Experimental Analysis of Paddling Efficiency of Elite and Non-elite Athletes with Instrumented Canoe Sprint C1

Carlo Rottenbacher, Giovanni Mimmi, Alberto Ramponi

Department of Structural Mechanics, University of Pavia, Italy
E-mail: rottenbacher@unipv.it, mimmi@ unipv.it

Keywords: Biomechanics, Canoeing, Paddling performance, Training techniques.

SUMMARY. Canoeing is an on-water sport admitted by the International Canoe Federation (ICF) and Canoe Sprint became an Olympic discipline in 1936: its programme includes events over 200 m, 500 m and 1000 m. There are numerous Canoe events in single (C1), double (C2) and four (C4) boats. In this discipline the canoeist is kneeling on one knee, and uses a single-bladed flat paddle. In the same way as kayaking, canoeing is a sport whereby propulsion of the boat is derived mainly from muscle actions of the upper body. Conversely, the kneeling position of the canoeist influences the dynamic behaviour of the hull and the force stroke exerted by the single-bladed paddle results in augmented 'fluctuation' of the average speed, in greater roll angle and wider pitch span of the canoe with respect to the kayak boat. Besides, the flat shape of the paddle determines the particular paddling technique.

In canoeing high forces must be applied at high stroke rates and athletes are coached both in stroke technique and power or resistance training. Elite athletes stand out for the style and efficiency of the stroke, for power and resistance and for skills in the race strategy. Biomechanical measures of canoeing is an important asset to improve performance. In addition comparing results from test to test enables monitoring of an athlete's yearly, and year-to-year improvement. Finally, the experimental analysis of the main kinematical and dynamical parameters allows to examine the shape of the force curves for stroke error detection purposes and to reduce the ineffective hull movements. In this paper the performance and the paddling technique of two elite and two non-elite canoeists are presented by means of an on-water experimental apparatus. Moreover a comparison between the drive phase of the stroke in kayaking and canoeing is proposed.

The goals of this research project were to (1) develop a system for on-the-water measurement of paddling performance in kayaking and canoeing, (2) demonstrate the potential of such a system to quantify efficiency and then (3) compare the main kinematical and dynamical parameters of single K1 and C1 boats and the technique differences in paddling style.

1 INTRODUCTION

While a lot of research has been carried out on rowing biomechanics and many studies on biomechanical parameters and mechanical efficiency in kayaking already exist [1,2], to our knowledge no on-water canoeing experimental works are available in scientific literature.

The aim of this paper is to present the results of a preliminary study to detect the main kinetic and dynamic parameters related to the canoeing activity. On the basis of the experience gained over years with kayak paddlers members of club Canottieri Ticino, CUS Pavia and Idroscalo Club Milano, the authors applied the same methodology and a similar experimental apparatus to analyze the canoeing paddling technique, to refine training and to improve performance. In these form of racing the boats are similar but in kayaking the paddler is seated and uses a two-blade paddle while the canoeist is kneeling on one knee, and uses a flat single-blade paddle with a t-grip. Both kayaking and canoeing are sports whereby propulsion of the boat is derived mainly from muscle actions of the upper body. The different position adopted by the paddler in the two type of boats plays an important role in the dynamic behaviour of the hulls. Moreover the force stroke exerted by the single-bladed paddle results in augmented 'fluctuation' of the average speed, in greater roll angle and wider pitch span of the canoe with respect to the kayak boat. Finally, the different shape of the blades [3] in the two disciplines has important consequences in the paddling techniques and in particular in the catch and stroke-end phase of the active part of the paddling stroke.

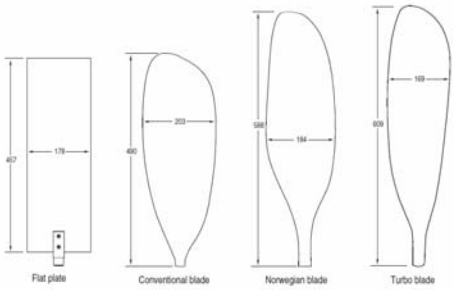


Figure 1: Different blade shapes in canoeing and kayaking (adapted from [3]).

