ADVANCES IN ROWING PHYSIOLOGY

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ADVANCES IN ROWING PHYSIOLOGY

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EDITORIAL
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Editorial: Advances in Rowing Physiology

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Keywords: Pacing, energy cost, overtraining, central fatigue, rowing ergometer

Editorial on the Research Topic

Advances in Rowing Physiology

INTRODUCTION

Almost 100 years ago, it was considered that *"the rowing of a crew in a racing shell with sliding seats is a form of exercise in which a greater total energy expenditure is attainable, for periods of five to 20 min, than under any other conditions. No other exertion comes so near to bringing the entire muscle mass of the body into maximal extension and contraction"* (Henderson and Haggard, 1925). Since then many studies confirmed this notion and showcased rowing as *"the ultimate challenge to the human body"* (Volianitis and Secher, 2009). The articles in this Research Topic address a range of questions relevant not only to Olympic rowing performance, but also to the recently increasingly popular indoor rowing.

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FEATURED PUBLICATIONS

The usual pacing pattern of elite competitive rowers, regardless of finishing position or sex (Garland, 2005), has been to row the first 500 m at a significantly faster pace than subsequent sections of a 2000 m race (Secher et al., 1982). Although there are notable tactical and psychological reasons for starting fast, at least for on-water rowing where the leader has visual control of the competition, it is not easy to identify physiological reasons why this has been the adopted strategy, as the power relationship between energy demand and speed of the boat should favor a more even pacing. Boillet et al. evaluated physiological and psychological responses to a rowing ergometer race using different pacing strategies (i.e., the "positive-split" compared to a "negative-split" or a "constant-split"). The race distance used in the study (1,500 m) is both a limitation and a strength, as the shortened distance has been selected for the Los Angeles 2028 Olympic Games. The "positive-split" strategy is associated with high blood lactate and high exertion levels and is the least appreciated by rowers. One speculative explanation why rowers are using the seemingly more "painful" pacing pattern could be offered by the association of rowing performance with the total amount of oxygen consumed during the race. An initial spurt allows for larger total volume of oxygen consumed and power produced, compared to a more even pacing (Volianitis et al., 2020).

However, the study of Mentzoni and Losnegard that analyses the pacing patterns of rowers in A-finals of recent World and European championships reveals that medalists currently adopt a more even pacing profile compared to that of the fourth–sixth place finishers, confirming the theoretical expectation that such pacing profile would be advantageous in rowing. Furthermore, considering that such even pacing discriminates competitors in World class rowing, it also suggests that the capability to cope with the possible mental challenges (e.g., maintaining confidence when not leading) maybe a trait of successful rowing performance.

The energy expenditure of elite open-class male rowers is extraordinarily high and it is predominantly supported by carbohydrate oxidation, as estimated by Winkert et al. Thus, a single training session may potentially precipitate glycogen depletion, indicating that availability and replenishment of glycogen stores may be a key factor for successful rowing training. Additionally, and perhaps more importantly, such high energy expenditure approaches the suggested maximum alimentary sustainable energy supply (~3 times the resting metabolic rate, Thurber et al., 2019), supporting the notion that there may be an upper energetic limit to rowing training volume (Mader and Hollmann, 1977). In this context, the study of Turner et al. suggests that inclusion of high intensity training can improve 2,000 m rowing performance (Ní Chéilleachair et al., 2017). Considering that high intensity training can reduce glycogen utilization during exercise of similar intensity (Burgomaster et al., 2006), it could provide a feasible training alternative when the energy demands of extensive low intensity training volume approach the biological alimentary ceiling.

The energy cost of rowing (ECR) has been described for on-water rowing, albeit by modeling the metabolic demand, from the estimated mechanical power required to maintain a given speed against estimated resistance, instead of measuring it (di Prampero et al., 1971). The study by Blervaque et al. is the first to evaluate the ECR for ergometer rowing, taking into account both the measured oxidative and the estimated glycolytic non-oxidative components. The findings demonstrate that ECR is negatively correlated with rowing performance but positively correlated with contribution of fat oxidation to energy supply in moderate-intensity exercises. These associations support the notion of metabolic flexibility (i.e., the ability to switch back and forth between lipid and carbohydrate oxidation, depending on energy demand and substrate availability at higher absolute workloads, Storlien et al., 2004) that has been shown across individuals of widely different metabolic capabilities (San-Millán and Brooks, 2018) and showcase its presence in elite rowers.

The power relationship between VO2 and boat velocity (Secher 1983) would predict an ergogenic effect of oxygen supplementation on rowing performance, albeit not obligatory (Volianitis et al.). Due to the synchronous movement pattern of the limbs during rowing, it seems that there is a central constraint preventing recruitment of the leg muscles during the two-legged exercise inherent to rowing (the leg "strength paradox," Secher 1975), whilst the arm muscles are not constrained by such central activation. Considering that the largest amount of work during rowing is performed by the large leg muscles, this unique neuromuscular constrain likely explains why an increase in VO2max does not necessarily increase the amount of work performed during rowing.

Another intervention that potentially has ergogenic effect on rowing performance is bicarbonate supplementation by means of enhanced blood buffer capacity and attenuation of fatigue (Nielsen et al., 2002). The study by Nielsen et al. estimates rowing-induced changes in plasma volume, induced by the rapid fluid-shift out of the blood into the tissues during even short-term maximal exercise (Kaltreider and Meneely, 1940), and suggests that administration of sodium bicarbonate is associated with attenuated decrease in plasma volume. The implication of these estimates is that studies evaluating the effect of sodium bicarbonate on performance should account also for plasma volume changes.

Overtraining and the associated symptoms of prolonged fatigue, trainability loss, decreased levels of recovery and unexplained strength declines often appears in elite competitors (Koutedakis and Sharp, 1998), including Olympic rowers (Koutedakis et al., 1995). Bizjak et al. assessed inflammatory and immunological markers to monitor cumulated training stress in highly trained rowers during competition vs preparation (i.e., high vs low metabolic stress) phases. The authors suggested that assessment of damage-associated molecular patterns, cytokines and cell surface expression of cellular immune markers are sensitive to the metabolic overload of the competition phase and can complement conventional clinical indicators in the prevention/management of overtraining. In the same context, Jürimäe et al. examined selected myokine responses to an endurance rowing training session in national level female rowers. The study concludes that the acute negative energy balance, induced by a single endurance rowing training session, elicits significant increases in plasma irisin, fibroplast-growth-factor-21, and follistatin levels and suggests that these biological markers are useful for the assessment of acute exercise stress in female rowers.

The Concept 2 (C2) rowing ergometer is widely used for off-water training and performance assessment, and its popularity has grown even outside the sport of rowing, as it can be found in most health clubs. However, despite the wide use of the C2 there are relatively limited data on its validity and accuracy. The method of generating resistance in the C2, by air-dampening, implies that the targeted mechanical output is critically influenced by the rower's effort and associated high variability (4–5% even in elite rowers, Treff et al., 2018) and, thus precludes any acceptable variability calculation due to lack of controlled rowing stroke parameters. However, Treff et al. controlled the inherent biological variability, by using a mechanical test rig (Mentz et al., 2020), and demonstrate that the accuracy of the C2 for a given mechanical power output is improved when the fluctuations in the rowing pace during the initial strokes of a rowing race are removed. Nevertheless, the significant underestimation of the first five strokes should be taken into account when conducting tests of short duration (e.g., 20s all-out effort) that are relevant not only when planning anaerobic training sessions, or as predictor of 2000 m rowing ergometer performances (Cerasola et al.), but also to the shortened race distance for the 2028 Olympic Games. The underestimation (~10%) of the mean power output, as well as the first five strokes, compared to that performed by the rower, is confirmed by Holt et al. who investigated the concurrent validity and reliability of three commercially available on-water rowing instrumentation systems and the C2 in comparison to bespoke instrumentation.

Finally, Alfőldi et al. present anthropometric and physiological characteristics of Hungarian successful rowers and confirm the importance of body mass for rowing performance as previously shown (Secher and Vaage, 1983). It might be noteworthy that the reduction of racing distance planned for the 2028 Olympic Games would most likely exacerbate the influence of body dimensions on rowing performance and further make rowing a sport for tall rather than for all, with implications for the universality of the sport (Koshla 1983).

In conclusion, this Research Topic presents the resent developments in various aspects of rowing and elucidates enquiries concerning race pace, energy cost and requirements, immune responses, ergometer validity and performance limitations that can shape future training methodologies. Future enquiries should address the implication of potential metabolic limitation in training volume (Winkert et al.) and the suggested shift to higher proportion of high intensity training, especially with consideration for the danger of overtraining. Such considerations will become more relevant if the race distance is reduced to 1,500 m at the Olympic Games in Los Angeles in 2028 that will dramatically alter the metabolic profile of the sport. Additionally, aspects of CBF and oxygen metabolism during maximal rowing remain unresolved (Volianitis et al., 2020) due to technical limitations of evaluating methodologies. Future technological developments are expected to provide real-time measures of cerebral perfusion and metabolism during high-intensity and maximal rowing.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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Irisin, Fibroplast Growth Factor-21, and Follistatin Responses to Endurance Rowing Training Session in Female Rowers

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Purpose: This study examined selected myokine responses to an endurance rowing training session, and whether metabolic demands of the acute aerobic rowing exercise together with training volume, aerobic capacity, and body composition variables affect potential exercise-induced changes in the myokine levels in female rowers.

Methods: Fifteen national level female rowers [18.3 ± 1.6 years; 172.0 ± 5.0 cm, 67.5 ± 8.8 kg; maximal oxygen consumption (VO_2max): 47.2 ± 7.9 ml.min.$^{-1}$ kg^{-1}] performed a 1-h rowing ergometer exercise at the intensity of 70% of VO_2max [distance: 12.1 ± 1.1 km; energy expenditure (EE): 639 ± 69 kcal; heart rate (HR): 151 ± 7 beats. min^{-1}] followed by a 30-min recovery period. Venous blood samples were collected before and after exercise, and analyzed for irisin, fibroplast growth factor-21 (FGF-21), and follistatin conentrations.

Results: Plasma irisin and FGF-21 concentrations were increased (by 8%; $p = 0.013$ and by 13%; $p < 0.0001$, respectively) immediately after the aerobic rowing exercise. Follistatin was significantly increased (by 11%; $p = 0.001$) only after the first 30 min of recovery. Exercise metabolic demand variables such as distance covered and total EE were correlated with the pre-to-post-exercise increases in FGF-21 concentrations ($r = 0.52$; $p = 0.047$ and $r = 0.68$; $p = 0.005$, respectively). Exercise-induced increases in irisin levels were related to aerobic capacity as measured by VO_2max ($r = 0.53$; $p = 0.041$) and training stress as measured by weekly training volume ($r = 0.54$; $p = 0.039$) in female rowers.

Conclusion: Acute negative energy balance induced by a single endurance rowing training session elicited significant increases in irisin, FGF-21, and follistatin levels in national level female rowers. While exercise-induced increases in FGF-21 levels were associated with exercise metabolic demand measures, exercise-induced increases in irisin concentrations were related to aerobic capacity and training stress measures in female rowers.

Keywords: myokines, metabolism, aerobic capacity, training stress, female athletes

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INTRODUCTION

Rowing training is mainly focused on improving aerobic capacity (Rämson et al., 2008; Jürimäe and Purge, 2021), and an increase in prolonged low-intensity endurance rowing training sessions has been observed during the last decades (Fiskerstrand and Seiler, 2004; Jürimäe and Purge, 2021). It appears that endurance training below anaerobic threshold (AnT) is the mainstay of success in rowing (Fiskerstrand and Seiler, 2004; Mäestu et al., 2005). However, in response to high-volume low-intensity rowing training sessions, some athletes may not be able to maintain sufficient energy intake (Rämson et al., 2008; Kurgan et al., 2018), which can lead to a negative energy homeostasis in these athletes (Jürimäe et al., 2011). The regulation of negative energy homeostasis and high training stress is also dependent on several peripheral factors that communicate the status of body energy stores to the brain (Jürimäe and Jürimäe, 2005; Jürimäe et al., 2011). These peripheral factors are also synthesized from adipose, muscle, and bone tissues, which may act as endocrine organs (Kirk et al., 2020). Accordingly, a recent study used such peripheral markers as tumor necrosis factor-alpha, interleukin-6 (IL-6), leptin, and insulin-like growth factor-1 to assess variations in energy homeostasis and training stress over a training year in elite female rowers (Kurgan et al., 2018). In addition, acute exercise-induced negative energy balance may also contribute to the regulation of these peripheral markers of energy homeostasis (Jürimäe and Jürimäe, 2005; Jürimäe et al., 2011). While adipose tissue produces different adipokines that are involved in the regulation of energy metabolism (Jürimäe et al., 2011), different myokines have also been reported to play an important role in energy metabolism during acute exercise (He et al., 2018; Kirk et al., 2020).

Various myokines have been suggested to mediate exercise-induced energy expenditure (EE; He et al., 2018, 2019), besides the most investigated and well known myokine, IL-6 (Rämson et al., 2008; Ives et al., 2011; Jürimäe et al., 2011; Kirk et al., 2020). These myokines include myostatin (Sliwicka et al., 2021), follistatin (Perakakis et al., 2018), irisin (Qiu et al., 2018), and fibroplast growth factor-21 (FGF-21; Larsen et al., 2020) that have recently emerged as potential mediators of exercise-induced energy metabolism in physically active individuals. Myostatin, a member of the transforming growth factor β family of cytokines and the first described peripheral signal from muscle tissue to fulfill the criteria of a myokine (He et al., 2018), is a negative regulator of muscle mass (Kirk et al., 2020). In contrast, follistatin is a myostatin-binding peptide that promotes skeletal muscle development through the activation of anabolic pathways (He et al., 2019). Myostatin and follistatin also exert metabolic benefits by reducing body fat mass (FM), browing of white adipose tissue (WAT) and improving glucose homeostasis (Braga et al., 2014; He et al., 2019). In addition, irisin is one of the more newly identified myokine, primarily secreted by muscle tissue and released into the circulation during exercise, resulting in an increased EE, reduced body FM and improved glucose metabolism (Boström et al., 2012). FGF-21 has also been proposed as a myokine with metabolic effects on glucose and lipid metabolism, and promoting body FM loss and WAT browning (Kirk et al., 2020; Khalafi et al., 2021). Recent studies have demonstrated that acute aerobic exercise sessions with different duration could be positively associated with increased circulating irisin (Qiu et al., 2018; Sliwicka et al., 2021), FGF-21 (Larsen et al., 2020; Khalafi et al., 2021), and follistatin (Perakakis et al., 2018; He et al., 2019) concentrations in individuals with different physical activity levels. However, it has also been suggested that acute exercise sessions represent potential influence for the myokine releases only when they are characterized by adequate intensity and/or stimuli of exercise (Fatouros, 2018; He et al., 2019). Furthermore, the amount of muscle mass involved during acute exercise may contribute to the post-exercise myokine release (Hansen et al., 2011; Qiu et al., 2018). To our best knowledge, no studies have yet investigated the effect of acute prolonged rowing exercise session on circulating irisin, FGF-21, and follistatin concentrations in female athletes. Accordingly, rowing is an exercise mode where all major muscle groups are involved and this type of exercise protocol produces greater energy stimulus (Rämson et al., 2008) that might be needed for exercise-induced myokine release in comparison with running or cycling exercises.

The purpose of the present investigation was to evaluate the effects of prolonged aerobic rowing training session on circulating irisin, FGF-21, and follistatin concentrations in female rowers. Another aim was to examine whether metabolic demand values of the acute rowing exercise together with training stress, aerobic capacity, and body composition variables affect potential exercise-induced changes in the myokine levels in female rowers. It was hypothesized that irisin, FGF-21, and follistatin concentrations will increase as a result of acute negative energy balance caused by aerobic rowing exercise, and that the increases in some myokine concentrations will be associated with metabolic demand measures of acute rowing exercise in female rowers.

MATERIALS AND METHODS

Participants

Fifteen national level female rowers with a rowing training experience of 5.1 ± 1.8 years participated in this study (**Table 1**). This investigation involves a further analysis of blood samples previously collected and analyzed, and inflammatory cytokine responses to endurance exercise have been previously reported in these female rowers (Jürimäe et al., 2018). All participants were eumenorrheic female rowers with a menstrual cycle duration of 24–35 days, and were not using oral contraceptive pills for at least 6 months preceding the study (Dean et al., 2003; Vaiksaar et al., 2011a). They were asked to document their menstrual cycles for at least 6 months together with the measurement of body mass on a weekly basis (Dean et al., 2003). To be included in the study, rowers had to be weight stable for the last 6 months (Dean et al., 2003), and have a body composition of more than 12% body fat to rule out potential endogeneous hypothalamic-gonadal endocrine axis dysfunction (Ives et al., 2011). Accordingly, the criterion to be weight-stable was that the body mass change was less than

TABLE 1 | Mean (±SD) subject characteristics in female rowers.

Variable	Mean ± SD
Age (years)	18.3 ± 1.6
Height (cm)	172.0 ± 6.0
Body mass (kg)	67.5 ± 8.8
Body fat %	28.4 ± 5.0
Fat mass (kg)	18.6 ± 5.1
Fat free mass (kg)	46.7 ± 5.8
Muscle mass (kg)	16.8 ± 2.5
AnT (W)	174 ± 30
HR at AnT (beats.min^{-1})	172 ± 7
HRmax (beats.min^{-1})	189 ± 6
Pmax (W)	241 ± 36
VO_2max (l.min^{-1})	3.2 ± 0.6
VO_2max/kg (ml.min.$^{-1}$ kg^{-1})	47.2 ± 7.9
Estradiol (pmol.l^{-1})	170.1 ± 75.1
Progesterone (nmol.l^{-1})	1.6 ± 0.6

AnT, anaerobic threshold; HR, heart rate; Pmax, maximal aerobic power; and VO_2max, maximal oxygen consumption.

3 kg during the 6-month training period (Dean et al., 2003). The study was conducted during the preparatory period for the competitive rowing season, where the main goal of training was to increase the aerobic base through extensive aerobic training sessions (Rämson et al., 2008). The mean training volume of studied female rowers was 7.3 ± 3.2 h.week^{-1}, and the training intensity was below AnT for approximately 90% of the entire training time (Rämson et al., 2008). All female rowers were fully familirized with the purpose, procedures, and possible risks of the study before providing their written consent to participate. None of the participants had any significant health problems or were taking any medication before the study period. The experimental protocol was conducted in accordance with the Declaration of Helsinki and was approved by the Medical Ethics Committee of the University of Tartu, Estonia.

Experimental Design

All participants completed one preliminary session followed by one experimental session during the follicular phase of the menstrual cycle (determined as days 7–11 from onset of menstruation, mean day 9 ± 2 for the main experimental session; Suh et al., 2002; Vaiksaar et al., 2011a). Menstrual cycle phase was later confirmed by estradiol and progesterone concentrations from the blood samples (Suh et al., 2002; Vaiksaar et al., 2011a,b). Preliminary testing included incremental rowing ergometer test, which was performed between 4:00 and 6:00 p.m. followed by body composition measurement. Main experimental testing consisted of an 1-h endurance rowing ergometer session that was conducted on the following day after the incremental rowing ergometer test between 4:00 and 6:00 p.m. (Vaiksaar et al., 2011b). Rowers were in a post-absorptive state having eaten a meal about 2 h before both exercise tests. Athletes were asked to maintain their usual daily dietary habits and everyday activities before testing. In addition, participants abstained from any dietary supplementation before the first visit to the laboratory (Vaiksaar et al., 2011a,b).

Measurements

Body Composition

The height (Martin metal anthropometer, GMP Anthropological Instruments, Zurich, Switzerland) and body mass (A&D Instruments Ltd., Oxfordshire, United Kingdom) of the rowers were measured to the nearest 0.1 cm and 0.05 kg, respectively. Body composition was measured *via* dual-energy X-ray absorptiometry using Lunar DPX-IQ Densitometer (Lunar Corporation, Madison, WI, United States) and analyzed for total body fat percent, FM, and fat free mass (FFM). In addition, lower-leg skeletal muscle mass (muscle mass) was calculated as the sum of legs' lean soft-tissue masses (Jürimäe et al., 2018). The coefficient of variation (CV) for body composition measurements was less than 2%.

Incremental Rowing Ergometer Test

Stepwise incremental rowing ergometer test was performed on a wind resistance-braked rowing ergometer (Concept II, Morrisville, VT, United States) to determine maximal oxygen consumption (VO_2max) and also target heart rate (HR) indices for a 1-h endurance exercise protocol (Jürimäe et al., 2001; Vaiksaar et al., 2011b). Participants were equipped with the instruments and sat quietly for 1 min on the rowing ergometer before starting to exercise at 40 W for 1 min. Workload was increased by 15 W after every minute until volitional exhaustion (Vaiksaar et al., 2011a,b). HR was recorded every 5 s during the test using Sporttester Polar 725X (Polar Electro Oy, Kempele, Finland). Respiratory gas exchange variables were measured throughout the test in a breath-by-breath mode using portable open circuit spirometry system (MetaMax 3B, Cortex Biophysik GmbH, Germany) and data were stored in 10 s intervals (Hofmann et al., 2007). Oxygen consumption (VO_2), carbon dioxide production (VCO_2), minute ventilation (V_E), breathing frequency (f_B), and tidal volume (V_T) were continuously measured. The mean respiratory exchange ratio (RER) and ventilatory equivalents of O_2 (V_E/VO_2) and CO_2 (V_E/VCO_2) were calculated from the recorded measurements (Hofmann et al., 2007). All data were processed by means of computer analysis using a standard software (MetaSoft; Cortex Biophysik GmbH, Germany) and VO_2max was obtained as described previously (Hofmann et al., 2007). Specifically, to determine that VO_2max was reached, attainment of the VO_2 plateau with increasing work rate was used as a criterion. However, when the VO_2 plateau was not observed, an RER exceeding 1.1 and a theoretical maximal cardiac frequency were used as a criteria. The test was designed to reach the maximum in approximately 15 min in each participant (Hofmann et al., 2007). AnT determination was performed using linear regression turnpoint analysis, which has been found to be reliable in determining the individual intensity for aerobic-anaerobic transition in rowers (Hofmann et al., 2007).

Main Experimental Session

The exercise session consisted of rowing on a rowing ergometer for 1 h at the intensity of 70% VO_2max (Jürimäe et al., 2001; Vaiksaar et al., 2011b). At first, rowers rested quietly for 10 min in a seated position, and baseline (PRE) blood samples were obtained. Blood samples were also collected immediately after the rowing session (POST) and after the first 30 min of the recovery period (POST-30). Target HR was set at the level obtained from the incremental test using a practical set ±2 beats.min^{-1} of 70% VO_2max (Jürimäe et al., 2001; Vaiksaar et al., 2011b). Participants were instructed to increase exercise intensity smoothly and the requested HR was achieved after the first 5 min. The exercise intensity at the requested HR corresponded to RER < 1 (Vaiksaar et al., 2011b). The rowers were instructed to maintain the target HR steady state for the entire exercise session and to reduce exercise intensity to accommodate the required HR steady state as needed (Jürimäe et al., 2001; Vaiksaar et al., 2011b). Respiratory gas exchange variables were measured throughout the 1-h rowing ergometer session in a breath-by-breath mode using a portable open circuit spirometry system (MetaMax 3B, Cortex Biophysik GmbH, Germany) as described above. Exercise EE was estimated from the RER using stoichiometric equations (Frayn, 1983), with the assumption that urinary nitrogen excretion rate was neglible (Venables et al., 2005). These equations have previously been used in females to assess submaximal exercise EE, during which the RER was <1 (Suh et al., 2002; Venables et al., 2005). In addition, rating of perceived exertion (RPE, 6–20 scale) was assessed (Borg, 1970) and capillary blood samples for enzymatic determination of blood lactate (Lange, Germany) were collected before and after the 1-h rowing ergometer exercise (Vaiksaar et al., 2011b).

Blood Analysis

A 10-ml blood sample was obtained, and blood plasma was separated and frozen at −20°C for subsequent analysis. All blood samples from the same individual were analyzed at the same time. Irisin was determined using ELISA kit using specific Irisin/FDNC5 monoclonal antibody (R&D Systems Inc., Minneapolis, MN, United States). This assay had intra- and inter-assay CVs 2.5 and 8.7%, respectively, and the least detection limit was 0.25 ng.ml^{-1}. FGF-21 was assessed by a commercially available ELISA kit (R&D Systems Inc., Minneapolis, MN, United States) with a minimum detectable level of 1.61 pg.ml^{-1}, and intra-assay CV 3.5% and inter-assay CV 5.2%. Follistatin was measured using commercially available ELISA kit (R&D Systems Inc., Minneapolis, MN, United States) with a minimum detectable level of 29 pg.ml^{-1}, and intra-assay CV 3.0% and inter-assay CV 10.0%. In addition, estradiol and progesterone were determined on Immulite 2000 (DPC, Los Angeles, CA, United States). The intra- and inter-assay CVs for estradiol were 5.3 and 6.5%, and for progesterone 5.4 and 3.4%, respectively. The routine complete blood counts were performed by our clinical hematology laboratory, and provided blood hemoglobin and hematocrit values. The CVs for all hematological variables were less than 2%. Plasma volume changes were estimated according to the method of Dill and Costill (1974).

Statistical Analysis

Statistical analyses were performed using SPSS software version 21.0 package for Windows (Chicago, IL, United States). Data are presented as mean ± SD. Evaluation of normality was performed with Shapiro-Wilks method. Data that were not normally distributed were logarithmically transformed prior to analyses to approximate normal distribution (Jürimäe et al., 2018). One-way ANOVA and least significant difference *post hoc* analysis tests were used to evaluate differences between time points (Vaiksaar et al., 2011b). In addition, effect size (ES) transformations were used to compare the magnitude of change in myokine values as a consequence of the aerobic rowing ergometer session. Differences between mean values of each measured myokine contrasting pre- to post-exercise levels were transformed to ESs (Rhea, 2004). ESs approximating <0.25, 0.25–0.49, 0.50–1.0, and >1.0 were categorized as trivial, small, moderate, and large changes, respectively (Rhea, 2004). Spearman correlations were used to evaluate bivariate relationships among different variables of interest (Jürimäe and Jürimäe, 2005). The level of significance was set at $p < 0.05$.

RESULTS

Plasma estradiol and progesterone concentrations confirmed the follicular phase of the menstrual cycle in female rowers (**Table 1**). The average HR at AnT (172 ± 7 beats.min^{-1}) corresponded to 91.0 ± 2.6% of their HRmax (189 ± 6 beats.min^{-1}) and AnT was achieved at 83.4 ± 6.7% of VO_2max (2.64 ± 0.44 l.min^{-1}). In the main experimental session, female athletes rowed over a distance of 12.1 ± 1.1 km, with a mean exercise HR of 151 ± 7 beats.min^{-1} or 79.6 ± 4.5% of the HRmax. Total EE of the 1-h aerobic rowing exercise trial was 639 ± 69 kcal with a mean EE rate of 10.6 ± 1.2 kcal.min^{-1}. Body mass was reduced ($p < 0.0001$) after the exercise trial from 67.5 ± 8.8 to 66.3 ± 8.9 kg. The mean RPE as an exercise intensity measure during the aerobic exercise was 12.6 ± 1.2. Before exercise, blood lactate concentration was 1.9 ± 0.6 mmol.l^{-1}, which did not change significantly as a result of the exercise trial (2.3 ± 1.0 mmol.l^{-1}). Changes in plasma volume as a result of the aerobic rowing exercise were small (−0.4 ± 1.7%).

