proceedings

Proceedings

A New Measurement System for Performance Analysis in Flatwater Sprint Kayaking †

Vincenzo Bonaiuto [1,*], Giorgio Gatta [2], Cristian Romagnoli [1,2], Paolo Boatto [3], Nunzio Lanotte [3,4] and Giuseppe Annino [1,5]

1 Sport Engineering Lab, Department Industrial Engineering, University of Rome Tor Vergata, I-00133 Rome, Italy; cristian.romagnoli2@unibo.it (C.R.); g_annino@hotmail.com (G.A.)
2 Department for Life Quality Studies University of Bologna, I-47037 Rimini, Italy, giorgio.gatta@unibo.it (G.G)
3 APLAB, I-00196 Rome, Italy; paolo.boatto@aplab.it (P.B.); nuziolanotte@aplab.it (N.L)
4 Department of Human Science and Promotion of Quality of Life, San Raffaele Open University of Rome, I-00166 Rome, Italy
5 School of Neuroscience, Faculty of Medicine and Surgery, University of Rome Tor Vergata, I-00133 Rome, Italy
* Correspondence: vincenzo.bonaiuto@uniroma2.it; Tel.: +39-06-7259-7402

† Presented at the 13th conference of the International Sports Engineering Association, Online, 22–26 June 2020.

Published: 15 June 2020

Abstract: The full comprehension of the impact with which each force is involved in kayak propulsion is very difficult. The measure of the force on the paddle or the stroke rate only is often not enough for the coach to identify the best actions useful to improve the performances of a kayaker. To this purpose, the synchronous measurement of all parameters involved in the kayak propulsion, both dynamic (force acting on paddle and foot brace) and kinematic (stroke frequency, displacement, velocity, acceleration, roll, yaw, and pitch of the boat) could suggest to the coach more appropriate strategies for better understanding of the paddler's motion and the relevant effects on the kayak behavior. Some simulation models, as well as measurement systems of increasing complexity, have been proposed in the recent years. In this paper, we present the e-Kayak system: A multichannel Digital Acquisition (DAQ) system specifically customized for flatwater kayaking. The system will be described in depth and its capability investigated through specific measurement results.

Keywords: Wireless Sensor Network; performance analysis; biomechanics; flatwater kayaking

1. Introduction

In flatwater sprint kayaking, fully comprehending the effectiveness of the paddling technique on the kayak's propulsion can be often very hard [1]. Kayaking is a cyclic sport, where the whole muscular kinetic chain of the athlete is involved to produce the forces that move the boat [2–5]. Moreover, different from rowing, where the force generated by the rower on the oar is transmitted to the hull through the oarlock, in kayaking the force exerted by the athlete to the paddle during the stroke is transmitted to the hull through his body itself via seat and footrest [6–8]. The kayaker, during the acceleration phase, has to generate propulsive forces greater than the resistive force offered by the water acting on the boat and, to a lesser extent, the resistance offered by the air. Furthermore, because the forces that the kayaker applies with the paddle act far from the axis of the craft, it is worth to note that each stroke will create a momentum, which will tend to turn the kayak [9]. Although these rotations are somewhat compensated for by the particular design of the hull, they also have to be balanced by the kayaker applying a force through the leg on the footrest on the active side. The same force can provide useful assistance to the kayaker in stabilizing the torso rotations that occur during each stroke movement. Consequently, a good paddling technique should be able to maximize the velocity and the forward acceleration, while minimizing all the other unnecessary rotations and accelerations along the axes of the boat. For this reason, only measuring the force on the paddle or the stroke rate is not enough for the coach to identify the findings that affect the paddling technique and to find the best actions to improve performance for this class of athletes [7,8,10,11]. For this purpose, to give the athlete useful suggestions in modifying his paddling technique, the coach has to investigate the effectiveness of it with respect to the resulting speed and the energy expenditure by the athlete. Therefore, he requires a DAQ (Digital Acquisition) system that allows the simultaneous measurement of the kinematics of the boat together with all the forces involved in the propulsion of the kayak: The forces exerted by the upper body musculature of the kayaker on the paddle and those applied by his legs on the footrest. In recent years, several simulation models [7–13], as well as electronic measurement systems specially designed for sprint kayaking [14–21], have been proposed in literature, or they are available on the market. Some of the measurement systems allow for the study of the force-time curves performed in laboratories on ergometers (non-specific conditions) or in specific race conditions (on water). Among them, some are provided by kinematic and others by dynamic sensors applied either on the boat or on the paddle or footrest. Therefore, most of these systems cannot simultaneously measure both kinematic and dynamic parameters and among these, only one has been designed for on water use [16].