Quantitative measurements of paddle forces during on-water [4,5] training offer a particularly suitable method to evaluate the techniques of paddling in realistic operative conditions.
The force applied to the paddle is the primary variable measured together with boat velocity and acceleration. On-water force analysis has two main functions though they complement each other. One function is concerned with the actual results that are produced, e.g. the peak force and impulse values. The data from on-water testing allows for an athlete to be compared against established standards for possible areas where improvements could be gained. In addition, comparing results from test to test enables the monitoring of an athlete's yearly, and year-to-year improvement. The second form of analysis uses the shape of the force curves for stroke error detection purposes and as such is mainly qualitative and can be joined by real-time video editing techniques. Since the shape of the curve can be related with the movement of the paddler and of the hull, different force curve shapes can indicate different technique faults.
A canoeing stroke can be summarized into 4 parts: 1-catch phase (immersion of the blade), 2-drive phase (propulsion or power), 3-exit phase (stroke end), 4- recovery phase (aerial preparation of the next stroke). Hence a stroke includes a propulsion (water phase) and an aerial phase and involves complex movements to accelerate and to direct the boat. The catch begins as advanced as possible with an angle of attack of the blade and the water surface of nearly 80°, with trunk flexion and a shoulder rotation. In case of a dexterous paddler, the right arm is completely stretched out while the left arm is partially inflected. The blade is fully immerged and the pulling action of the blade starts with a strong rotation of the shoulders that implies the right arm pulling and the left arm supplying a push power. The trunk extends and the pelvis is moved ahead to counteract the pulling movements that continue with the bending of the right arm. As the blade reaches the level of the left knee the propulsion is almost finished and the correction, or steering action, takes place. In fact due to the single-side paddling, the canoe would rotate leftwards; to avoid this, a 90°

rotation of the blade with its internal side turned aft (i.e to the stern of the canoe) is effected. In this way the blade acts as a rudder to adjust the direction of the hull with minimum resistance. In the same time the right knee pushes ahead to equilibrate the paddler-canoe system and, together with a trunk right shift, compensates the lateral overturning movement induced by the blade. (It is important to notice that, the experienced paddlers tend to substitute an outwards movement for this rotation of the blade). Finally the exit phase implies the shoulders rotation with a concurrent trunk extension while the wrists extra-rotation during the recovery phase allows the blade to get to the initial position at the start of the paddling cycle. This complex paddling technique is carried on and refined with a long lasting and continuous training by the canoeists. Moreover the effect of stroke rate on average velocity and on the application and the exertion of the force during the drive phase of the stroke cycle is strongly related to some paddling parameters such as the stroke length, the grip width and the angle of attack which is the angle at which the blade enters the water.
A quantitative methodology based on a stand alone on-water instrumentation and acquisition system allows the coaches and the athletes to better understand the mechanical principles underlying this particular paddling technique and to implement a more effective training method.

2 SUBJECTS, MATERIALS AND METHODS

2.1 *Subjects*

The tests were performed on 4 athletes of different experience: two national and international class canoeists and two juniores category paddlers recruited from CUS Pavia and trained by national-grade coach Antonio Mortara. The different levels of preparation allow to highlight the complex technique of paddling which requires the subject to be talented but also entails strong effort and continuous training.
The athletes in this study had no current episode of low back pain or any other serious illness or injury. All subjects were familiarized with the experimental device (instrumented boat and paddle and instrumentation system) through a warm up session.
The main anthropometric characteristics of the athletes involved are listed in Table 1.

Subject	**Age**	**Gender**	**Height [cm]**	**Mass [kg]**	**Dominant arm**	**Class**
F	**28**	**M**	**172**	**80**	**Right handed**	**International**
G	**18**	**M**	**170**	**78**	**Left handed**	**International**
H	**17**	**M**	**187**	**84**	**Right handed**	**Juniores**
I	**17**	**M**	**168**	**60**	**Right handed**	**Juniores**

Table 1: Anthropometric data.