Circulating irisin concentration was significantly increased (by 8%; $p = 0.013$) as a result of rowing exercise trial (**Figure 1**). Significant increment immediately after the exercise as well as after 30 min of recovery was also seen in FGF-21 level (by 13%; $p < 0.0001$ and by 14%; $p < 0.0001$, respectively), while post-exercise increase in follistatin (by 4%) was not significant ($p = 0.065$). However, follistatin was significantly increased after the first 30 min of recovery (by 11%; $p = 0.001$) in comparison with the pre-exercise value (**Figure 1**). The magnitude of increase in irisin was trivial (ES = 0.18), while the magnitude of increases in FGF-21 (ES = 0.28) and follistatin (ES = 0.31) were small as a result of aerobic rowing exercise.

From the metabolic demand measurements of the 1-h aerobic rowing ergometer exercise trial, the mean distance covered ($r = 0.52$; $p = 0.047$) and total EE ($r = 0.68$; $p = 0.005$) values were significantly correlated with the pre-to-post-exercise increase in FGF-21 concentration. Metabolic demand measurements of 1-h aerobic rowing ergometer exercise were not associated with the pre-to-post-exercise increases in other measured myokine

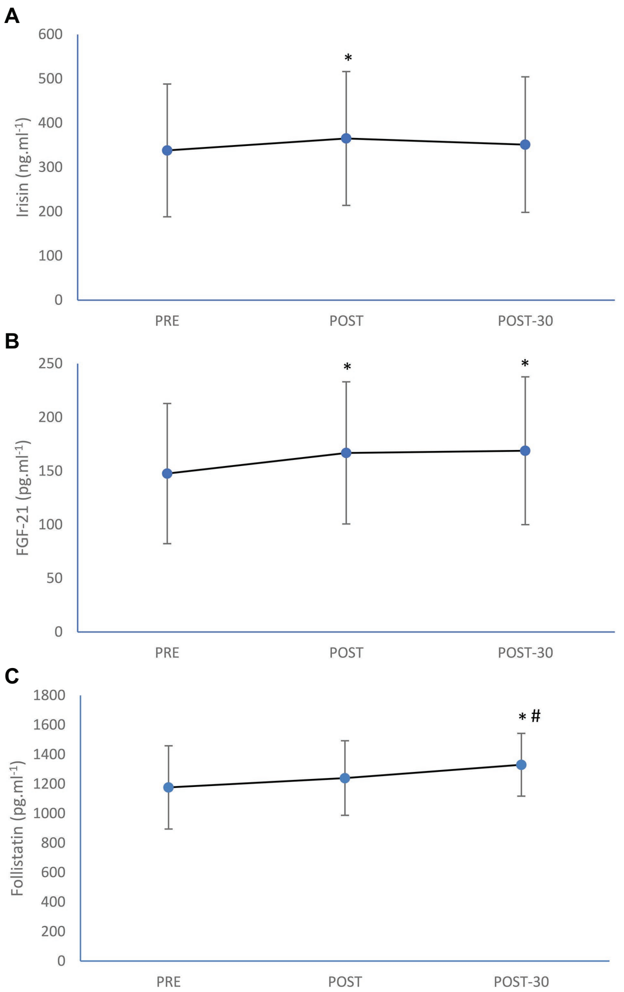

FIGURE 1 | Mean (±SD) irisin **(A)**, fibroplast growth factor-21 (FGF-21; **B**), and follistatin **(C)** concentrations before (PRE), immediately after (POST), and after 30-min rest (POST-30) of 1-h of prolonged rowing exercise in female rowers. *Significantly different from PRE; $p < 0.05$. #Significantly different from POST; $p < 0.05$.

values ($r < 0.36$; $p > 0.05$). In addition, significant correlations of the pre-to-post-exercise increases in irisin level with VO_2max ($r = 0.53$; $p = 0.041$) and weekly training volume ($r = 0.54$; $p = 0.039$) were observed. Age, aerobic capacity, body composition including muscle mass, sex hormone, and training volume variables were not further related to exercise-induced increases in any measured myokine concentrations ($r < 0.47$; $p > 0.05$).

DISCUSSION

The present study assessed the responses of specific myokines to an aerobic rowing exercise session that could be involved in metabolic regulation of the exercise stress in female athletes. Therefore, the used prolonged rowing exercise provided a valid reflection of sport-specific endurance capacity in female rowers (Jürimäe et al., 2001, 2021). Specifically, the intensity of the prolonged rowing exercise corresponded to the intensity of aerobic threshold as measured by blood lactate concentrations, which did not change significantly during the exercise trial (before: 1.9 ± 0.6 mmol.l^{-1}; after: 2.3 ± 1.0 mmol.l^{-1}). In addition, although the level of exercise intensity did not cause any significant changes in plasma volume, all measured plasma myokine values were corrected for exercise-induced plasma volume changes similarly to recent relevant acute exercise studies (Kouvelioti et al., 2019; Larsen et al., 2020; Jürimäe et al., 2021). Accordingly, the post-exercise increases in measured myokine concentrations in female rowers appear to be truly induced by exercise as also reported by previous acute exercise studies with non-athletic male participants (He et al., 2018, 2019). Furthermore, exercise-induced increases in FGF-21 levels were related to the amount of metabolic reaction as indicated by the total EE of the rowing exercise (Vaiksaar et al., 2011b). In contrast, the measured exercise intensity values such as the mean RPE and HR of the rowing exercise (Nieman et al., 2012) were not related to the pre-to-post-exercise changes in any measured myokine values. The results of the present study demonstrate that irisin, FGF-21, and follistatin could be regarded as signals for metabolic reaction for the energy requirements during and after aerobic rowing exercise, while FGF-21 levels can be used as an indicator for the amount of energy metabolism in female rowers.

In the current study, significant increase (by 8%; $p = 0.013$) in circulating irisin level immediately after the aerobic rowing exercise was observed, while the increase was trivial (ES = 0.18) in magnitude in female rowers. Only few studies have investigated the response of irisin to acute exercise in athletes, and increases (Kabasakalis et al., 2020), no change (Vassalle et al., 2020; Joro et al., 2021) or even decreases (Sanderson et al., 2020) in irisin concentrations as a result of acute exercise have been observed. In contrast to our results, circulating irisin levels have been reported to be more sensitive to exercise intensity that is known to be an important stimulator for irisin release (Fatouros, 2018; Kabasakalis et al., 2020). It has been argued that for circulating irisin concentration to increase, the acute exercise parameters should induce relatively high blood lactate production in athletes (Kabasakalis et al., 2020). The biological role of irisin as a moderator of energy metabolism in response to acute exercise still remains not fully elucidated (Fatouros, 2018; Sliwicka et al., 2021), although irisin is considered to be a factor regulating muscle adaptation, including stimulation of glucose uptake and lipid metabolism (Arhire et al., 2019; Lee and Jun, 2019; Jaworska et al., 2021). Typically, previous studies have reported increases in irisin concentrations immediately after different acute exercises with the effect being independent of the mode of exercise session (i.e., running or cycling) in healthy men (Daskalopoulou et al., 2014; Huh et al., 2014; Fatouros, 2018; Qiu et al., 2018), and a meta-analysis showed that the mean magnitude of post-exercise increase in irisin concentration across studies is around 15% in non-athletic individuals (Fox et al., 2017). However, there are also recent studies demonstrating no acute exercise effects and no differences between conditions (i.e., moderate intensity continuous training, sprint interval training, high-intensity interval training, or resistance training) for circulating irisin levels in healthy non-athletic participants (He et al., 2018, 2019; Reycraft et al., 2020). It has also been argued that irisin may be a marker of muscle damage and act as a protective agent (Vaughan et al., 2015), and also that irisin may provide an anti-inflammatory protection in fat cells as a result of acute exercise (Fatouros, 2018). In addition, our findings suggest that the level of aerobic capacity and weekly training stress of female rowers may influence post-exercise irisin release. Specifically, acute exercise-induced increases in plasma irisin concentrations were related to VO_2max ($r = 0.53$; $p = 0.041$) and weekly training volume ($r = 0.54$; $p = 0.039$) in female rowers. Similarly, Fox et al. (2017) suggested that fitness level might be the major predictor of exercise-induced irisin release, while other studies have observed that exercise-induced irisin secretion is independent of fitness level (Huh et al., 2014; Qiu et al., 2018). However, the subjects in these studies were recreationally active male individuals (Huh et al., 2014; Qiu et al., 2018) and not athletes, as were the studied participants in our study. In addition, muscle mass and sex hormone values were not associated with pre-to-post-exercise increases in irisin concentrations in studied female rowers. In accordance, different stages of menstrual cycle did not influence irisin release in response to 90 min of aerobic running exercise in recreationally trained women with normal menstrual cycle (Kraemer et al., 2014). Taken together, the results of our acute rowing exercise session suggest that a not yet exactly defined exercise stimulus is needed for a post-exercise increase in irisin concentration, and post-exercise increase in irisin level may also depend on the physical condition of the studied female rowers. However, there is lack of data in athletes to make a definitive conclusion about the role of irisin in energy metabolism of acute exercise.

The present investigation showed that a 1-h aerobic rowing ergometer exercise with an EE of 639 ± 69 kcal over a distance of 12.1 ± 1.1 km increased plasma FGF-21 concentration by 13% ($p < 0.0001$) although the magnitude of increase was small (ES = 0.28). Recently, circulating FGF-21 concentration was increased immediately after a marathon race in male recreational marathon runners (Larsen et al., 2020), while another study observed no increases in FGF-21 levels immediately after 30-min of running exercise at the intensities of 50 and 80% of VO_2max in healthy male volunteers (Kim et al., 2013). However, significant increases in FGF-21 concentrations were found 1-h post-exercise in both exercise intensity conditions, while the increase in post-exercise FGF-21 level was significantly higher after exercise with higher intensity (i.e., 80% of VO_2max) in comparison with the corresponding value after exercise with lower intensity (i.e., 50% of VO_2max; Kim et al., 2013). Accordingly, a dose-response relationship between plasma FGF-21 and exercise intensity was suggested (Kim et al., 2013). In addition, He et al. (2019) assessed the response of circulating FGF-21 concentration to increasing running exercise loads, and found that the amount of exercise load modified the FGF-21 response to acute exercise in healthy untrained men. Specifically, higher exercise load at the intensity of AnT (total EE of 762 ± 118 $kcal.h^{-1}$) produced significantly higher post-exercise FGF-21 response in comparison with a lower exercise load at the intensity of maximum fat oxidation rate (total EE of 480 ± 160 $kcal.h^{-1}$; He et al., 2019). In accordance, our female rowers demonstrated that the pre-to-post-exercise increase in plasma FGF-21 level was related to metabolic demand measurements including the mean distance covered ($r = 0.52$; $p = 0.047$) and total EE ($r = 0.68$; $p = 0.005$) of the performed rowing exercise. Based on the role of FGF-21 on glucose uptake and lipolysis (Kim et al., 2013; Khalafi et al., 2021), it is suggested that exercise-induced increased FGF-21 level mediates beneficial effects of acute exercise on glucose and lipid metabolism. In addition, to our best knowledge, this is the first study in athletes, which showed that circulating FGF-21 level was significantly elevated as a result of acute endurance exercise and that exercise-induced EE as an indicator of acute exercise stress was significantly associated with pre-to-post-exercise increases in FGF-21 level. Accordingly, circulating FGF-21 concentration could be used as a marker of energy homeostasis and exercise stress in female rowers. However, this issue needs further investigations in athletes before any conclusions may be drawn.

Follistatin has been reported to bind myostatin in order to inactivate it, and consequently promote skeletal muscle development (Hansen et al., 2011; Perakakis et al., 2018). Interestingly, He et al. (2018) reported that the increase in myostatin concentration upon acute exercise termination occurred concomitantly with an increase in follistatin only 3-h after acute high-intensity interval treadmill running exercise in non-athletic men. Similarly, 3-h bicycle exercise at the intensity of 50% of VO_2max did not cause an immediate post-exercise increase in circulating follistatin concentration, while plasma follistatin increased during the recovery period peaking 3-h after exercise in healthy untrained males (Hansen et al., 2011). In the present study, circulating follistatin concentration was significantly increased only after the first 30-min of recovery from the 1-h aerobic rowing exercise in female rowers. Therefore, the increase in follistatin magnitude was small (ES = 0.31). In another study, follistatin level was increased immediately after 36 min of moderate-intensity run on treadmill in healthy untrained men and continued to increase 1 h after recovery period (Perakakis et al., 2018). In accordance, because follistatin concentration was significantly higher after the first 30 min of recovery period in comparison with the corresponding value obtained immediately after the rowing exercise, we cannot exclude a further increase in follistatin concentration over a longer period in our studied female rowers. Moderate increases in serum follistatin levels have been observed to occur for few days after the eccentric exercise-induced muscle damage in healthy men (Philippou et al., 2017). It has been suggested that post-exercise increases in follistatin levels stimulate the energy turnover in skeletal muscle to meet the energy demands during recovery from exercise (Philippou et al., 2017; Perakakis et al., 2018), while the exercise-induced increase in follistatin may also be dependent on the muscle mass recruited during the exercise bout (Hansen et al., 2011). Taken together, the specific exercise mode and protocol, where about 70% of all body muscles are involved in rowing (Rämson et al., 2008), provided a sufficient stimulus to increase plasma follistatin concentration already after the first 30-min of recovery period of the acute rowing exercise in studied female rowers. However, further studies with athletes are needed to better understand the suitability of using circulating follistatin concentration as a myokine marker to characterize acute exercise stress in trained athletes.

The main strength of the investigation is the study population consisting of trained female athletes, who make up a rather homogeneous group of subjects in terms of specific aerobic performance, body composition, and also sex hormone variables. However, it has to be considered that the results of the present study cannot be extrapolated to other populations such as sedentary individuals, people with obesity and aging individuals. Another strength of the investigation is that, to the best of our knowledge, this was the first study that measured irisin, FGF-21, and follistatin responses to exercise simultaneously in female athletes and used direct measurement of oxygen consumption in order to assess the metabolic demands of the aerobic rowing exercise. The main limitations of the present investigation are the observational study design with no control trial and the absence of the longer and more frequent sampling period during recovery after exercise trial. In addition, the lack of measurement of some important myokines such as myostatin is another limitation of the present study. Accordingly, more research is needed to analyze the effect of acute training loads measuring myokines together with specific adipokines and osteokines with a longer recovery period to better characterize acute exercise stress and negative energy balance in female athletes. Finally, another research area should focus on studying these myokines as markers of chronic exercise stress and possible overtraining in various athletic populations.

In summary, our study demonstrated that circulating plasma irisin and FGF-21 concentrations were increased immediately after the prolonged endurance rowing training session, while follistatin levels were elevated after the first 30-min of recovery period in female rowers. Metabolic demand values (covered distance and EE) of the rowing exercise session were related to the exercise-induced increases in circulating FGF-21 levels, whereas aerobic capacity as measured by VO_2max and training stress as measured by weekly training volume were correlated with exercise-induced increases in irisin concentrations. These results suggest that plasma irisin, FGF-21, and follistatin levels could be used as biological markers of acute exercise stress in female rowers.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Medical Ethics Committee of the University of Tartu. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

JJ, SV, PP, and VT designed the study. SV and PP performed the research. JJ wrote the manuscript. SV, PP, and VT reviewed and edited the manuscript. All authors contributed to the article and approved the submitted version.

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A New Fitness Test of Estimating VO_{2max} in Well-Trained Rowing Athletes

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Background: This study was designed to investigate the validity of maximal oxygen consumption (VO_{2max}) estimation through the Firstbeat fitness test (FFT) method when using submaximal rowing and running programs for well-trained athletes.

Methods: Well-trained flatwater rowers (n = 45, 19.8 ± 3.0 years, 184 ± 8.7 cm, 76 ± 12.9 kg, and 58.7 ± 6.0 mL·kg^{-1}·min^{-1}) and paddlers (n = 45, 19.0 ± 2.5 years, 180 ± 7.7 cm, 74 ± 9.4 kg, and 59.9 ± 4.8 mL·kg^{-1}·min^{-1}) completed the FFT and maximal graded exercise test (GXT) programs of rowing and running, respectively. The estimated VO_{2max} was calculated using the FFT system, and the measured VO_{2max} was obtained from the GXT programs. Differences between the estimated and measured VO_{2max} values were analyzed to assess the accuracy and agreement of the predictions. Equations from the previous study were also used to predict the VO_{2max} in the submaximal programs to compare the accuracy of prediction with the FFT method.

Results: The FFT method was in good agreement with the measured VO_{2max} in both groups based on the intraclass correlation coefficients (>0.8). Additionally, the FFT method had considerable accuracy in VO_{2max} estimation as the mean absolute percentage error (≤5.0%) and mean absolute error (<3.0 mL·kg^{-1}·min^{-1}) were fairly low. Furthermore, the FFT method seemed more accurate in the estimation of VO_{2max} than previously reported equations, especially in the rowing test program.

Conclusion: This study revealed that the FFT method provides a considerably accurate estimation of VO_{2max} in well-trained athletes.

Keywords: maximal aerobic capacity, flatwater rowers, flatwater paddlers, submaximal fitness test, treadmill running, rowing

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INTRODUCTION

Maximal oxygen consumption (VO_{2max}) is defined as the maximal capacity of the pulmonary, cardiovascular, and muscular systems to deliver and utilize oxygen, which can reflect an individual's cardiorespiratory fitness (Saltin and Strange, 1992; Bassett and Howley, 1997; Levine, 2008). Measurement of VO_{2max} provides important outcomes for both physical performance and health status in general (Brink-Elfegoun et al., 2007), and it is frequently used to assess the aerobic capacity of professional or amateur athletes (Shephard, 2009). Therefore, VO_{2max} is often used in endurance sports to provide training and athletes' performance information to coaches (Midgley et al., 2009; Sartor et al., 2013).

VO_{2max} can be measured through direct methods with a metabolic gas measurement system, with the athlete performing a maximal graded exercise test (GXT) until exhaustion. This is regarded as the gold standard as it can obtain an accurate value of VO_{2max} (Beltz et al., 2016). However, as it is time-consuming and there is an economic burden, the use of direct measurement methods is limited. In addition, the exhausting exercise program affects the training arrangement of the season (Montgomery et al., 2009; Tanner and Gore, 2013; Riebe et al., 2018). From this perspective, indirect methods of estimating VO_{2max} based on the submaximal exercise program seem to be a good choice for athletes or teams, and these can frequently be used during the training season.

Previous studies have reported several indirect methods for estimating VO_{2max} in athletes based on running programs (Tsiaras et al., 2010; Marsh, 2012; Matabuena et al., 2018). Marsh (2012) found a four-stage incremental running program estimating VO_{2max} well, and the equation was fairly accurate [standard error of estimate (SEE) = 3.98-4.08 $mL \cdot kg^{-1} \cdot min^{-1}$; r = 0.642-0.646], as recommended by the American College of Sports Medicine. However, this equation is more suitable for males than for females, as the correlation data were conducted in male athletes. Other studies also reported submaximal VO_{2max} predictive equations [(SEE) = 2.52–3.51 $mL \cdot kg^{-1} \cdot min^{-1}$; r = 0.85–0.91] for the amateur exercise population (Larsen et al., 2002; Vehrs et al., 2007).

Klusiewicz et al. (2016) developed a predictive equation (r = 0.711) based on the PWC170 obtained from a submaximal rowing program (Klusiewicz and Faff, 2003), which was later validated to assess the aerobic fitness of rowers. The equation based on the rowing programs had not reached an accuracy similar to that from the equation based on the running programs, with correlation coefficients of 0.55 in male rowers (Klusiewicz and Faff, 2003) and R^2 values of 0.79 and 0.64 in male and female rowers, respectively, Klusiewicz et al. (2016). Thus, the present study was designed to develop a new indirect method of VO_{2max} estimation for both male and female rowing athletes.

Recently, a new system [Firstbeat fitness test (FFT)] was used for the indirect estimation of VO_{2max}. The estimated VO_{2max} value is automatically generated after collecting heart rate (HR) data from a configurable test program (rowing or running) using Firstbeat sports software (Firstbeat, Jyvaskyla, Finland). Studies have revealed that the Firstbeat VO_{2max} estimation system is valid in nonathletic populations (Kraft and Roberts, 2017; Kyröläinen et al., 2018; Anderson et al., 2019; Passler et al., 2019). To the best of our knowledge, no study has reported the accuracy of this system in estimating VO_{2max} in well-trained athletes. Therefore, this study was designed to investigate the accuracy of VO_{2max} estimation based on the FFT system when using submaximal rowing and running programs. In addition, this study aimed to evaluate the cross-validation of previous VO_{2max} predictive equations in both submaximal running (Marsh, 2012) and rowing programs (Klusiewicz et al., 2016), providing more information on the VO_{2max} estimated by the FFT system to coaches and sports scientists. The hypothesis for this study was that the FFT method could provide accurate VO_{2max} estimation in well-trained athletes, which would varify a new accurate option for estimating VO_{2max} in athletic population.

MATERIALS AND METHODS

The FFT system was used to estimate the participants' VO_{2max} values, which were also compared to the VO_{2max} values from the direct method measurement of the GXT programs. Additionally, a cross-validation design was used to evaluate the validation of the VO_{2max} estimation when compared to other classical predictive equations based on submaximal rowing (Klusiewicz et al., 2016) and running programs (Marsh, 2012).

Participants

A total of 90 well-trained athletes were recruited from Zhejiang Water Sports Training Center and divided into two groups based on the sports items (i.e., rowers and paddlers): 45 flatwater rowers (23 males and 22 females) in the ROW group and 45 flatwater paddlers (29 males and 16 females) in the RUN group (participant characteristics are shown in **Table 1**). This study was conducted according to the guidelines in the Declaration of Helsinki and was approved by the ethical committee of Zhejiang Institute of Sports Science (ZJSS201909162). All participants were informed of the details of the entire program and signed an approved informed consent document.

Procedures

Figure 1 shows the flow diagram of this study. First, submaximal FFT programs were performed, the ROW group athletes performed a submaximal incremental rowing test and the RUN group athletes performed a submaximal running test. Every athlete's HR (Firstbeat, Jyvaskyla, Finland) was collected during the programs, and the estimated VO_{2max} value was obtained from FFT program. After 3–5 days of recovery from the submaximal program, the participants performed a maximal graded rowing (ROW group athletes) or running program (RUN group athletes) to obtain the measuredVO_{2max} value using a breath-by-breath metabolic measurement system, which was regarded as the golden standard test of VO_{2max} (Fletcher et al., 2013). All experimental tests were performed at the same time frame during the regular training period (9:00–12:00, 15:00–18:00) in a quiet and air-conditioned laboratory (temperature, 18–23°C; humidity, 40–60%). The participants were asked to avoid heavy load training 7 days before the tests and during the recovery days, as well as abstain from caffeine and alcohol for 24 h before testing.

FFT Program

The ROW group athletes performed a submaximal incremental rowing test on the rowing ergometer (model E, Concept 2, Morrisville, VT, United States), while the RUN group athletes performed a submaximal running test on the treadmill (H/P/Cosmos, Nussdorf, Germany). According to previous studies (Marsh, 2012; Klusiewicz et al., 2016), a multistage incremental test program with up to 85% maximal HR (HR_{max}) was suggested to provide reliable predicted VO_{2max}.

TABLE 1 | Descriptive characteristics of the participants.

	ROW group			RUN group		
	Male (*n* = 23)	Female (*n* = 22)	All (*n* = 45)	Male (*n* = 29)	Female (*n* = 16)	All (*n* = 45)
Age (years)	20.7 ± 3.6	19.0 ± 2.1	19.8 ± 3.0	18.7 ± 2.3	19.5 ± 3.0	19.0 ± 2.5
Height (cm)	190.7 ± 5.4	176.6 ± 4.7	184 ± 8.7	184.0 ± 4.6	171.4 ± 5.0	180 ± 7.7
Body mass (kg)	84.5 ± 3.6	67.0 ± 8.9	76 ± 12.9	78.7 ± 7.0	65.7 ± 7.0	74 ± 9.4
Training experience (years)	4.7 ± 3.1	3.9 ± 2.1	4.3 ± 2.6	3.7 ± 1.9	4.6 ± 2.2	4.0 ± 2.1

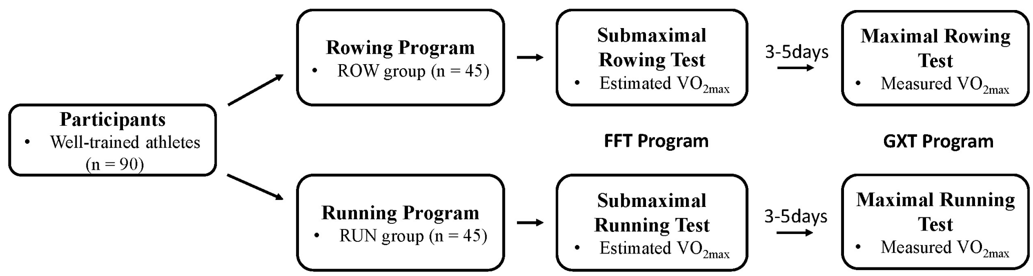

FIGURE 1 | Experimental tests diagram.

To determine the appropriate intensity for the submaximal programs, a pilot study of 10 athletes (five rowers and five paddlers) was conducted to obtain the physiological responses for different stages, especially the last stage on the rowing ergometer or running treadmill. The submaximal incremental exercise test program consisting of four 3-min rowing exercises (an initial workload of 160 W in male athletes and 120 W in female athletes) and treadmill running (an initial running speed of 9 km/h in male athletes and 8 km/h in female athletes) was designed based on the pilot study and then performed by the ROW and RUN group athletes, respectively. Detailed information on the two programs is shown in **Supplementary Table 1**. The Firstbeat HR chest belt was used to record the HR during the entire test program. All rowers completed FFT rowing program and paddlers completed FFT running program. Finally, the Firstbeat Sports software (version 4.7.3.1, Jyvaskyla, Finland) automatically produced estimated VO_{2max} values based on the collected HR data of the submaximal FFT program.

GXT Program

The ROW group athletes performed a maximal incremental rowing test program (Tanner and Gore, 2013) on the Concept II rowing ergometer, with an initial workload of 160 W in males and 120 W in females. The RUN group athletes performed the Bruce running program on a treadmill (Riebe et al., 2018). Detailed information on the two maximal programs is shown in **Supplementary Table 2**. A breath-by-breath metabolic measurement system (Quark PFT Ergo, Cosmed, Rome, Italy) was used to record the respiratory gas information throughout the whole GXT procedure in both the ROW and RUN groups. The system was calibrated in advance by following the manufacturer's instructions. During the testing process, the rating of perceived exertion (RPE) on the Borg scale (6–20) and the HR (SZ990, Cosmed, Rome, Italy) were also recorded at the end of each stage manually. The achievement of VO_{2max} was identified when meeting at least two of the three following criteria (Howley et al., 1995): (1) achievement of the oxygen consumption plateau with an increasing workload, (2) respiratory exchange ratio (RER) reached $\geq$1.10, and (3) the HR reaching within 10 beats of the age-adjusted HR_{max} upon using the equation, 220 - age. The value of the measured VO_{2max} was defined as the highest 30-s average value of VO_2 measured during GXT (Midgley et al., 2007).