In this paper, we present a new electronic measurement system suited for flatwater kayaking application. The system allows measuring both kinematic and dynamic parameters, allowing the coaches to study the propulsion of the kayak and support the athletes in improving their performance.

2. Materials and Methods

2.1. Measurement System

The e-Kayak system is a digital acquisition system based on the DAQuino [22–24]. This is a modular DAQ architecture composed of up to eight slave nodes connected to a master one via a high performance 2.4 GHz wireless link (ISM Band). Such a system is a versatile architecture, easily customizable for specific sport applications complying with the particular features required by coaches and researchers. The system hosts, inside the master node, a 9-axis IMU (Inertial Measurement Units) and a GPS (Global Positioning System), while force sensors have been applied on the paddle and footrest, the force sensors respectively hosted by two different slave nodes. Therefore, the system will be composed of a master node and pairs of slave nodes for each of the kayakers belonging to the crew of the boat. Figure 1 depicts a possible configuration of the system designed for a K2 boat (i.e., with two paddlers in the kayak).

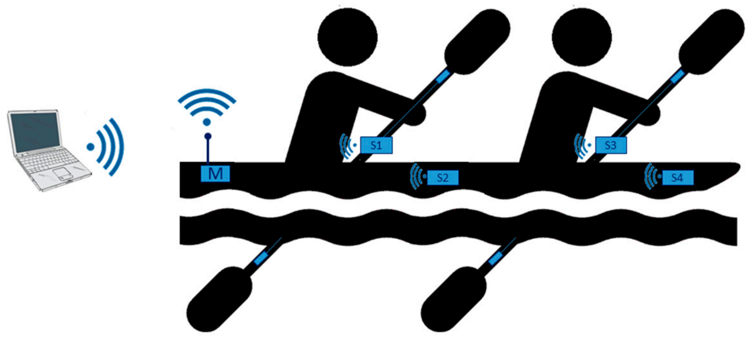

Figure 1. DAQuino configuration for K2 kayaking.

The master node is the core of the system. It has to manage the data collection from IMU and GPS (kinematic data) and by the sensors located on the slave nodes (dynamic data) and store them in a local digital memory. Moreover, by a simple webpage over a dedicated WLAN, the user is able to monitor a reduced set of parameters for an immediate feedback, download the whole training or race session, and verify the state of charge of the batteries on both master node and slave nodes. The GPS device (based on the Venus822A chip by Skytraq Technology Inc.) allows frequency update up to 50 Hz, and the IMU (based on the MPU 9250 by TDK Co.) a maximum sampling frequency of 50 Hz. The master node's weight is very limited (about 450 g); it can be easily compensated with an appropriate sizing of the ballast. The slave node for the measure of the deformation of the shaft has been designed to be installed inside it (weight 30 g only). A proper design allows its installation in a barycentric and unobtrusive position. The force sensor consists of four waterproof strain gauges (KFW-5-120—Kyowa) connected in Wheatstone full-bridge configuration. In particular, each pair of them has been placed, in the left and right side of the shaft, at a distance of 53 cm from the tip blades. The measure of the forces on the footrest is carried out by using the same strain gauges connected in a Wheatstone half-bridge configuration on the back of the footrest itself. The setup of the whole system requires a few minutes for positioning the master node on the boat and for the zero adjusting procedure of the IMU.

