Publisher: Taylor & Francis & European College of Sport Science
Journal: *European Journal of Sport Science*
DOI: 10.1080/17461391.2021.1930190

Whole-body kinematics during a simulated sprint in flat-water kayakers

Running head: Kinematics of sprint kayakers

Authors: Filippo BERTOZZI[1], Simone PORCELLI[2,3], Mauro MARZORATI[2],
Andrea M. PILOTTO[2,4], Manuela GALLI[5,6], Chiarella SFORZA[1,2,*], Matteo ZAGO[5,6]

Authors affiliations: [1]Department of Biomedical Sciences for Health, Università degli Studi di Milano, Milan, Italy; [2]Institute of Biomedical Technologies, National Research Council, Segrate, Italy; [3]Department of Molecular Medicine, University of Pavia, Pavia, Italy; [4]Department of Medicine, University of Udine, Udine, Italy; [5]Department of Electronics, Information and Bioengineering (DEIB), Politecnico di Milano, Milan, Italy; [6]E4Sport Lab, Politecnico di Milano, Milano, Italy.

ORCiDs and emails:
Filippo BERTOZZI: 0000-0003-2240-5394, filippo.bertozzi@unimi.it
Simone PORCELLI: 0000-0002-9494-0858, simone.porcelli@itb.cnr.it
Mauro MARZORATI: 0000-0003-1093-2162, mauro.marzorati@itb.cnr.it
Andrea M. PILOTTO: andrea.pilotto1@gmail.com
Manuela GALLI: 0000-0003-2772-4837, manuela.galli@polimi.it
Chiarella SFORZA: 0000-0001-6532-6464, chiarella.sforza@unimi.it
Matteo ZAGO: 0000-0002-0649-3665, matteo2.zago@polimi.it

MS # TEJS-2020-0350 submitted to the European Journal of Sport Science on March 27th, 2020; R1 October 20th, 2020

[*]Corresponding author:
Prof. Chiarella Sforza, MD
Dipartimento di Scienze Biomediche per la Salute, Università degli Studi di Milano
Via Mangiagalli 31, 20133, Milan, Italy
chiarella.sforza@unimi.it
phone +39 02 503 15385 - 15384
fax +39 02 503 15387

Abstract

Success in sprint kayaking depends on the propulsive power generated by trunk, pelvis, shoulder and lower limb movements. However, no studies have examined whole-body kinematics over a simulated distance. We aimed to study the changes in movement patterns of kayakers performing a 500-m kayak sprint. Eleven young K1 sprint kayakers (3 females; age: 16.5±1.9 years, height: 174.1±7.1 cm, weight: 66.1±6.2 kg) performed an incremental test on a kayak ergometer to assess their Peak Oxygen Uptake ($\dot{V}O_{2peak}$). They then performed a 500-m sprint trial on the same ergometer, and the positions of 40 reflective markers were recorded to assess whole-body kinematics. Joint angles over time were computed for the trunk and right shoulder, hip, knee, and ankle. Changes of joint kinematics during the test were assessed with Statistical Parametric Mapping, calculating at each time node the linear regression between joint angles waveforms and the time of the rowing cycle, $p<0.05$. Cardiometabolic responses confirmed that the participants achieved a maximal effort ($\dot{V}O_2$ and HR reached 99±11% and 94±6% of peak values, respectively). Paddle velocity negatively correlated with sprint time. The shoulder (elevation, rotation and flexion), trunk (lateral flexion and rotation) and hip (abduction) angles significantly changed over time in different phases of the stroke cycle during the simulated sprint. No significant differences over time were found for knee and ankle flexion. A high-intensity sprint may affect shoulder, trunk and hip kinematics of kayak paddling. The kinematic analysis of kayakers' paddling during simulated metabolic-demanding tasks can provide useful insights to coaches and athletes.

Keywords: paddling; ergometer; fatigue; statistical parametric mapping; movement patterns.

INTRODUCTION

Flat-water sprint kayaking is an Olympic sport whose objective is to complete the race in the shortest possible time. Male and female kayakers compete in K1, K2, or K4 categories, based on the number of athletes in each kayak. Races occur on a straight flat-water course over the distances of 200, 500, or 1000 meters. Success in sprint kayaking competition is primarily dependent on average velocity over the given distance (Hay & Kaya, 1998). Velocity depends both on propulsive power, generated by the active action of the kayaker on the water using the paddle, and passive drag, which slows the kayak down during a stroke cycle (Michael et al., 2009, 2012).

To generate and maintain the propulsive power, the kayak paddling technique involves the synergic action of the trunk, upper and lower limb muscles alternating right and left strokes in a cyclic manner (Begon et al., 2010). The flat-water kayaking stroke is an asymmetrical movement with one side being in a water phase, propelling the kayak, while the other side is in an aerial phase. Several studies have identified trunk, pelvis and shoulder kinematics as crucial for kayak propulsion during the paddling performance (Bjerkefors et al., 2019; Brown et al., 2011; Hamacher et al., 2018; Wassinger et al., 2011). However, researchers have also demonstrated that lower limbs kinematics must be taken into account as an influential factor for successful performance since they are not only a passive link with the kayak but instead they actively contribute to pelvis and trunk rotation through an alternated pedaling motion (Begon et al., 2010; Nilsson & Rosdahl, 2016).

Kinematic analysis of kayaking on water is mainly based on video analysis (Brown et al., 2011; Vaquero-Cristóbal et al., 2013). Although on-water investigations evaluate kayakers' performance in ecological settings, this approach has some methodological pitfalls and it is not as accurate as a motion capture system (Limonta et al., 2010). Moreover, it does not allow to evaluate kinematic changes of lower limbs, since they are hidden in the kayak deck (Begon et al., 2010). A useful way to better investigate the biomechanics of kayaking is to capture whole-body kinematics during simulated race conditions on sport-specific ergometers (Bjerkefors et al., 2018). Previous studies suggested that kayak ergometers can simulate the metabolic and cardiorespiratory demands of real on-water kayaking

(Begon et al., 2009; Fleming, Donne, Fletcher, et al., 2012; Gomes et al., 2012; Michael et al., 2012; Van Someren et al., 2000).