2.2 *Boat and paddle*

A Plastex Dominator C1 canoe with an overall length 5200 mm, beam 380 mm and mass 15 kg was prepared for the tests, whilst two sprint paddles with different stiffness: Kajner Kenu Nyilas (10851) with t-grip (5727) and Bracsa Canoe 21.5 were instrumented with strain gauges to analyze the shape of the force curves exerted during the paddling.

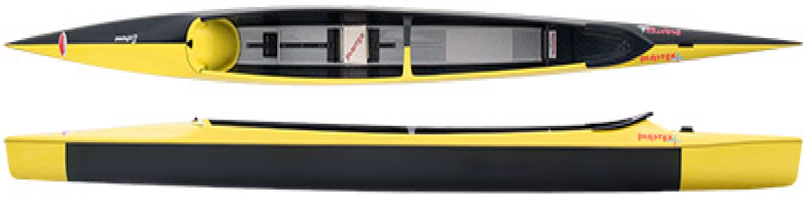


Figure 2: Plastex Dominator canoe.

Figure 3: Canoe paddle.

2.3 *Experimental apparatus and protocol*

The experimental tests were carried out to correlate different parameters such as the force exerted, the acceleration and hull speed of the boat during the warm up phase and during the simulation of the race pace over 200 m.

The experimental apparatus consists of:

- calibrated magnetic speed sensor to detect the on-water speed (Speedcoach).
- two half bridge strain gage sensors glued on the handle of the flat blade to measure the force and the centre of application of the force. In fact we assume that, similarly to the case of a kayak blade, the resultant of the reaction forces between the paddle and the water is directed orthogonal to the blade plane and consequently to the central axis of the bar, according to [5].
- Somat 2300 data acquisition system with bridge and analogic transducers module.
- Arduino module with three axial accelerometers and two gyros to measure the acceleration in the three main directions of the boat (longitudinal, transversal and vertical axis) and the angular velocity of the hull.

Moreover, in order to examine the muscular metabolism involved during the sprint race, lactate accumulation tests were also performed in collaboration with the Interdepartmental Research Centre of Biology and Sport Medicine of the University of Pavia – 'Salvatore Maugeri' Foundation.

Before participating to the tests the subjects were fully informed about the aim of the experimental study and gave their informed consent to the procedure. Each subject adhered to the following protocol:

- a warm up and adaptation phase
- 200 m sprint test at race pace.

Finally, the more experienced athlete F performed also a series of tests to compare two different paddles.

3 RESULTS AND DISCUSSION

The tests were repeated by the canoeists along the same portion of Ticino river upstream with a low running water (v < 0.5m/s).

3.1 *Stroke shape analysis and technique refinement in elite and non-elite athletes*

The first part of the experimental training session was devoted to the comparison of the stroke shape in athletes with different level of skill and expertise. In particular, the data analysis, by means of the on-purpose acquisition device, allows to detect and highlight the main differences in the water phase duration. In order to enhance the comparison, the curves are normalized with respect to the duration of each water phase; as depicted in Figure 4, the experienced athlete keeps the force till approximately the 70% of the stroke length and then rapidly pulls out the blade while the junior athlete, exerts a decreasing effort after the force peak at the beginning.

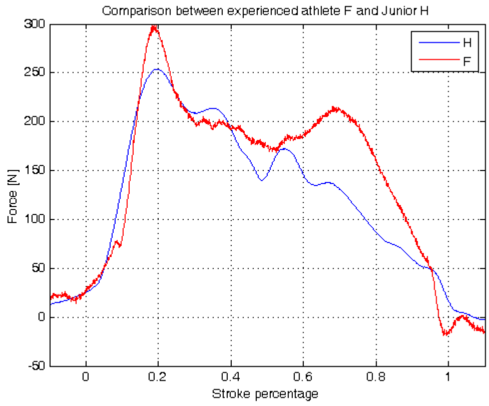


Figure 4: Normalized stroke shape comparison between experienced and junior athlete.