Strokes Number= 32.00
Delta Time= 30.74 s
Stroke Rate= 62.46
Mean Velocity= 3.67 m/s
Max Paddle Force= 81.60 N
Travelled Distance= 111.30 m

#	Peak Force	Mean Force	Wet Time	Air Time	TimeToPeak	Mean/Peak	Mean Acc	Force Impulse
1	69.60	52.45	0.34	0.34	0.00	75.35	0.79	17.83
2	72.00	52.89	0.54	0.36	0.20	73.46	1.08	27.50
3	73.20	57.70	0.52	0.32	0.16	78.82	1.36	28.85
30	76.80	51.89	0.52	0.52	0.20	67.56	1.17	25.94
31	73.20	51.41	0.52	0.52	0.14	70.23	1.22	25.70
32	74.40	52.96	0.48	0.00	0.14	71.18	1.22	24.36
Mean values	75.75	54.72	0.51	0.47	0.18	72.29	1.22	27.07
Dev Std	4.03	3.07	0.04	0.08	0.03	2.91	0.15	2.50

Figure 2. DAQuino: Example of report.

2.2. Methods and Data Analysis

The e-Kayak system has been tested on several training sessions and, in this paper, some measurement results on a female athlete (A written informed consent was obtained after familiarization and explanation of the benefit and risks involved in the procedures adopted. The study was approved by the Ethical Committee of the School of Sports and Exercise Science—University of Rome "Tor Vergata"—Faculty of Medicine and Surgery. Moreover, all the tests were carried out in accordance with the Declaration of Helsinki.) (age 24, height 163 cm, weight 67 kg) will be presented in order to highlight the capabilities offered by the system. These measurements have been collected during a training session of K1 boats in flat water, and some of them will be reported in this paper. The system has been installed on a NELO4 boat while a paddle BRACA-SPORT Mod. BRACA-IV has been equipped with the force sensors. Both the dynamic sensors and the kinematic ones from the IMU have been synchronously acquired at a sampling frequency of 50 Hz. The velocity and the distance have been measured through the GPS at the update frequency of 20 Hz that allows measuring the fluctuations of the velocity at each stroke (intra-cyclic velocity). The collected data have been analyzed using a custom program (Matlab R2018b by The MathWorks Inc., USA) used to automatically detect, by the analysis of the paddle force–time curves, the length of the strokes. The same software has been used for the computation of those parameters (i.e., time values and levels of force) that are commonly used by the coaches for the performance assessment.

3. Results

Figure 2 depicts the output report of the software that, in the first section, quotes some data of the trial under test as the number of strokes, the stroke rate, the mean velocity, and the displacement. Later, for each stroke, it has reported the peak and mean level of the force, the wet and recovery time, the time taken to reach the peak level of force, the ratio between the values of peak and mean force, the value of the mean acceleration during the peak, and the area of the force pulse.

Figure 3 depicts the force measured on the paddle (blue) versus the forward acceleration of the boat (orange). The measure of the forward acceleration acquired synchronously with the force impressed by the paddler is an interesting parameter in the assessing of the effectiveness of the paddling because it allows for evaluation of the progression of the boat in the presence of a possible imbalance between the left and right arm [6].