During sprint competitions, in which kayakers express an uninterrupted maximum effort to maintain high velocities, the impact of the development of muscle fatigue on the performance should be considered. Many studies focused on the evaluation of biomechanical key factors related to successful performance in kayaking (Brown et al., 2011; Kendal & Sanders, 1992; Limonta et al., 2010; López-Miñarro et al., 2012; McDonnell et al., 2012; Michael et al., 2009; Vaquero-Cristóbal et al., 2013), but, to date, little research has studied the time-course of whole-body kinematics during a simulated kayak race (Bjerkefors et al., 2018, 2019). Existing studies examined the kinematics during 20 stroke cycles, which only accounts for a few seconds of paddling. This approach has potentially overlooked kinematic changes caused by the onset of fatigue during a complete race.

The analysis of kinematics over time during a simulated race would provide important information to coaches and kayakers concerning fatigue-induced changes of joints angles. In young kayakers, it could also be useful to evaluate and correct the technique in a population critically influenced by biological maturation (Vaquero-Cristóbal et al., 2013; Zago et al., 2020). Therefore, we aim to study the evolution of whole-body kinematics of young kayakers performing a 500-m simulated kayak sprint carried out at maximal intensity, verified by the acquisition of physiological data, on a sport-specific ergometer. We hypothesize that the joint angles during the simulated sprint could change as a result of fatigue and in turn induce adaptations or compensatory strategies that would impact on performance and the risk of overuse injuries.

METHODS

The participants took part in two different experimental sessions: an incremental test to exhaustion to assess the Peak Oxygen Uptake ($\dot{V}O_{2peak}$) and a 500-m simulated sprint on a kayak ergometer. Whole-body kinematics of each participant was recorded over the sprint trial with a motion capture system and then analyzed to find changes in the movement patterns.

Participants

Eleven young K1 sprint kayakers (3 females; mean age: 16.5±1.9 years, mean height: 174.1±7.1 cm, mean weight: 66.1±6.2 kg) participated in the study. At the time of the test, participants were all members of the Canoeing and Kayak Italian Federation, and they had a training experience from 6 to 9 years and a training volume of 22±2 $h \cdot week^{-1}$. All participants competed in U16, Junior and U23 national championships, two participants competed also in U16 and Junior World Championships. They had no history of injuries or back pain which could have influenced their kayaking technique in the past years. All procedures were in accordance with the Declaration of Helsinki; the study was approved by the Institutional ethic committee (University of Milan, n. 19/17). All participants and/or their parents signed an informed consent in accordance with institutional ethical guidelines.

Procedures

Incremental test

The kayakers performed an incremental test to assess their Peak Oxygen Uptake ($\dot{V}O_{2peak}$). The test was carried out using a stationary kayak ergometer (SpeedStroke, KayakPro, USA). The kayakers individually adjusted their seat and footrest positions on the ergometer to simulate as closely as possible their usual kayak setup. Subsequently, they performed brief bouts of exercise to familiarize themselves with the equipment. After a few minutes of resting, participants performed a 3-min constant work rate exercise at low intensity (40/50 W). The work rate was then increased every minute (+15/20 W) managing stroke frequency and wind-braked flywheel resistance. The test was conducted to exhaustion and it terminated when participants were not able to maintain the stroke frequency required. A metronomic acoustic device helped kayakers to keep the selected paddling frequency. Vocal encouragement was allowed during the test to ensure high motivation (Pilotto et al., 2019). Pulmonary ventilation (VE), oxygen consumption ($\dot{V}O_2$), carbon dioxide output ($\dot{V}CO_2$) and respiratory exchange ratio (RER) were measured breath-by-breath by means of a metabolic cart (Vyntus CPX, CareFusion, Germany), which was calibrated before each measurement session. Heart rate (HR) values were obtained using a wearable HR monitor band (Polar A300, Finland). The gas exchange threshold (GET) was determined by two independent investigators by using the "V-slope" method and "secondary criteria" (Beaver et al., 1986). At rest and at various times (1, 3, and 5 min) into the recovery, 20 μL of capillary blood was obtained from the athlete's preheated earlobe for the determination of blood lactate concentration ($[La^-]_b$) by an enzymatic method (Biosen C-line, EKF, Germany); the analyzer was frequently calibrated with a standard solution containing 12 $mmol \cdot L^{-1}$ of lactate. After the exercise, participants provided a rating of perceived exertion (RPE, 6–20 Borg scale) (Borg, 1982).

Sprint trial

After at least 48 hours of recovery, kayakers performed a 500-m sprint trial on the same kayak ergometer. Before the sprint, participants warmed-up for 5 minutes on the ergometer and set all its regulations according to their usual kayak setup. During the trial, oxygen uptake and HR were recorded with the same procedures of the incremental test, as well as $[La^-]_b$ and RPE after the trial. During the sprint trial, the instantaneous positions of 40 passive reflective markers (tragi, forehead, 7th cervical spine, acromia, sternal manubrium; right and left lateral and medial humeral epicondyles, radius and ulna styloid processes, 3rd metacarpals, sacrum, posterior-superior and anterior-superior iliac spines, greater trochanters, lateral and medial femoral epicondyles, patella, tibia, lateral malleoli, calcanei, 1st and 5th metatarsal heads) were recorded at 60 Hz with a 9-camera optoelectronic motion capture system (SMART- E, BTS, Milano, Italy). Before each data acquisition, the calibration of the instrument was executed according to manufacturer's guidelines: a static calibration to define the global reference frame of the system, and a dynamic calibration to identify the acquisition volume, and the determination of camera internal parameters, through a minimization iterative process, with an accuracy of 0.35 mm. Moreover, markers coordinates were acquired for a few seconds in the anatomical position to calibrate the individual model.

