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Physiological and Biomechanical Characteristics of Olympic and World-Class Rowers—Case Study

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Abstract: In this study, we quantified relevant biophysical characteristics of two elite rowers across a wide range of intensities. Two <40-year-old male and female Olympic and World Championship finalists performed a 7 × 3 min protocol plus 1 min maximal effort on a rowing ergometer. The intensity increase resulted in maximum values of 79.4 ± 2.4 and 69.7 ± 1.5 mL/min/kg for oxygen uptake, 179.3 ± 5.7 and 152.5 ± 2.9 L/min for ventilation, 170 ± 1 and 173 ± 0 bpm for heart rate, 10.6 and 15.8 mmol/L for blood lactate concentration, and 38.1 ± 0.03 and 38.8 ± 0.03 °C for core temperature for the male and female rowers. The percentage of power corresponding to a previously conducted maximum 2000 m rowing ergometer test and the work at each step increased from 49 to 127 and 42 to 103% and from 226.8 to 398.9 J and 174.0 to 250.0 J, from low to extreme intensities, for the male and female. Concurrently, there was a decrease in cycle length and propulsive time, followed by an increase in maximal handle drive velocity, with the rise in rowing intensity. These world-class rowers seem capable of maintaining physiological and technical profiles (and a remarkable capacity to generate substantial power) at this phase of their careers possibly due to long-term engagement in elite-level training. Biophysical data provide valuable referential information for guiding rowers to improve their performance.

Keywords: physiology; biomechanics; performance; training; rowing

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1. Introduction

World-class rowing performance involves a very high level of physical exertion and requires well-developed aerobic and anaerobic capacities to achieve optimal performance. Specifically, the 2000 m race, one of the most well-known rowing competitions, can take 5.5 to 8.0 min depending on boat type, gender and age [1,2]. While it is worth noting that some performance-related variables may show age-related declines [3], it is important to recognize the exceptional cases of rowers who have consistently achieved top results well into their late careers like Sir Steve Redgrave and Eskild Ebbesen [4]. Since oxygen uptake is highly correlated with rowing performance and is a critical measure for training prescriptions in rowing [5,6], studies suggest an age-related stabilization or even decline after the age of 20 [7,8], with similar behavior between sexes [9].

Rowing performance is highly dependent on maximal VO_2, which is measured in many rowing programs using incremental step protocols on rowing ergometers. These tests have shown a close correlation with 2000 m ergometer performance [10–12] and are very useful for establishing training zones and monitoring performance. Notwithstanding the benefits of using a standard protocol, the development of a specific method to characterize VO_2 in female rowers is of potential value. A tailored approach may provide deeper insights into gender-specific exercise tolerance and physiological function, improving the ability to understand and address women's unique physiological responses and performance concerns, contributing to more effective and targeted training strategies [13]. Additionally, rowing requires powerful moments, especially during the underwater propulsive phase. The ability to generate power quickly is critical to accelerating the boat and maintaining optimal speed [14], as well as maintaining effective technique.

In addition, kinematic analysis provides useful information on technical changes that may occur during a rower's training season and career by monitoring the biomechanical effects of loading on the ability to maintain precision of movement. Since obtaining physiological, technical and performance data from elite rowers by field testing (on water) is extremely difficult due to small sample sizes, challenging testing procedures and the possibility of equipment damage, their assessment in the laboratory using incremental protocols on rowing ergometers has been accepted as a valid alternative [15,16]. These protocols are also well suited to measuring the kinetics of blood lactate concentration ($[La^-]$), which allows the determination of the anaerobic threshold and the establishment of different training intensity domains [11,15]. Since rowing is an outdoor sport, with the main competitions being held in summer, information on rowers' core temperature can be critical as it can affect rowers' cardiovascular response to thermoregulation, leading to impaired muscle contraction [17]. As elite rowers are difficult to reach and monitor, especially those with a long career, the aim of the current study was to quantify the physiological, technical and performance characteristics of two elite rowers across a wide range of workloads. We hypothesized that, despite having long rowing careers, these rowers would still be able to demonstrate high-level results and maintain well-developed performance determinants.

2. Materials and Methods

A male and a female Olympic finalist (in the 2012 and 2016 Games in both cases, and also in 2021 in the case of the female rower), who were also World and European Championship finalists, volunteered to participate in the current study (Table 1). Both rowers are specialists in sculling and sweep rowing; the male rower's best results were 4th place in the Rio Olympics, World Champion in 2019 and European Champion in 2022, and the female rower's were 6th place in the Rio Olympics and 7th place in the Tokyo Olympics. At the time of this study, they were in the competitive period (pre-competition phase), completing 10–12 training sessions per week (75–85% aerobic-based training), with two strength sessions per week. They were recruited via personal contact and provided written informed consent after a full explanation of the study's purpose, benefits and risks. The experimental procedures were approved by the local University Ethics Committee (CEFADE 27 2020) following the Helsinki Declaration and the guidelines of the World Medical Association for research on humans.