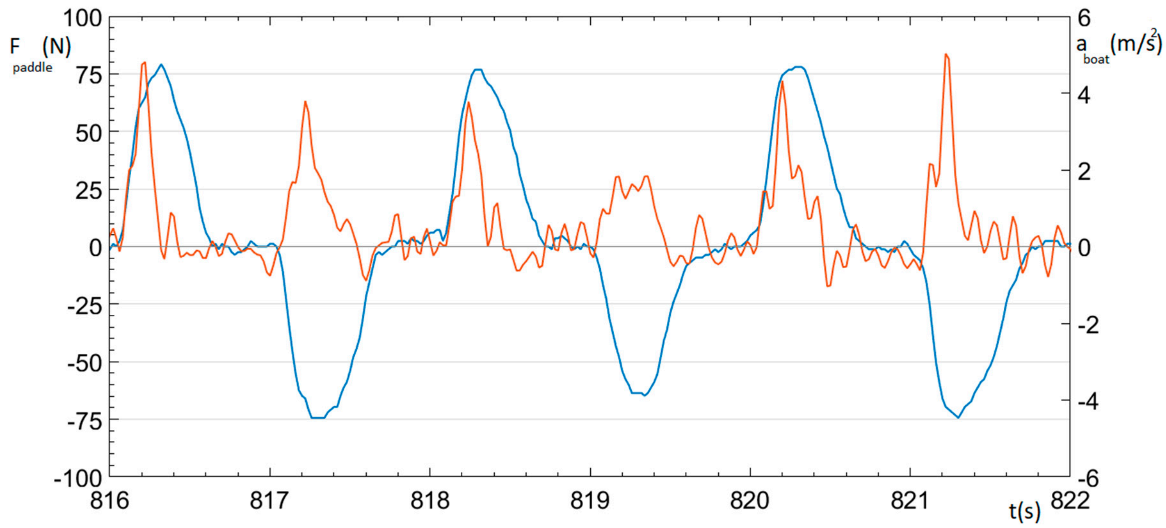

Figure 3. Boat's forward acceleration (orange) vs. force on the paddle (blue).

Figure 4 depicts the force measured on the paddle (blue) versus the velocity of the boat (orange). In particular, it depicts an acquisition of the first thirty seconds of a simulation of the start of a race. As you can see, it is possible to observe the increase, in the first part of the figure, of the velocity until it reaches the steady-state value.

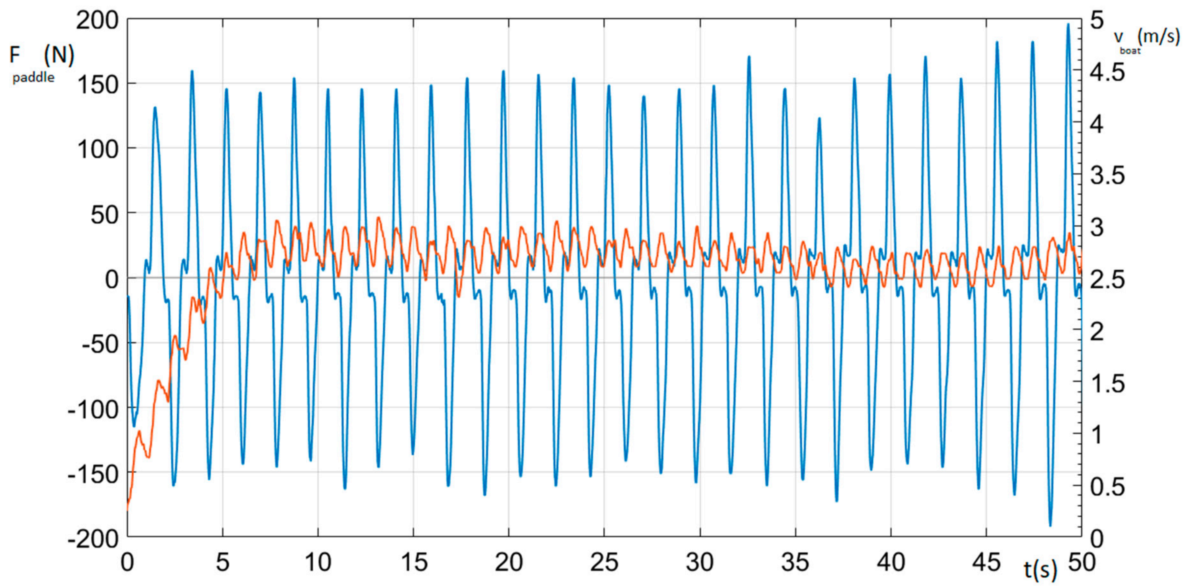

Figure 4. Boat's velocity (orange) vs. force on the paddle (blue).

4. Discussion

In Figure 3, the positive side of the curve represents the force exerted by the left arm while the negative represents that exerted by the right one. The forward acceleration curve (orange) results for most of the strokes are proportional to the force impressed. The subject shows a negligible imbalance in the force pulled on the paddle with a slight prevalence on the left side. When this unbalance is bigger, it will cause a rotation of the boat around its vertical axis, thus increasing the resistance to forward motion of the hull by affecting both surface and wave drag and, consequently, the forward acceleration presents a more noticeable reduction.