Data processing

Markers' raw coordinates were interpolated and filtered at 10 Hz (Butterworth zero-lag, 2nd-order low-pass filter). The stroke cycles were defined as two consecutive draw and transition phases of right and left upper limbs, in this order (Fleming, Donne, & Fletcher, 2012). The first frame of each cycle (0%) was identified as the time point when the right ulna styloid process marker reached the maximum displacement in the anterior-posterior direction (the catch) with respect to the global coordinate system of the laboratory (Bjerkefors et al., 2018; McDonnell et al., 2012). The end of each cycle (100%) was set at the following catch of the same side. Stroke frequency was computed as the ratio between the number of strokes during the sprint and the total sprint time. Stroke duration was measured for each stroke cycle as the time between the initial and finale frames. Stroke length was defined as the horizontal displacement of the metacarpal marker, representing the contact point with the paddle, during each stroke cycle (Michael et al., 2012). Similarly, paddle velocity was estimated from the velocity of the metacarpal marker during the stroke cycle. After verifying no significant differences between sides, the right side was chosen as representative for joint kinematics. Local reference systems were created for arm, trunk, pelvis, thigh, shank and foot segments. Three-dimensional (3D) joint angles were computed for shoulder, trunk, and hip as the relative rotations of segments' local reference systems (Cardan ZYX convention). In particular, hip and trunk angles were computed as the relative rotation of thigh and trunk local coordinate systems relative to the pelvis segment; shoulder angles were computed as the rotation of the arm segment's local coordinate system relative to the trunk system. The knee and ankle joints were modelled as one degree-of-freedom hinge joints (thus computing sagittal-plane flexion and constraining abd/adduction and rotation), as the rotation of the shank segment relative to the thigh segment and the foot segment relative to the shank segment respectively. Kinematic data were extracted for the 11 to 20 cycles (thus following the stabilization of movement patterns), and for the last ten cycles of the sprint trial for each participant. Custom MATLAB (v2019a, Mathworks Inc., Natwick, USA) routines were developed for data analysis.

Statistical analyses

Shapiro-Wilk test confirmed that data were normally distributed. All measurements are presented as mean values and standard deviations (SD). Paired Student's *t*-test was used to compare differences in metabolic responses between the incremental test and the simulated sprint. An analysis of correlation with sprint time was performed for stroke duration, stroke length and paddle velocity. Changes of joint kinematics during the test were assessed with Statistical Parametric Mapping (SPM). SPM allows to analyze the entire 1D time-continuous curve, rather than arbitrary values, and draw inferential conclusions based on the random behavior of a 1D observational field composed by a set of time series (Pataky, 2010). The scalar output statistic, SPM{*t*}, was calculated at each time node for the linear 1D regression between the instantaneous joint angles and the time during the corresponding cycle. Statistical significance was set at 5%. Significant positive/negative correlation clusters (i.e. adjacent periods of significant correlation) indicate that the angle increased/decreased during the test.

In addition, to graphically represent joint kinematics change over time, line density plots were generated for each angle using all the available curves from every participant, following a procedure explained in (Gløersen et al., 2018): individual lines were color-coded according to the time the cycle occurred during the test, fading from green (beginning of the test) to red (end of the test), and mapped into a 101x300x3 RGB (red-green-blue) color matrix. The more an area of the plot is green/red, the more the curves (joints kinematics) in that area belong to the beginning/end of the test.

RESULTS

Metabolic data

Table 1 shows the metabolic data of the incremental test and the sprint trial. At the end of the incremental test, $\dot{V}O_{2peak}$ was 3.286±0.555 ($l \cdot min^{-1}$) and HR_{peak}, was 192±8 bmp. $[La^{-}]_{b}$ averaged 8.54±1.56 mmol/L and RPE was 17±1. Figure 1 depicts $\dot{V}O_2$, $\dot{V}CO_2$ and HR data for a representative participant during the incremental test.

At the end of the sprint trial $\dot{V}O_2$ and HR peaked 3.243±0.542 ($l \cdot min^{-1}$) and 180±11 bpm respectively. $[La^{-}]_{b}$ resulted 10.85±2.23 mmol/L and RPE 17±1.

The paired t-test showed no differences between the two tests in $\dot{V}O_{2peak}$, $\dot{V}CO_{2peak}$, VE_{peak} and RPE, while significant differences were found in HR_{peak}, $[La^{-}]_{b}$ and RER.

Kinematic data

The average duration of the sprint trial was 127.7±9.1 (s) and kayakers performed 128±7 stroke cycles with a frequency of 60±3 ($strokes \cdot min^{-1}$).

Figures 2 depicts the scatter plots between sprint time and stroke duration, stroke length, and paddle velocity respectively. No significant correlation was found for stroke duration ($p=0.257$, $r=0.03$), while stroke length ($p<0.001$, $r=-0.16$) and paddle velocity ($p<.001$, $r=-0.21$) showed a significant negative correlation with sprint time.

Whole-body kinematics during the stroke cycles are presented in Figure 3. For each analyzed joint and movement, vertical white lines indicate the periods of the stroke cycle where the joint range of movement (RoM) is significantly correlated with time according to SPM. At the end of the sprint, shoulder elevation movement decreased ($r=-0.38$) from 49% to 78% of the stroke cycle, and the joint was more externally rotated ($r=-0.39$) from 63% to 93%, and less flexed ($r=-0.26$) from 0% to 23%. There was a significant positive correlation for trunk lateral flexion ($r=0.26$, from 3% to 41%) and rotation ($r=0.26$, from 48% to 96%), meaning a more upright and less rotated position of the segment in the relevant periods during the last cycles. The flexion/extension movement showed no significant correlation with time. Hip abduction positively correlated with time from 0% to 40% (r=0.31) and negatively from 48% to 81% (r=-0.24) of the stroke cycle, meaning that the joint was more abducted in the first period and less abducted in the second. No significant correlations were found for hip rotation and flexion/extension movements, and for knee and ankle flexions in any period of the stroke cycle.

DISCUSSION

This study evaluated the time-course of movement patterns during a simulated kayak sprint. In recent years, several studies aimed to assess the effect of fatigue on the kinematics of various sport-specific tasks (Benjaminse et al., 2019; Zago et al., 2019). More specifically, a recent study presented the fatigue-induced kinematic changes in recreational rowers (Willwacher et al., 2020). However, to the Authors' knowledge, no previous study investigated the whole-body kinematic time-course during an uninterrupted kayak paddling task, performed on an ergometer at maximal intensity. Using SPM, data analysis was conducted on the whole time series for the cycles from 11 to 20 and the last ten, and not just on isolated, arbitrary parameters, thus reflecting the complete movement patterns during the paddling cycles and avoiding possible discarding of important data (Pataky, 2010). Results demonstrated that during the sprint joint kinematics significantly changed over time at shoulder (elevation, rotation and flexion), trunk (lateral flexion and rotation) and hip (abduction) levels. No significant changes in knee or ankle flexion angles were found during the time-course of the trial.

