a greater mean velocity and yields a profile that tends to be a triangular rather than rectangular shape. Thus, it is not surprising that in this study the athletes sought to remove the paddle shortly after achieving the vertical blade position to rapidly start the next stroke.

In summary, the results showed that the force profile becomes more rectangular in shape with increasing SR and performance. The results suggested that best performances are achieved when the F_{mean} is close to F_{peak} , that is, the $F_{\text{mean}}/F_{\text{peak}}$ ratio approaches 1.0, reflecting a rectangular shape.

The paddling technique plays a fundamental role in kayaking performance. Analysis of the force–time curve variables and force profile should be a prime objective in terms of technique analysis. In the current study, the force profile became more rectangular in shape with increasing SR. To obtain the rectangular force profile, the athletes need to take the paddle blade out of the water close to the instant when the propulsive forces are still close to the peak force, rather than prolonging the stroke during an inefficient part. This enables optimal propulsive impulse at high SRs. In addition, kayak paddlers should seek a rapid increase in force immediately after blade entry. This pattern should be sought when training at race pace and in competition.

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