Table 1. Anthropometric characteristics and rowing experience of the male and female rowers.

Variable	Male	Female
Age (years)	37	35
Height (cm)	187	186
Weight (Kg)	79.9	77.8
Body mass index (Kg/m^2)	23.12	22.51
Rowing experience (years)	21	16

2.1. Experimental Design

This was a single-measurement case study, and the rowers visited the laboratory facilities (22 °C ambient temperature and 60% humidity) to complete an incremental intermittent protocol until voluntary exhaustion using a rowing ergometer (Concept II model D, fixed, Morrisville, VT, USA). Cardiorespiratory-, technical-, power- and core temperature-related variables were continuously measured, and [La^-] values were collected between the steps and at the end of the test.

2.2. Methodology

Body mass and height were obtained before the experimental session using a digital scale with a built-in stadiometer (SECA, Hamburg, Germany, model 220). The experimental rowing protocol consisted of 7 × 3 min rowing with 30 W load increments (starting at 180 and 120 W for the male and the female participants, respectively) and 30 s rest periods plus 1 min maximal effort [10,18]. Pulmonary gas exchange was measured breath-by-breath using a calibrated gas analyzer (K5, Cosmed, Rome, Italy) [19]. Erroneous breaths were excluded, and only data between the mean ± 3 SDs were considered (and subsequently smoothed with a moving and time average of three breaths and 10 s) [20]. Maximal VO_2 was determined using primary and secondary criteria, particularly a plateau despite an increase in power [20–22]. Heart rate (HR) was measured continuously by a Garmin Edge 830 monitor (Garmin, Olathe, KS, USA) that telemetrically emitted to the K5 portable unit. Capillary blood samples (5 µL) for [La^-] assessment were collected from the earlobe during the 30 s rest intervals and at the 1st, 3rd, 5th and 7th min post-test (until a peak value was reached) using a Lactate Pro 2 (Arkay, Inc., Kyoto, Japan) [15,19]. The initial sample was discarded to eliminate contaminants and ensure measurement accuracy. Capillary blood collection involved applying controlled pressure to the finger, minimizing volume variations for consistent results [23]. The lactate–power curve was used to assess the anaerobic threshold using the least squares method [24,25]. The low–moderate, heavy, severe and extreme intensities were established as follows: (i) the steps under and at the anaerobic threshold; (ii) the step(s) above the anaerobic threshold; (iii) the step at which maximal VO_2 was reached; and (iv) the 1 min maximum exertion at the end of the protocol [20,26]. Intraabdominal core temperature was continuously retrieved from low-frequency radio waves transmitted from gastrointestinal capsules to an external logger (e-Viewer Performance monitor, BodyCAP, Hérouville-Saint-Clair, France) at 15 s intervals [27].

Power was obtained using rowing ergometer computer software (PM5) [28]; the obtained power per step was then divided by each rower's body mass, and work was calculated as the product of the power and the propulsive time of each step. Kinematic data were recorded using eight video cameras (Miqus, Qualisys AB, Göteborg, Sweden) at 100 Hz and 720 p resolution, with a calibration error under 0.50 mm [29]. Full-body markerless kinematics with 6° of freedom were obtained using the Theia markerless (v2023.1.0.3161_ P14, Kingston, ON, Canada) software [30]. The rowing rate, cycle length, propulsive time, and maximal seat and handle velocity were measured from the catch to finish position of the rowing cycle [19]. The catch factor was considered the time difference between the change in the direction of the seat and handle (with negative values indicating the onset of seat velocity before the handle), and the rhythm was defined as the ratio between the propulsive time and the cycle total duration [31].

2.3. Statistical Analysis

Descriptive statistics were employed, mean and standard deviations were reported for all variables (IBM® Corp, Armonk, NY, USA, SPSS® Statistics 27.0.1.0), and one-way repeated-measures ANOVA with Tukey post hoc analysis was performed to compare the intensity domains. To compare gender differences, a one-way ANOVA for independent samples with Tukey post hoc analysis was used to compare the intensity domains. Statistical significance was set at $p \leq 0.05$.