While stroke duration did not change during the sprint, stroke length and paddle velocity significantly decreased. In particular, paddle velocity is considered as an essential feature for kayak sprint performance, affecting the propulsive power and the whole kayak velocity (Michael et al., 2012). The kayakers, although with some inter-individual variations, decreased their paddling performance towards the end of the sprint. Acute fatigue induced by the high-intensity sprint may have caused this decrease in performance. However, differences in training and paddling techniques among kayakers could have caused individual adjustments in response to the accumulated fatigue.

The shoulder pattern resembled the results obtained by Bjerkefors et al. (2018). At the start of the pull phase of the right stroke, in correspondence to the maximal forward reach, the shoulder is elevated at more than 40°. Then, during the pull phase kayakers adducted the shoulder until half of the stroke cycle, when the abduction angle increased again during the pull phase of the contralateral side. SPM showed a decrement of the shoulder elevation at the end of the sprint from half of the cycle to about 80%. Indeed, when kayakers had performed several stroke cycles, the elevation of the right shoulder significantly decreased during the left stroke, with a maximal extent of about 10°. During the right stroke, shoulder rotation remained almost constant in the first half of the cycle, with a RoM of nearly 10°. During the left stroke a negative correlation with time was found and the angle increased, enhancing the internal rotation of the right shoulder. At the end of the sprint, during the pull phase of the left stroke, the right shoulder remained externally rotated, with a difference of about 10° relative to the beginning of the sprint test. Therefore, it seems that stroke repetitions, in association with elevated metabolic and cardiovascular demand, critically affected the normal patterns of shoulder elevation and rotation during the contralateral pull phase (Wassinger et al., 2011). Also for shoulder flexion a negative correlation was identified. At the end of the sprint, the right shoulder resulted less flexed in the first part of the stroke cycle (0-20%). This pattern, along with the reduced movement of the trunk at the end of the sprint, could lead to a less pronounced forward reach, significantly impairing the pull phase and, as a consequence, the propulsive power during the final stage of a sprint race. Moreover, Toohey et al. (2019) in a 3-year prospective study demonstrated that most sprint kayakers were susceptible to sustain more than one injury during the period of the study, with most injuries affecting the upper limbs and in particular the shoulder. Some studies suggested a possible relation of injuries with abnormal movement patterns and poor technique (Griffin et al., 2020; Lovell & Lauder, 2001; Michael et al., 2012); Wassinger et al. (2011) theorized a possible role of central and peripheral fatigue for this kind of injuries in kayakers. Abnormal shoulder patterns when fatigued can enhance the risk of injuries through the mechanical impingement of subacromial structures (Hagemann, 2004; Klich et al., 2019; Wassinger et al., 2011).

The trunk plays a dominant role in the sprint kayak technique (Brown et al., 2011; Hamacher et al., 2018; Limonta et al., 2010). Good trunk mobility can affect the overall performance since it is strictly related to the upper limb's capacity to produce propulsive power during the pull phase (Michael et al., 2009; Wassinger et al., 2011). Participants' trunk patterns were analogous to those previously found by Bjerkefors et al. (2018). We found that, towards the end of the test, kayakers increased the lateral flexion of the trunk in the ipsilateral side of the stroke. This could be interpreted as a consequence of the shoulder movement reduction in the same portion of the stroke cycle and confirmed the results found by Willwacher et al. (2020) in recreational rowers. Considering trunk rotation, a negative correlation during the final part of the cycle expresses the reduced rotation towards the right side just before the right catch and pull phase. A diminished RoM during this phase could impair the ability of kayakers to produce an optimal forward reach and propulsive power. Similar to the results of other studies (Bjerkefors et al., 2018, 2019), the trunk flexion exhibited the lowest RoM and no correlations with the time of exercise were found, demonstrating that the kayakers were accustomed to maintain a nearly stable trunk position in the sagittal plane.

The hip joint was analyzed given its substantial role in transferring the power output generated by lower limbs to the upper part of the body (Begon et al., 2010). Hip rotation and flexion, despite a moderate variability, showed no correlation with time. Therefore, we can presume no influence of the high-intensity exercise on these variables throughout the sprint. On the contrary, hip abduction showed two significant correlation clusters, one positive during the initial phase of the cycle and one negative in the second half after the left catch. As well as for trunk lateral flexion, and being strictly related to this movement, we hypothesize that an increased abduction during the final cycles of the trial could help to compensate for the reduced contribution of upper limbs during the pull phase.

We found no significant correlation for knees and ankle flexion. Despite the importance of lower limbs' contribution for sprint performance, accounting for approximately 20% to the stroke force (Nilsson & Rosdahl, 2016), it seems that fatigue in the simulated sprint did not affect these movement patterns. This could be because the sprint task was performed on an ergometer where lower limbs, although linked to a closed kinetic chain, were not strictly tied to the footrest as in a kayak.

Overall, shoulder, trunk and hip joints show modified movement patterns towards the end of the sprint. These changes may have a relationship with the paddling performance since kayakers, despite inter-individual differences, seemed to reduce the paddle velocity in the last stroke cycles.

The results of the incremental test confirmed that the kayakers reached exhaustion at the end of the protocol. Participants' $\dot{V}O_{2peak}$ reached high values, underlining optimal levels of cardiorespiratory fitness; the heterogeneity of the sample, composed by kayakers of both sexes, could explain the variability of this parameter. RER exceeding the 1.10 cut-off (1.13±0.04), HR_{peak} and $[La^-]_b$ over 8 mM at the end of the test, confirmed the exhaustion at both central and peripheral levels (Midgley et al., 2007). Moreover, since the kayakers provided a post-test RPE score higher than 17, also high levels of subjective fatigue were achieved.