The main features of the stroke techniques in elite and non-elite canoeists can be summarized through the parameters listed in Table 2.

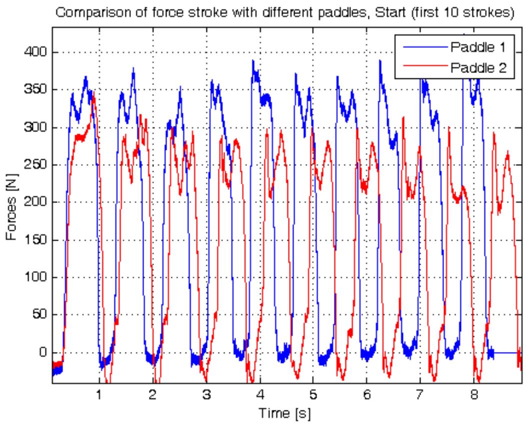
Athlete	Time [s]	Stroke rate (Sr) [spm]	%Water phase	Peak Force [N]	Power/Mass ratio [W/kg]	Velocity (V) [m/s]	(V/Sr)*100
F	**49,7**	**64**	**61**	**347**	**4.66**	**4,02**	**6,25**
G	**49,8**	**67**	**58**	**423**	**5.93**	**4.01**	**5.95**
H	**54,2**	**62**	**62**	**280**	**3.5**	**3.69**	**5.97**
I	**53,0**	**63**	**62**	**200**	**2.77**	**3.77**	**5.98**

Table 2: Main performances of the athletes.

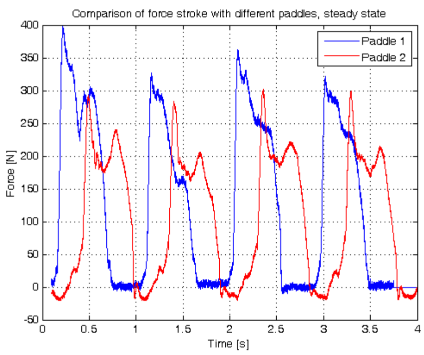
In particular the factor representing the ratio of the mean power over the subject’s mass (Power/Mass ratio) seems to indicate that a suitable physique to produce endurance, muscle, balance and coordination is a necessary asset but the elapsed time in the race simulation and consequently the velocity development by each athlete suggest the importance of a refined technique.

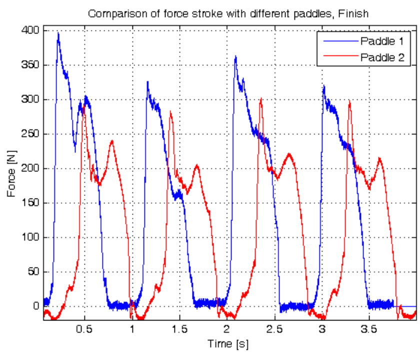
3.2 *Stroke shape in elite athlete with different paddles*

The experimental device was also tested to analyze the stroke shape with two different paddles. In order to enhance performance, in the last years coaches and athletes have sought for an improvement in the power of the stroke more than in the stroke rate; an increasing in stiffness of the paddle was the answer, but the new implements involve different paddling techniques. The athlete G performed a 200 sprint race with a classic paddle (Kajner, Paddle 2) and then, after a monitored rest, carried out the same test with a classic sprint stiffened paddle (Bracsa, Paddle 1). In Figure 5 the comparison of the two paddles during the test simulation is reported; the race time is divided into the three main phases: Start, steady state and Finish.



a)





b) c)

Figure 5: Stroke shape comparison between two different canoe paddles
a) Start phase (first 10 strokes), b) steady-state and c) Finish phase.

Figure 6 compares the normalized stroke force shape to enhance the differences; in particular it is evident the existence of a delay in the application of the peak force and the hollow in the central part of the classic paddle whilst the stiffened paddle (Paddle1) allows to reach the peak force at the very beginning of the water phase and permits a slow decreasing till the exit.