3. Results

The physiological, mechanical and kinematic results are displayed in Tables 2 and 3. Differences were observed in the physiological and kinematic variables across the intensity domains. Regarding the most-used variables for training, the oxygen uptake increased for both rowers from low to severe ($p < 0.01$ and 0.001), corresponding to an increase of 74 and 47% for the male and the female, respectively. In addition, a difference of 14% between the male and female participants in the severe intensity domain (the step at which the maximal VO_2 was reached) was observed. An increase in respiratory frequency, ventilation and carbon dioxide production from low to severe and a decrease in the extreme intensity domain was observed ($p < 0.002$, 0.001 and 0.001 for the male and $p < 0.03$, 0.001 and 0.002 for the female rower, respectively). The respiratory quotient increased from low to extreme ($p < 0.001$ for the male and the female). The HR increased from low to extreme intensity for the male participant ($p < 0.001$), while an increase from low to severe and a decrease in the extreme intensity was observed for the female participant ($p < 0.001$). The blood lactate concentration increased across the intensity domains for both participants from 1.4 to 10.6 and from 1.2 to 15.8 mmol/L at low and extreme intensities for the male and the female, respectively. Differences were also observed in core temperature across the intensity domains for both rowers ($p < 0.001$).

Table 2. Mean and standard deviation values for selected biophysical responses at different intensities in an intermittent incremental rowing protocol for the male rower.

Variables	Low	Moderate	Heavy	Severe	Extreme
Physiological					
Oxygen uptake (mL/min/kg)	45.6 ± 1.2	65.9 ± 0.3 *	70.9 ± 2.6 *	79.4 ± 2.4 *#	62.9 ± 10.4 *
Respiratory frequency (b/min)	39.7 ± 1.1	51.8 ± 0.8 *	55.4 ± 3.1 *	66.3 ± 2.6 *#+	70.5 ± 0.9 *#+
Ventilation (L/min)	83.0 ± 2.6	136.8 ± 1.9 *	152.2 ± 5.4 *	179.3 ± 5.7 *#	174.2 ± 6.1 *#
Carbon dioxide production (mL/min/Kg)	36.7 ± 1.2	58.5 ± 0.4 *	64.0 ± 2.8 *	76.2 ± 1.8 *#	65.4 ± 1.6 *#§
Respiratory quotient	0.8 ± 0.0	0.8 ± 0.0 *	0.9 ± 0.0 *	1.0 ± 0.0 *#+	1.1 ± 0.2 *
Heart rate (bpm)	117 ± 1	148 ± 1 *	157 ± 0 *#	164 ± 0 *#+	170 ± 1 *#+§
Blood lactate (mmol/L)	1.4	2.2	3.2	4.5	10.6
Core temperature (°C)	37.0 ± 0.02	37.1 ± 0.06 *	37.5 ± 0.09 *#	37.8 ± 0.08 *#+	38.1 ± 0.03 *#+§
Mechanical Power					
Power (W)	210	300	330	360	539
Power (W/Kg)	2.6	3.8	4.1	4.5	6.8
Work (J)	226.8	285.0	300.3	313.3	398.9
Kinematic					
Rowing rate (cycles/min)	20	26	29	31	40
Rowing cycle length (m)	1.56 ± 0.01	1.53 ± 0.01 *	1.52 ± 0.01 *#+	1.49 ± 0.01 *#+	1.42 ± 0.03 *#+§
Propulsive time (s)	1.08 ± 0.01	0.95 ± 0.01 *	0.91 ± 0.01 *#+	0.87 ± 0.01 *#+	0.74 ± 0.02 *#+§
Maximal seat velocity (m/s)	1.19 ± 0.03	1.32 ± 0.03 *	1.29 ± 0.04 *+	1.37 ± 0.05 *#+	1.31 ± 0.04 *§
Maximal handle drive velocity (m/s)	1.86 ± 0.02	2.03 ± 0.02 *	2.08 ± 0.02 *#+	2.13 ± 0.02 *#+	2.35 ± 0.02 *#+§
Catch factor (ms)	−20 ± 10	−20 ± 10	−20 ± 10	−20 ± 10	20 ± 10
Rhythm (%)	37 ± 1.3	42 ± 0.50 *	44 ± 0.58 *#+	46 ± 0.50 *#+	50 ± 0.96 *#+§

*, #, + and § Different from low, moderate, heavy and severe, respectively ($p \leq 0.05$).