The cardiometabolic data obtained at the end of the sprint trial show that the task seems to be in line with the high-intensity profile of a real sprint race (Borges et al., 2015). $\dot{V}O_2$ and HR values, along with physiological indexes, RER higher than 1.10 and $[La^-]_b$ close to 10 mM, and subjective RPE higher than 17, indicate that kayakers performed the sprint near to their maximal performance capability. Indeed, no significant differences were found with respect to the incremental test in $\dot{V}O_2$, $\dot{V}CO_2$, VE and RPE confirming the maximal intensity. Instead, the differences in HR and $[La^-]_b$, although they reached fairly high values, could be due to the different protocols of the two tests, influencing the heart rate and blood lactate accumulation over time. Therefore, also considering the decrease of paddle velocity, we can reasonably hypothesize that kayakers developed fatigue at the end of the sprint.

Despite interesting results and possible implications, some limitations have to be addressed. The heterogeneity of the sample could have influenced data variability, exhibiting the plausible differences of young kayakers paddling technique. Since the findings are based only on 500-m sprint, future studies should aim to evaluate time-course kinematics changes over different distances. Moreover, the present study is based on procedures on a kayak ergometer. Although ergometers may replicate the metabolic demands of the sport, the laboratory represents a less ecological environment compared to an on-water race and the movement patterns on-water may be different.

CONCLUSION

This is the first study, to our knowledge, investigating the time-course of whole-body kinematics variables related to flat-water paddling during a simulated sprint race in young kayakers. By analyzing the whole kinematic time series at the beginning and at the end of the sprint, we identified differences in shoulder, trunk, and hip angles at specific periods of the stroke cycle. In contrast, lower limbs showed no changes over time of the sprint. Moreover, paddle velocity decreased over time indicating a possible performance reduction towards the end of the sprint. These results suggest that cardiovascular and metabolic demand during a high-intensity exercise may affect shoulder, trunk and hip kinematics of kayak paddling. This information can be helpful for coaches in understanding the effect of fatigue on joint angles during a race, suggesting them to focus on these technical movements during paddling to prevent a performance decrease when kayakers perform a metabolic-demanding task.

ACKNOWLEDGEMENTS

The Authors reported no potential conflict of interest.

The Authors are grateful to the “Circolo Sestese Canoa e Kayak” Team for the availability and to the athletes who participated in the study.

REFERENCES

Beaver, W. L., Wasserman, K., & Whipp, B. J. (1986). A new method for detecting anaerobic threshold by gas exchange. *Journal of Applied Physiology*, *60*(6), 2020–2027. https://doi.org/10.1152/jappl.1986.60.6.2020

Begon, M., Colloud, F., & Lacouture, P. (2009). Measurement of contact forces on a kayak ergometer with a sliding footrest–seat complex. *Sports Engineering*, *11*(2), 67–73. https://doi.org/10.1007/s12283-008-0011-2

Begon, M., Colloud, F., & Sardain, P. (2010). Lower limb contribution in kayak performance: Modelling, simulation and analysis. *Multibody System Dynamics*, *23*(4), 387–400. https://doi.org/10.1007/s11044-010-9189-8

Benjaminse, A., Webster, K. E., Kimp, A., Meijer, M., & Gokeler, A. (2019). Revised Approach to the Role of Fatigue in Anterior Cruciate Ligament Injury Prevention: A Systematic Review with Meta-Analyses. *Sports Medicine*, *49*(4), 565–586. https://doi.org/10.1007/s40279-019-01052-6

Bjerkefors, A., Rosén, J. S., Tarassova, O., & Arndt, A. (2019). Three-dimensional kinematics and power output in elite para-kayakers and elite able-bodied flat-water kayakers. *Journal of Applied Biomechanics*, *35*(2), 93–100. https://doi.org/10.1123/jab.2017-0102

Bjerkefors, A., Tarassova, O., Rosén, J. S., Zakaria, P., & Arndt, A. (2018). Three-dimensional kinematic analysis and power output of elite flat-water kayakers. *Sports Biomechanics*, *17*(3), 414–427. https://doi.org/10.1080/14763141.2017.1359330

Borg, G. A. V. (1982). Psychophysical bases of perceived exertion. *Medicine and Science in Sports and Exercise*, *14*(5), 377–381. https://doi.org/10.1249/00005768-198205000-00012

Borges, T. O., Dascombe, B., Bullock, N., & Coutts, A. J. (2015). Physiological Characteristics of Well-Trained Junior Sprint Kayak Athletes. *International Journal of Sports Physiology and Performance*, *10*(5), 593–599. https://doi.org/10.1123/ijspp.2014-0292

Brown, M. B., Lauder, M., & Dyson, R. (2011). Notational analysis of sprint kayaking: Differentiating between ability levels. *International Journal of Performance Analysis in Sport*, *11*(1), 171–183. https://doi.org/10.1080/24748668.2011.11868538

Fleming, N., Donne, B., & Fletcher, D. (2012). Effect of Kayak Ergometer Elastic Tension on Upper Limb EMG Activity and 3D Kinematics. *Journal of Sports Science & Medicine*, *11*(3), 430–437. http://www.ncbi.nlm.nih.gov/pubmed/24149350

Fleming, N., Donne, B., Fletcher, D., & Mahony, N. (2012). A biomechanical assessment of ergometer task specificity in elite flatwater kayakers. *Journal of Sports Science & Medicine*, *11*(1), 16–25. http://www.jssm.org

Gløersen, Ø., Myklebust, H., Hallén, J., & Federolf, P. (2018). Technique analysis in elite athletes using principal component analysis. *Journal of Sports Sciences*, *36*(2), 229–237. https://doi.org/10.1080/02640414.2017.1298826

Gomes, B. B., Mourão, L., Massart, A., Figueiredo, P., Vilas-Boas, J. P., Santos, A. M. C., & Fernandes, R. J. (2012). Gross efficiency and energy expenditure in kayak Ergometer exercise. *International Journal of Sports Medicine*, *33*(8), 654–660. https://doi.org/10.1055/s-0032-1301907

Griffin, A. R., Perriman, D. M., Neeman, T. M., & Smith, P. N. (2020). Musculoskeletal Injury in Paddle Sport Athletes. *Clinical Journal of Sport Medicine*, *30*(1), 67–75. https://doi.org/10.1097/JSM.0000000000000565

Hagemann, G. (2004). Shoulder pathoanatomy in marathon kayakers. *British Journal of Sports Medicine*, *38*(4), 413–417. https://doi.org/10.1136/bjsm.2002.003699

Hamacher, D., Krebs, T., Meyer, G., & Zech, A. (2018). Does local dynamic stability of kayak paddling technique affect the sports performance? A pilot study. *European Journal of Sport Science*, *18*(4), 491–496. https://doi.org/10.1080/17461391.2018.1435726

Hay, J. G., & Kaya, M. (1998). *Stroke length, Stroke rate and boat speed in flatwater sprint kayaking and canoeing, Report to U.S. Olympic Committee and U.S. Canoe and Kayak Team*.

