ANALYSIS OF THE ON-WATER PADDLING FORCE PROFILE OF AN ELITE KAYAKER

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The purpose of this study was to develop a system (FPaddle system) to quantify the forces generated on each side of the kayak paddle (left and right), in the blades' plane of maximal force application and in other planes, and to gain more insights about the on-water paddling force profile and associated variables. Using the FPaddle system forces applied on the paddle by an elite female kayaker were measured. Results suggested that the use of strain gages on two different planes provides more detailed information about the forces applied on the paddle throughout the paddling stroke including the exit phase relatively to the used of strain gages only in the plane of maximal force application.

KEY WORDS: kayak, paddle, force measurement.

INTRODUCTION: The way the forces are applied at different stages of kayak paddling is a crucial factor with regard to optimising performance. Force measurement systems to quantify kayak on-water stroke force have been used by Aitken and Neal, 1992; Sperlich and Baker, 2002; and Sturm et al., 2010. The location of the strain gages on the paddle shaft was the same for the studies and assumed that the force of interest is the force that is perpendicular to the plane of the blade. However, the force produced and the component in the desired direction of travel depends on the pitch angle of the blade (variation of the angle of the blade plane to the flow) (Sanders & Kendal, 1992), and others variables such as blade shape and size (Usoskin cited in Hérnandez & Marcos, 1993).
According to Sperlich and Baker (2002) on-water force analysis allows the comparison of the athletes' results with established norms to indentify possible areas of improvement and monitoring year-to-year improvement. Analysis of the shape of the force curves can be used also for stroke error detection (differences in force curve shapes can indicate different technique faults).
The goal of this study was to develop a system to measure the forces generated on each side of the paddle (left and right) in the blades' plane of maximal force application and in other planes. A second aim was to gain more insights about the on-water paddling force profile and associated variables.

METHODS: A female subject (30 years old; 168,3 cm and 67,1 kg), 2009 world flatwater medallist, was tested using her kayak and paddle (wing blade type). To quantify forces generated during the paddling stroke the '*FPaddle'* system was developed. The system comprises of deformation sensors, a transducer, a transmitter and radio receiver, and signal processing software. The athletes' paddle was instrumented with four strain gages for composite materials (Micro-Measurements® & SR-4®) attached to each side of the paddle shaft. Two strain gages measured the strain on the shaft in the plane of the blade (SG-L). The other two strain gages were placed with their axis parallel to the longitudinal axis of the paddle shaft in a plane at 90º to the other two strain gages (SG-T). All the strain gages were on the paddle shaft at the same longitudinal position from the blades' tip, arranged in a quarter-bridge circuit (V-Link® Wireless Voltage Node – placed inside the kayak) and recording at a sampling rate of 512 Hz. During data collection the FPaddle was working in a wireless communication system and transferring in real time to the 3DM-GX2® Software Development Kit.

The experimental procedures were conducted in a 25 m indoor swimming pool. The athlete was instructed to perform the maximum number of strokes that the pool length allowed. Commencement of data collection coincided with a start signal that also signalled the paddler to commence paddling. Calibration of the strain gages was achieved by loading the paddle with masses (from 5 to 35 kg in 5 kg steps) at one grip position (normally used by the athlete) while supporting it in the centre of the paddle blade and at the grip on the opposite side. The process was performed for both paddle sides and for the four strain gages. Strong linear relationships were found between the force applied to the paddle and the change in resistance within the Wheatstone bridge for both sides and strain gages ($r=-1.00$, $p<0.00$).

Based on force data collected it was possible to visualize a detailed force profile for each paddle stroke as well as assessing the following variables from the SG-L: the peak force, the time taken to reach peak force and the time of contact of the paddle blade with the water. For the SG-T the analysis took into account the force profile during the on-water phases of the stroke and the highest value reached. All results are presented as mean±S.D..

RESULTS: The FPaddle system allowed the acquisition of real-time force data and its in-land visualization. The data were separated into 1st stroke (athlete started from a stationary position) and strokes performed on the left and on the right sides. The first part of the results' presentation is related to the data acquired from the strain gages positioned parallel to the maximum force plane (SG-L). As suggested by Sperlich and Baker (2002) the on-water force was analysed from two viewpoints, one concerned with the actual results that are produced (Table 1), and the other concerned with the shape analysis of the force curves (Figure 1).

Table 1
Intra-stroke performance description of the paddle force. Mean and SD data are presented for peak force, time to peak and wet time of paddle for left (n=3) and right sides (n=3) and for the start stroke (n=1), SG-L.

	1st Stroke	**Left Paddle**		**Right Paddle**	
		Mean	SD	Mean	SD
Peak force (N)	285.69	286.99	±6.17	303.35	±7.27
Time to peak (s)	0.68	0.36	±0.07	0.28	±0.08
Wet time of paddle (s)	0.84	0.68	±0.08	0.49	±0.09

In terms of force curve profile it is observable that the 1st stroke has a different shape compared with the strokes performed with the kayak in motion (Figure 1). After the start, the following strokes, both left and right, presented an initial rapid increase in force, probably due to the impact of the paddle blade on the water – when it reaches a 1st peak. However, after that, there was a decrease on force followed again by an increase and a plateau (Figure 1b,c). Subsequently, the force applied begun to decrease until the paddle exits the water. In each paddling side it was possible to observe a reduction in the paddling duration time due to the fact that paddling frequency was increasing.