Compared to the previously performed 2000 m maximal test (in the month prior to the experiments), the power output in each intensity domain (low, moderate, heavy, severe and extreme intensity) corresponded to 49, 71, 78, 85 and 127% and 42, 58, 67, 75 and 103% for the male (425 W) and the female (360 W) rower, respectively. Also, as displayed in Tables 1 and 2, the work and rowing rate increased and the cycle length decreased across the intensity domains for both rowers. Additionally, the propulsive time decreased ($p < 0.001$) while the handle velocity increased along with the progressive demanding exertions ($p < 0.001$). The seat velocity for the male rower remained similar between the moderate and heavy intensities, while it was similar for the female rower between the heavy and severe intensities (even if the seat initiated the propulsive phase before the handle did, which can be observed by reference to the negative values for the catch factor) ($p < 0.001$).

Table 3. Mean and standard deviation values for selected biophysical responses at different intensities in an intermittent incremental rowing protocol for the female rower.

Variables	Low	Moderate	Heavy	Severe	Extreme
Physiological					
Oxygen uptake (mL/min/kg)	47.4 ± 1.6	57.8 ± 1.4	60.4 ± 2.1	69.7 ± 1.5 *	50.1 ± 0.6 #+§
Respiratory frequency (b/min)	41.8 ± 0.3	48.6 ± 2.1	49.4 ± 1.9	57.2 ± 0.7 *	53.2 ± 4.3
Ventilation (L/min)	80.1 ± 1.3	107.3 ± 1.3 *	117.0 ± 1.6 *#	152.5 ± 2.9 *#+	127.6 ± 5.8 *§
Carbon dioxide production (mL/min/Kg)	38.2 ± 0.7	51.7 ± 1.1 *	54.1 ± 0.5 *	73.0 ± 1.5 *#+	51.2 ± 4.5 §
Respiratory quotient	0.8 ± 0.0	0.9 ± 0.0 *	0.9 ± 0.0	1.1 ± 0.0 *#+	1.1 ± 0.1 *
Heart rate (bpm)	134 ± 1	159 ± 0 *#	168 ± 1 *#	173 ± 0 *#+	169 ± 1 *#§
Blood lactate (mmol/L)	1.2	2.4	3.6	6.7	15.8
Core temperature (°C)	37.1 ± 0.01	37.5 ± 0.07 *#	37.8 ± 0.09 *#	38.1 ± 0.09 *#+	38.8 ± 0.03 *#+§
Mechanical Power					
Power (W)	150	210	240	270	360
Power (W/Kg)	1.9	2.7	3.1	3.5	4.8
Work (J)	174.0	212.1	237.6	237.6	259.0
Kinematic					
Rowing rate (cycles/min)	21	24	26	34	46
Rowing cycle length (m)	1.55 ± 0.01	1.53 ± 0.01 *	1.53 ± 0.01 *	1.39 ± 0.12 *	1.27 ± 0.08 *#+§
Propulsive time (s)	1.16 ± 0.01	1.01 ± 0.01 *	0.99 ± 0.01 *#	0.88 ± 0.11 *#+	0.70 ± 0.03 *#+§
Maximal seat velocity (m/s)	1.27 ± 0.02	1.39 ± 0.02 *	1.40 ± 0.03 *	1.28 ± 0.15 *#+	1.23 ± 0.14 #+
Maximal handle drive velocity (m/s)	1.43 ± 0.05	1.65 ± 0.02 *	1.72 ± 0.05 *#	1.95 ± 0.26 *#+	2.39 ± 0.12 *#+§
Catch factor (ms)	−10 ± 10	10 ± 10	−10 ± 10	−20 ± 10 *#+	−20 ± 10 *#+
Rhythm (%)	40 ± 0.50	39 ± 0.70 *	43 ± 0.81 *#	50 ± 0.51 *#+	54 ± 2.50 *#+§

*, #, + and § Different from low, moderate, heavy and severe, respectively ($p \leq 0.05$).

Additionally, differences were observed between the genders in terms of VO_2 (heavy, severe and extreme intensities; $p < 0.05$), respiratory frequency (severe and extreme intensities; $p < 0.05$), ventilation (moderate, heavy, severe and extreme intensities; $p < 0.05$), carbon dioxide production (moderate, heavy and extreme intensities; $p < 0.05$), respiratory quotient (low intensity; $p < 0.05$), HR (low, moderate, heavy and severe intensities; $p < 0.05$) and core temperature (low, moderate, heavy, severe and extreme intensities; $p < 0.05$). Differences in the kinematic variables, rowing cycle length (severe and extreme intensities; $p < 0.05$), propulsive time (low, moderate, heavy and extreme intensities; $p < 0.05$), maximal seat velocity (low, moderate and heavy intensities; $p < 0.5$), maximal handle drive velocity (low, moderate, heavy, severe and extreme intensities; $p < 0.05$), catch factor (low, moderate and severe intensities; $p < 0.05$) and rhythm (low, moderate, heavy, severe and extreme intensities; $p < 0.05$), were observed.