Statistical Analysis

All data were presented as mean ± standard deviation. The Shapiro–Wilk test was performed to test the normality of the outcome variables. Then Pearson's correlation between the estimated VO_{2max} values from the submaximal test programs and the measured VO_{2max} values from the direct method using the GXT program was performed to assess the correlation magnitude and coefficient of determination (R^2). To assess the accuracy of the estimation, the mean absolute percentage error (MAPE) and mean absolute error were calculated. The intraclass correlation coefficient (ICC) was used to determine the agreement between the estimated VO_{2max} values and measured VO_{2max} values. Furthermore, the Bland-Altman plot was used to investigate the level of agreement with the 95% limits of agreement (Bland and Altman, 1986). All statistical analyses were performed using IBM SPSS Statistics software for Windows (version 24 IBM, Armonk, NY, United States), and statistical significance was set at $P < 0.05$.

RESULTS

Accuracy of VO_{2max} Estimation From FFT

Table 2 shows the VO_{2max} values measured by GXT programs and the HR, RPE, and RER in the last stage of the GXT

TABLE 2 | Results of the maximal graded exercise test.

	ROW group			RUN group		
	Male **(n = 23)**	**Female** **(n = 22)**	**All** **(n = 45)**	**Male** **(n = 29)**	**Female** **(n = 16)**	**All** **(n = 45)**
HR at VO_{2max} (bpm)	189.0 ± 4.5	190.8 ± 5.3	189.9 ± 4.9	198.0 ± 5.2	193.3 ± 8.5	196.3 ± 6.9
RPE at VO_{2max} (6–20)	18.2 ± 1.1	18.2 ± 0.9	18.2 ± 1.0	18.9 ± 0.8	18.8 ± 1.1	18.9 ± 0.9
RER at VO_{2max}	1.13 ± 0.1	1.11 ± 0.1	1.12 ± 0.1	1.13 ± 0.1	1.08 ± 0.1	1.11 ± 0.1
VO_{2max} (mL·kg^{-1}·min^{-1})	60.7 ± 5.9	56.7 ± 5.5	58.7 ± 6.0	62.3 ± 3.4	55.6 ± 4.0	59.9 ± 4.8

HR, heart rate; RPE, rating of perceived exertion on Borg scale 6–20; RER, respiratory exchange ratio; and VO_{2max}, maximal oxygen consumption.

TABLE 3 | The correlations and differences between the estimated VO_{2max} from FFT and the measured VO_{2max} from GXT.

	Gender	Estimated VO_{2max} (mL·kg^{-1}·min^{-1})	Measured VO_{2max} (mL·kg^{-1}·min^{-1})	CE (mL·kg^{-1}·min^{-1})	t	r	ICC	MAE (mL·kg^{-1}·min^{-1})	MAPE (%)
ROW									
	Male (n = 23)	62.5 ± 6.0	60.7 ± 5.9	1.8 ± 3.6	2.429*	0.798*	0.736*	3.0 ± 2.6	5.3
	Female (n = 22)	57.5 ± 6.3	56.7 ± 5.5	0.7 ± 3.3	1.047	0.851*	0.841*	2.7 ± 2.0	4.8
	All (n = 45)	60.0 ± 6.0	58.7 ± 6.0	1.3 ± 3.5	2.501*	0.834*	0.818*	2.9 ± 2.3	5.0
RUN									
	Male (n = 29)	63.2 ± 4.8	62.3 ± 3.4	0.9 ± 2.6	1.838	0.851*	0.787*	2.2 ± 1.6	3.5
	Female (n = 16)	58.0 ± 4.4	55.6 ± 4.0	2.4 ± 2.4	3.902*	0.837*	0.727*	2.7 ± 2.0	5.0
	All (n = 45)	61.3 ± 5.3	59.9 ± 4.8	1.4 ± 2.6	3.624*	0.868*	0.834*	2.4 ± 1.7	4.1

CE, constant error, arithmetic mean of the difference between estimated and measured VO_{2max}; t, t value from paried sample t-test; r, pearson correlation coefficient; ICC, intraclass correlation coefficient; MAE, mean absolute error; and MAPE, mean absolute percentage error.
**Statistically significant ($P \leq 0.05$).*

program, and **Table 3** shows the estimated VO_{2max} from the FFT and the analysis of correlations and differences between the two VO_{2max} values. The results showed that the estimated VO_{2max} was significantly overestimated in both ROW [constant error (CE) = 1.3 ± 3.5 mL·kg^{-1}·min^{-1}, t [44] = 2.501, and P = 0.016] and RUN (CE = 1.4 ± 2.6 mL·kg^{-1}·min^{-1}, t [44] = 3.624, and $P < 0.001$) submaximal test programs (**Table 3**). However, the results of the ICC revealed that the estimated VO_{2max} from the FFT had a good level of agreement with the directly measured VO_{2max} from the GXT in both the ROW (0.818, $P < 0.001$) and RUN groups (0.834, $P < 0.001$). Additionally, the results also showed a fairly low MAPE in both the ROW and RUN groups (ROW, 5.0%; RUN, 4.1%), which also verified that the FFT was considerably accurate in VO_{2max} estimation. Furthermore, linear regression plots demonstrated a good predictive model of the FFT method in both the rowing (R^2 = 0.695, $P < 0.001$, and SEE = 3.35 mL·kg^{-1}·min^{-1}; **Figure 2A**) and running submaximal programs (R^2 = 0.753, $P < 0.001$, and SEE = 2.43 mL·kg^{-1}·min^{-1}; **Figure 2B**).

Level of Agreement Between the Estimated VO_{2max} From the FFT and the Directly Measured VO_{2max} From the GXT Program

The Bland-Altman plots also demonstrated an agreement between the estimated VO_{2max} from the FFT and the directly measured VO_{2max} from the GXT program (**Figure 3**). The findings revealed that the estimated VO_{2max} had fairly low mean differences (bias) in both the ROW (**Figure 3A**) and RUN (**Figure 3B**) groups (bias: 1.29 mL·kg^{-1}·min^{-1} for rowing and 1.42 mL·kg^{-1}·min^{-1} for running). Furthermore, the FFT rowing program had a larger range of bias than that in the running program when estimating VO_{2max} from the FFT [upper to lower limits of agreement (ULoA-LLoA): 13.56 mL·kg^{-1}·min^{-1} vs. 10.32 mL·kg^{-1}·min^{-1}, respectively].

Comparison Between the FFT Method and Previous Predictive Equations

We then examined previous equations that predict VO_{2max} based on Klusiewicz et al.'s (2016) and Marsh's (2012) studies using the HR and PWC170 (the equations and the predicted VO_{2max} are shown in **Table 4**) and compared them to the directly measured VO_{2max} from the GXT program. It was found that although Eq. 1 had a fairly accurate prediction of VO_{2max} in the rowing program, the FFT method had better accuracy and lower error terms for the overall ROW group (CE = 2.9 ± 2.3 mL·kg^{-1}·min^{-1} and ICC = 0.818), as well as in both male (CE = 3.0 ± 2.6 mL·kg^{-1}·min^{-1} and ICC = 0.736) and female (CE = 2.7 ± 2.0 mL·kg^{-1}·min^{-1} and ICC = 0.841) subgroups. In addition, in the RUN group, Eqs 2, 3 had similar validity coefficients (r = 0.655 and 0.671, respectively) and level of agreement (ICC = 0.615 and 0.586, respectively) when the athletes performed the running program. However, in the female subgroup, neither Eq. 2 nor 3 showed a significant correlation with directly measured VO_{2max} from the GXT program. Moreover, Eq. 2 had a nonsignificant

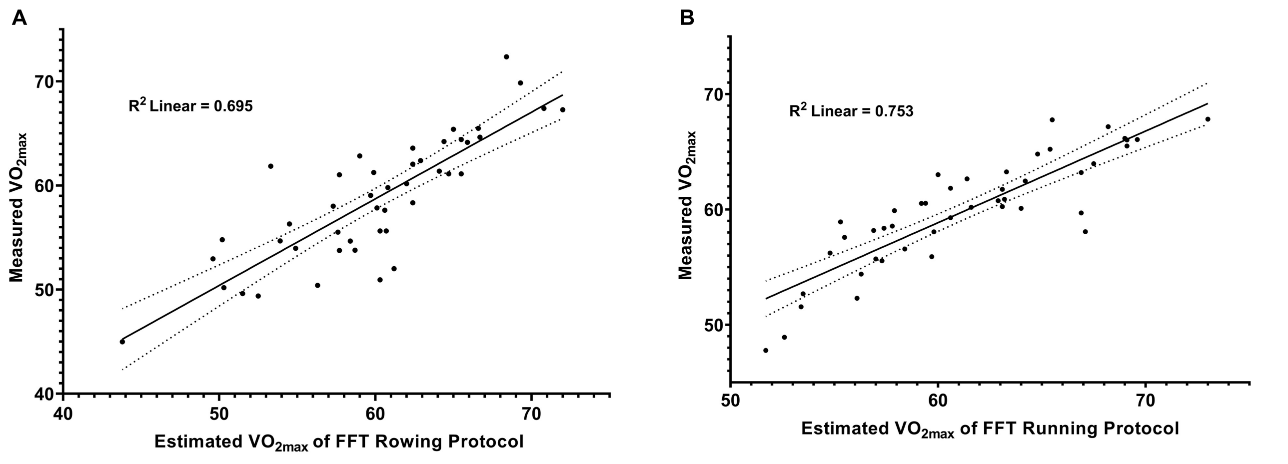

FIGURE 2 | The linear regression plots between the estimated VO_{2max} from FFT and measured VO_{2max} by GXT. **(A)** The FFT rowing program and **(B)** The FFT running program. The coefficient of determination (R^2) and 95% confidence interval bounds (dotted line) are also depicted.

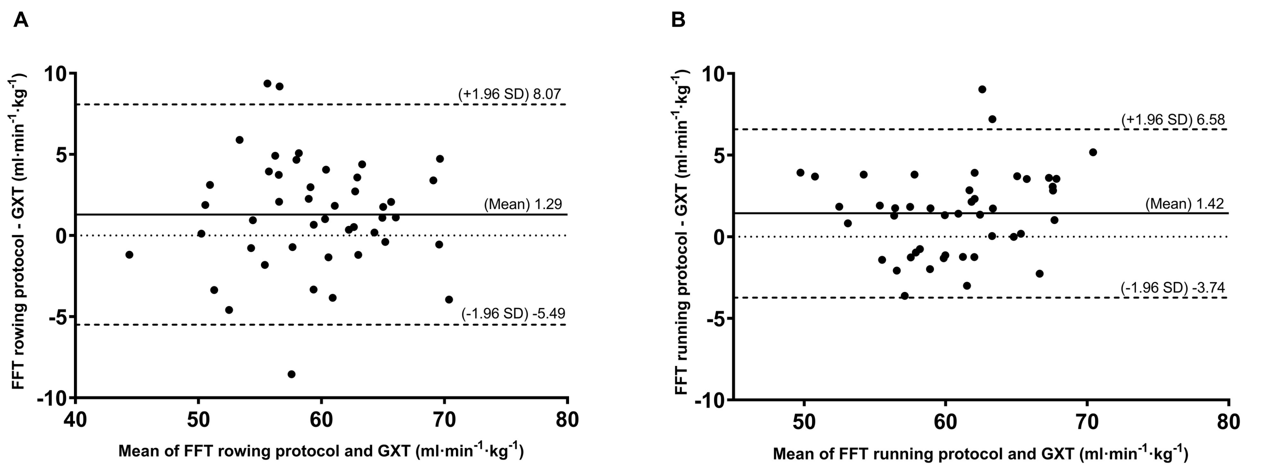

FIGURE 3 | Bland-Altman plots between the estimated VO_{2max} from FFT and measured VO_{2max} by GXT. **(A)** The FFT rowing program and **(B)** The FFT running program. Mean biases (solid line), ±95% limits of agreement (dashed line), and equality (dotted line) are also depicted.

difference [t (44) = 1.238, $P > 0.05$] and lower predictive errors (CE = 0.7 ± 3.7 mL·kg^{-1}·min^{-1}, MAPE = 4.8%) than did Eq. 3.

DISCUSSION

This study aimed to investigate the accuracy of the FFT method for VO_{2max} estimation using submaximal programs, such as rowing or running, in well-trained athletes. Good levels of agreement between the estimated VO_{2max} from the FFT and the measured VO_{2max} from the GXT and < 10% MAPE were observed in the current study, which met the criteria suggested by Nelson et al. (2016). Additionally, the coefficient of determination (**Figure 2**) indicated that the FFT method accounted for 69.5% and 75.3% of the variance of VO_{2max} in the ROW and RUN groups, respectively, suggesting that the FFT method estimated VO_{2max} well. Furthermore, the results also illustrated that FFT methods were more accurate in predicting VO_{2max} than the previous predictive equations when using the same submaximal programs in well-trained athletes. These findings indicate that the FFT method can be a fairly accurate option for obtaining VO_{2max} in well-trained athletes. Such submaximal tests can be more widely applied in the sports setting, such as in an individualized training or intervention approach, and during a repeated baseline testing setting.

Analysis of Estimated VO_{2max} Using the FFT Method

Novelty Analysis

Previous studies have developed several equations for predicting VO_{2max} when using submaximal programs in rowing or running exercise (Lakomy and Lakomy, 1993; Vehrs et al.,

TABLE 4 | Descriptive examination of the correlations and differences between other indirect methods and the measured VO_{2max}.

Methods	Reference	Predicted VO_{2max} ($mL·kg^{-1}·min^{-1}$)	CE ($mL·kg^{-1}·min^{-1}$)	*t*	*r*	ICC	MAE ($mL·kg^{-1}·min^{-1}$)	MAPE (%)
Equation 1	Klusiewicz et al., 2016							
	Male (*n* = 23)	65.7 ± 6.1	5.0 ± 5.6	4.310*	0.568*	0.427*	6.0 ± 4.5	10.3
	Female (*n* = 22)	59.5 ± 5.9	2.8 ± 3.5	3.701*	0.807*	0.723*	3.9 ± 2.3	6.9
	All (*n* = 45)	62.7 ± 6.7	3.9 ± 4.8	5.513*	0.721*	0.604*	5.0 ± 3.8	8.6
Equation 2	Marsh, 2012							
	Male (*n* = 29)	62.1 ± 2.8	-0.2 ± 2.8	-0.333	0.602*	0.600*	2.2 ± 1.7	3.5
	Female (*n* = 16)	57.8 ± 2.6	2.2 ± 4.5	1.954	0.125	0.099	3.6 ± 3.8	6.9
	All (*n* = 45)	60.6 ± 3.4	0.7 ± 3.7	1.238	0.655*	0.615*	2.7 ± 2.5	4.8
Equation 3	Marsh, 2012							
	Male (*n* = 29)	64.0 ± 3.5	1.7 ± 2.3	4.116*	0.787*	0.704*	2.3 ± 1.7	3.6
	Female (*n* = 16)	59.2 ± 3.4	3.6 ± 5.2	2.728*	0.008	0.006	4.8 ± 4.2	9.0
	All (*n* = 45)	62.3 ± 4.2	2.4 ± 3.7	4.352*	0.671*	0.586*	3.1 ± 3.0	5.6

CE, constant error, arithmetic mean of the difference between estimated and measured VO_{2max}; t, t value from paried sample t-test; r, pearson correlation coefficient; ICC, intraclass correlation coefficient; MAE, mean absolute error; and MAPE, mean absolute percentage error.
**Statistically significant ($P \leq 0.05$).*
Equation 1: VO_{2max} ($mL·kg^{-1}·min^{-1}$) in males = (3.2131 + 0.0076 × PWC170) / body mass, VO_{2max} ($mL·kg^{-1}·min^{-1}$) in females = (2.4138 + 0. × PWC170) / body mass.
Equation 2: VO_2 ($mL·kg^{-1}·min^{-1}$) = (speed ($m·min^{-1}$) × 0.2) + (gradient × speed ($m·min^{-1}$) × 0.9) + 3.5, where the estimated maximal speed was calculated as following steps, (1) linear regression was used based on steady-state heart rate values and running speed were obtained for each stage of the submaximal running test, (2) the linear line was then extrapolated to estimated maximal heart rate (220 – age) to determine the value of estimated maximal speed.
Equation 3: VO_{2max} ($mL·kg^{-1}·min^{-1}$) = VO_2-stage 4 + b (HRmax – HR-stage 4), where the VO_2-stage 4 was calculated based on the steady-state HR in stage 4 of the submaximal running test as the Eq. (2), HRmax refers to estimated maximal heart rate (220 – age), and the additional coefficient b is calculated from b = (VO2-stage 4 – VO2-stage 3) / (HR-stage 4 – HR-stage 3), which is the ratio of the difference between the estimated VO2 of last two stages of submaximal running test and corresponding change of steady-state heart rate.

2007; Akay et al., 2011; Kendall et al., 2012; De Brabandere et al., 2018). Kendall et al. (2012) found an accurate predictive equation [percentage of total error (%TE) = 5.1%, R^2 = 0.707, and %SEE = 4.6%] based on critical velocity and anaerobic rowing test trials. Other studies (Vehrs et al., 2007; Akay et al., 2011) also showed accurate equations for predicting VO_{2max} (r = 0.91, SEE = 2.54 $mL·kg^{-1}·min^{-1}$; r = 0.94, SEE = 1.80 $mL·kg^{-1}·min^{-1}$) using only the single-stage submaximal treadmill jogging test in healthy adults. However, these equations were developed for the nonathletic population and should be used with caution for well-trained athletes. The findings of this study revealed that the FFT method had a fairly accurate VO_{2max} estimation for well-trained rowers and paddlers and that the FFT method has been proven to accurately estimate VO_{2max} in nonathletic populations (college students, healthy adults, and recreational runners; Kraft and Roberts, 2017; Kraft and Dow, 2019; Passler et al., 2019). However, the rowing exercise program was not included. In the present study, the validity of the FFT method was verified in estimating VO_{2max} in well-trained rowers using a specific submaximal rowing test program.

Analysis of Comparison Between the FFT Method and Previous Predictive Equations

In the rowing program, although the results showed that the previous predictive equation (Eq. 1) by Klusiewicz et al. (2016) had a fairly accurate prediction of VO_{2max}, the FFT method showed even higher accuracy and lower error terms in all groups, as well as in both the male and female subgroups (**Table 4**). Interestingly, the estimated VO_{2max} from both the FFT method and Eq. 1 showed a significant overestimation of VO_{2max} (FFT, 1.3 ± 3.5 $mL·kg^{-1}·min^{-1}$; Eq. 1, 3.9 ± 4.8 $mL·kg^{-1}·min^{-1}$). Well-trained athletes have a lower HR at the same intensity than the nonathletic population and have a relatively higher predicted VO_{2max} value based on the linear regression model, which may be the main reason. In addition, the estimation of VO_{2max} from the FFT method in the female subgroup had a nonsignificant difference and a lower MAPE than that in the male subgroup, indicating that the FFT method may provide a more accurate estimation of VO_{2max} in female athletes than that in male athletes when using the rowing program.

In the running program, Marsh (2012) created two equations for estimating VO_{2max} that were suitable for different populations. The present study used these two equations to estimate VO_{2max} in well-trained athletes in the submaximal treadmill running program and found that they all had acceptable accuracy for the overall group. The two equations had similar validity coefficients and agreement levels. However, both equations showed poor accuracy in the female subgroup, which was probably due to the fact that these equations were cross-validated in male athletes instead of in female athletes in the study by Marsh (2012). Similar to the rowing program, the FFT method demonstrated a more accurate prediction of VO_{2max} than these two equations for the overall group. Additionally, the FFT method also had an accurate VO_{2max} estimation in the female subgroup, which was better than that from the two equations. The FFT method modifies equations in the software based on the relevant background variables (e.g., activity class, training zone, and HR variability) and then improves the accuracy of the VO_{2max} estimation, which could explain this phenomenon.

Analysis of Estimating Bias From the FFT Method

Sartor et al. (2013) have argued that many HR-based submaximal test programs are known to underestimate VO_{2max} because the workload is not high enough to promote adequate parasympathetic withdrawal and concomitant sympathetic activation. The tendency of underestimation was discovered in previous FFT-related studies (Anderson et al., 2019; Passler et al., 2019). Unlike those findings, this study found that the FFT method overestimated VO_{2max} in both the rowing and running programs. A pilot study to detect suitable workloads in submaximal programs may contribute to this phenomenon. Previous studies have indicated that individualized submaximal testing has been utilized in running (Vesterinen et al., 2017), rowing (Otter et al., 2015), and cycling (Lamberts et al., 2011), and high correlations have been found between power or speed at 90% HR_{max} and maximal endurance performance. Other studies also concluded that an optimal submaximal test program includes a proper target intensity, and different workloads for different characteristics may yield a more accurate prediction (Sartor et al., 2013). This study used workloads that may be close to maximal in some individuals, especially in the running program, which may overestimate VO_{2max}.

Practical Application of the FFT Method

Taken together, using the FFT method for VO_{2max} estimation has several practical advantages in the evaluation of aerobic capacity in well-trained athletes. First, only a wearable HR device is needed, and the HR data are recorded during the submaximal testing program available in the software; then, the estimated VO_{2max} value with acceptable accuracy would be automatically calculated. Additionally, the FFT method only requires submaximal tests, and multiple athletes can be tested simultaneously, making its use more feasible during the busy training schedule compared to the direct measurement method for VO_{2max} in the laboratory. Thus, the FFT method can be considered as a potentially convenient and cost-effective alternative to measure the maximal aerobic capacity of well-trained athletes, especially for rowing and running.

Analysis of Limitations

This study had some limitations. The first one is the lack of information regarding the underlying equation of VO_{2max} estimation for the reason that the exact equation can not be obtained from the company. Second, unlike rowers, the lack of sports event-specific testing (paddling ergometer) in paddlers may limit the applicability of the results. However, the running program was performed in this study for the reason that the achievement of VO_{2max} by treadmill running is consistent with paddling ergometer in well-trained paddlers (Augusto Rodrigues dos Santos et al., 2012). Nonetheless, further studies are needed to develop and investigate the predictive models of the FFT method based on submaximal rowing and running programs, not only in terms of validity but also reliability.

CONCLUSION

The results of the present study indicate that the FFT method provides a considerably accurate estimation of VO_{2max} in well-trained rowers, kayakers, and canoeists, which can be considered as a potentially convenient and cost-effective alternative to measure the maximal aerobic capacity of well-trained athletes, especially for rowing and running.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author/s.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Ethics Committee of Zhejiang Institute of Sports Science, Hangzhou, China. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

AUTHOR CONTRIBUTIONS

WG, HF, and QC performed the material preparation, and data collection and analysis. WG and O-PN wrote the draft of the manuscript. WG, O-PN, and XC conducted the revision. XC supervise the whole program. All authors contributed to the conception and design of this study and approved the final manuscript.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fphys.2021.701541/full#supplementary-material

Supplementary Table 1 | Submaximal FFT programs for both the ROW group and RUN group.

Supplementary Table 2 | GXT grograms for both the ROW group and RUN group.

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Differences in the Anthropometric and Physiological Profiles of Hungarian Male Rowers of Various Age Categories, Rankings and Career Lengths: Selection Problems

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Background: Little is known about the anthropometric and physiological profiles of lower-ranking athletes who aspire to rise to the pinnacle of their profession.

Aim: The aim of this study was to create anthropometric and physiological profiles of Hungarian male rowers of different age categories (15–16, 17–18, and over 18 years), sports rankings and career lengths.

Materials and Methods: Anthropometric and physiological profiles were created for 55 juniors, 52 older juniors and 23 seniors representing seven of the largest Hungarian rowing clubs. One-way independent analysis of variance (ANOVA) was used to compare arithmetic means.

Results: Rowers in older age categories were significantly taller (185.0 ± 5.0 cm vs. 183.0 ± 7.3 cm vs. 178.7 ± 7.2 cm) and heavier (81.1 ± 8.8 kg vs. 73.7 ± 8.4 kg vs. 66.8 ± 12.3 kg) than their younger peers, with significantly higher BMI values and larger body dimensions. Compared to younger athletes, rowers in older age categories also covered 2,000 m significantly faster (6.6 ± 0.3 min vs. 6.9 ± 0.4 min vs. 7.5 ± 0.5 min) while developing significantly more power (372.2 ± 53.0 W vs. 326.8 ± 54.5 W vs. 250.6 ± 44.6 W). Similarly, seniors and older juniors had higher values of maximal oxygen uptake and force max (by 6.2 and 7.0 ml/kg/min, and by 263.4 and 169.8 N). Within the older juniors, internationally ranked rowers had significantly greater body height (+ 5.9 cm), body mass (+ 6.1 kg), sitting height (+ 2.7 cm), arm span (+ 7.9 cm), limb length (+ 3.73 cm) and body surface area (+ 0.21 m^2). They also rowed 2,000 m significantly faster (–0.43 min, $p < 0.001$) and had significantly higher values of power (+ 58.3 W), relative power (+ 0.41 W/kg), jump height (+ 4.5 cm), speed max (+ 0.18 m/s) and force max (+ 163.22 N).

Conclusion: The study demonstrated that potential differences in anthropometric and physiological profiles are more difficult to capture in non-elite rowers, and that the final outcome may be determined by external factors. Therefore, athletes with superior aptitude for rowing are more difficult to select from among lower-ranking rowers, and further research is needed to determine specific training requirements to achieve the maximum rowing performance.

Keywords: rowing, age categories, ranking, seniority, anthropometric and physiological characteristics

INTRODUCTION

Rowing is a sport discipline that has been extensively studied (Shephard, 1998). Penichet-Tomás et al. (2019) defines it as a cyclic sport with a strength endurance nature in which successful performance depends on technical (Baudouin and Hawkins, 2004; Shaharudin and Agrawał, 2016), anthropometric/biomechanical (Bourgois et al., 2000; Battista et al., 2007; Alacid et al., 2011; Forjasz, 2011; Almeida-Neto et al., 2020) and physiological characteristics (Messonier et al., 1997; Slater et al., 2005; Mikulić, 2008; Jürimäe et al., 2010; Majumdar et al., 2017; Maciejewski et al., 2019).

Performing simulations of official competitions can be of great value for evaluating and advancing athletes' performance (Keenan et al., 2018; Penichet-Tomás et al., 2019). To improve rowing training methods and the selection of athletes with superior aptitude for the sport, it is useful to conduct both studies that assess the motor development of rowers and those that examine the relationship between rowers' anthropometric and physiological characteristics and the results that they obtain (Koutedakis, 1989; Lawton et al., 2011). The anthropometric characteristics of athletes often reflect the physiological, functional, and biomechanical demands of their specific sport as well as modifications associated with training and diet (Battista et al., 2007). However, as Mikulić (2008) points out, some characteristics (e.g., anthropometric length and breadth measurements) are almost exclusively genetically determined and can be difficult to change *via* training. Therefore, precise information regarding the anthropometric and physiological status of rowers is a fundamental issue in contemporary rowing.