Kendal, S. J., & Sanders, R. H. (1992). The Technique of Elite Flatwater Kayak Paddlers Using the Wing Paddle. *International Journal of Sport Biomechanics*, *8*(3), 233–250. https://doi.org/10.1123/ijsb.8.3.233

Klich, S., Pietraszewski, B., Zago, M., Galli, M., Lovecchio, N., & Kawczyński, A. (2019). Ultrasonographic and Myotonometric Evaluation of the Shoulder Girdle After an Isokinetic Muscle Fatigue Protocol. *Journal of Sport Rehabilitation*, 1–6. https://doi.org/10.1123/jsr.2019-0117

Limonta, E., Squadrone, R., Rodano, R., Marzegan, A., Veicsteinas, A., Merati, G., & Sacchi, M. (2010). Tridimensional kinematic analysis on a kayaking simulator: Key factors to successful performance. *Sport Sciences for Health*, *6*(1), 27–34. https://doi.org/10.1007/s11332-010-0093-7

López-Miñarro, P. A., Muyor, J. M., & Alacid, F. (2012). Influence of hamstring extensibility on sagittal spinal curvatures and pelvic tilt in highly trained young kayakers. *European Journal of Sport Science*, *12*(6), 469–474. https://doi.org/10.1080/17461391.2011.575476

Lovell, G., & Lauder, M. (2001). Bilateral Strength Comparisons among Injured and Noninjured Competitive Flatwater Kayakers. *Journal of Sport Rehabilitation*, *10*(1), 3–10. https://doi.org/10.1123/jsr.10.1.3

McDonnell, L. K., Hume, P. A., & Nolte, V. (2012). An observational model for biomechanical assessment of sprint kayaking technique. *Sports Biomechanics*, *11*(4), 507–523. https://doi.org/10.1080/14763141.2012.724701

Michael, J. S., Rooney, K. B., & Smith, R. M. (2012). The dynamics of elite paddling on a kayak simulator. *Journal of Sports Sciences*, *30*(7), 661–668. https://doi.org/10.1080/02640414.2012.655303

Michael, J. S., Smith, R., & Rooney, K. B. (2009). Determinants of kayak paddling performance. *Sports Biomechanics*, *8*(2), 167–179. https://doi.org/10.1080/14763140902745019

Midgley, A. W., McNaughton, L. R., Polman, R., & Marchant, D. (2007). Criteria for determination of maximal oxygen uptake: A brief critique and recommendations for future research. *Sports Medicine*, *37*(12), 1019–1028. https://doi.org/10.2165/00007256-200737120-00002

Nilsson, J. E., & Rosdahl, H. G. (2016). Contribution of leg-muscle forces to paddle force and kayak speed during maximal-effort flat-water paddling. *International Journal of Sports Physiology and Performance*, *11*(1), 22–27. https://doi.org/10.1123/ijspp.2014-0030

Pataky, T. C. (2010). Generalized n-dimensional biomechanical field analysis using statistical parametric mapping. *Journal of Biomechanics*, *43*(10), 1976–1982. https://doi.org/10.1016/j.jbiomech.2010.03.008

Pilotto, A. M., Rasica, L., Scalise, G., Annoni, S., La Torre, A., Marzorati, M., & Porcelli, S. (2019). New On-Water Test for the Assessment of Blood Lactate Response to Exercise in Elite Kayakers. *Medicine and Science in Sports and Exercise*, *51*(12), 2595–2602. https://doi.org/10.1249/MSS.0000000000002077

Toohey, L. A., Drew, M. K., Bullock, N., Caling, B., Fortington, L. V., Finch, C. F., & Cook, J. L. (2019). Epidemiology of elite sprint kayak injuries: A 3-year prospective study. *Journal of Science and Medicine in Sport*, *22*(10), 1108–1113. https://doi.org/10.1016/j.jsams.2019.06.002

Van Someren, K. A., Phillips, G. R. W., & Palmer, G. S. (2000). Comparison of physiological responses to open water kayaking and kayak ergometry. *International Journal of Sports Medicine*, *21*(3), 200–204. https://doi.org/10.1055/s-2000-8877

Vaquero-Cristóbal, R., Alacid, F., López-Plaza, D., Muyor, J. M., & López-Miñarro, P. A. (2013). Kinematic variables evolution during a 200-m maximum test in young paddlers. *Journal of Human Kinetics*, *38*(1), 15–22. https://doi.org/10.2478/hukin-2013-0041

Wassinger, C. A., Myers, J. B., Sell, T. C., Oyama, S., Rubenstein, E. N., & Lephart, S. M. (2011). Scapulohumeral kinematic assessment of the forward kayak stroke in experienced whitewater kayakers. *Sports Biomechanics*, *10*(2), 98–109. https://doi.org/10.1080/14763141.2011.569563

Willwacher, S., Koopmann, T., Dill, S., Kurz, M., & Brüggemann, G.-P. (2020). Dorsal muscle fatigue increases thoracic spine curvature in all-out recreational ergometer rowing. *European Journal of Sport Science*, ahead-of-print, 1–7. https://doi.org/10.1080/17461391.2020.1737242

Zago, M., Esposito, F., Bertozzi, F., Tritto, B., Rampichini, S., Galvani, C., Galli, M., & Sforza, C. (2019). Kinematic effects of repeated turns while running. *European Journal of Sport Science*, *19*(8), 1072–1081. https://doi.org/10.1080/17461391.2019.1578416

Zago, M., Moorhead, A. P., Bertozzi, F., Sforza, C., Tarabini, M., & Galli, M. (2020). Maturity offset affects standing postural control in youth male soccer players. *Journal of Biomechanics*, *99*, 109523. https://doi.org/10.1016/j.jbiomech.2019.109523

Figure 1: Pulmonary oxygen consumption ($\dot{V}O_2$, red circles) and carbon dioxide production ($\dot{V}CO_2$, blue circles) for a representative participant during the incremental test. Heart rate (HR) data (black squares) are also presented. Each data point indicates breath-by-breath or beat-to-beat values averaged every 10 s. The vertical solid lines indicate different phases of the test.