4. Discussion

An increase in cardiorespiratory and metabolic variables was evident in rowing from the low to the severe intensity domains. When reaching the severe intensity, the observed maximal VO_2 values were in line with those for world-class male and female heavyweight rowers of younger age (male and female) [28,32,33]. These values also agree with longitudinal data reported for a 40-year-old world-class lightweight male rower [4]. In fact, high values for maximal VO_2 at younger ages and long-term engagement in endurance training seem to be necessary to perform at an elite level during a long career [4,34,35]. The HR values observed throughout the protocol were lower than those reached by younger rowers performing at maximal efforts [36], which is likely attributable to the aging process that involves a decline in cardiac output and impacts cardiorespiratory function, particularly during maximal efforts [36]. [La^-] values are related to rowers' adaptations to endurance training, which increase their fatigue tolerance and clearance ability over their careers [5].

Moreover, these values are considered important predictors of performance; the higher the workload, the higher the level at which a rower will be able to perform [2].

In addition, the rise in core temperature follows, as expected, the intensity increment throughout the protocol, which can hinder aerobic power and endurance capacity, alongside attenuated oxygen delivery to the working muscles [17]. The displayed rise in both the respiratory coefficient and [La^-] values with rowing intensity indicate a progressive recruitment of type II muscles fibers that are highly dependent on glycolytic energy supply [24,37]. This indicates significant metabolic acidosis after the aerobic–anaerobic transition that interferes decisively with rowing cycle frequency and leads to technical changes [37]. Despite an expected age-related decline in muscle strength and power [38], these rowers were able to increase their power across the intensity domains, reaching over 100% of their power in a 2000 m indoor maximum test performed close to the experiments' date.

The increase in power was also supported by the rise in the cycle rate, reducing the rowing cycle length and propulsive time [39,40]. The shorter length and propulsive time values affected the seat and handle velocities as a result of the power increase, probably due to the increase in the angular velocity of the body segments [41]. From moderate to heavy intensities (male) and from heavy to severe intensities (female), it appears that the handle velocity compensates for the reduction in seat velocity contributing to power maintenance, which may be advantageous for individuals with well-developed upper-body muscles [31]. The increase in rhythm values is related to the decrease in cycle propulsive time, as they are also dependent on rowing cycle rate, length and power [31].

In the extreme rowing intensity domain, despite the higher power output, a decrease in power intensity per rowing cycle was observed, likely due to the increasing fatigue that occurred throughout the protocol. In fact, a decrease in the ability to utilize oxygen, an increase in the respiratory coefficient and [La^-] values, and a rise in core temperature that may have hindered the contractile capacity of the muscles were also observed [17,37]. Additionally, there was a reduction in the propulsive time (due to a reduction in cycle length and a higher cycle rate) and in the seat velocity, which appears to have been compensated for by an increase in the maximal handle velocity during the propulsive phase.

The findings of the study align with prior research on gender-related variances in biophysical responses across various intensity domains, spanning from low to extreme intensities [42,43]. Such physiological distinctions are commonly linked to central factors, including smaller heart size and lower haemoglobin mass in females, potentially constraining their ability to efficiently deliver oxygen to skeletal muscles [44–46]. Furthermore, males generally have a higher ATP synthesis capacity, being able to sustain muscle contractions for longer, due to their elevated aerobic and anaerobic power along with muscle content, as can be seen from the higher power in the same intensity domain and the ability to produce higher levels of power at extreme intensity [47,48]. For more detailed information on gender differences, a customized test procedure for females may be helpful to better optimize training prescriptions [6,13].

5. Conclusions

This case study demonstrates that rowers who have experienced very demanding and rigorous training over a long period of time, along with favorable social, economic, nutritional and medical status, appear to be able to maintain high levels of cardiorespiratory and metabolic fitness while preserving their technical skills. Despite the expected decline in some biophysical variables with age, these rowers showed a remarkable ability to perform at a significant international level. These rowers have an extensive record of high-level results over their careers, with medal results in the most relevant championships. The current study provides insights into the biophysical monitoring of two Olympic rowers along a large spectrum of intensity domains, providing valuable referential information for researchers and coaches, particularly for rowers at the same age and level. These data could be crucial for improving testing procedures and adapting training programs, being particularly beneficial for rowers with extensive training experience.

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