In sports demanding high force production, muscle mass may be closely associated with performance outcomes (Peterson et al., 2006; Kavvoura et al., 2018). In these sports in general and in Olympic rowing in particular, greater fat-free body mass may favor increased performance in competition (Schranz et al., 2010; Penichet-Tomás et al., 2019). In addition, given the importance of force production, anthropometric variables (i.e., body mass, body height, length of legs and body span) and muscular strength endurance of the trunk and upper and lower limbs are also associated with rowing performance (Majumdar et al., 2017; Maciejewski et al., 2019).

Reports on the anthropometric characteristics of adult rowers (females and males) stress the importance of body mass (Secher and Vaage, 1983; Bourgois et al., 2000; Forjasz, 2011; Giroux et al., 2017; Maciejewski et al., 2019) and body size and proportions (Hebbelinck et al., 1980; Mikulić, 2008; Schranz et al., 2010; Majumdar et al., 2017; Penichet-Tomás et al., 2019) as determinants of success in rowing at the international level. A comparative study of male and female fixed-seat rowers revealed that body height was the best predictor of performance in male rowers, and muscle mass—in female rowers (Penichet-Tomas et al., 2021). This observation could suggest that high lean body mass and a favorable power-to-body mass ratio are better predictors of success than high body mass because increased body mass and BMI negatively impacted on career attainment (Winkert et al., 2019).

More detailed analyses have also taken other factors into account in relation to anthropometric and physiological characteristics and performances in motor tests and sport competitions. These factors include different rowing modalities, such as sliding seat or fixed seat rowing (Penichet-Tomás et al., 2019); different boat types, i.e., sweeping or sculling (Claessens et al., 2005); events, e.g., single scull, skiff, or coxless pair (De Larochelambert et al., 2020); position occupied in the boat (Lawton et al., 2011); weight category, i.e., heavyweight or lightweight (Steinacker, 1993); ranking, e.g., world and Olympic champions vs. club members and college/university rowers (Mikulić and Ružić, 2008); and age, e.g., juniors vs. older juniors vs. seniors (Mikulić, 2008). These analyses have shown that, in general, more successful rowers are typically taller and heavier than less successful ones (Bourgois et al., 2000). Junior rowers are generally similar to adult heavyweight rowers in stature, except that the juniors tend to be lighter (Mikulić, 2008). Physiologically speaking, elite rowers differ from their less successful peers in terms of a higher average VO_{2max}, and they typically have better technique, with a more efficient recovery phase (particularly with regard to the timing of forces at the catch), a faster stroke rate and a stronger, more consistent and effective propulsive stroke (Hagerman, 1984; Smith and Spinks, 1995; Hofmijster et al., 2007; Lawton et al., 2011). If all other factors are equal, rowers who can maintain greater net propulsive forces will achieve faster boat speeds (Smith and Spinks, 1995; Lawton et al., 2011).

In addition to size and physique, relative body proportions are important in rowing, in particular relative arm length and leg length (Claessens et al., 2005). A report comparing medalists and non-medalists at world championships indicated that the more successful lightweight rowers were more mesomorphic and less endomorphic and tended to have a shorter sitting height and longer upper and lower extremities (Rodriguez, 1986), which increase biomechanical efficiency. These findings are consistent with those of reports on heavyweight rowers (Kleshnev and Kleshnev, 1998; Shephard, 1998). Proportionally longer arms and legs not only correspond to a larger size but also give sweep rowers a biomechanical advantage due to the increased length of the levers (Piotrowski et al., 1992; Skład et al., 1993, 1994; Claessens et al., 2005; Penichet-Tomás et al., 2019). The best younger oarsmen also tend to be taller and heavier and have greater length, breadth and girth than their less successful peers (Bourgois et al., 2000; Mikulić, 2008; Forjasz, 2011).

A 2,000 m Olympic rowing competition requires a mixture of aerobic and anaerobic power (Wolf, 2016). These events require maximum exertion for a duration of five to 7 min (Steinacker et al., 1986). During this time, the relative anaerobic contribution ranges from 21 to 30% (Secher, 1993), which means that, in addition to a large aerobic capacity, a highly developed anaerobic capacity is also essential for successful international performance (Hagerman, 1984; Mäestu et al., 2005).

In general, rowing imposes heavy physiological demands, requiring a high degree of power and endurance, and a successful performance also requires a high level of technical proficiency (Secher, 1990; Keenan et al., 2018). According to Jurišić et al. (2014), aerobic metabolism provides 75–80% of the energetic demands during a rowing competition. Thus, as would be expected, elite rowers display impressive aerobic capacities: the VO_{2max} of internationally successful rowers regularly exceeds 5 l/min, it exceeds 6.0 l/min fairly often, and it sometimes reaches or exceeds 6.5–7.0 l/min at ventilation values above 240 l/min (Secher, 1993; Steinacker, 1993; Jurišić et al., 2014).

In sliding-seat Olympic rowing, around 75–80% of the power produced by successful elite rowers during a rowing stroke comes from their legs, and around 20–25% from their arms (Cosgrove et al., 1999). Various researchers have mentioned the ability of rowers to tolerate relatively high lactic acid (LA) concentrations during both rowing (Steinacker et al., 1999; Jürimäe et al., 2000) and leg press exercises that were conducted at individual physical working capacity (PWC) (calculated as heart rate (HR) 205–1/2 age) (Jürimäe et al., 2010). During the leg press exercise test, the subjects achieved a mean of 113.4 ± 38.5 repetitions with a mean duration of 450.2 ± 99.1 s, a mean HR of 137.4 ± 14.2 beats min^{-1}, and a mean LA concentration of 7.62 ± 2.83 mmol l^{-1}. The practical significance of these findings is that rowing exercise should stimulate increased oxygen uptake and raise the threshold (in terms of percentage of maximum oxygen uptake) at which blood LA concentration begins to increase substantially (Jurišić et al., 2014).

A review of the literature indicates that most published studies described the profiles of highly successful athletes and/or compared them with the profiles of lower-ranking rowers. Meanwhile, variables such as age category, ranking and length of the sports career have been explored by very few researchers. Moreover, there is a general scarcity of studies that approach the subject in a comprehensive manner and analyze intermediate rowers who have not yet achieved international success. Therefore, it remains unknown whether endogenous factors (anthropometric and physiological characteristics) determine the success of intermediate level athletes, or whether other external factors (such as organizational factors) also play a role. Trainers working with intermediate rowers could find it more difficult to capture minor differences in the anthropometric and physiological profiles of athletes that differ in ranking and career length. As a result, the elements of the training program may not be adapted to specific training goals, which can undermine the program's effectiveness. It should also be noted that the number of athletes characterized by lower rowing performance is much higher than the number of elite athletes who win the most prestigious rowing championships. Hungarian rowers belong to the latter group. Only one Hungarian rower qualified for the Tokyo 2021 Olympic Games in Tokyo, and he ultimately came tenth in the men's single scull category. Therefore, this study had two objectives: (a) to develop anthropometric and physiological profiles of Hungarian male rowers belonging to different age categories (15–16, 17–18, and over 18 years), had different sports rankings (international vs. club) and different career lengths (seniority levels); (b) to identify and explain potential differences between the analyzed groups of athletes who do not represent the highest level of rowing performance.

MATERIALS AND METHODS

Participants

The study was conducted in Gyor rowing club, and the sample consisted of 130 male rowers from the seven largest Hungarian rowing clubs. The study lasted for three consecutive days in the middle of the racing season (8 days after one rowing regatta and 7 days before the next rowing regatta). The participants were selected by targeted sampling (based on the researchers' arbitrary decision), and all rowers from the seven clubs were analyzed in the sampling process. The participants differed in ranking and length of sports career. Each rower was assigned to one of the three age categories: juniors ($N = 55$, range: 15–16 years), older juniors ($N = 52$, range 17–18 years), and seniors ($N = 23$; over 18 years). The senior group was relatively young, and the oldest senior rower was only 22. The following inclusion criteria were applied in the targeted sampling procedure: rowers in all age groups had to hold a valid competition license and participate in national and/or international competitions for minimum 1 year. All rowers had valid medical certificates; they participated regularly in training, and they did not limit their physical activity levels (for whatever reason) to the extent that could significantly affect their motor fitness. The training program was consistent with the guidelines of the Hungarian Rowing Federation Training Plan: 12–13 h/week for 15- to 16-year-olds, 14–15 h/week for 17- to 18-year-olds, and 16–17 h/week for 19- to 22-year-olds. The aerobic-to-anaerobic training ratio in the above groups was 80:20%, 75:25 and 70:30%, respectively. Athletes with an international ranking participated in training camps organized by the Hungarian Rowing Federation two to three times a year (depending on age group). It was hypothesized that the anthropometric and physiological characteristics of the rowers, as well their performance while rowing a 2,000 m distance and on motor tests would differ depending on their age, ranking, and length of sports career.

This research was conducted in line with the guidelines and policies of the Health Science Council, Scientific and Research Ethics Committee (IV/3067-3/2021/EKU), Hungary, and in accordance with the Declaration of Helsinki. Each participant was provided with detailed information about the purpose of the study, potential risks, measurement methods, and the techniques in motor tests that could be practiced during training sessions held directly before the study. All rowers gave voluntary informed consent to participate in the study by signing consent forms.

Procedures, Data Collection and Equipment

Each rower was subjected to anthropometric and physiological tests in the middle of the 2020 racing season. On day one, anthropometric features were measured, on day two, the athletes performed motor tests, and on day three, they covered a distance of 2,000 m.

The coaches in charge of the rowers in the sports clubs helped us with the measurements. At all times, the coaches were instructed not to engage the subjects in any strenuous training the day before the testing took place. Each subject was always tested in the morning and the participants were instructed to eat a light meal (800–1,200 kcals) containing mainly carbohydrates (60–70%) not later than 3–4 h before the study (Williams, 1999). Body height was measured to the nearest 1 mm with a calibrated Soehlne Electronic Height Rod 5003 (Soehlne Professional, Germany) according to standardized guidelines. Body mass (measured to the nearest 0.1 kg), BMI and body composition characteristics, such as body fat percentage (BFP) and skeletal muscle mass (SMM), were determined by bioelectrical impedance with an InBody 720 body composition analyzer. The remaining anthropometric characteristics, such as sitting height [cm], arm span [cm], limb length [cm] and BSA [m^2], were measured with the use of the Weiner and Lourie (1969). Skin fold measurements (biceps, triceps, scapula, suprailiac, abdomen, thigh, lower leg) were obtained using a Harpenden caliper.

Estimation of Relative Body Fat Content

The calipermetric estimation of relative body fat content that was developed by Parízková (1961) was used. This procedure requires the measurement of five skinfold thicknesses: over the biceps and triceps, subscapular, suprailiac and medial calf. The sum of the five skinfold values is multiplied by 2; the product is then used to look up the estimated relative body fat content in a table.

Countermovement Jumping

The power output of the lower extremities and the height attained by the center of body mass during vertical jumps were measured with a PJS-4P60S force plate ("JBA" Zb. Staniak, Poland) with a 400 Hz sampling rate (Gajewski et al., 2018; Batra et al., 2021). The force plate was connected *via* an analog-to-digital converter to a PC with MVJ v.3.4 software ("JBA" Zb. Staniak, Poland). The amplifier was connected to a PC *via* an A/D converter. Measurements were performed using the MVJ v. 3.4 software package ("JBA" Zb. Staniak, Poland). In the physical model that was used for calculations, the subject's body mass was treated as a point affected by the vertical components of external forces: the force of gravity acting on the body and the vertical component of the platform's reactive force. Each subject performed three counter-movement jumps (CMJ) with maximal force. A CMJ is a vertical jump from a standing erect position, preceded by a counter- movement of the upper limbs and lowering of the body mass center before take-off. Each subject was asked to perform a countermovement jump from the force plate to determine maximal force [N] and the rate of displacement [m/s]. From these measurements, jump height (by integrating ground reaction forces) [cm] and peak power [W] were determined. Using the body mass of the subject, the relative peak power [W/kg] was calculated.

2,000 m Maximal Rowing Ergometer Test

The participants were asked to perform an all-out 2,000 m test a certified rowing ergometer (Concept 2 D-model). The screen of the ergometer was set to display the number of meters remaining, the average 500 m time and the accumulated time.

The power output in watts (W) was measured over 2,000 m. The calculation of watts was performed as follows: First, the distance was defined: distance = (time/number of strokes) × 500. In the next step, the concept of a "split" was clarified: split = 500 × (time/distance). The watts were calculated as 2.8/(split/500). There were slight differences in intensity due to individual changes in stroke value and ability to keep the 500 m split time constant. Prior to all tests, each participant warmed up for 6 min on a 500 m distance. Participants then rested for 6 min, during which time they performed stretching exercises. The estimated relative aerobic capacity ($ErVO_2$) was calculated by using the formula of McArdle et al. (2007) for men: $ErVO2 = (Y \times 1000)/BM$, where BM is body mass, and $Y = [BM < 75\ kg; 15.1- (1.5 \times time)]; BM = > 75\ kg; 15.7- (1.5 \times time)]$. The power delivered over 2,000 m was divided by body weight to obtain the relative performance (rW 2k).

Due to time and logistical constraints, including the need to perform a relatively high number of separate measurements within three consecutive days in a specific club to minimize disturbances to the athletes' training and changes in their condition, this study did not examine heart rates (HR) and all indicators of acid-base balance, such as the concentration of lactic acid in the blood, alkaline deficiency or excess, blood pH and current molecular pressure of CO_2.

Statistical Analysis

Measurements were statistically processed with Statistica PL, v. 13.5. Based on the median length of participation in rowing competitions (juniors, 3 years; older juniors, 5 years; seniors, 7 years), the athletes in each age category were further divided into two subcategories: greater and lesser seniority. The rowers were ranked as international (participants in international competitions) or club (participants in inter-club competitions at the national level) level. Normality was verified with the Shapiro–Wilk test. It was checked that all tested features have normal distributions. Therefore, for comparisons of two arithmetic means, Student's *t*-test was used. To compare three arithmetic means, one-way analysis of variance (ANOVA) was used. If ANOVA indicated a significant difference, Tukey's Honestly Significant Difference (HSD) test was used for *post hoc* analysis. Cohen's d was used as a measure of the effect size of differences between male and female rowers, and it interpreted according to the modified thresholds (Cohen, 1988) for sports sciences (Hopkins, 2016) as trivial (0.2), small (0.21–0.6), moderate (0.61–1.2), large (1.2–1.99) and very large (>2.0). Statistical significance was set at $p \leq 0.05$.

RESULTS

Analysis 1: Anthropometric and Physiological Characteristics

Table 1 presents the anthropometric characteristics, body composition, motor performance and physiological characteristics of the male rowers in the following age categories: juniors (15–16 years), older juniors (17–18 years) and seniors (18–22 years). Senior and older junior rowers were significantly larger than junior rowers in terms of height and body mass (height: + 6.25 and 4.32 cm, respectively; body mass: 14.32 and 6.88 kg; *p*-values for all comparisons are given in **Table 1**) with a moderate to large effect size. Seniors were also significantly heavier than older juniors (+ 7.44 kg; $p = 0.011$) with a moderate effect size. Regarding BFP, seniors had a significantly higher value than juniors and older juniors (+ 4.28 and + 3.83%, respectively; $p = 0.006$ and $p = 0.014$, respectively) with a moderate effect size. FFM did not differ significantly between these groups. Although older groups had significantly higher BMI than younger groups, the values of all groups were within the norms (20.8–23.72 kg/m^2) with a moderate to large effect size. Sitting height and arm span were significantly less in the youngest group than in the other two groups (for both comparisons, $p < 0.001$), but these measurements did not differ significantly between the older juniors and the seniors. Body surface area was also significantly larger in older groups than in younger groups (*p*-values ranged from $p = 0.017$ to $p < 0.001$), and the effect size ranged from 0.8 to 1.3, but the groups did not differ significantly in terms of limb length, skin fold thickness or body fat measured by Pařízková's formula.

The seniors covered the 2,000 m distance in a significantly shorter time than the older juniors and juniors (respective differences: 0.31 min and 0.95 min; $p = 0.019$ and $p < 0.001$; $d = 0.8$ and $d = 2.0$), and older juniors covered this distance 0.64 min faster than juniors ($p < 0.001$) with a large effect size ($d = 1.4$). The peak power that was generated also differed significantly between these groups: seniors generated 45.4 W more than older juniors and 121.7 W more than juniors ($p = 0.002$ and $p < 0.001$; $d = 0.8$ and $d = 2.6$, respectively); older juniors surpassed juniors by 76.3 W ($p < 0.001$). Senior and older junior rowers also had significantly higher maximal oxygen uptake than juniors (by 6.2 and 7.0 ml/kg/min; $p = 0.002$ and $p < 0.001$; $d = 0.5$ and $d = 0.9$, respectively) and force max (by 263.4 and 169.8 N; $p < 0.001$ and $p = 0.009$; respectively). In terms of jump height, speed max and relative peak power (RPM), seniors and older juniors did not differ significantly, but these values were significantly lower in the juniors than in the older juniors (by 4.57 cm, 0.15 m/s, 3.98 W/kg; $p < 0.001$, $p = 0.003$ and $p = 0.006$; $d = 0.8$ and $d = 0.55$, respectively).

Analysis 2: Ranking of Rowers

In the groups of older juniors and juniors, significant differences in the studied characteristics were associated with differences in ranking (club vs. international). The older juniors had the larger number of significant differences between these ranking categories (**Table 2**). In this age group, the internationally ranked rowers were significantly taller (+ 5.88 cm, $p = 0.0027$) and heavier (+ 6.1 kg, $p = 0.0078$), and they had a longer sitting height (+ 2.67 cm, $p = 0.0058$), arm span (+ 7.90 cm, $p = 0.0051$), limb length (+ 3.73 cm, $p = 0.0058$), and BSA (+ 0.21 m^2, $p = 0.0028$). Rowers in the older junior category with an international ranking were significantly taller (+ 5.88 cm, $p = 0.0027$) and heavier (+ 6.1 kg, $p = 0.0078$) than their club level peers, and they had a longer sitting height (+ 2.67 cm, $p = 0.0058$), arm span (+ 7.90 cm, $p = 0.0051$), and limb length (+ 3.73 cm, $p = 0.0058$), as well as a larger BSA (+ 0.21 m^2, $p = 0.0028$) with a moderate to large effect size. In addition, they covered the 2,000 m distance in significantly less time (−0.429 min, $p < 0.0001$) and developed greater peak power (+ 58.3 W, $p < 0.0001$) and relative peak power (+ 0.41 W/kg, $p = 0.0037$) with a moderate to large effect size. In motor tests, they obtained higher jump height (+ 4.5 cm, $p = 0.0325$), speed max (+ 0.178 m/s, $p = 0.0255$), and force max (+ 163.22 N, $p = 0.0373$) with a moderate effect size.

Regarding the juniors, two of their characteristics differed significantly between the ranking categories: international level juniors achieved higher power (+ 29.91 W, $p = 0.0274$) and covered 2,000 m in a shorter time (−0.342 min, $p = 0.0271$). These groups also differed in terms of some other characteristics, although the differences were not statistically significant.

Analysis 3: Length of Rowers' Sports Careers

In all age categories, the length of the athletes' sports career was not associated with significant differences in anthropometric characteristics, body components, results of motor performance tests, and time to complete a 2,000 m distance ($p > 0.05$) with a trivial to small effect size. The only exception was the level of adipose tissue in lower leg skin, which was significantly higher (difference: + 3.48 mm, $p = 0.044$) in the group of rowers that had competed for a shorter time, which is probably due to chance. Interestingly, however, even though the differences were not statistically significant, senior and older junior rowers tended to have higher body mass (+ 1.40 kg and + 2.68 kg, respectively), fat percentage (+1.86% and +0.71%, respectively), and BMI (+ 0.61 kg/m^2 and 1.45 kg/m^2, respectively).

DISCUSSION

Anthropometric and Body Composition Profiles

Rowers in specific age categories were assessed in terms of skeletal structure (body height, body mass, sitting height, arm span, limb length, BMI, BSA), body composition (BFP, SMM) and thickness of skin folds (biceps, triceps, scapula, suprailiac, abdomen, thigh, lower leg). It was found that rowers in older

TABLE 1 | Comparison of arithmetic means of men's anthropometric, physiological and motoric parameters depending on the age categories.

Characteristics	Age category [years]									Difference		HSD *p*-value (*post hoc*)			Cohen's *d*		
	15–16 (*N* = 55)			17–18 (*N* = 52)			19–22 (*N* = 23)										
	Mean	SD	Min-max	Mean	SD	Min-max	Mean	SD	Min-max	*F*	*p*	1–2	2–3	1–3	1–2	2–3	1–3
Body height [cm]	178.70	7.22	162.1–193.4	183.02	7.27	167.7–197.4	184.96	4.98	174.4–194.0	8.66	<0.001	0.004	*ns*	<0.001	0.66	0.16	1.11
Body mass [kg]	66.82	12.27	39.6–115.0	73.70	8.43	56.6–89.7	81.14	8.80	62.1–100.0	16.72	<0.001	0.002	0.011	<0.001	0.66	0.86	1.34
Body fat [%]	12.39	5.54	4.0–28.9	12.84	5.39	5.3–33.0	16.67	4.33	9.4–22.9	5.38	0.006	*ns*	0.014	0.006	0.07	0.84	0.79
Skeletal muscle mass [%]	41.90	5.04	14.1–52.6	43.30	3.47	27.2–49.2	41.12	3.83	29.9–46.6	2.50	*ns*	*ns*	*ns*	*ns*	0.32	0.60	0.42
BMI [kg/m^2]	20.82	2.97	15.02–31.00	21.98	2.10	18.28–29.47	23.72	2.43	18.28–27.88	10.63	<0.001	0.049	0.018	<0.001	0.42	0.64	0.90
Sitting height [cm]	92.50	4.60	79.4–100.3	95.33	3.56	87.5–105.1	96.56	2.04	93.9–100.1	11.87	<0.001	<0.001	*ns*	<0.001	0.67	0.40	1.00
Arm span [cm]	181.13	13.00	104.3–196.0	188.43	8.56	168.5–203.0	189.29	5.53	179.7–197.5	8.58	<0.001	<0.001	*ns*	0.004	0.66	0.12	0.71
Limb length [cm]	101.01	4.07	92.1–111.0	102.40	4.98	90.3–111.4	103.02	3.98	96.5–113.8	2.14	*ns*	*ns*	*ns*	*ns*	0.29	0.13	0.20
BSA [m^2]	1.67	0.36	0.89–3.08	1.88	0.26	1.32–2.31	2.09	0.25	1.50–2.63	16.87	<0.001	<0.001	0.017	<0.001	0.69	0.80	1.25
Skin fold thickness [mm] *Biceps*	7.04	3.57	2–20	5.69	3.13	3–21	5.96	2.69	3–12	2.44	*ns*	*ns*	*ns*	*ns*	0.39	0.08	0.32
Triceps	14.16	5.66	5–29	12.08	4.50	5–26	12.65	4.57	5–20	2.36	*ns*	*ns*	*ns*	*ns*	0.39	0.12	0.28
Scapula	10.96	4.57	4–31	9.96	3.16	6–23	10.70	3.48	3–18	0.91	*ns*	*ns*	*ns*	*ns*	0.37	0.11	0.35
Suprailiac	9.95	5.66	4–33	8.26	3.76	4–21	8.52	2.29	5–13	2.04	*ns*	*ns*	*ns*	*ns*	0.40	0.20	0.26
Abdomen	14.06	6.89	5-42	12.29	4.81	5-26	12.48	3.82	7-22	1.44	*ns*	*ns*	*ns*	*ns*	0.28	1.12	0.30
Thigh	20.36	7.84	6-46	18.45	7.54	7-39	18.48	6.01	4-29	1.04	*ns*	*ns*	*ns*	*ns*	0.31	0.14	0.27
Lowerleg	14.07	6.27	4-30	12.31	5.99	5-30	13.39	4.46	4-22	1.18	*ns*	*ns*	*ns*	*ns*	0.29	0.18	0.31
Body fat [%] *)	23.03	4.04	13.8-31.5	21.86	4.14	14.5-30.9	22.43	3.62	12.2-26.6	1.13	*ns*	*ns*	*ns*	*ns*	0.22	0.14	0.15
Peak power [W]	250.55	44.60	138-322	326.80	54.48	210-435	372.22	52.96	292-461	54.99	<0.001	<0.001	0.002	<0.001	0.47	0.84	2.56
RPP [W/kg]	3.76	0.53	2.11-4.71	4.42	0.51	3.10-5.31	4.59	0.45	3.57-5.35	30.74	<0.001	<0.001	*ns*	<0.001	1.26	0.34	1.62
Time 2,000 m [min]	7.51	0.51	6.85–9.09	6.87	0.41	6.20–7.90	6.56	0.32	6.08–7.08	46.61	<0.001	<0.001	0.019	<0.001	1.35	0.79	2.02
ErVO_2 max [mL/kg/min]	66.43	9.49	38.32–82.47	73.44	6.31	56.69–88.19	72.61	5.59	60.76–84.99	11.59	<0.001	<0.001	*ns*	0.005	0.87	0.75	0.54
Jump height [cm]	36.02	4.97	23.5–44.4	40.59	7.62	24.7–58.9	38.44	6.31	22.9–51.0	6.86	0.001	<0.001	*ns*	*ns*	0.71	0.30	0.54
Speed max [m/s]	2.59	0.19	2.06–2.91	2.74	0.29	1.97–3.33	2.66	0.24	2.08–3.09	5.43	0.005	0.003	*ns*	*ns*	0.40	0.14	0.34
Force max [N]	1, 551.35	323.58	899–2,317	1, 721.19	283.77	1,180–2,712	1,814.74	272.22	1,328–2,548	7.75	<0.001	0.009	*ns*	0.001	0.55	0.33	0.84
RPM [W/kg]	48.43	5.69	34.8–60.9	52.41	7.88	30.2–63.4	49.39	6.04	36.3–63.2	4.90	0.009	0.006	*ns*	*ns*	0.58	0.40	0.17

**) Pařízková's formula; ns, not statistically significant; RPP, relative peak power; RPM, relative maximal power; ErVO_2, estimated relative maximal aerobic capacity; Cohen's d, effect size.*

TABLE 2 | Comparison of arithmetic means of older junior male rowers anthropometric, physiological and motoric parameters depending on the ranking categories.