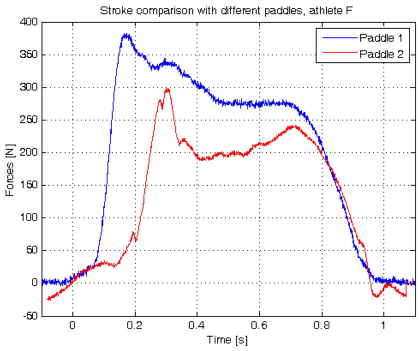
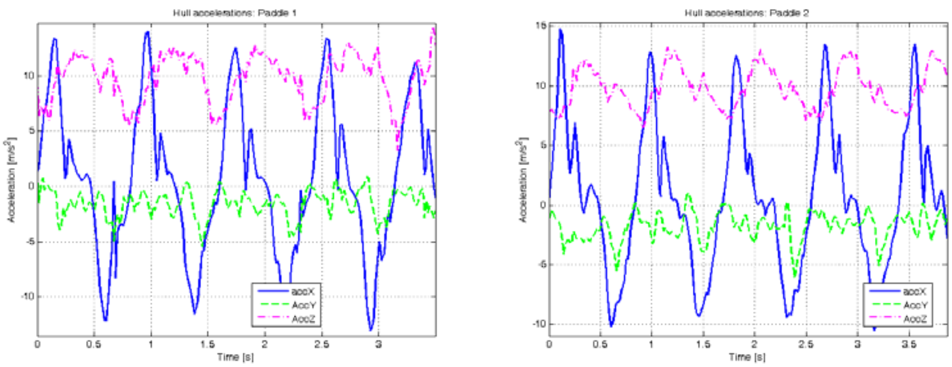


Figure 6: Normalized stroke shape comparison between two different canoe paddles.

The different attitude of the two paddles under test is also evident by the comparison shown in Figure 7 between the hull accelerations.



a) b)

Figure 7: Hull accelerations: athlete G, a) Paddle 1; b) Paddle 2.

3.3 *Stroke shape comparison: Canoe vs Kayak*

The different type of paddle (one-sided in canoeing and two-sided in kayaking) together with the different shape of the blades adopted in the two disciplines has important consequences in the paddling techniques and in particular in the catch and stroke-end phase, as reported in Figure 8. The comparison of the normalized drive phases, in case of canoe and kayak blade, highlights the difference in the catch and in the active part of the stroke: in particular in canoeing the main effort is produced in the initial part with a consequent slow decreasing of the exerted force until the 75% of the water phase and then a rapid exit of the blade occurs. Conversely a typical racing kayak stroke involves a second maximum peak (in which the very peak force is applied) around the 40-60% of the water phase and a consequent slower decrease.

Discipline	Time [s]	Stroke rate (Sr) [spm]	%Water phase	Peak Force [N]	Power/Mass ratio [W/kg]	Velocity (V) [m/s]	(V/Sr)*100
Canoa	**49,7**	**66**	**60**	**385**	**5.29**	**4,00**	**6,10**
Kayak	**40,2**	**137**	**80 (R+L)**	**436 (R+L)**	**5,29**	**4,98**	**3,63**

Table 3: Performances of canoeists (2 subjects) and kayakers (mean value over 5 subjects).