The mean velocity represents a fundamental appearance in the assessment of the propulsive effectiveness of the kayaker. The importance of investigating the synchronization and timing of the movements between the upper and lower body of the athlete in order to maximize performance has been widely reported in the literature. The exact timing between these movements to improve the effects of the paddling force is still debated among coaches.

The measure of velocity compared with the force signal (Figure 4) represents a useful key in the assessment of the effectiveness of the paddling technique, where the goal is to prove if it has been obtained an improvement in the velocity with the same amount of force exerted by the athlete. In particular, in the figure, you can note that the velocity, starting from zero, reaches the steady state after about 7 s. It is worth noting the fluctuant wave shape of the velocity inside each stroke (intra-cyclic velocity) increasing when the paddle force applied by the kayaker exceeds the drag force and, successively, falling down when, during the air phase, no force applied on the paddle has been measured.

5. Conclusions

In flatwater sprint kayaking, the paddler performances can be improved by a more effective paddling technique that consists of the improvement of the propulsive power together with a reduction of the water drag by a proper checking of yaw and roll. This paper presented the e-kayak system, a multichannel DAQ system suited for flatwater sprint kayak. The system manages the synchronous acquisition of both dynamic and kinematic parameters, allowing an accurate assessment of the paddling technique in specific training environment providing feedback to both athletes and coaches that is useful in supporting them to improve the knowledge of propulsion phases. Moreover, it allows us to highlight, quickly, several technical flaws, identify the best equipment and support, in K2 or K4, and provide helpful criteria for the selection of crews' members.

Acknowledgments: The authors wish to thank Guglielmo Guerrini for devising and initiating the project, Stefano Grillo at Circolo Canottieri Aniene for support in the tests, Giampiero Pastore and Dario Dalla Vedova and IMSS for providing logistic support and technical advice.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Gomes, B.; Viriato, N.; Sanders, R.; Conceição, F.; Vilas-Boas, J.P.; Vaz, M. Analysis of the on-water paddling force profile of an elite kayaker. In Proceedings of the ISBS-Conference Proceedings Archive, Porto, Portugal, 27 June–1 July 2011; Volume 1.
2. Vos, J.; Kimmich, H.; Mäkinen, J.; Ijsenbrandt, H.; Vrijens, J. Telemetry of dynamic forces in endurance sports. In *Proceedings of the Biotelemetry II*; Karger Publishers: Basel, Switzerland, 1974; pp. 106–108.
3. Aitken, D.A.; Neal, R.J. An On-Water Analysis System for Quantifying Stroke Force Characteristics during Kayak Events. *Int. J. Sport Biomech.* **1992**, *8*, 165–173.
4. Mimmi, G.; Rottenbacher, C.; Regazzoni, M. Evaluating paddling performances through force acquisitions with a specially instrumented Kayak ergometer. *J. Biomech.* **2006**, *39*, S543.
5. Logan, S.M.; Holt, L.E. Sports Performance Series: The flatwater kayak stroke. *Natl. Strength Cond. Assoc. J.* **1985**, *7*, 4–11.