Characteristics	Ranking category				Difference		Cohen's *d*
	International (*N* = 24)		Club (*N* = 28)				
	Mean	SD	Mean	SD	*t*	*p*	
Body height [cm]	186.18	5.23	180.30	7.74	3.15	0.003	0.97
Body mass [kg]	76.98	6.23	70.88	9.13	2.77	0.008	0.79
Sitting height [cm]	96.77	3.24	94.10	3.40	2.88	0.006	0.83
Arm span [cm]	192.68	6.04	184.78	8.79	3.71	0.001	1.19
Limb length [cm]	104.41	3.96	100.68	5.18	2.88	0.006	0.80
BSA [m^2]	1.99	0.19	1.78	0.28	3.14	0.003	0.88
Peak power [W]	356.54	41.38	298.24	50.60	4.40	< 0.001	1.26
RPP [W/kg]	4.63	0.42	4.22	0.52	3.05	0.004	0.87
Time 2,000 m [min]	6.65	0.27	7.08	0.41	−4.30	< 0.001	1.24
Jump height [cm]	43.01	6.04	38.51	8.31	2.20	0.033	0.62
Speed max [m/s]	2.84	0.21	2.66	0.32	2.30	0.026	0.67
Force max [N]	1, 809.08	249.97	1, 645.86	293.47	2.14	0.037	0.61

age categories had higher body mass, BMI, and BSA than their younger peers. Compared to the juniors, seniors and older juniors had greater body height, sitting height, and arm span. These results are similar to those of a study of Croatian rowers by Mikulić (2008). In that study, Croatian champions and members of the Croatian national team were classified into elite seniors (28.1 ± 3.0 years), sub-elite juniors (22.16 ± 2.8 years), and elite juniors (17.6 ± 0.4 years). They found that the elite seniors were taller and heavier than the sub-elite juniors (+ 5.4 cm, 4.3 kg) and the juniors (+ 5.1 cm, + 11.1 kg).

Rowers with larger body dimensions (body mass, body height, length of lower and upper extremities) achieve proportionally better rowing performances (Cosgrove et al., 1999; Yoshiga and Higuchi, 2003; Mikulić, 2008). This is probably the reason why, in the present study, the seniors and older juniors, who had larger body dimensions than the juniors, covered 2,000 m faster and developed more peak power, RPP and force max over this distance, while achieving a higher $ErVO_{2max}$. However, with regard to jump height, speed max, and RPM, only the older juniors differed significantly from the juniors.

Hungarian rowers in the senior age group had significantly higher values of BFP than older juniors and juniors. A similar phenomenon was observed in Croatian elite rowers, where BFP was lower in the juniors than in the elite and sub-elite seniors, although no difference was observed between the two groups of seniors (Mikulić, 2008). Similar differences were found in Belgian rowers: compared to non-finalists, finalists were heavier and taller with greater length, breadth (expect for the bicristal diameter), and girth (Bourgois et al., 2000).

In the present study, many of the differences in anthropometric characteristics between the international and club level rowers were not statistically significant. These results are properly interpreted as inconclusive, as explained by the guidelines of the American Statistical Association (Wasserstein and Lazar, 2016) and many other experts (e.g., Greenland et al., 2016; Amrhein et al., 2017). Therefore, the present results are not necessarily in disagreement with the findings of Secher (1975), who found that the body mass of internationally competitive rowers was greater than that of club rowers, or the results of Penichet-Tomás et al. (2019), who reported that higher-performing rowers had significantly larger anthropomorphic measurements than lower-performing ones. Our assumptions were confirmed by the fact that all of the examined rowers were only aspiring to become elite performers, and none of them was a finalist of prestigious rowing regattas. In addition, the senior group was relatively young (19–22 years), whereas the average age of male and female single scullers in the Olympic finals has risen by roughly 7 years, from around 24–31 (World Rowing, 2015). The above can be attributed to the fact that elite rowers' efficiency remained stable because their oxygen uptake at 300 W was similar at the ages of 25 and 31. Some elite rowers, such as Steven Redgrave and Eskild Ebbesen, won their last Olympic titles at the age of 38 and 40, respectively (Nybo et al., 2014). Thus, it would be interesting to perform another study with a different sample of Hungarian rowers or measure the same individuals in the following years to see if the differences between the groups being compared would continue to be statistically non-significant when taking rankings and length of sporting career into account. The only exception was the group of older juniors, where significant differences in anthropometric and physiological characteristics were noted between rowers with international and club rankings, and where the studied parameters were more favorable in the former category of athletes. There are several reasons why older juniors with an international ranking had an advantage over their peers with a club ranking. Firstly, these athletes had participated in the highest number of training camps (qualification rounds) during the selection of the Hungarian national team. Secondly, they were most successful in rowing events, both in terms of the scored results and the rank of rowing regattas.

The mean body mass of the senior rowers in this study (81.14 kg) is similar to that of the elite Olympic rowers measured by Forjasz (2011), which ranged from 80 to 85 kg. The Hungarian senior rowers in the present study had a mean height of 184.96 ± 4.98 cm, which is also very similar to what Forjasz (2011) measured.

In the present study, the differences in FFM between age categories were not statistically conclusive. However, Mikulić (2008) found that FFM was greater in elite seniors than in elite juniors (+ 6.1 kg). Moreover, rowing performance has generally been found to correspond closely to FFM values (Cosgrove et al., 1999; Yoshiga et al., 2000), and FFM is considered one of the best predictors of performance (Ingham et al., 2002; Riechman et al., 2002). Thus, it would be interesting to investigate the FFM of Hungarian rowers with a different sample, and perhaps combine those results with the results of this study *via* statistical meta-analysis.

For rowers, BMI values of approx. 24 kg/m^2 are considered optimal olympic rowing (Barrett and Manning, 2004; Claessens et al., 2005; Sanada et al., 2009), but the BMI of traditional rowers is sometimes higher (Penichet-Tomas et al., 2021). The mean BMI value of the elite seniors in the present study (23.72 kg/m^2) was very close to this benchmark, while those of all the other rowers were within normal limits (range: 20.82–23.72 kg/m^2). However, when considering these results, it is important to remember that the BMI does not give reliable information about the body composition of sports athletes and does not allow an important distinction to be made between the distribution of fat and muscle tissue in the lower and upper half of the body (Garrido-Chamorro et al., 2009; Mazić et al., 2009).

Physiological and Motor Performance Profile

The results of the study presented here support the conclusion of Jurišić et al. (2014) that aerobic metabolism predominantly determines success in a 2,000 m rowing race on a simulator. Although lactate anaerobic threshold was not assessed in this study, older rowers finished the 2,000 m simulation in significantly less time than their younger counterparts while attaining higher values of $ErVO_{2max}$ and RPP. In addition, the older rowers developed significantly more power than their younger peers, and the seniors and older juniors developed significantly higher force max values than the juniors although the difference between the seniors and older juniors was not statistically significant.

The mean VO_{2max} values of the junior, older junior and senior Hungarian rowers examined in the present study were higher than those reported for Croatian rowers (Mikulić, 2008) (66.43, 73.44, and 72.61 mLmin^{-1} kg^{-1} vs. 62.5, 55.3, and 58.4 mLmin^{-1} kg^{-1}, respectively). When combining all these results with those of a study of Croatian 12–13-year-old rowers (VO_{2max}: 48.8 mLmin^{-1} kg^{-1}) (Mikulić and Ružić, 2008), it appears that there is a general trend of VO_{2max} values increasing during the early years of training when rowers are at younger ages. This increase could be due in part to the fact that the growth processes of men continue up to 21 years of age, and these processes contribute substantially to rowing performance (Almeida-Neto et al., 2020). However, an analysis of changes in the maximal oxygen uptake at certain ages of Polish male rowers showed substantial improvement at 19–19.9 and 21–22 years (Klusiewicz et al., 2014). Maximal oxygen uptake, which is the gold standard for cardiorespiratory fitness, is a multifactorial trait influenced by environmental factors (e.g., exercise training) and genetic factors (Rankinen, 2011; Mann et al., 2014; Williams et al., 2017). However, improvements in cardiorespiratory fitness in response to exercise training vary greatly between individuals, with some people responding well or very well ("responders" or "high-responders") to exercise training, whereas others do not respond so well following similar exercise training (Mori et al., 2009; Bouchard et al., 2015; Williams et al., 2017).

Finally, it should be remembered that the differences in performance between these Hungarian, Croatian and Polish rowers may also be due to variations in the conditions in which they were tested. Visual and verbal feedback may be factors that can substantially improve rowing performance over 2,000 m (Stine et al., 2019).

In conclusion, these results for Hungarian rowers are in line with those of the previous studies cited in the introduction of this paper that suggest that a rower's height and length are proportional to his/her level of rowing performance (e.g., Yoshiga and Higuchi, 2003; Mikulić, 2008). In the future, different age categories should be compared to optimize training outcomes in rowers. On the one hand, a clear improvement in the performance of Hungarian male rowers transitioning to an older age category could indicate that the selected training methods are adequate. However, minor differences in the anthropometric and physiological profiles of rowers with a different ranking and different career length could imply that the selection of training approaches is not optimal, which suggests that other measures are needed to fully tap the performers' potential in this stage of the training process. For example, to achieve high-level rowing performance, the training program of rowers should include the development of strength and endurance capacity with the aim of increasing muscle mass, aerobic capacity and metabolic efficiency, and decreasing percent body fat (Lakomy and Lakomy, 1993; Warmenhoven et al., 2018; Durkalec-Michalski et al., 2019). Such activities are an indispensable part of the selection process, and they could be lacking among Hungarian rowers in the preparation process.

The lack of significant differences in individual age categories when variables such as ranking and competition seniority were taken into account stands in contrast to numerous studies conducted by other authors. However, these authors compared the finalists of major rowing events with intermediate rowers. Meanwhile, the examined group of Hungarian rowers had both club and international ranking, but the latter had not scored spectacular success in the international arena. As a result, the analyzed population was less diverse in terms of anthropometric and physiological profiles, and potential differences were much more difficult to capture. From the practical point of view, trainers may find it difficult to select the most promising rowers because the final result can be influenced by external factors (organizational, financial or motivational) that are not directly linked with endogenous factors (anthropometric and physiological characteristics).

In our opinion, this is one of the first studies to address this issue, but definitive conclusions cannot be drawn at this stage of research, which is why further studies of Hungarian rowers spanning a longer period of time are needed.

Strengths and Limitations

This paper makes a novel contribution to the literature by providing information about the anthropometric and physiological characteristics of Hungarian rowers who are relatively young and are only aspiring to become elite athletes. This study makes the first ever attempt to capture differences in the anthropometric and physiological characteristics of intermediate rowers. In our opinion, the above fact is a definite strength of the study because the number of non-elite athletes significantly exceeds the number of rowing champions who constitute a relatively small group. This approach contributes to the novelty of our study, but our findings are difficult to compare with those reported by other authors due to the general lack of research addressing intermediate athletes. The size of the analyzed sample was relatively large in comparison with similar studies (Mikulić, 2008; Klusiewicz et al., 2014); therefore, the formulated conclusions can be viewed with a relatively high degree of confidence.

The fact that HR values (minimum, average and maximum) and lactate anaerobic threshold values could not be included in the study because measurements were performed within a timeframe of three consecutive days is a limitation of this study. Despite the above, the study generated valuable insights about differences between age categories, including measurements of VO_{2max} values which are considered the gold standard for cardiorespiratory fitness. To complement our findings, acid-base balance indicators, including blood pH, partial pressure of CO2 in arterial blood (pCO2), HCO_3^- ion concentration, and alkaline deficiency or excess (BE), should be examined in the future. Repeated measurements involving the same athletes during different training periods could also generate interesting results.

CONCLUSION

Hungarian rowers in older age categories have higher values of anthropometric and physiological characteristics than younger ones. Within the older juniors but not in the other age categories, these characteristics are significantly better in rowers with an international ranking than in those with a club ranking. Within these age categories, length of sports career was not associated with significant differences between rowers.

The study revealed that potential differences in anthropometric and physiological characteristics are more difficult to identify in rowers who are not elite athletes and differ in age, ranking and length of the sport career than when rowing champions are compared with the remaining, lower-ranking rowers. As demonstrated on the example of Hungarian rowers, the ultimate success of intermediate rowers is determined not only by endogenous factors associated with training and anthropometric and physiological characteristics, but also by external factors (organizational, financial, and motivational). Further research is needed to confirm the present findings. For instance, it would be interesting to investigate whether athletes with optimal training conditions are more successful than those with less favorable training conditions. Future studies should also involve advanced statistical analyses, such as partial correlation analysis, to identify variables that exert the greatest influence on rowers' performance. It would be interesting to perform a longitudinal study that examines how these characteristics change or remain the same as the season progresses, or even over several years of the athletes' sports careers. These repeated examinations could provide an opportunity to assess more accurately whether the relationships between anthropometric and physiological characteristics and the results obtained in motor tests should play an important role in the process of sports selection.

DATA AVAILABILITY STATEMENT

The Excel data used to support the findings of this study are restricted by the Ethics Committee of the University of Warmia and Mazury in Olsztyn (UWM), Poland in order to protect participants' privacy. Data are available from RP, E-mail: podstawskirobert@gmail.com for researchers who meet the criteria for access to confidential data.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Health Science Council, Scientific and Research Ethics Committee (IV/3067-3/2021/EKU). Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

AUTHOR CONTRIBUTIONS

RP designed this study. ZA, FI, IS, and RP contributed to data collection. KB and RP analyzed and interpreted the data and drafted the final version. RP and FI drafted the primary manuscript and with the assistance of ZA. All authors critically reviewed and approved the manuscript prior to submission.

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Concurrent Validity of Power From Three On-Water Rowing Instrumentation Systems and a Concept2 Ergometer

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Purpose: Instrumentation systems are increasingly used in rowing to measure training intensity and performance but have not been validated for measures of power. In this study, the concurrent validity of Peach PowerLine (six units), Nielsen-Kellerman EmPower (five units), Weba OarPowerMeter (three units), Concept2 model D ergometer (one unit), and a custom-built reference instrumentation system (Reference System; one unit) were investigated.

Methods: Eight female and seven male rowers [age, 21 ± 2.5 years; rowing experience, 7.1 ± 2.6 years, mean ± standard deviation (SD)] performed a 30-s maximal test and a 7 × 4-min incremental test once per week for 5 weeks. Power per stroke was extracted concurrently from the Reference System (*via* chain force and velocity), the Concept2 itself, Weba (oar shaft-based), and either Peach or EmPower (oarlock-based). Differences from the Reference System in the mean (representing potential error) and the stroke-to-stroke variability (represented by its SD) of power per stroke for each stage and device, and between-unit differences, were estimated using general linear mixed modeling and interpreted using rejection of non-substantial and substantial hypotheses.

Results: Potential error in mean power was decisively substantial for all devices (Concept2, –11 to –15%; Peach, −7.9 to −17%; EmPower, −32 to −48%; and Weba, −7.9 to −16%). Between-unit differences (as SD) in mean power lacked statistical precision but were substantial and consistent across stages (Peach, ∼5%; EmPower, ∼7%; and Weba, ∼2%). Most differences from the Reference System in stroke-to-stroke variability of power were possibly or likely trivial or small for Peach (−3.0 to −16%), and likely or decisively substantial for EmPower (9.7–57%), and mostly decisively substantial for Weba (61–139%) and the Concept2 (−28 to 177%).

Conclusion: Potential negative error in mean power was evident for all devices and units, particularly EmPower. Stroke-to-stroke variation in power showed a lack of measurement sensitivity (apparent smoothing) that was minor for Peach but larger for the Concept2, whereas EmPower and Weba added random error. Peach is therefore recommended for measurement of mean and stroke power.

Keywords: Peach PowerLine, Weba OarPowerMeter, Nielsen-Kellerman EmPower, technical error of measurement, systematic error, between-unit differences, Concept2, random error

INTRODUCTION

Rowing instrumentation systems provide a comprehensive measure of performance given their ability to assess both technical and physical components of rowing performance and enable instantaneous quantitative feedback to the rower (Lintmeijer et al., 2019; Holt et al., 2020). Instantaneous feedback of power output has been shown to improve training intensity adherence by 65% in rowers compared to boat velocity, stroke rate, and coach feedback alone (Lintmeijer et al., 2019). Furthermore, on-water power measurement in rowing has potential widespread value in the quantification of external training load, analysis of race demands, and performance monitoring *via* power-based benchmarks, all of which have been achieved with instrumentation systems in cycling (Schumacher and Mueller, 2002; Nimmerichter et al., 2011; Sanders and Heijboer, 2019). However, before rowing instrumentation systems can be used with some certainty, their validity must first be established. Knowledge of the systematic error and random error associated with measures of power from rowing instrumentation devices will inform the interpretation of a meaningful change or difference in power for the given device.

Different types of rowing instrumentation systems exist and can be located on at the oarlock or on the oar shaft. Instrumentation systems located on the oarlock measure forces occurring at the pin resulting from the transfer of force applied at the handle to the oar blade. Oar shaft-based instrumentation systems are positioned on the oar's inboard (the section of oar shaft between the handle and the point of the oar's rotation at the oarlock) and calculate the moment of force applied to the handle from the deflection of the oar throughout the stroke (Kleshnev, 2010).

The validity of power measurement off-water has been investigated using mechanical sensors attached to Concept2 ergometer models A and D, with negative systematic error estimates of 5–8% reported (Lormes et al., 1993; Boyas et al., 2006). However, the validity of power from on-water instrumentation systems is yet to be established. Research investigating the validity of rowing instrumentation systems has focused on oarlock-based Peach PowerLine devices (Peach Innovations, Cambridge, United Kingdom), encompassing static (Laschowski and Nolte, 2016), or dynamic linear force application and static angle assessment (Coker et al., 2009). Eight Peach sculling units had reasonable concurrent validity for measures of force up to 555 N and angle between −80° to 60°, with standard error of the estimate (SEE) values of 7.16 ± 2.56 N for force and 0.9° ± 0.9° SEE for angle (Coker et al., 2009). Very large correlations between applied and measured forces of up to 432 N were also reported for eight sculling (r = 0.985) and nine sweep (r = 0.986) Peach units, although a negative error of 2% was observed for Peach (Laschowski and Nolte, 2016). However, the testing methods of these studies do not reflect a rowing-specific pattern of force application or oarlock angular rotation. Force at the oarlock throughout a rowing stroke increases to a peak mid-drive with a subsequent decrease from mid-drive to the end of the drive phase, and therefore do not reflect the static force application used in previous validity studies. Similarly, the measurement of catch and finish oarlock angles during a rowing stroke occur during rotation at each end of the stroke when the oar changes direction, which is not reflected in the static measurement of oarlock angle used previously. As such, the applicability of results from previous validity studies to the measurement of power on-water is unknown. Furthermore, the validity of power measures has not been investigated in Peach or other commercially available rowing instrumentation systems such as the Nielsen-Kellerman EmPower (Kleshnev, 2017) and Weba Sport OarPowerMeter in peer-reviewed research. Therefore, the aim of this study was to assess the concurrent validity of power measures from Peach PowerLine, Nielsen-Kellerman EmPower, Weba Sport OarPowerMeter sweep rowing instrumentation systems, and a Concept2 ergometer with an instrumented Swingulator team sweep system through a dynamic, on-water rowing specific range of oar angles and force applications.

MATERIALS AND METHODS

Participants

Eight female (age 21.6 ± 3.1 years; height 175.9 ± 4.1 cm; and body mass 76.7 ± 5.4 kg, mean ± standard deviation [SD]) and seven male (age 20.9 ± 2.0 years; height 189.7 ± 8.4 cm; and body mass 86.2 ± 11.0 kg) trained rowers with 7.1 ± 2.6 years experience at a national level who were actively participating in the sport at the time of the study and had competed in the previous rowing season volunteered for this study. Six of the participants (five females and one male) had previously represented Australia at International Regattas. Participants

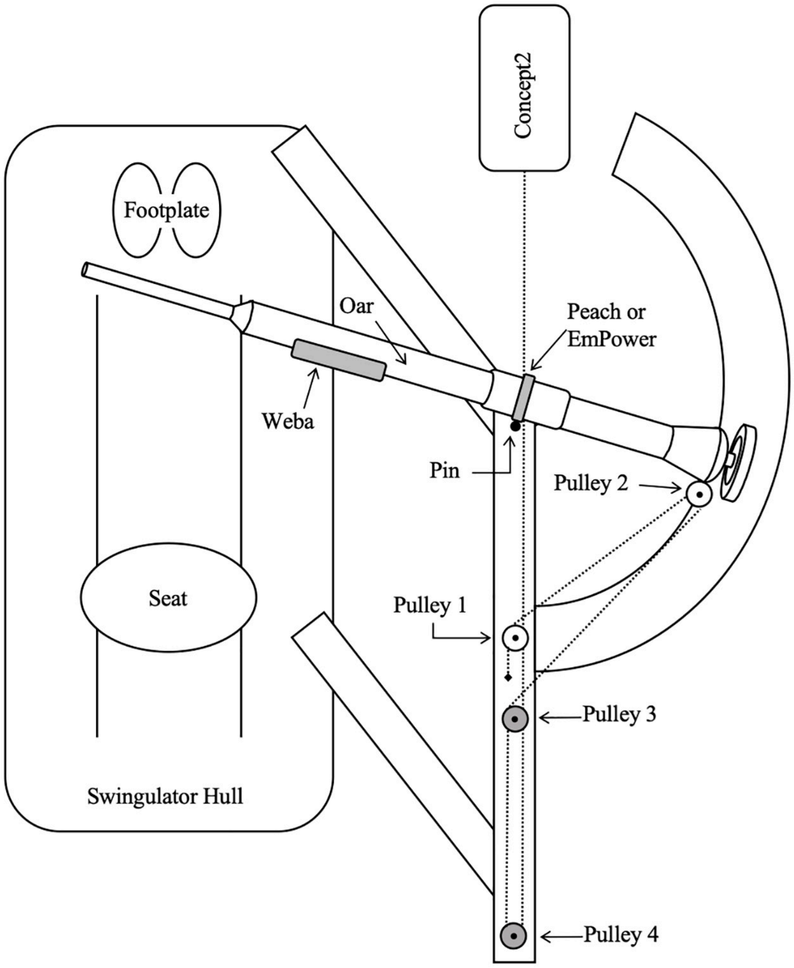

FIGURE 1 | Birds-eye view diagram (not drawn to scale) of Swingulator-system illustrating location of devices. Pin, point of oar rotation. Pulley 2 is attached to the oar, Pulleys 3 and 4 are located on the underside of the Swingulator framing. Dashed line represents the Concept2 chain and Swingulator cord which passes under the framing after Pulley 2. The black diamond near Pulley 1 indicates the anchor point of the Swingulator cord.

provided informed consent prior to commencement of the study. The study was approved by the University Human Research Ethics Committee.

Equipment

All rowing was performed on an instrumented Swingulator team sweep trainer (Rowing Innovations Inc., Williston, VT, United States) with a Concept2 ergometer (Model D with PM5 monitor, Concept2 Inc., Morrisville, VT, United States) attachment. The Swingulator was used as it enables the simulation of on-water sweep rowing in a controlled land-based environment, where power could be recorded from the Reference System, Weba, Concept2, and Peach or EmPower simultaneously. The Swingulator also allowed instrumentation with mechanical sensors (as described in the next paragraph) to provide a comparative measure of power for the assessment of concurrent validity. When using the Swingulator the rower holds the handle of an oar with a shortened outboard which sits in an oarlock, the end of the oar's outboard (between the oar's collar and blade-end) connects to a cable which passes through four pulleys before connecting to the chain of the Concept2, which provides resistance during the drive phase of the rowing stroke (**Figure 1**). Oar inboard (between the oar's handle and collar) and total oar lengths were set to 114.5 and 177 cm, respectively, with span (distance between the pin and the center of the hull) set to 84.3 cm.

The Concept2 drag factor was set to 80 units for females and 100 units for males, which were lowered by 30 units from typical settings to account for the greater resistance of the Swingulator-Concept2 system. Mechanical sensors (hereafter referred to as the Reference System) were attached to the Swingulator, similar to that used previously on Concept2 ergometers (Macfarlane et al., 1997; Boyas et al., 2006), and included a quadrature optical encoder (HEDS-5500 Optical Encoder) coupled inline to the Concept2's chain, allowing finite linear displacement to be measured with regard to a fixed reference mark. A force transducer (DACELL UMMA-K200) was housed in a custom attachment (Küsel Dësign, Melbourne, VIC, Australia) at Pulley

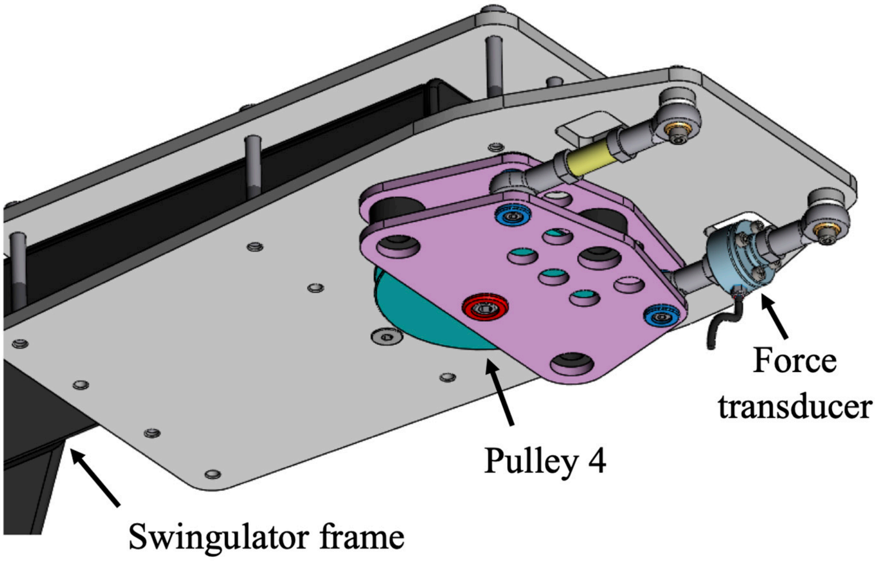

FIGURE 2 | Custom Swingulator attachment with force transducer at Pulley 4.

4 on the Swingulator assembly (**Figure 2**), enabling the measurement of force applied through the Swingulator cord when a participant pulled on the oar handle. Static testing of the force transducer without attachment to the Swingulator against a known mass between 0.2 and 85.8 kg was undertaken to verify the linearity characteristics and the voltage-force-mass relationship, which had an *R*-squared (R^2) value of 1.00. The quadrature optical encoder was assessed in pilot testing using a Vicon analysis system (T-40 series, Vicon Nexus v2.7, Oxford, United Kingdom) with a 14-mm diameter reflective marker attached to the Concept2 chain. An R^2 value of 0.99 was found between the quadrature optical encoder and the Vicon analysis system for the measurement of Concept2 chain displacement.

Calibration of the Reference System's force and displacement measurement on the Swingulator was performed every 7 days throughout the study. For force calibration, the oar handle was locked perpendicular to the Swingulator's hull and loaded with a known mass (1000.4 N; 101.98 kg). Calibration of the quadrature optical encoder was achieved by movement of the chain through its full range on the Swingulator (∼2030 mm). Although calibration of the Reference System could not be performed prior to each testing session due to the timeframes involved, the analysis allowed the error introduced between sessions that was associated with the Reference System to be partitioned out from that introduced by the other devices, and is reported in the results section.