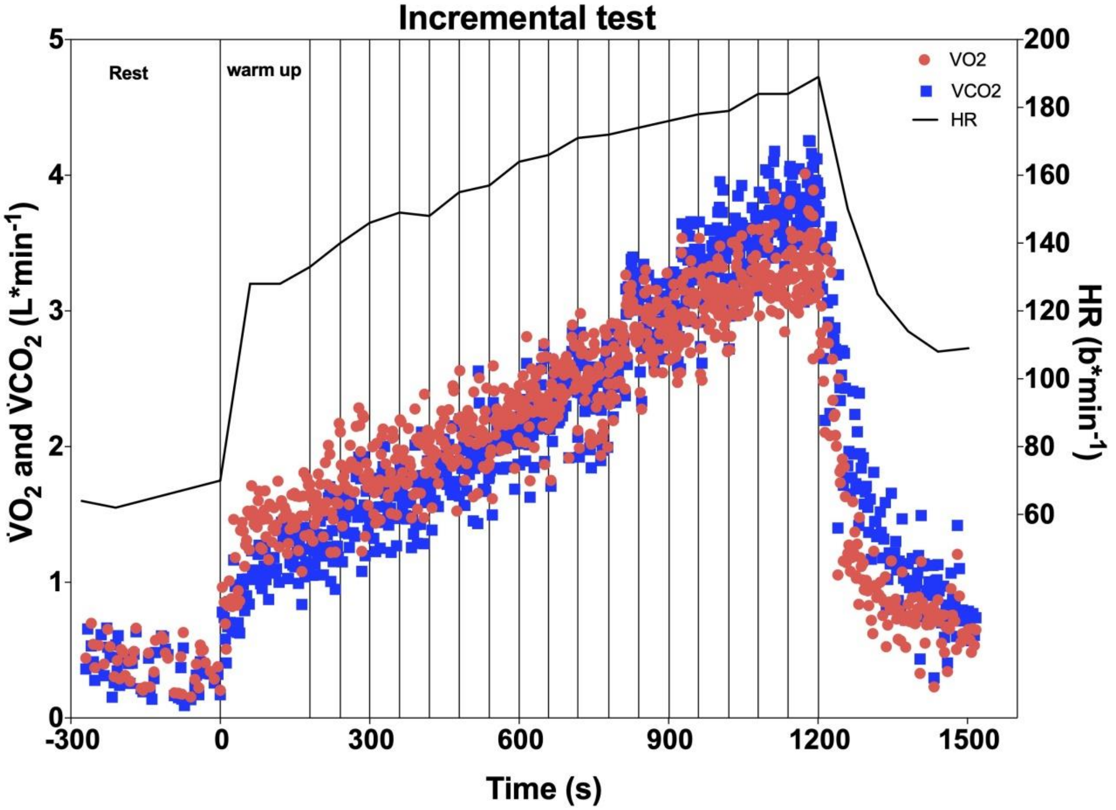

Figure 2: Scatter plots between sprint time and (a) stroke duration (triangles); (b) stroke length (squares); (c) paddle velocity (circles). The solid lines represent the regression lines of each scatter plot.

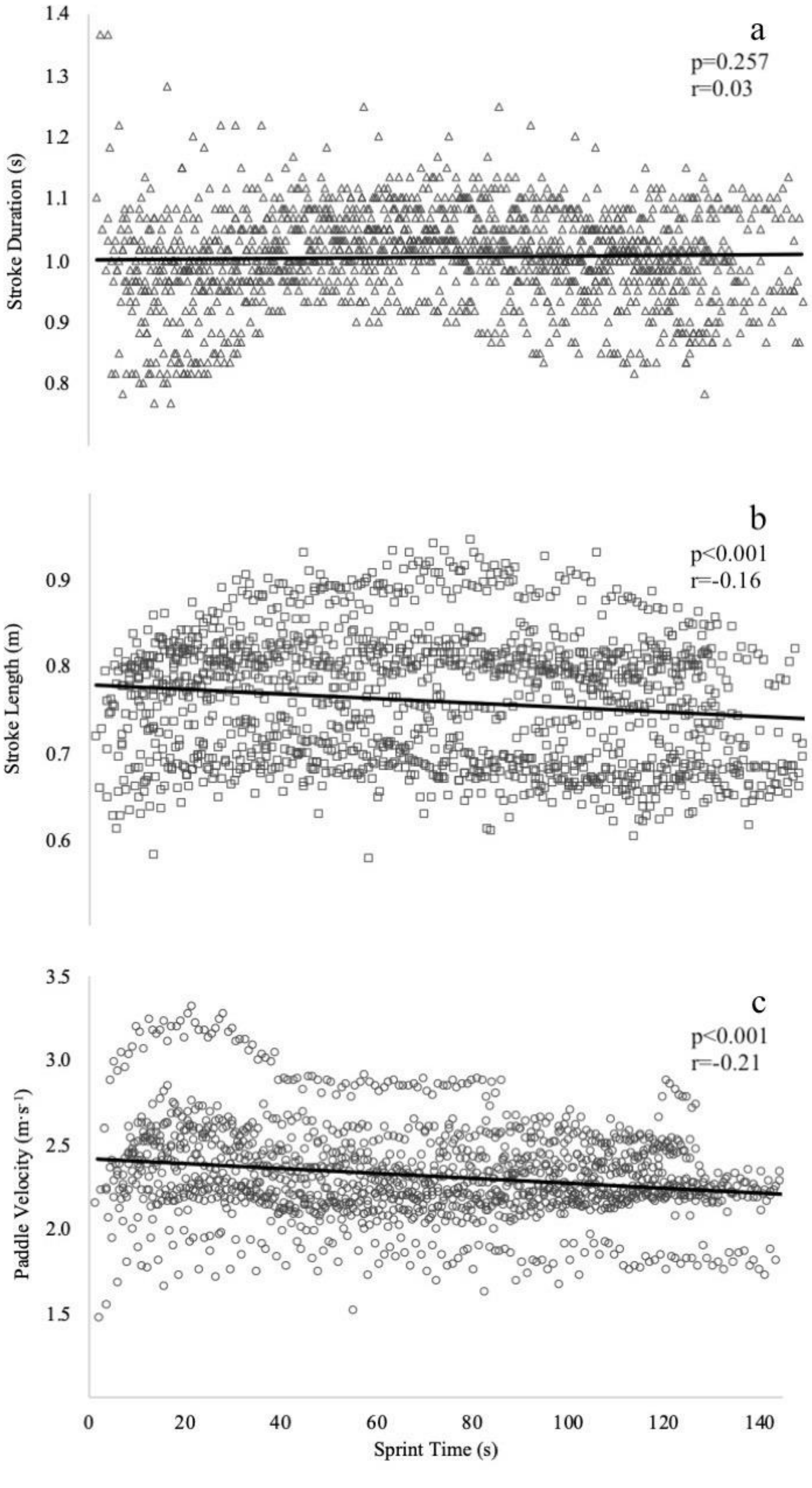
a
p=0.257
r=0.03
Stroke Duration (s)
1.4
1.3
1.2
1.1
1.0
0.9
0.8
b
p<0.001
r=-0.16
Stroke Length (m)
0.9
0.8
0.7
0.6
c
p<0.001
r=-0.21
Paddle Velocity (m·s-1)
3.5
3.0
2.5
2.0
1.5
0
20
40
60
80
100
120
140
Sprint Time (s)