6. Michael, J.S.; Rooney, K.B.; Smith, R.M. The dynamics of elite paddling on a kayak simulator. *J. Sports Sci.* **2012**, *30*, 661–668.
7. McDonnell, L.K.; Hume, P.; Nolte, V. A deterministic model based on evidence for the associations between kinematic variables and sprint kayak performance. *Sports Biomech.* **2013**, *12*, 205–220.
8. Kendal, S.J.; Sanders, R.H. The Technique of Elite Flatwater Kayak Paddlers Using the Wing Paddle. *Int. J. Sport Biomech.* **1992**, *8*, 233–250.
9. Limonta, E.; Squadrone, R.; Rodano, R.; Marzegan, A.; Veicsteinas, A.; Merati, G.; Sacchi, M. Tridimensional kinematic analysis on a kayaking simulator: Key factors to successful performance. *Sport Sci. Health* **2010**, *6*, 27–34.
10. Nakashima, M.; Kitazawa, A.; Nakagaki, K.; Onoto, N. Simulation to clarify the effect of paddling motion on the hull behavior of a single kayak in a sprint race. *Sports Eng.* **2016**, *20*, 133–139.
11. Nakashima, M.; Ito, S.; Nakagaki, K. Simulation of sprint canoe paddling. *Sports Eng.* **2019**, *22*, 1.
12. Nakashima, M.; Yamazaki, S.; Yue, J.; Nakagaki, K. Simulation analysis of paddling motions in a single kayak: Development of a comprehensive dynamic model of a paddler, paddle and hull. *Proc. Inst. Mech. Eng. Part P: J. Sports Eng. Technol.* **2014**, *228*, 259–269.
13. Harfield, P.; Halkon, B.; Mitchell, S.; Phillips, I.; May, A. A Novel, Real-time Biomechanical Feedback System for Use in Rowing. *Procedia Eng.* **2014**, *72*, 126–131.
14. Baker, J. Evaluation of biomechanic performance related factors with on-water tests. In *Proceedings of the* International *Seminar on Kayak-Canoe Coaching and Science*; University of Gent Press: Gent, Belgium, 1998; pp. 50–66.
15. Warmenhoven, J.; Cobley, S.; Draper, C.; Smith, R. Over 50 Years of Researching Force Profiles in Rowing: What Do We Know? *Sports Med.* **2018**, *48*, 2703–2714.
16. Gomes, B.B.; Ramos, N.V.; Conceição, F.A.; Sanders, R.; Vaz, M.A.; Vilas-Boas, J.P. Paddling Force Profiles at Different Stroke Rates in Elite Sprint Kayaking. *J. Appl. Biomech.* **2015**, *31*, 258–263.
17. Gomes, B.; Viriato, N.; Sanders, R.; Conceição, F.; Vaz, M.; Vilas-Boas, J.P. Analysis of single and team kayak acceleration. In Proceedings of the ISBS-Conference Proceedings Archive, Porto, Portugal, 27 June–1 July 2011; Volume 1.
18. Pelham, T.; Holt, L.; Burke, D.; Carter, A. Accelerometry for paddling and rowing. In Proceedings of the ISBS-Conference Proceedings Archive, Amherst, MA, USA, 23–26 June 1993; Volume 1.
19. Begon, M.; Colloud, F.; Lacouture, P. Measurement of contact forces on a kayak ergometer with a sliding footrest–seat complex. *Sports Eng.* **2009**, *11*, 67–73.
20. Sturm, D.; Yousaf, K.; Eriksson, M. A wireless, unobtrusive Kayak Sensor Network enabling Feedback Solutions. In Proceedings of the 2010 International Conference on Body Sensor Networks, Singapore, 7–9 June 2010.
21. Niu, L.; Kong, P.W.; Tay, C.S.; Lin, Y.; Wu, B.; Ding, Z.; Chan, C.C. Evaluating On-Water Kayak Paddling Performance Using Optical Fiber Technology. *IEEE Sens. J.* **2019**, *19*, 11918–11925.
22. Bonaiuto, V.; Boatto, P.; Lanotte, N.; Romagnoli, C.; Annino, G. A Multiprotocol Wireless Sensor Network for High Performance Sport Applications. *Appl. Syst. Innov.* **2018**, *1*, 52.
23. Bonaiuto, V.; Boatto, P.; Gatta, G.; Lanotte, N.; Romagnoli, C.; Annino, G. A Multipurpose DAQ System for Sports Applications. *Sport Eng.* **2020**, submitted.
24. Bonaiuto, V.; Gatta, G.; Romagnoli, C.; Boatto, P.; Lanotte, N.; Annino, G. A Pilot Study on the e-Kayak System: A Wireless DAQ Suited for Performance Analysis in Flatwater Sprint Kayaks. *Sensors* **2020**, *20*, 542.