The concurrent validity of power from Peach PowerLine (Peach Innovations, Cambridge, United Kingdom), EmPower (Nielsen-Kellerman, Boothwyn, PA, United States), Weba (OarPowerMeter, Weba Sport, Wien, Austria) sweep instrumentation devices and the Concept2 ergometer were tested. Differences in concurrent validity between different units for each device was also assessed through testing of six Peach units, five EmPower units, and three Weba units. Peach and EmPower units were attached to the Swingulator's pin, replacing the oarlock. Peach and EmPower baseplates were attached to the pin at 90° to the Swingulator's hull (as per manufacturer's instructions) using a straight edge and goniometer (EZ Read, Jamar, Performance Health, IL, United States). Weba devices were placed facing the participant on the inboard of the oar shaft, as per manufacturer's instructions.

Calibration procedures for Peach, EmPower, and Weba devices were performed in accordance with manufacturer instructions immediately prior to each testing session. Calibration of the oarlock angle for Peach and EmPower devices was achieved using a goniometer and straight edge to set the unit's angle as 0° when the oarlock's flat edge was 90° to the Swingulator's hull. An additional angle calibration routine was performed for EmPower units using the calibration tool supplied by the manufacturer, successful calibration for this additional process was determined by the unit itself. Force for Peach and EmPower devices was calibrated *via* zeroing the unit's force measure with the oar removed. Calibration of Weba devices was achieved *via* the hanging of a known mass (198.3 N; 20.22 kg) ∼10 cm from the handle tip with the oar's outboard held in a horizontal position on a bench with the Weba unit facing downward.

Testing Protocol

The study was conducted in a temperature-controlled environment (21.1 ± 1.0°C; 48.6 ± 9.9% RH). Participants performed five testing sessions on the Swingulator team sweep trainer separated by 7.0 ± 2.0 days, including one initial familiarization session. A schematic of the testing session procedures is illustrated in **Figure 3**. Testing sessions included a 10-min warm-up of low-intensity rowing interspersed with three maximal 10-stroke efforts, then a maximal 30-s rowing test at a self-selected stroke rate. Following a subsequent 10 min

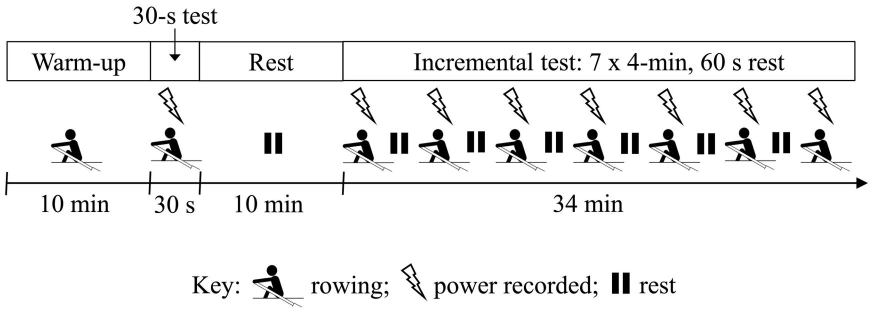

FIGURE 3 | Schematic of testing session protocol showing periods of rowing (rower icon), rest (pause icon), and when power was recorded from the five devices (lightning icon). Participants performed the same protocol in each of the five testing sessions, which were separated by 7 days.

rest period participants undertook a 7 × 4-min incremental test at self-selected stroke rates, including a final maximal 4-min stage (Tanner and Gore, 2013). A 60-s recovery period was performed between each stage of the incremental test. Participants were instructed to maintain a prescribed power for Stages 1–6 of the incremental test, which were individualized based on the participants most recent 2000-m ergometer test (Tanner and Gore, 2013), and adjusted to account for the perceived resistance of the Swingulator in comparison to rowing on a standard Concept2 ergometer. The familiarization session further guided the prescription of prescribed power for Stages 1–6, which remaining constant across the final four testing sessions. Participants were instructed to row full-length strokes for the 30-s test and throughout the 7 × 4-min test. The 30-s maximal and 7 × 4-min incremental tests were selected for the assessment of concurrent validity as they are performed as part the participants' regular rowing testing and were therefore familiar to participants, and provided measures of power across intensities ranging from very low to maximal.

The Reference System, Concept2, and Weba were tested concurrently for all testing sessions. The use of Peach or EmPower was alternated per testing session, with each participant performing either two or three testing sessions with each device. The testing order of Weba, Peach, and EmPower units was randomized. Peach units were tested in a total of 37 testing sessions, including 20 sessions on bow side and 17 sessions on stroke side, with individual units assessed in 2–8 sessions each. EmPower units were tested in a total of 38 testing sessions, including 20 sessions on bow side and 18 sessions on stroke side, with individual units assessed in 4–9 sessions each. Weba units were tested in a total of 75 testing sessions, including 40 sessions on bow side and 35 sessions on stroke side, with individual units assessed in 23–27 sessions each.

Data Analysis

Power per stroke was recorded for Peach and EmPower by their respective head units and exported to a comma-separated values (CSV) file. Power per stroke for Weba was recorded on a Lenovo Tab 4 8 tablet (Lenovo Group Ltd., Beijing), data could not be exported from the tablet so the tablet's screen was recorded and power per stroke manually entered into Microsoft Excel with the manually entered data checked against the recording for input errors. Power per stroke was recorded from the Concept2 using the app PainSled (version 1.1.0, Charlotte Intellectual Properties, LLC, Charlotte, NC, United States) and exported to CSV files.

Chain displacement and force from the Reference System was recorded at 271.7 Hz and filtered in MATLAB (R2019b, The MathWorks, Inc., Natick, MA, United States) using a low-pass fourth order Butterworth filter with cut-off frequencies of 6 and 13 Hz for displacement and force data, respectively. The choice of cut-off frequencies were informed by residual analysis (Winter, 1990) and supported by visual inspection of raw and smoothed curves.

The corresponding oarlock angle for a given chain position was calculated using chain position and oarlock angle data collected by the Vicon motion analysis system in previous testing of the Swingulator-Concept2 system. Oarlock angle was plotted over chain position during the drive phase of the stroke (between the maximal negative oar angle and the subsequent maximal positive oar angle per stroke), and fitted with a second order polynomial trendline that had an R^2 value of 1.00 (**Figure 4A**) to derive *a*, *b*, and *c*, in Equation 1:

$$P_C = P_M - \left(\frac{b + \left(\sqrt{b^2 - 4 \cdot a \cdot (c - \theta)} \right)}{2 \cdot a} + P_M \right) \quad (1)$$

where P_C is the corrected chain position, P_M is the measured chain position, b is 49.81, a is 7.63, c is −51.21, and θ is the initial oarlock angle at rest.

The calculated oarlock angle (θ_C) was then derived by:

$$\theta_C \;=\; a \cdot {P_C}^2 + b{\cdot}P_C - c \quad (2)$$

Due to the geometry of the Swingulator system, force measured at Pulley 4 was corrected relative to the calculated oar angle. A static force of 198.4 N was applied to the oar handle at 11 oarlock angles ranging between 40.75° and −60.75° on each of bow and stroke sides. First force was predicted (F_P) using Equation 3:

$$F_P = \frac{0.5 \cdot (i/o) \cdot F_A}{cos \cdot (90 - (\sigma + \phi)/2)} \quad (3)$$

where i was the distance between the pin and the point of force application at the oar handle (1031 mm), o was the distance between the pin and the point on the oar that aligned with the

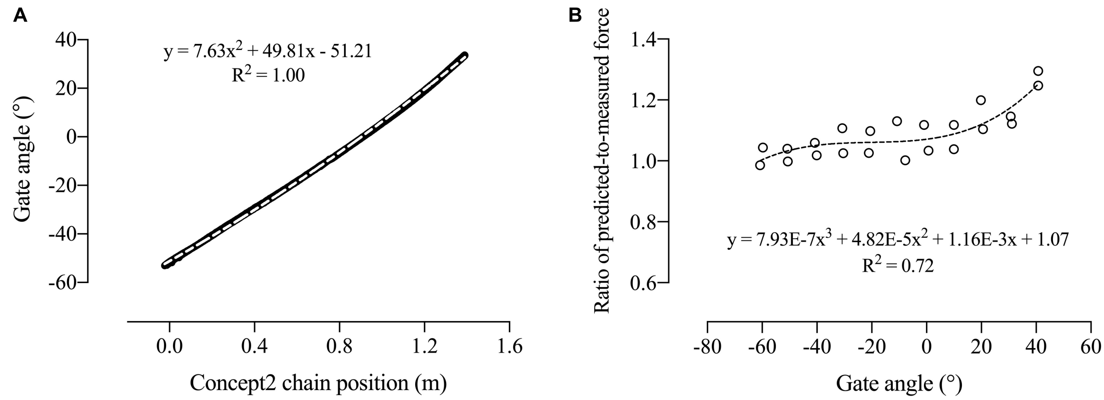

FIGURE 4 | Oarlock angle plotted against Concept2 chain position used to derive *a*, *b,* and *c* in Equation 1 **(A)**; and the ratio of predicted-to-measured force plotted against oarlock angle used to derive the coefficients *d*, *e*, *f*, and *g* in Equation 4 **(B)**. Dashed lines represent the fitted trendlines.

center of Pulley 2 (599 mm), F_A was the force applied to the oar's handle (198.4 N), σ is the angle between the oar shaft and the Swingulator cord on the inner (**Figure 5**) side of Pulley 2, and ϕ is the angle between the oar shaft and the Swingulator cord on the outer side of Pulley 2.

The ratio of predicted-to-measured force was then calculated, plotted against oarlock angle, and fitted with a third order polynomial trendline that had an R^2 value of 0.72 (**Figure 4B**) to derive *d*, *e*, *f*, and *g* in Equation 4 for corrected force (F_C):

$$F_C = F_A \times (d \cdot \theta_C{}^3 + e \cdot \theta_C{}^2 + f \cdot \theta_C + g) \quad (4)$$

where θ_C is the calculated oarlock angle from Equation 2, *d* is 7.93E−7, *e* is 4.82E−5, *f* is 1.16E−3, and *g* is 1.07.

Instantaneous work (W_i) was then calculated from P_C and F_C for each sample:

$$W_i = \left(\frac{F_{C1} + F_{C2}}{2}\right) \times (P_{C2} - P_{C1}) \quad (5)$$

where F_{C1} and P_{C1} indicate the previous data point and F_{C2} and P_{C2} indicate the current data point.

Power per stroke was calculated using Visual 3D (version 6.3, C-Motion, Inc., Germantown, MD, United States) from stroke work over stroke time. Stroke time was calculated as the number of samples between consecutive finish positions (the maximum P_C per stroke) multiplied by 0.00368 s (corresponding to the sample rate of 271.7 Hz). Stroke work was calculated as the integral of W_i over the drive phase (from the catch to finish position of the current stroke). Power per stroke was then calculated as stroke work divided by stroke time and exported from Visual 3D into Microsoft Excel where it was aligned by stroke number with power from Peach or EmPower, Weba, and the Concept2 for each stage.

The first and last two strokes per stage were excluded from analyses from each device to eliminate some inconsistencies between the devices at the onset and termination of rowing. Outliers defined as strokes where power was greater than seven SDs from the stage mean power for that device were also excluded; 24 such outliers were identified, but only for Weba units. The magnitude of seven SD was chosen based on time series graphs and represented visually obvious outliers that might prompt the practitioner to disregard the data or repeat the test. This value was chosen as a reasonable compromise between removing data that clearly should be excluded, but not removing data that would not have been visually obvious to practitioners when using devices in the field. Occasionally, errors relating to the recording of devices (both human and device errors) resulted in missing strokes or whole stages for certain device units. Stages where a device had more than five missing strokes were excluded from the analyses for that device. A total of 14 stages were missing or excluded for the Reference System, which were also excluded for the other devices. The number of additional stages missing data or excluded due to missing strokes were 3 for Peach, 1 for EmPower, 6 for Weba, and 32 for the Concept2 (of which the stages excluded due to missing data were split between the 30-s test and Stage 7 and were related to not all strokes being recorded successfully by the PainSled app). After the exclusion of stages with missing data, the mean percentage of strokes missing from analyses (including those excluded as outliers) in each stage were: ≤0.1% for the Reference System and EmPower; ≤0.2% for Peach; ≤0.4% for Weba Stages 1–7, but 2.2% for the 30-s test; and ≤0.5% for the Concept2 Stages 1–7, but 6.5% for the 30-s test. Following the exclusion of these strokes and stages, additional outliers were identified as stages with a standardized residual greater than 4 after running the model (Hopkins et al., 2009). Two Weba stages were identified as outliers from the analysis of mean power, and eight stages (one for the Concept2, five for EmPower, and two for Weba) were identified as outliers from the analysis of the SD of power. All stages identified as outliers were included in the analyses as such data would not be identifiable and therefore not removed when devices are used in the field. The data analyzed in this study is available in an online repository (see Data Availability Statement).

Statistical Analysis

Although the data consisted of individual values of mean power for each stroke from each of the five devices, the values for EmPower, Weba, and the Concept2 could not be aligned reliably with those of the Reference System, as can be seen in an example

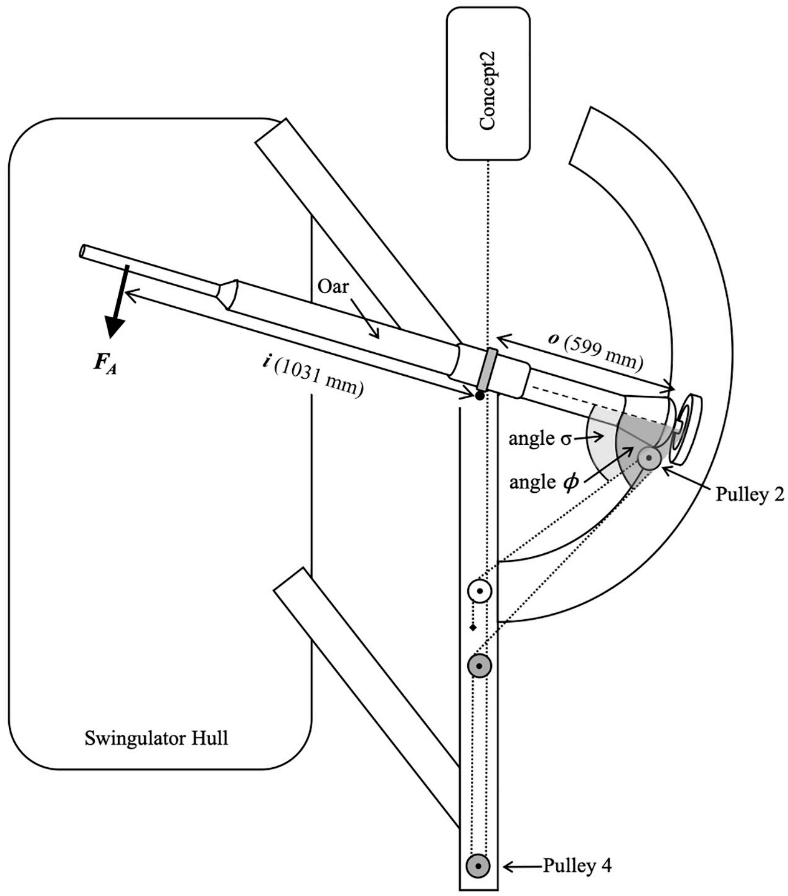

FIGURE 5 | Free body diagram of Swingulator-system illustrating the location of the applied force (F_A), distance i, distance o, angle σ, and angle ϕ in Equation 3.

of the data from one stage in **Figure 6**. A repeated-measures analysis of the individual stroke values was therefore not possible. Instead, the mean power for the 30-s stage and for each stage of the incremental test was analyzed with a mixed model, using a separate analysis for each stage. The same model was applied to the SD of power for each stage, representing the stroke-to-stroke variability in power within a stage (note: this is a lengthy section with detailed statistical methods and might be skipped by the applied reader).

The general linear mixed-model procedure (Proc Mixed) was used to perform the analysis in the Studio On-demand for Academics edition of the Statistical Analysis System (version 9.4, SAS Institute, Cary NC, United States). The dependent variable was the log of the mean and the log of the log of the factor SD. The fixed effects were device identity and device identity interacted with Reference System power to estimate, respectively, systematic error (representing the difference in mean power from the Reference System for a given device) and proportional error (representing the change in mean error for a given change in the Reference System's mean power or the Reference System's stroke-to-stroke variability in power) for each device. With these fixed effects, a separate residual for each device (estimated as a variance and expressed as an SD) was specified to represent technical error of measurement (TEM) (random session-to-session changes in error) of the device. Random effects of increasing complexity were added to the model to account for and reduce what turned out to be substantial residual variance. The final random effects (estimated as variances and expressed as SD) were: device identity interacted with unit identity (representing differences in error between units for Weba, Peach, or EmPower devices; a separate variance was estimated for each device); session identity (representing differences between the testing sessions that were experienced equally by the three devices in the given session and therefore potentially changes in the Reference System between sessions); and participant identity (representing differences between participants; a separate variance was estimated for each device, to allow for each device responding uniquely to each participant's rowing style). A random effect representing differences in proportional error between each unit of each device was also investigated; the effect was unclear for all devices but consistent with trivial for Peach and Weba, so this effect was not included in the final model. For the analysis of the SDs (stroke-to-stroke variations), random effects representing differences between participants and potential session-to-session differences arising from the Reference System are not presented, but are

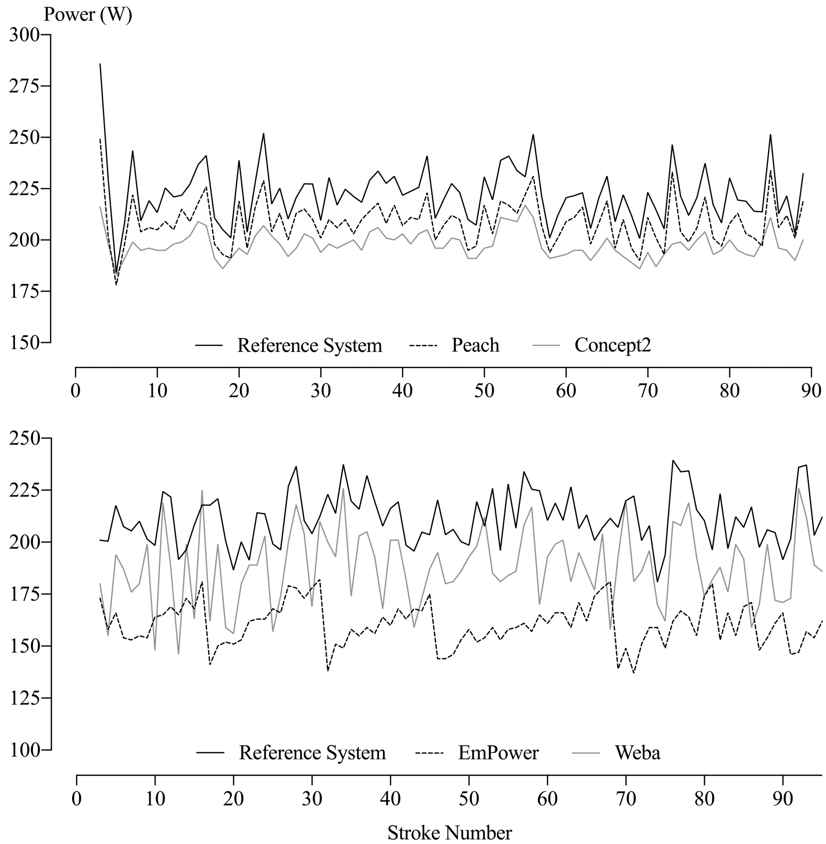

FIGURE 6 | Power per stroke for each device during Stage 5 of two consecutive testing sessions by the same participant. Data for the Weba and Concept2 were recorded in every session but for reasons of clarity are not shown for the Weba (above) or the Concept2 (below).

available on request, as are the residuals representing the TEM for the SDs of each device.

Plots of residuals vs. predicteds were examined for outliers and evidence of non-uniformity. To ensure correct interpretation of the random effects and residuals, analyses of mean power were also performed by including data for an additional device simulating the Peach: the data for this device were those of the Reference System, but with added random error of 5% for each session, and with five units simulated by adding 3, 6, 9, 12, and 15% to the Reference System values. Finally, to investigate the extent to which changes in error in each device between sessions (evident as the residuals) arose from random changes in the device, mean correlations of the residuals of each device with the other devices were computed for each stage (expected values of 0.00, if the session-to-session error arose entirely separately in each device), and mean correlations of the residuals of each stage with the other stages were computed for each device (expected values approaching 1.00, if the session-to-session error in each device was consistent across the stages in a given session).

A smallest substantial change in power of 1.0% was assumed from the 1.0% race-to-race variation in 2000-m race times of elite rowers (corresponding to a 0.3% smallest substantial change in rowing velocity) and the assumption that power is proportional to velocity cubed (Smith and Hopkins, 2011). Corresponding magnitude thresholds were based on the factors for competitive performance (Hopkins et al., 2009) and are used to provide a practical description of the magnitude of error relative to the magnitude for a meaningful change in performance (i.e., the smallest substantial change in power); for positive changes in power these were $<1.0\%$ trivial, $\geq 1.0\%$ small, $\geq 3.0\%$ moderate, $\geq 5.5\%$ large, $\geq 8.6\%$ very large, and $\geq 14\%$ extremely large; for negative changes the thresholds were $>-1.0\%$ trivial, $\leq -1.0\%$ small, $\leq -2.9\%$ moderate, $\leq -5.2\%$ large, $\leq -8.0\%$ very large, and $\leq -12\%$ extremely large. To evaluate the magnitudes of SDs representing between-unit differences in mean power and the residuals, the magnitude thresholds were one-half of those in the above scales (Smith and Hopkins, 2011): $<0.5\%$ trivial, $\geq 0.5\%$ small, $\geq 1.5\%$ moderate, $\geq 2.7\%$ large, $\geq 4.2\%$ very large, and $\geq 6.7\%$ extremely large. Magnitudes of proportional error were assessed for a 10% difference in Reference System mean power; the usual two between-subject SDs (Hopkins et al., 2009) was not appropriate, given the wide range in power between participants arising from the inclusion of males and females.

Magnitude thresholds for comparing the mean SDs of power (representing the mean stroke-to-stroke variability in power within a stage) were the usual factor thresholds for hazards and counts (Hopkins et al., 2009); for factor increases (which would occur when a device adds noise to the participant's stroke-to-stroke variability, as demonstrated by Weba in comparison to the Reference System in **Figure 6**) the thresholds were <1.11 (11%) trivial, ≥ 1.11 small, ≥ 1.43 (43%) moderate, ≥ 2.0 (100%) large, ≥ 3.3 (230%) very large, and ≥ 10 (900%) extremely large; for factor decreases (which would occur when a device lacks measurement sensitivity for stroke-to-stroke variations in power, as demonstrated by the Concept2 in comparison to the Reference System in **Figure 6**) the thresholds were >0.90 (-10%) trivial, ≤ 0.90 small, ≤ 0.70 (-30%) moderate, ≤ 0.50 (-50%) large, ≤ 0.30 (-70%) very large, and ≤ 0.10 (-90%) extremely large. To evaluate the magnitudes of SDs representing between-unit differences in the mean SD in power, the magnitude thresholds are one-half of those for factor increases: <1.05 (5.4%) trivial, ≥ 1.05 small, ≥ 1.2 (20%) moderate, ≥ 1.41 (41%) large, ≥ 1.83 (83%) very large, and ≥ 3.16 (220%) extremely large. Magnitudes of proportional error were assessed for a two between-subject SD in the Reference System mean SD of power (Hopkins et al., 2009), because gender differences were not expected to affect between-subject differences in the SD expressed in percent units.

The thresholds for comparing the SDs were justified by using simulation (with spreadsheets) to investigate the extent to which noise and a loss in measurement sensitivity (apparent smoothing) for power per stroke modify effects involving power per stroke as either a predictor or a dependent variable. The effect of power per stroke as a predictor with added noise is attenuated by a factor equal to the square of the ratio of the SD of true power per stroke (represented by the Reference System) divided by the SD of the predictor (represented by the device), when the effect of the predictor is expressed per unit of the predictor (as stated by Hopkins et al., 2009); however, when expressed per 2 SD of the predictor, the effect is attenuated by the ratio of the SDs without squaring. Effects when power per stroke is a predictor with a lack of measurement sensitivity are *increased* by a factor equal to the ratio of the SD of true power per stroke divided by the SD of the predictor, when the effect of the predictor is expressed per unit of the predictor; however, when expressed per 2 SD of the predictor there is negligible attenuation of the effect ($<5\%$) when the ratio of measured/true SD is >0.7. For effects when power per stroke is a dependent variable with added noise, there is no modification of the effect magnitude (as stated by Hopkins et al., 2009). Effects when power per stroke is a dependent variable with a lack of measurement sensitivity are attenuated by a factor equal to the ratio of the SD of the dependent variable divided by the SD of true power per stroke, when the ratio is >0.7; for a reduction in measurement sensitivity (e.g., ratio of SDs = 0.6), the attenuation is a little greater than the ratio (0.65). In summary, noise or a lack of measurement sensitivity of power per stroke does not modify effects in two scenarios, but it modifies effects by factors given by the ratio of the SDs in three scenarios (effect attenuation in two, effect amplification in one) and by the square of the ratio in one scenario. We therefore opted to assess the effect of noise and a lack of measurement sensitivity by assessing the ratio of the SDs, and we used the thresholds for ratios of hazards and counts, since it seems reasonable to consider that modifications of an effect magnitude by a factor of 0.9 (or its inverse, 1.11) through to 0.1 (or its inverse 10) represent thresholds for small through to extremely large. Researchers should be aware that square roots of these thresholds will apply to a noisy predictor per unit of the predictor, but that there is no effect on the magnitude per 2 SD of a predictor with a modest lack of measurement sensitivity, and no effect on magnitude with a noisy dependent.

Sampling uncertainty in the estimates of effects is presented as 90% compatibility limits in the tables. For those who prefer a frequentist interpretation of sampling uncertainty, decisions about magnitudes accounting for the uncertainty were based on one-sided interval hypothesis tests, where an hypothesis of a given magnitude (substantial, non-substantial) was rejected if the 90% compatibility interval fell outside that magnitude (Aisbett et al., 2020; Hopkins, 2020). p-Values for the tests were the areas of the sampling distribution of the effect (t for means, z for random-effect variances, Chi-squared for residual variances) falling in the hypothesized magnitude, with the distribution centered on the observed effect. Hypotheses of inferiority (substantial negative) and superiority (substantial positive) were rejected if their respective p-values (p_- and p_+) were <0.05; rejection of both hypotheses represents a decisively trivial effect in equivalence testing. For residual variances, only the tests of superiority and non-superiority were relevant. When only one hypothesis was rejected, the p-value for the other hypothesis, when >0.25, was interpreted as the posterior probability of a substantial true magnitude of the effect in a reference-Bayesian analysis with a minimally informative prior (Hopkins, 2019) using the following scale: >0.25, possibly; >0.75, likely; >0.95, very likely; >0.995, most likely (Hopkins et al., 2009); the probability of a trivial true magnitude ($1 - p_- - p_+$) was also interpreted, when >0.25, with the same scale. Probabilities were not interpreted for effects that were unclear (those with inadequate precision at the 90% level, defined by failure to reject both hypotheses, $p_- > 0.05$ and $p_+ > 0.05$). Effects with adequate precision at the 99% level ($p_- < 0.005$ or $p_+ < 0.005$) are in bold in the tables; these represent effects that have a conservative low risk of error or noise. The hypothesis of non-inferiority (non-substantial-negative) or non-superiority (non-substantial-positive) was rejected if its p-value ($p_{N-} = 1 - p_-$ or $p_{N+} = 1 - p_+$) was <0.05, representing a decisively substantial effect in minimal-effects testing: very likely or most likely substantial.