Figure 3: Group mean curves of joint angles normalized to the duration (0–100%) of the stroke cycle. (a) Shoulder elevation, (b) shoulder rotation, (c) shoulder flexion, (d) trunk lateral flexion, (e) trunk rotation, (f) trunk flexion, (g) hip rotation, (h) hip abduction, (i) hip flexion, (j) knee flexion and (k) ankle flexion. Mean curves are presented for the initial (cycles 11-20) and ending part (last 10 cycles) of the sprint trial (green and red lines, respectively). Line density around the means represents the kinematic change over time: colors code refers to the time within the test when each cycle occurred. The x-axis value 0% represents the beginning of the pull phase on the right side and 100% represents the return to the beginning of the same phase on the ipsilateral side. The white vertical lines represent the start and the end of each phase in which a significant correlation with race time was found (significant cluster, Statistical Parametric Mapping, p<0.05).

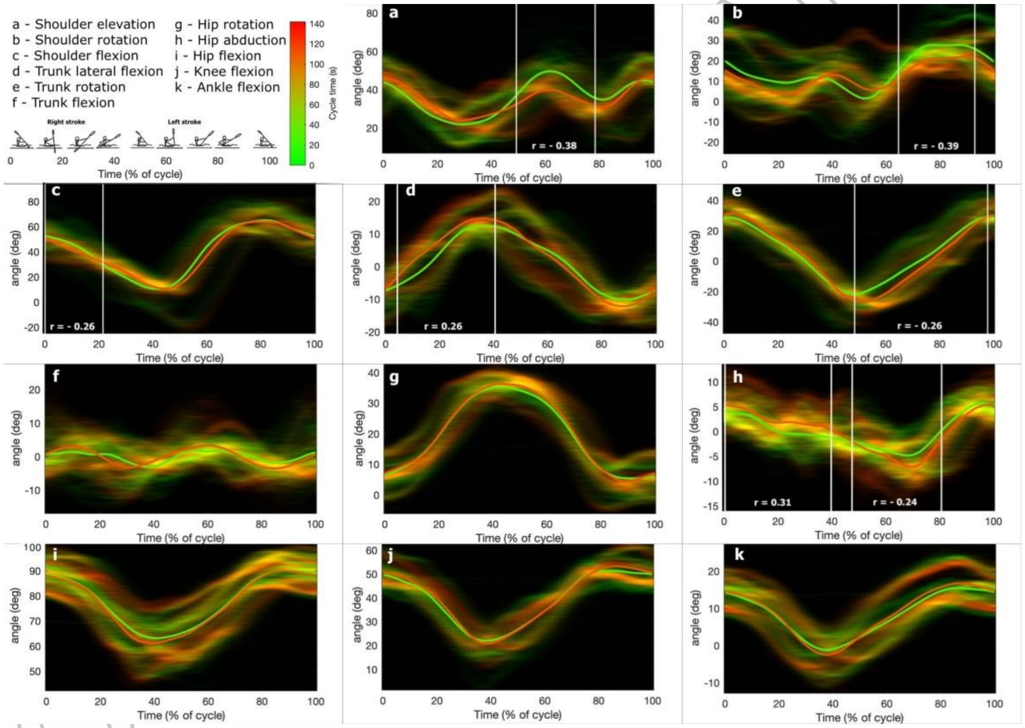

Table 1: Respiratory, cardiovascular and metabolic values (mean and SD) of the young kayakers at the end of the incremental test and the sprint trial, and statistical significance (paired t-test) of the differences between the two tests.

	Incremental test			**Sprint trial**		**p**
	Mean	**SD**		**Mean**	**SD**	
$\dot{V}O_{2peak}$ (l·min^{-1})	3.286	0.555		3.243	0.542	0.693
$\dot{V}CO_{2peak}$ (l·min^{-1})	3.698	0.632		3.811	0.632	0.340
RER	1.13	0.04		1.18	0.07	0.029
VE_{peak} (l·min^{-1})	123.3	22.1		116.8	20.1	0.138
HR_{peak} (b·min^{-1})	192	8		180	11	0.003
$[La^-]_b$ (mmol/L)	8.54	1.56		10.85	2.23	0.003
RPE	17	1		17	1	1.000
GET (l·min^{-1})	2.528	0.336				
GET (b·min^{-1})	171	11				

$\dot{V}O_2$: oxygen uptake; $\dot{V}CO_2$: carbon dioxide production; RER: respiratory exchange ratio; VE: pulmonary ventilation; HR: heart rate; GET: gas exchange threshold; b$[La]^-$: peak of blood lactate concentration; RPE: rate of perceived exertion