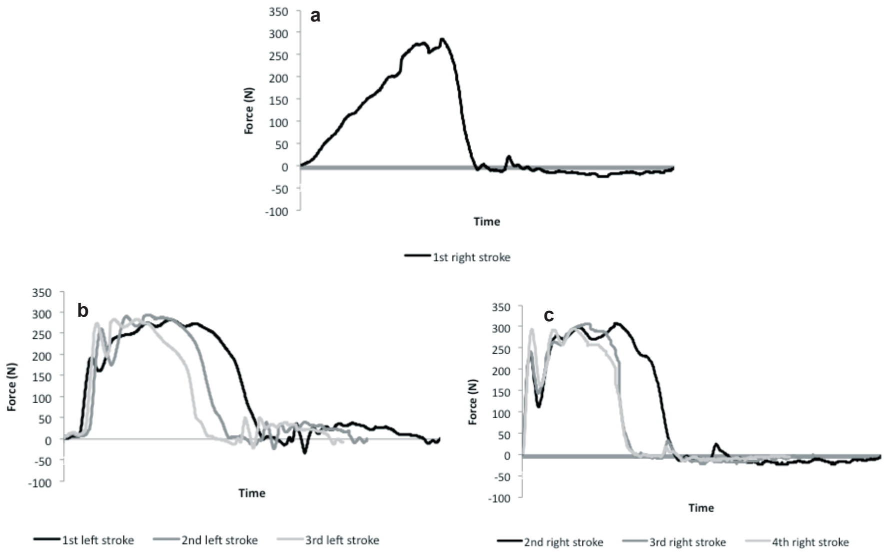

Figure 1: Force profile of the starting stroke (a) and three strokes in each side (left (b) and right (c)) by an elite female kayaker – SG-T.

In respect to the data collected from the strain gages positioned at 90º with the plane of maximum force application (SG-T) (Figure 2) it is observable that when the blade comes in contact with the water, there are applied forces that deformed the shaft towards the convex side of the blade (Figure 2a,b – dark line) and towards the rounded leading edge of the wing blade (Figure 2a,b – light line). Both strain gages reach their maximum deformation at approximately the same time. At the end, when the force values of the SG-L begun to target zero (it is being reach the paddling exit phase) there is observable a sudden change (the SG-T values go from negative to positive) in deformation in opposite direction of the rounded blade edge (Figure 2 – light line) representing the exit phase.

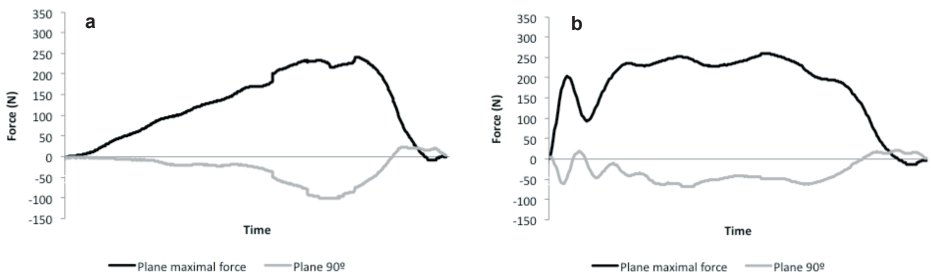

Figure 2: Force profile of two example strokes (on-water phases) with data from the SG-L and SG-T. Starting stroke (a) and a stroke performed with the kayak in movement (b).

DISCUSSION: the 1st stroke force curve shape is consistent with the starting technique used, since, in this stroke, the paddle blade was already in the water before the start. A force curve shape with two peaks has not been reported in previews studies. The differences may be due to the fact that the strokes analysed in the present study were collected during a kayak start, performed at maximum intensity and by an elite athlete. In the study by Aitken and Neal (1992) the mean peak force was around 200.6N and 213.5N for the left and right strokes respectively, compared with the present study were the values were higher and around

286.99N and 303.35N, respectively. The decrease in force immediately after the initial rise in both SG-L and SG-T may be explained in part by the elastic response of the paddle shaft due to its degree of stiffness. Also can be a response of the muscular mass that is accelerating the blade out of water to the time it reaches the water and finds higher resistance. This analysis has to take into consideration one of the study's limitation, the small sample size confined to an athlete, although an elite kayaker.

Due to the rounded leading edge on the wing blade, that according to Usoskin (cited in Hérnandez & Marcos, 1993) is exposed to high pressures in the concave side, applied force increases the perpendicular deformation (SG-T) as well as in the plane of maximum force application (SG-L). This fact is in keeping with the lateral motion that characterizes the paddling technique with a wing blade (Sanders & Baker, 1993).

The changes between negative and positive values in the deformation of the SG-T is also in line with the suggestions of Usoskin (cited in Hérnandez & Marcos, 1993) and Sanders and Kendal (1992) about the change of the pitch angle of the blade during the on-water displacement, changing the direction of force and pressure on the blade. Although, the introduction of the wing blade enabled a 'cleaner exit' that the earlier blades, i.e. when the paddler is withdrawing the blade at the end of the stroke he/she finds minimal forces counter to the desired direction of travel (Sanders & Baker, 1993), based on the present study, the results from the SG-T show that the highest counter forces during the exit phase were 20.56 $\pm$ 1.52 N. The highest value was obtained in the starting stroke (23.27 N). There is a lack of values from other studies with wing blades and even with laminate blades (blade shape prior to the wing) to confirm the greater efficiency of the wing blade on the exit phase and even to compare different shape and sizes of wing blades.

CONCLUSION: The development of the FPaddle system allowed the collection of paddling force with wireless data transmission to the investigators' bases. The use of strain gages on two different planes gave more detailed information about the forces applied on the paddle shaft and about the exit phase of the paddling stroke.

This analysis will be continued in order to analyse which paddling force profiles are associated with skilled performances. Moreover, combining this information with data from paddle blade position, could allow studying the mechanisms of generating force with a wing blade to explain the paddling propulsion on kayak including the relative contributions of drag or lift forces).

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