RESULTS

The power per stroke throughout a stage for the five devices is exemplified in **Figure 6**. The mean and SD (representing the stroke-to-stroke variation in power) of the individual values of power per stroke in **Figure 6** for each device (along with those of all the other stages and testing sessions) provided the data for the subsequent analyses.

The mean power of each of the five devices across all testing sessions and participants for each stage is shown in **Figure 7** (left), with SD bars representing between-unit differences in the mean power. The mean stroke rates performed for each stage were: 30-s test, 43.8 ± 7.0 (stroke min^{-1}, mean ± SD); Stage 1, 18.0 ± 1.0; Stage 2, 19.4 ± 1.0; Stage 3, 21.2 ± 1.2; Stage 4, 23.0 ± 1.4; Stage 5, 24.8 ± 3.0; Stage 6, 27.3 ± 1.7; and Stage 7, 32.7 ± 1.9.

Systematic Error

The difference in mean power from the Reference System (representing systematic error) across the eight stages were all decisively substantial and negative (rejection of the non-inferiority hypotheses, $p_{N-} < 0.05$), and are presented in **Table 1**. Magnitudes were very large in most stages for Peach, extremely large for EmPower, and mostly very large to extremely large for Weba and the Concept2. Within each device, there is a consistent percent error across Stages 1–7, as shown by the near-equal spacing from Reference System values with a log scale on the *y*-axis in **Figure 7**. All devices showed relatively greater systematic error in the 30-s test.

Differences from the Concept2 in mean power across the eight stages are presented in **Table 2**. Magnitudes were trivial to moderate and mostly positive for Peach, but most were either unclear (the superiority and inferiority hypotheses were not rejected, p_+ and $p_- > 0.05$) or were only likely substantial (rejection of only the inferiority hypotheses, $p_- < 0.05$). In comparison to the Concept2, mean differences in power for EmPower were negative, extremely large, and decisively substantial. Mean differences in power from the Concept2 for Weba ranged from positive to negative and were trivial to moderate, but most were unclear.

TABLE 1 | Mean systematic error across the stages for Peach, EmPower, Weba, and the Concept2. Data are mean (%), ±90% compatibility limits, with observed magnitude and *p*-values for inferiority and superiority tests (p_-/p_+).

	Peach	EmPower	Weba	Concept2
30-s test	**−16.9, ±2.7; e.large****** >0.999/<0.001	**−47.7, ±8.1; e.large****** 0.999/0.001	**−15.4, ±3.9; e.large****** 0.996/0.003	**−15.2, ±0.8; e.large****** >0.999/<0.001
Stage 1	**−10.5, ±3.4; v.large****** 0.999/0.001	−32.3, ±9.1; e.large*** 0.98/0.02	−15.5, ±6.0; e.large*** 0.99/0.01	**−13.9, ±1.6; e.large****** >0.999/<0.001
Stage 2	**−7.9, ±4.3; Large***** 0.99/0.005	**−32.9, ±7.1; e.large***** 0.995/0.005	**−13.4, ±3.9; e.large****** 0.996/0.003	**−13.0, ±1.7; e.large****** >0.999/<0.001
Stage 3	**−8.8, ±4.0; v.large***** 0.995/0.002	−32.2, ±9.5; e.large*** 0.99/0.01	−12.4, ±4.1; v.large*** 0.99/0.01	**−12.3, ±0.6; v.large****** >0.999/<0.001
Stage 4	**−10.0, ±4.6; v.large***** 0.99/0.003	−33.2, ±9.5; e.large*** 0.98/0.02	**−10.5, ±2.4; v.large****** >0.999/<0.001	**−11.9, ±0.7; v.large****** >0.999/<0.001
Stage 5	**−11.3, ±5.9; v.large***** 0.99/0.005	−33.6, ±14.3; e.large*** 0.98/0.02	**−9.5, ±3.1; v.large****** 0.998/0.001	**−11.2, ±0.7 v.large****** >0.999/<0.001
Stage 6	**−10.1, ±5.1; v.large***** 0.99/0.003	−34.5, ±9.8; e.large*** 0.99/0.01	**−7.9, ±3.0; Large****** 0.996/0.002	**−11.3, ±0.6; v.large****** >0.999/<0.001
Stage 7	**−11.2, ±4.2; v.large****** 0.998/0.001	−35.4, ±8.5; e.large*** 0.99/0.01	**−9.6, ±3.1; v.large***** 0.99/0.004	**−11.6, ±0.6; v.large****** >0.999/<0.001

Scale of magnitudes: >−1%, trivial; ≤−1%, small; ≤−2.9%, moderate (mod); ≤−5.2%, large; ≤−8.0%, very large (v.large); and ≤−12.4%, extremely large (e.large).

*Reference-Bayesian likelihoods of substantial change: *possibly; **likely; ***very likely; and ****most likely.*

*The symbols *** and **** indicate rejection of the non-superiority or non-inferiority hypothesis (p_{N-} or p_{N+} <0.05 and <0.005, respectively).*

Effects in bold have adequate precision at the 99% level ($p < 0.005$).

Proportional Error in Systematic Error

Proportional error for a change in power, representing the percentage change in mean error for a 10% change in the Reference System mean power, was estimated for each stage for Peach, EmPower, Weba, and Concept2. Magnitudes of proportional error for a change in power were trivial in most stages for Peach (−2.8% for the 30-s test, and −0.7 to 0.2% for the other stages) and were either unclear or only possibly or likely trivial for most stages. For EmPower, proportional error was trivial to moderate (−4.4% for the 30-s test, and −2.2 to −0.6% for the other stages) and were either unclear or only possibly or likely substantial for most stages. Proportional error was trivial for Weba (−0.6% for the 30-s test, and −0.6 to −0.3% for the other stages) and most effects were possibly or likely trivial. For the Concept2 proportional error was trivial in most stages (0.8% for the 30-s test, and −1.6 to 0.7% for the other stages) with adequate precision that was likely trivial for most stages.

Between-Unit Differences in Systematic Error

Between-unit differences in mean power (the SD bars in **Figure 7** left) summarize the relative error of the units for a given device, reflecting the degree of differences in systematic error between the units. Only one Concept2 unit was assessed, so no between-unit differences were established for this device. With the exception of one stage for Weba, all the SDs were positive, but unclear. Despite being unclear, the random-effect solutions for the device units (representing the systematic error of each unit) showed evidence of consistent relative error across the stages for most units (data not shown). The observed magnitudes for between-unit differences in mean power were very large in most stages for Peach (an SD of 1.8% for the 30-s test, and 3.6–7.6% for the other stages), extremely large in most stages for EmPower (17% for the 30-s test, and 3.5–9.3% for the other stages), and trivial to large for Weba (1.3% for the 30-s test, and −0.3 to 3.9% for the other stages).

Between-Session Error and Between-Participant Error

The SD representing error potentially introduced by the Reference System between sessions were unclear in all but one stage. Observed magnitudes were positive in most stages and small to moderate (−1.6% for the 30-s test, and 1.1–1.8% for the other stages).

Differences in error between participants, estimated as a SD for each device, were unclear for most stages. The observed differences were positive and moderate to very large for Peach (5.0% for the 30-s test, and 2.1–4.5% for the other stages), negative and extremely large for EmPower (−10% for the 30-s test, and −7.0 to −7.8% for the other stages), positive in most stages and small to moderate for Weba (1.6% for the 30-s test, and −0.5 to 4.2% for the other stages), and positive and small in most stages for the Concept2 (0.9% for the 30-s test, and 0.8–3.7% for the other stages).

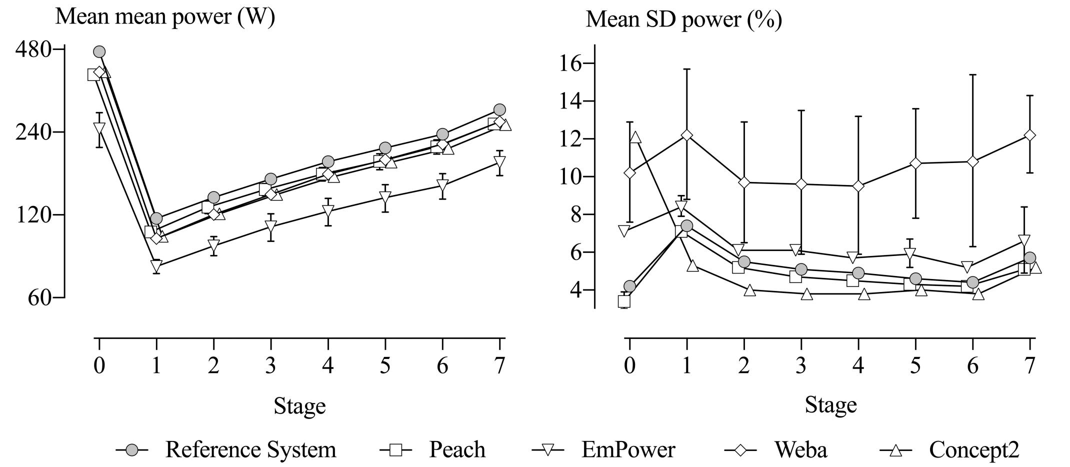

FIGURE 7 | Means of the mean (left) and SD (right) of power for each device in each stage for all the testing sessions. SD bars represent between-unit SD for the means and SD. The Reference System and the Concept2 have no SD bars, as only one unit was tested. SD bars on the right are omitted from some stages for Peach and EmPower, reflecting negative variance. Stage 0 represents the 30-s maximal test.

The residual SD representing the TEM in mean power between sessions (random session-to-session changes in error) was decisively substantial for all stages in Peach, EmPower, Weba, and for most stages for the Concept2, as shown in **Table 3**. Observed magnitudes were large to very large for Peach, extremely large for EmPower and Weba, and small to large for the Concept2.

Not shown in the tables are the fixed and random effects for the simulated device, which were used to ensure correct interpretation of the mixed model. The effects for the simulated device, including the residuals, were all consistent with the simulated values. The mean correlations of the technical error residuals of each device with the other devices for each stage ranged from −0.22 to 0.16; this range is consistent with sampling variation when the expected value is 0.00, if the session-to-session error arose entirely separately in each device. The mean correlations of the residuals of each stage with the other stages for each device ranged from 0.92 to 0.98 for the simulated device (where the expected value is 1.00, if the session-to-session error in each device was consistent across the stages in a given session); the ranges for the other devices were: Peach, 0.29–0.77; Empower, 0.73–0.92; Weba, 0.30–0.73; and Concept2, 0.64–0.89. For each device, the lowest mean correlation occurred for the 30-s stage; without this stage the mean correlations were all ∼0.8–0.9, which reflects consistent error across the stages.

Mean Standard Deviation of Power, Representing Measurement Sensitivity to Stroke-to-Stroke Variations in Power (Random Error)

The mean SD for the Reference System (right in **Figure 7**) shows that the participants' true stroke-to-stroke variability in power output was lowest in the 30-s test, highest in Stage 1, declined through Stages 2–6, then increased again for the maximal effort in Stage 7. Differences of each device from the Reference System in the mean SD of power are evident in **Figure 7** and are presented in **Table 4**. Positive differences are consistent with additional noise in stroke-to-stroke variation in power (EmPower and Weba, as demonstrated in comparison to the Reference System in **Figure 6**), and negative differences are consistent with a lack of measurement sensitivity (Peach and the Concept2, as demonstrated in comparison to the Reference System in **Figure 6**). Magnitudes were trivial to small and negative for Peach and were possibly, likely, or decisively trivial or substantial. Differences from the Reference System in the SD for EmPower were positive and trivial to moderate and possibly or likely substantial in most stages. For Weba, differences in the SDs from the Reference System were positive, moderate to large and decisively substantial in most stages. The Concept2 showed a positive and large mean SD difference from the Reference System for the 30-s test, but negative and mostly small differences for the other stages that were possibly or decisively substantial.

Proportional Error in the Mean Standard Deviation of Power

Proportional error in the SD of power for a 2-SD change in the Reference System was likely trivial for Peach in most stages (2.7% for the 30-s test, and −5.8 to 1.1% for the other stages), small and likely substantial in most stages for EmPower (−43% for the 30-s test, and −24 to −10% for the other stages), small and decisively substantial in most stages for the Concept2 (−53% for the 30-s test, and −29 to −0.4% for the other stages), and moderate and decisively substantial in most stages for Weba (−43% for the 30-s test, and −42 to −23% for the other stages).

Between-Unit Differences in the Mean Standard Deviation of Power

Between-unit differences in the mean SD of power are illustrated by the SD bars in **Figure 7** (right). Positive between-unit variance for Peach is evident in six stages and was likely or

TABLE 2 | Differences from the Concept2 in mean systematic error across the stages for Peach, EmPower, and Weba. Data are mean (%), ±90% compatibility limits, with observed magnitude and *p*-values for inferiority and superiority tests (p_-/p_+).

	Peach	EmPower	Weba
30-s test	−2.0, ±3.2; Small 0.72/0.06	**−38.3, ±9.6; e.large****** 0.998/0.001	−0.2, ±4.3; Trivial 0.35/0.27
Stage 1	3.9, ±4.2; Moderate** 0.03/0.89	−21.4, ±8.0; e.large*** 0.98/0.01	−1.9, ±6.7; Small 0.61/0.20
Stage 2	5.9, ±5.0; Large** 0.02/0.94	−22.9, ±7.9; e.large*** 0.99/0.01	−0.5, ±4.3; Trivial 0.41/0.24
Stage 3	4.0, ±4.6; Moderate** 0.04/0.88	−22.8, ±10.8; e.large*** 0.98/0.02	−0.1, ±4.6; Trivial 0.32/0.28
Stage 4	2.1, ±5.2; Small 0.14/0.66	−24.2, ±12.5; e.large*** 0.97/0.03	1.6, ±2.8; Small 0.06/0.65
Stage 5	0.0, ±6.6; Trivial 0.39/0.38	−25.2, ±15.9; e.large*** 0.96/0.03	1.9, ±3.5; Small 0.08/0.69
Stage 6	1.4, ±5.8; Small 0.23/0.55	−26.2, ±10.9; e.large*** 0.98/0.02	3.8, ±3.4; Moderate** 0.02/0.93
Stage 7	0.4, ±4.8; Trivial 0.29/0.42	−26.9, ±9.6; e.large*** 0.99/0.01	2.2, ±3.3; Small 0.05/0.79

Scale of magnitudes: <1 and >−1%, trivial; ≥1 or ≤−1%, small; ≥3.0 or ≤−2.9%, moderate (mod); ≥5.5 or ≤−5.2%, large; ≥8.5 or ≤−8.0%, very large (v.large); and ≥14.2 or ≤−12.4%, extremely large (e.large).
*Reference-Bayesian likelihoods of substantial change: *possibly; **likely; ***very likely; and ****most likely.*
*The symbols *** and **** indicate rejection of the non-superiority or non-inferiority hypothesis (p_{N-} or p_{N+} <0.05 and <0.005, respectively).*
Likelihoods are not shown for effects that were unclear at the 90% level (failure to reject any hypotheses: $p > 0.05$).
Effects in bold have adequate precision at the 99% level ($p < 0.005$).

TABLE 3 | Technical (residual) error of measurement representing session-to-session error for mean power recorded by Peach, EmPower, Weba, and the Concept2. Data are SD (%), ±90% compatibility limits, with observed magnitude and *p*-values for the superiority test (p_+).

	Peach	EmPower	Weba	Concept2
30-s test	5.1, ±1.7 v.large**** >0.999	26.0, ±9.3 e.large**** >0.999	12.4, ±2.4 e.large**** >0.999	3.5, ±1.2 Large**** >0.999
Stage 1	6.6, ±2.0 v.large**** >0.999	18.6, ±5.7 e.large**** >0.999	11.5, ±2.1 e.large**** >0.999	0.9, ±0.0 Small** 0.90
Stage 2	4.1, ±1.5 Large**** >0.999	18.0, ±5.7 e.large**** >0.999	9.6, ±1.7 e.large**** >0.999	1.3, ±1.5 Small**** >0.999
Stage 3	4.3, ±1.5 v.large**** >0.999	18.6, ±6.7 e.large**** >0.999	9.6, ±1.8 e.large**** >0.999	0.5[a] Trivial –
Stage 4	4.7, ±1.5 v.large**** >0.999	17.9, ±6.4 e.large**** >0.999	7.6, ±1.4 e.large**** >0.999	1.1, ±3.3 Small*** 0.99
Stage 5	4.5, ±1.7 v.large**** >0.999	18.9, ±7.2 e.large**** >0.999	7.7, ±1.4 e.large**** >0.999	1.4, ±1.3 Small**** >0.999
Stage 6	4.0, ±1.4 Large**** >0.999	17.7, ±6.2 e.large**** >0.999	7.8, ±1.4 e.large**** >0.999	1.6, ±1.1 Moderate**** >0.999
Stage 7	4.8, ±1.7 v.large**** >0.999	17.3, ±6.0 e.large**** >0.999	7.2, ±1.4 e.large**** >0.999	1.4, ±5.8 Small**** 0.997

Scale of magnitudes: <0.5%, trivial; ≥0.5%, small; ≥1.5%, moderate (mod); ≥2.7%, large; ≥4.2%, very large (v.large); and ≥6.9%, extremely large (e.large).
[a]*The mixed model failed to produce compatibility limits for this residual.*
*Reference-Bayesian likelihoods of substantial change: *possibly; **likely; ***very likely; and ****most likely.*
*The symbols *** and **** indicate rejection of the non-superiority or non-inferiority hypothesis (p_{N-} or p_{N+} <0.05 and <0.005, respectively).*
Reference-Bayesian likelihoods of trivial change: [0]possibly; [00]likely; [000]very likely; and [0000]most likely.

decisively trivial in most of these stages (SDs of 13% for the 30-s test, and 0.6–3.3 for the other stages). Positive between-unit variance for EmPower is evident in three stages and ranged from small to moderate (8.6, 12, and 24% for Stages 1, 5, and 7, respectively) but were unclear. The other stages for Peach and EmPower showed negative variance. Positive between-unit variance was observed in all stages for Weba and was moderate in most stages (25% for the 30-s test, and 19–40% for the other stages); although the estimates all were unclear, the random-effect solutions for Weba units showed that specific units tended to have consistent error across the stages (data not shown). As with the analysis of means, no between-unit differences were possible for the Concept2.

DISCUSSION

This is the first study to assess the concurrent validity of power output from on-water rowing instrumentation systems. Additionally, the comparison of power from on-water instrumentation systems to that from a Concept2 Model D rowing ergometer had not been investigated previously and provides valuable insight into differences between on- and off-water measures of power in rowing. The devices were assessed over a wide range of intensities and stroke rates, and in an on-water rowing-specific range of motion for Peach, EmPower, and Weba, promoting the applicability of findings from this study for use of these devices on the water. Negative systematic error was evident for all devices in comparison to the Reference System, whereby mean power was lower in all devices than the Reference System; systematic error was of similar magnitude for Peach, Weba, and the Concept2, but was greater in EmPower. Less measurement sensitivity of stroke-to-stroke variations in power were observed in comparison to the Reference System for the Concept2 and Peach, but were negligible in Peach where concurrent variations in power with the Reference System were observed (**Figure 6**). EmPower and Weba added random error (noise) to stroke-to-stroke variations in power in comparison to the Reference System (**Figure 6**). There was some evidence of substantial between-unit differences in mean power for Peach, EmPower and Weba, but the SDs representing between-unit differences all were unclear. Between-unit differences were not

TABLE 4 | Differences in the mean SD of power from the Reference System across the stages for Peach, EmPower, Weba, and the Concept2. Data are mean (%), ±90% compatibility limits, with observed magnitude and p-values for inferiority and superiority tests (p_-/p_+).

	Peach	EmPower	Weba	Concept2
30-s test	**–16, ±11; Small**** 0.85/0.005	**57, ±27; Moderate****** <0.001/0.998	139, ±110; Large*** 0.01/0.98	**177, ±46; Large****** <0.001/>0.999
Stage 1	**–3.0, ±4.0; Trivial^{0000}** 0.004/<0.001	14, ±16; Small*^{0} 0.02/0.64	61, ±74; Moderate** 0.03/0.93	**–27.8, ±3.6; Small****** >0.999/<0.001
Stage 2	**–4.4, ±3.6; Trivial^{000}** 0.009/<0.001	**9.7, ±5.9; Trivial^{0}*** <0.001/0.35	73, ±84; Moderate** 0.03/0.94	**–27.9, ±4.6; Small****** >0.999/<0.001
Stage 3	**–6.5, ±4.0; Trivial^{00}** 0.07/<0.001	**20, ±13; Small**** <0.001/0.88	88, ±82; Moderate*** 0.02/0.97	**–24.3, ±8.2; Small***** 0.99/<0.001
Stage 4	**–6.4, ±5.1; Trivial^{00}** 0.11/<0.001	**15.5, ±8.4; Small**** <0.001/0.81	91, ±78; Moderate*** 0.02/0.97	**–20.8, ±9.6; Small*^{0}** 0.96/<0.001
Stage 5	**–5.2, ±5.4; Trivial^{00}** 0.07/<0.001	29, ±26; Small** 0.09/0.90	126, ±95; Large*** 0.01/0.99	**–13.1, ±11.4; Small*^{0}** 0.68/0.003
Stage 6	**–3.9, ±5.3; Trivial^{000}** 0.03/<0.001	**17, ±14; Small**** 0.001/0.77	136, ±148; Large*** 0.02/0.97	**–13.8, ±10.9; Small*^{0}** 0.90/0.01
Stage 7	**–9.7, ±6.9; Trivial^{0}*** 0.47/<0.001	15, ±29; Small 0.05/0.60	109, ±65; Large*** 0.01/0.99	**–7.2, ±8.1; Trivial^{0}*** 0.27/0.002

Scale of magnitudes: <11 and >−10%, trivial; ≥11 or ≤−10%, small; ≥43 or ≤−30%, moderate (mod); ≥100 or ≤−50%, large; ≥230 or ≤−70%, very large (v.large); and ≥900 or ≤−90%, extremely large (e.large).
*Reference-Bayesian likelihoods of substantial change: *possibly; **likely; ***very likely; and ****most likely.*
*The symbols *** and **** indicate rejection of the non-superiority or non-inferiority hypothesis (p_{N-} or p_{N+} <0.05 and <0.005, respectively).*
Reference-Bayesian likelihoods of trivial change: ^{0}possibly; ^{00}likely; ^{000}very likely; and ^{0000}most likely.
The symbols ^{000} and ^{0000} indicate rejection of the superiority and inferiority hypothesis (p_- and p_+ <0.05 and <0.005, respectively).
Effects in bold have adequate precision at the 99% level (p < 0.005).

apparent in the SD of power (i.e., units did not differ in their measurement sensitivity or noise) for Peach and EmPower, whereas Weba units differed in their amount of noise, but again all the SDs were unclear.

Systematic Error

Differences from the Reference System in device mean power inform potential systematic error for the given device. It should be noted that the Reference System does not provide a criterion measure of power, rather, concurrent validity in comparison to the Reference System is reported. Calculation of power from the Reference System includes a correction for force relative to oar angle (see section "Materials and Methods"), where error for the Reference System may have been introduced. The consistent ∼10% difference in mean power for Peach, Weba, and the Concept2 from the Reference System may therefore reflect positive systematic error for the Reference System whereby true power is closer to that of Peach, Weba, and the Concept2. Only the Concept2 has been investigated previously for its validity of power output, where negative systematic error of ∼7% was found in comparison to instrumentation similar to that used in the current study (Boyas et al., 2006). Most of the apparent systematic error in the current study may therefore be coming from the devices rather than the Reference System. The greater negative systematic error for EmPower in comparison to the other devices may be related to the stepped pattern in power output sometimes evident during testing (as illustrated in **Figure 6** for EmPower).

Differences from the Concept2 in mean power for Peach, EmPower, and Weba can be used by practitioners to inform expected differences between on- and off-water power outputs, and the extent to which differences are related to device measurement or the technical demand of on-water rowing. Power output at high intensities is lower on-water than on a Concept2 ergometer over the same test duration (Vogler et al., 2010). Over a 2000-m time trial, a ∼15% lower mean power has been observed on-water with Peach than for the same test on a Concept2 ergometer (personal observations of two of the authors). However, differences in mean power between Peach and the Concept2 in the current study were only ∼1% for high intensities (Stages 6 and 7). The smaller difference between the Peach and Concept2 at high intensities in the current study than that observed when these devices are used in the field suggests the systematic error differences between the two devices contribute only a small portion of the overall difference between on- and off-water power. The remaining discrepancy between on- and off-water power that is not related to systematic error differences between the devices may therefore reflect a reduction in the power that is applied on-water in comparison to that applied on a Concept2 ergometer. The differing technical demand of on-water rowing in comparison to rowing on an ergometer (Kleshnev, 2005) may constrain the power applied during high intensity efforts on-water, as demands such as the entry and exit of the oar from the water will influence the power applied on water, but do not contribute to a rowing stroke on a Concept2 ergometer.

Readers may notice that Concept2 power reported for the maximal stages (30-s test and Stage 7) is relatively low for trained rowers. The low Concept2 power recorded corresponds with the observed ∼14% lower Concept2 power values on the Swingulator at the same heart rate, and the higher perceived effort reported by athletes for the same given power in comparison to those on the Concept2 when used independently from the Swingulator (authors own observations, data not shown). The added resistance through the Swingulator's pulley system and the indirect force application at the oar (as opposed to in line with the chain when applied at the Concept2 handle) may explain the lower maximal Concept2 power achieved when on the Swingulator.

Proportional Error in Systematic Error

The systematic error magnitudes reported are relative to the corresponding mean power per stage, and therefore may differ at different magnitudes of power. Proportional error (the change in systematic error for a 10% change in mean power) represents the relationship between power and systematic error, enabling practitioners to estimate the relative systematic error for a given power output, such as during a race start or short high-intensity intervals where power output is very high. Proportional error was evident only for Peach and EmPower, and only for the 30-s test, where it was negative. Negative proportional error would produce a greater underestimation of power in comparison to the Reference System at higher power outputs, which is evident in the greater negative systematic error observed for the 30-s test in comparison to the other stages for Peach and EmPower in **Table 1**. It is possible that the proportional error for the 30-s test in Peach and EmPower is related to the location of measurement of these devices at the oarlock (**Figure 1**), as proportional error was consistently trivial for Weba and the Concept2 (which were located at different positions on the Swingulator system). Although rowing performance tests rarely encompass durations as short as 30 s, practitioners should be aware of the negative proportional error introduced by Peach and EmPower at very high power outputs.