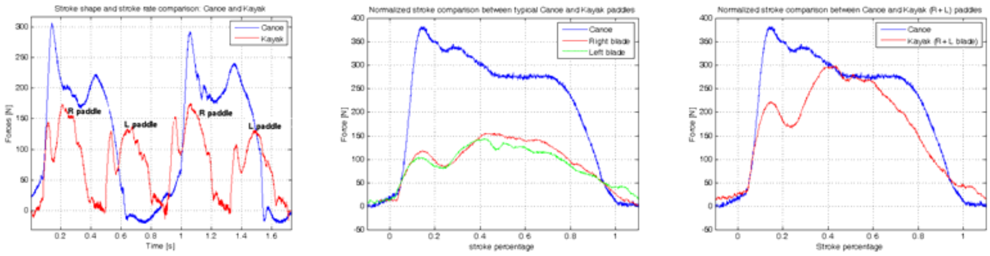
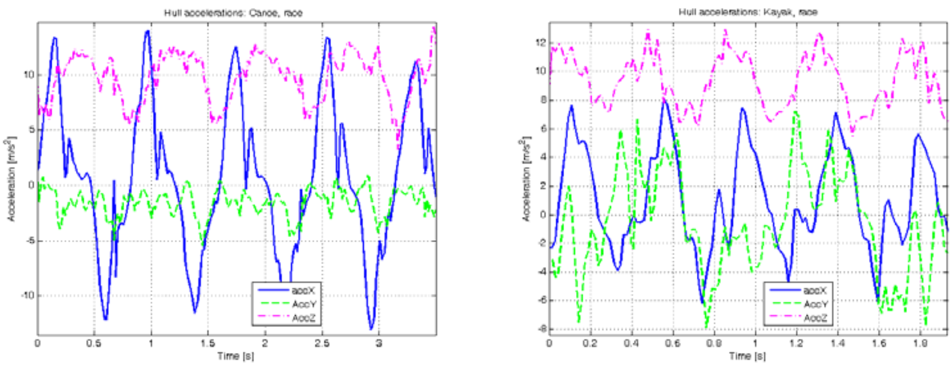


Figure 8: Stroke rate and normalized stroke shape comparison between typical canoe and kayak paddle.

The different position adopted by the canoeist (kneeling on one knee while the kayaker is seated) together with the single-bladed paddle results in augmented ‘fluctuation’ of the average speed, in greater roll angle and wider pitch span of the canoe with respect to the kayak boat. In particular, in Figure 9 the hull accelerations along the three main directions (x,y,z) are reported and compared.



a) b)

Figure 9: Hull accelerations: a) Canoe; b) Kayak.

4 CONCLUSIONS

In this paper experimental tests, performed by elite and non-elite athletes of C1 in training sessions along the same portion of Ticino river, are presented; the concise analysis of the stroke shape highlights the importance of a quantitative measurement of the athletic performance. A brief comparison between the different paddling techniques in canoeing and kayaking is also proposed.

The main kinematical and dynamical parameters involved are compared by means of instrumented boats and paddles with a stand-alone data acquisition system to detect forces, estimate position of the blade propulsion centre (EPPC), accelerations and hull speed of the boat.

Remark 1. For experimental testing to be effective and meaningful the sciences including biomechanics must have a sound systematic approach. There is a logical connection between race analysis, on-water testing, training evaluation and athlete's performance.

Remark 2. The low-cost on purpose experimental device tuned up for the tests has been proven to be effective for the on water measurements and paddling technique analysis.

Remark 3. This study, as a part of an extensive biomechanical research on paddling, will provide the theoretical rationale for coachers, elite and non elite canoeists to see the need to personalize their training methods and to refine their paddling technique on the basis of their actual own stroke force profiles.

Acknowledgments The authors whish to thank all who participated in this study and collaborated in the research.

References

[1] Sperlich, J., Baker, J., "Biomechanical testing in elite canoeing", in *Proc. XX International Symposium on Biomechanics in Sports*, Caceres, Extremadura, Spain, July 1-5, 2002.

[2] Kerwin, D., "Biomechanics, technology and coaching" in *Proc. XXVII International Symposium on Biomechanics in Sports*, Limerick, Ireland, July 17-21, 2009.

[3] Sumner, D., Sprigings, E.J., Bugg, J.D., Heseltine, J.L., "Fluid forces on kayak paddle blades of different design", *Sports Engineering* **6**, 11-20 (2003).

[4] Aitken, D., Neal, R "An on-water analysis system for qualifying stroke force characteristics during kayak events", *Int J Sport Biomech* **8**, 165-173 (1992).

[5] Rottenbacher, C., Bonandrini, G., Mimmi, G., "Evaluation of Paddling Performances through Force Acquisitions with a Specially Instrumented Kayak" in *Proc. of Aimeta 2007- XVIII Congresso di Meccanica Teorica e Applicata*, Brescia, September 11-14, 2007.