Between-Unit Differences in Systematic Error

Based on the between-unit differences in mean power, use of the same unit for repeated measurements or comparing rowers is recommended to remove any potential error introduced by individual units. Although between-unit differences were unclear, specific units showed consistent error across the stages, indicating real differences exist between units. Furthermore, the magnitude of between-unit differences ranged up to large or extremely large for all devices. The unclear effects representing between-unit differences is due not only to the limited number of units assessed for each device, but also to the substantial session-to-session TEM (the random variation in mean power arising between sessions), which reduced the ability to partition error to specific units.

Between-Session Error and Between-Participant Error

Differences in mean power between sessions, representing the overall TEM, was partitioned *via* random effects into error introduced by the Reference System across all devices in each session (∼1%), error arising from different participants with each device (Peach ∼3.5%, EmPower ∼−8%, Weba ∼3%, and Concept2 ∼2%), and the residual TEM (i.e., the error introduced by each device in each session; Peach ∼4.5%, EmPower ∼19%, Weba ∼9%, and Concept2 ∼1.5%). Together the error introduced by these three sources (the Reference System, that for different participants, and the residual TEM) reflect the total error introduced between sessions. Although mostly unclear, the error introduced by the Reference System between sessions was smallest of these three random effects and would represent only a small fraction of the overall TEM. The Reference System was therefore reliable relative to the other devices. Although the Reference System is not a criterion or gold-standard measure of power in the current study (rather it provides a comparative measure for assessing the concurrent validity of the other devices), the error arising from a criterion measure is an important component of the total error observed in validity studies that is often overlooked, and should be considered in future research examining device validity.

The extent to which device error differed between participants was generally unclear, but at least this sample may provide insight into the effect of different rowing styles on device measurement. The positive between-participant differences for Peach, Weba, and the Concept2 may reflect differences in the error introduced by these devices when measuring power from differing rowing styles. Differences between participants in their pattern of force application, catch, and finish angles (or chain position in the case of the Concept2), drive phase durations, or recovery phase durations could be factors contributing to between-participant differences in systematic error. However, further research is needed to better understand the differences in device error arising between participants and whether rowing style and device error are related. The negative between-participant differences for EmPower imply that more error is introduced when testing the same participant (i.e., the noise added to stroke-to-stroke variations in power) than when testing different participants, which is likely related to the stepped pattern in power output occasionally occurring within a stage for EmPower (as illustrated in **Figure 6**).

The correlations between the residuals supported the interpretation of the residuals as TEM arising independently in each device between sessions. In reliability studies, TEM combines with biological variability (e.g., variability in the power a participant can produce between testing sessions) to give the typical or standard error of measurement in such studies. The residual technical error observed here should therefore be smaller than the typical error observed elsewhere in reliability studies. However, the ∼4.5% TEM observed for Peach is larger than the typical (standard) error of measurement of 1.3–2.2% found for Peach between three 500-m trials in elite scullers (Coker, 2010). The ∼1.5% TEM observed for the Concept2 lies within the range of the 1.3 and 2.8% standard error of measurement values reported for 2000- and 500-m test distances on the Concept2 (Soper and Hume, 2004), but would allow for little biological variability between tests. It is possible that the stationary testing set-up on the Swingulator in the present study could contribute to technical error in some way, at least for Peach and the Concept2, that would not arise when the devices are used as intended, either on-water (in the case of Peach, and possibly also EmPower and Weba), or without attachment to the Swingulator (in the case of the Concept2).

Mean Standard Deviation of Power, Representing Measurement Sensitivity to Stroke-to-Stroke Variations in Power (Random Error)

The shallow "∪" shape across Stages 1–7 illustrated by the Reference System in its mean SD of power in **Figure 7** (right) demonstrates that the participants' true stroke-to-stroke variability in power output decreased from Stages 1–6. The reduction in variability, particularly over Stages 1–3, is likely due to the difficulty associated with maintaining a consistent power output when the prescribed power is easier than the participants are familiar with. The increase in participant variability in Stage 7 may reflect pacing strategy in this maximal stage, such as a fast start and fast finish, or the inability to maintain a desired target power output. The least stroke-to-stroke variability was evident in the 30-s test (Stage 0), which was likely due to the short test duration, where pacing strategy and fatigue have limited contribution.

The positive differences from the Reference System in the mean SD of power for EmPower and Weba represent random error (noise) in the signal output of these devices. The small to moderate random errors for EmPower would produce modest attenuation of rowing performance predicted by power per stroke for submaximal and maximal intensities over 4 min, but a considerable attenuation of effects for maximal intensities over short durations (∼30 s). The Weba would produce considerable attenuation of rowing performance predicted by power per stroke over all intensities assessed in this study. These attenuations would reduce the ability to detect true effects with power per stroke as a predictor.

Peach appeared to closely follow the stroke-stroke variation in power measured by the Reference System (as shown in **Figure 6**), although the analysis of the mean SD of power indicated a small amount of measurement sensitivity was lost in comparison to the Reference System. The mostly trivial difference in measurement sensitivity would result in little attenuation of relationships between power per stroke and rowing performance. Future research investigating individual stroke power (if the individual strokes could be aligned consistently) would enable the partitioning of stroke-to-stroke variation in power into the variation arising from the participant, random error (if any) in the Reference System, and any lack of measurement sensitivity (as negative variance) in Peach.

The Concept2 demonstrated a reduced measurement sensitivity in comparison to the Reference System, which improved from Stages 1 to 7, whereas considerable random error was apparent for the 30-s test. Inspection of the stroke-to-stroke data for the Concept2 revealed greater differences from the Reference System over the first ∼5 strokes due to a gradual increase in power from the Concept2 at the start of each stage. These findings are consistent with those of Boyas et al. (2006), who found a reduction in the magnitude of negative systematic error for the Concept2 when they excluded the first three strokes from analysis. The gradual increase in power demonstrated by the Concept2 at the start of each stage (when the flywheel is stationary) likely reflects the increase in flywheel velocity due to the inertia of the flywheel, given that the acceleration of the flywheel is used to calculate power (Boyas et al., 2006; Dudhia, 2017). The effect of a lack of measurement sensitivity would therefore be reduced in later stages, as initial differences from the Reference System at the start of the stage contribute a smaller proportion of the total number of strokes per stage as stroke rate increases. The lack of measurement sensitivity observed for the Concept2 would result in small attenuations of rowing performance predicted by power per stroke.

Proportional Error in the Mean Standard Deviation of Power

The mostly trivial proportional error in the SD of power for Peach showed that there was reasonable consistency in the variation of power per stroke in comparison to the Reference System (as illustrated in **Figure 6**). The negative proportional error in the SD of power for EmPower and Weba represents a reduction in the magnitude of noise introduced to stroke-to-stroke measures of power by these devices when true (Reference System) stroke-to-stroke variation is higher. The negative proportional error observed for the Concept2 probably represents a decrease in measurement sensitivity at higher values of stroke-to-stroke variation, which will have some explanation in terms of the detection of fluctuations in flywheel velocity.

Between-Unit Differences in the Mean Standard Deviation of Power

The occurrence of both positive and negative variance for between-unit differences in the mean SDs for Peach and EmPower likely arise from sampling variation, whereby a true variance of practically zero can be expected to produce some positive and some negative estimates of variance. The positive and negative between-unit variances in the mean SDs observed across the stages for Peach and EmPower are therefore consistent with no real differences between the units in their measurement of stroke-to-stroke SD. Conversely, the consistency observed in the magnitude of positive variance across the stages is evidence of real differences between Weba units, notwithstanding the uncertainty of the effects. Use of the same Weba unit for repeated measurements of power per stroke would remove any potential error introduced by between-unit differences, although the magnitude of random error added by Weba to stroke-to-stroke measurements of power (as illustrated in **Figure 7**, right) is such that Weba is not recommended for the assessment of power per stroke. Some Weba units might also introduce substantial random error into the measurement of mean power in a 2000-m time trial; for example, if the SD of power per stroke for a unit was 16%, the error in the mean of ∼256 strokes in the trial would be $16/\sqrt{256} = 1\%$, which represents substantial error.

Practical Applications

Peach

- Practitioners should be aware that power output measured by Peach is likely lower than that performed by the rower by ∼10%, but up to ∼17% at maximal power outputs over short (30 s) durations.
- Power measured by Peach is close to that of the Concept2 (within 2%), but differences of up to 6% exist between the two devices at power outputs below ∼150 W. Differences greater than 2% in power between Peach and Concept2 observed by practitioners therefore likely reflect differences in the application of power relating to the increased technical demand in on-water rowing.
- The TEM for Peach was ∼5% which represents large to very large errors being introduced between sessions. Negligible session-to-session reliability is represented by TEM values of <0.5%.
- Peach can be used with confidence for assessments of stroke-to-stroke power and of relationships between power and rowing performance, given its negligible lack of measurement sensitivity (∼−6% difference from the Reference System in the mean SD of power, and up to 16% at maximal efforts over 30 s).

EmPower

- Practitioners should be aware that power measured with EmPower devices may be substantially lower (∼25%) than when measured with Peach, Weba, or Concept2 devices. It is therefore advisable that practitioners use the same device when comparing measures of power output, particularly when using EmPower.
- The TEM for EmPower was ∼18% which represents extremely large errors being introduced between sessions. Negligible session-to-session reliability is represented by TEM values of <0.5%.
- EmPower is best used to assess mean power rather than power per stroke owing to the noise in its signal output, which was represented by random error estimates of ∼15% and up to 57% at maximal efforts over 30 s. Negligible random error magnitudes are <11% for stroke-to-stroke measures of power.

Weba

- Practitioners should be aware that power output measured by Weba is likely lower than that performed by the rower by ∼10%, but is similar (within ∼5%) to that of Peach and the Concept2.
- The TEM for Weba was ∼10% which represents extremely large errors being introduced between sessions. Negligible session-to-session reliability is represented by TEM values of <0.5%.
- Weba is best used to assess mean power rather than power per stroke owing to the noise in its signal output, which was represented by random error estimates of 61–139%. Negligible random error magnitudes are <11% for stroke-to-stroke measures of power.

Concept2

- Practitioners should be aware that power output measured by Concept2 is likely lower than that performed by the rower by ∼10%, but is similar (within ∼5%) to that of Peach and Weba.
- The TEM for Concept2 was ∼1.5% and was lower than that for Peach, Weba, and EmPower. Negligible session-to-session reliability is represented by TEM values of <0.5%, nonetheless the magnitude of error introduced by the Concept2 between sessions is only small.
- Concept2 measurement sensitivity for the assessment of stroke-to-stroke power is ∼20% lower in comparison to the Reference System. When assessing stroke-to-stroke power practitioners should exclude the first ∼5 strokes or use tests involving rolling starts to account for the greater negative offset in power associated with stationary starts on the Concept2.

CONCLUSION

Mean power was found to be lower in comparison to the Reference System for all devices. Magnitudes of negative systematic error were similar for Peach, Weba, and the Concept2, but larger for EmPower. Stroke-to-stroke variations in power were consistent between Peach and the Reference System, but a small reduction in measurement sensitivity was evident for the Concept2, whereas EmPower and Weba introduced noise. There was some evidence of between-unit differences in mean power for Peach, EmPower, and Weba, and in the SD of power (stroke-to-stroke fluctuations) for Weba. The findings of this study can be used by practitioners to inform the interpretation of meaningful change in measures of power when using the devices assessed.

DATA AVAILABILITY STATEMENT

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found below: Open Science Framework at doi: 10.17605/OSF.IO/HQ4W2, https://osf.io/hq4w2/.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Victoria University Human Research Ethics Committee (VUHREC). The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

AH, RA, RS, WH, and KB designed the study and wrote the manuscript. AH collected the study data. VR contributed to data analyses. WH performed the statistical analyses. All authors contributed to the article and approved the submitted version.

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High-Intensity Interval Training and Sprint-Interval Training in National-Level Rowers

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Purpose: The effects of two different high-intensity training methods on 2,000 m rowing ergometer performance were examined in a feasibility study of 24 national-level rowers aged 18–27 years (17 males, 2,000 m ergometer time trial 6:21.7 ± 0:14.6 (min:s) and seven females, 2,000 m ergometer 7:20.3 ± 0:12.1. Habitual training for all participants was ~12–16 h per week).

Methods: 16 high-intensity ergometer sessions were completed across two 3-week periods. Participants were allocated into two groups according to baseline 2,000 m time. High-intensity interval session-sprint-interval session (HIIT-SIT) completed eight HIIT (8 × 2.5 min intervals; 95% of 2,000 m wattage) followed by eight SIT (three sets of 7 × 30 s intervals; maximum effort). SIT-HIIT completed eight SIT sessions followed by eight HIIT sessions. Both a 2,000-m time trial and a progressive incremental test finishing with 4 min "all-out" performance were completed before and after each 3-week phase.

Results: Both groups showed similar improvements in 2,000 m time and 4 min "all-out" distance after the first 3 weeks (2,000 m time: HIIT-SIT: −2.0 ± 0.6%, mean ± 90% CL, $p = 0.01$; SIT-HIIT: −1.5 ± 0.3%, $p = 0.01$) with no significant difference between groups. HIIT-SIT demonstrated the greatest improvements in submaximal heart rate (HR) during the progressive incremental test with eight sessions of HIIT showing a greater reduction in submaximal HR than eight sessions of SIT. The net improvement of 16 high-intensity sessions on 2,000 m time was −2.5% for HIIT-SIT (−10.6 ± 3.9 s, $p = 0.01$) and – 2.2% for SIT-HIIT (−9.0 ± 5.7 s, $p = 0.01$) and for 4 min "all-out" performance was 3.1% for HIIT-SIT (36 ± 25 m, $p = 0.01$) and 2.8% for SIT-HIIT (33 ± 27 m, $p = 0.01$).

Conclusion: Eight sessions of high-intensity training can improve 2,000 m ergometer rowing performance in national-level rowers, with a further eight sessions producing minimal additional improvement. The method of high-intensity training appears less important than the dose.

Keywords: rowing, training methodology, ergometer, performance, coaching

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INTRODUCTION

A 2,000-m rowing race takes 5:30–8:00 min (depending on the racing category) and typically begins with a short supra-maximal start (~45 s), followed by 4–6 min of near maximal intensity, and finishes with another supra-maximal burst of 45–60 s. The race intensity distribution typically requires 70–75% of total energy from aerobic metabolism and 25–30% from anaerobic metabolism (Hagerman, 1984). Despite a substantial contribution from anaerobic metabolism, profiling of the training practices of elite rowers demonstrated that ~83% of training was undertaken at low intensities, 15–16% at or near anaerobic threshold and only 1–4% at high intensities (Tran et al., 2015). Current trends in cycling or running involve regular high-intensity, short-duration work bouts to drive physiological adaptation and performance improvement. The inclusion of high-intensity training, of both long and short work intervals, in addition to low-intensity endurance training purportedly yields superior improvements in endurance performance than low-intensity endurance training alone (Seiler, 2010; Stöggl and Sperlich, 2014).

Both high-intensity interval session (HIIT) and sprint-interval training (SIT) are increasingly common training methods used to stimulate adaptation in a range of endurance sports. Both training methods center on a reduction in training volume and increased training intensity to provide the stimulus for improved performance. The main difference between the training methods is the time domain of both the work and rest components, yielding a difference in the intensity distribution for each method. HIIT has been defined as a series of repeated short to moderate length intervals (up to 5 min in duration) completed at an intensity between the lactate threshold and maximal oxygen consumption (VO2max), separated by short and incomplete recovery periods, usually with a work:rest ratio ~ 1:1 (Laursen and Jenkins, 2002). HIIT primarily stimulates peripheral muscle metabolic changes in the short-term (Westgarth-Taylor et al., 1997; Weston et al., 1997; Burgomaster et al., 2005), while structural cardiovascular adaptations emerge over the long-term (Laursen et al., 2005; MacInnis and Gibala, 2017). Only three studies with varying intervention durations (4–8 weeks) have investigated the effect of HIIT on 2,000 m ergometer rowing performance. The improvements in performance ranged from 1.3 to 1.9% (5.0–8.2 s; Driller et al., 2009; Akca and Aras, 2015; Stevens et al., 2015; Ní Chéilleachair et al., 2017).

SIT and RST originated as a training method in team sports and selected endurance sports but is uncommon in rowing. RST is defined as three or more maximal short duration (≤30 s) efforts, interspersed with incomplete recovery periods (≤60 s) totaling up to ~15 min of sprint work (Millet et al., 2019). The terms SIT and RST are largely interchangeable in rowing and stimulate a high degree of neuromuscular and metabolic stress (Bishop et al., 2011), with the aerobic contribution increasing as a function of successive sprints (Bogdanis et al., 1996). In trained runners, RST improved 1,500 m time by 21 s (6%) after 7 weeks, despite a reduction in training volume of 50% (Gunnarsson and Bangsbo, 2012). Elite cyclists have shown improvements of 3.5–4.4% in a variety of key performance measures (e.g., 20 min self-paced time trial and peak aerobic power) after completing only nine RST sessions (Ronnestad et al., 2020).

To our knowledge, there are no published investigations that have directly compared the effects of short-term HIIT and SIT training in national- to elite-level rowers. Other sports, including cycling and running (Laursen et al., 2002; Gunnarsson and Bangsbo, 2012; Ronnestad et al., 2020), have been examined for this purpose, and we sought to extend this work to rowing. The aim of this study was to compare the effects of two successive training blocks of HIIT and SIT on 2,000 m ergometer rowing performance in national-level rowers. A secondary aim was to examine the time course of changes over the 16 sessions, irrespective of the training intervention, by comparing the two training blocks.

MATERIALS AND METHODS

Participants

Thirty national- to elite-level rowers volunteered to participate in this study. A total of 24 rowers completed the entire study and were included in the final data analysis. Participants included 17 male rowers (age 22 ± 4 years; body mass 84.2 ± 12.7 kg; 2,000 m ergometer time 6:21.7 ± 0:14.6; mean ± SD) and seven female rowers (age 21 ± 1 years; body mass 66.7 ± 6.9 kg; 2,000 m ergometer time 7:20.3 ± 0:12.1) recruited from clubs and state institutes or academies of sport across Australia. The participants had competed at a national or international level in the previous season, consistently trained on-water 7–10 sessions per week. All participants were healthy, free from injury, and undertaking regular training sessions in adherence with COVID-19 guidelines prior to the study. Approval to conduct this study was provided by the University of Canberra Human Research Ethics Committee (approval 2020/444). All participants provided written informed consent after explanation of the aims, benefits, and risks of the study.

Experimental Design

A feasibility study was conducted to verify the likely effects of HIIT and SIT before a full randomized controlled trial study could be conducted (Whitehead et al., 2014). A longitudinal randomized cross-over design with two 3-week training conditions was employed to compare the effects of HIIT and SIT (**Figure 1**). Participants were informed that there was no clear advantage of one training type over the other. Participants performed baseline (PRE) testing and were then allocated randomly to either HIIT-SIT or SIT-HIIT, based on their 2,000 m performance test. Groups were counterbalanced in each training location to account for variability in training programs. HIIT-SIT completed 3 weeks of HIIT followed by 3 weeks of SIT, while SIT-HIIT completed 3 weeks of SIT followed by 3 weeks of HIIT. No additional high-intensity sessions were completed by rowers during this study to ensure all participants completed the same number of high-intensity workouts. All other training within each

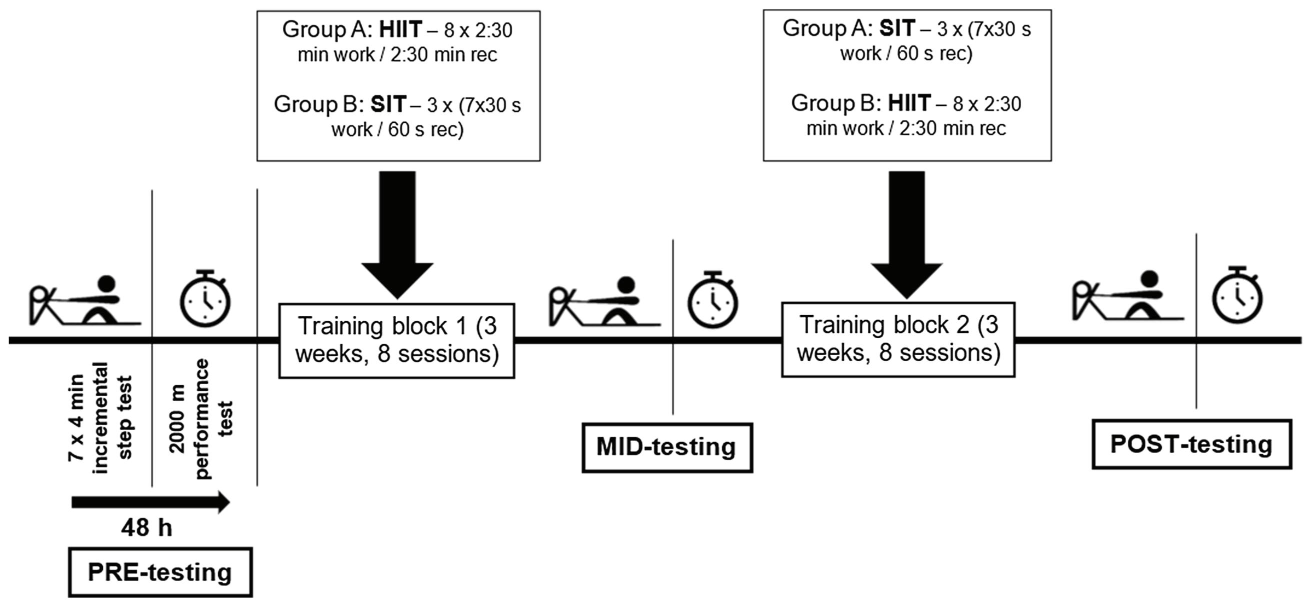

FIGURE 1 | Experimental design showing PRE, MID, and POST-testing time points interspersed with training allocations according to GROUP.

training location was prescribed by the coach and programmed to maintain within-subject consistency to standardize differences in training stimulus between the groups, or across the two training blocks. No control group was employed in the study as per previous recommendations for a feasibility study (Whitehead et al., 2014).

During each 3-week block, the participants completed a total of eight high-intensity training sessions of a single training method (HIIT or SIT) interspersed with their normal training (4–5 on-water, 3 strength, and 2–3 non ergometer cross-training). Training load (hours, % of time spent in training heart rate (HR) zones) was prescribed and remained stable for each individual across both 3-week training blocks. In a pilot study, the training load of a single HIIT and SIT session was determined, and the number of intervals and additional work prescribed to ensure each HIIT and SIT session created a standardized training stress for each individual. Training stress score was assessed using the T2-minute method (Tran et al., 2014), and pilot work facilitated modification of the high-intensity work bouts to ensure training stress score was matched across training styles. Following the first 3 weeks of training, participants had 1-week of light training (volume reduced by ~20%) during which they were re-tested (MID) and then assigned to the other training method. Following second 3-week training, block participants were re-tested (POST). All testing as well as HIIT and SIT training sessions were completed on a stationary Concept II rowing ergometer (Concept II Model D or E; Concept II Inc., Morrisville, United States). Minimum target workloads for HIIT in first 3-week intervention were based on the participant's PRE 2,000 m mean power output. Target workloads for HIIT in second 3-week intervention were based on participant's MID 2,000 m mean power output. All participants were provided with mobility, stretching, and muscular activation exercises to minimize the risk of overuse injury as a result of the introduction of high-intensity training sessions.

Testing Protocol

Testing consisted of two sessions separated by 48 h and undertaken in accordance with COVID-19 restrictions, either in socially distanced groups or in a home environment. Day 1 of testing was undertaken 3 days following completion of the final high-intensity ergometer session, and day 2 of testing was undertaken a further 2 days later. Participants were familiar with the testing procedure and ergometer. The use of different ergometer models across the study was deemed acceptable given previous work showing testing on different models of the Concept II ergometer elicits near identical physiological responses (Vogler et al., 2007). The test–retest reliability of well-trained rowers on a Concept II ergometer is 0.7 ± 0.3% (mean ± 95% CL; Schabort et al., 1999).

On day 1 of testing participants completed a 7 × 4-min incremental ergometer step test (Rice and Osborne, 2013), with a 2,000-m ergometer time-trial undertaken 48 h later. To minimize diurnal variation of performance, each participant completed testing at approximately the same time of day throughout the study (Nugent et al., 2019), and on the same model ergometer. In the 24-h period prior to testing, the participants were instructed to avoid any strenuous activity, and consumption of alcohol. Before each testing session the ergometer drag factor was adjusted to correspond with the rower's weight and gender category in accordance with Rowing Australia testing protocols (Rice and Osborne, 2013). These drag factors were 95 for lightweight women, 105 for lightweight men and heavyweight women, and 115 for heavyweight men.

7 × 4-min Incremental Step Test

Following a light warm-up, participants completed a 7 × 4-min incremental step test, interspersed with 1 min recovery periods. The starting workload and increments between workloads were individualized based on each participant's best 2,000 m ergometer time in the previous 12 months (Rice and Osborne, 2013). Workloads 1–6 were submaximal and workload 7 was a maximal effort, acting as a 4-min time-trial (4minTT). Each participant was required to hold their prescribed power outputs for workload 1–6, and then instructed to cover as much distance as possible during workload 7. Power output, stroke rate, and HR were recorded on the ergometer work monitor and averaged during each of the 4 min workload periods. The rating of perceived exertion (RPE) was recorded during the recovery period using the Borg 6–20 scale (Borg, 1970). Distance covered in the final 4 min and mean power output were recorded as the criterion dependent variables.

2,000 m Performance Test

Participants undertook stretching and a self-selected 30 min warm-up prior to each 2,000 m testing session. The display module on the ergometer was set to record the mean power output and stroke rate for each 100 m increment. HR was recorded continuously throughout the test (Wahoo Tickr; Wahoo Fitness, Georgia, United States) and RPE recorded immediately upon completion. Max HR was reported as the maximum HR recorded during either test. Time to complete 2,000 m and mean power output were recorded as the criterion dependent variables.

Training Intervention Protocols

HIIT or SIT sessions were completed three times per week for 3 weeks, yielding eight sessions in total (only two sessions were completed in the final week to allow for additional recovery before testing the following week). Each intervention session replaced a normal endurance training session in the program. Power output, HR, and RPE were recorded for each set of each session. In addition to the training intervention sessions, training consisted of 4–5 endurance sessions, 3 strength sessions, and 2–3 cross training sessions per week. In some training locations, on-water was not possible due to local COVID-19 restrictions; therefore, cycling and running were substituted for in for on-water sessions. The ergometer monitor was set to display the work and rest interval duration. Both sessions lasted ~60 min.

High-Intensity Interval Training

Each HIIT session consisted of a 10-min self-selected warm-up, repeated before every session, followed by eight intervals at ≥95% of 2,000 m mean power output. Each interval was 2.5 min in duration separated by a 2.5-min recovery period (Millet et al., 2019). Participants were instructed to try and improve their mean power output each session. After the completion of each work interval, HR and RPE data were recorded with an extra 2.5 min break following interval 4.

Sprint-Interval Training

Each SIT session consisted of a 10-min self-selected warm-up, repeated before every session, followed by three sets of seven "all-out" (~130% of 2,000 m mean power output) intervals using full length strokes. Each interval was 30 s in duration and interspersed with 60 s of recovery (Laursen et al., 2002). The stroke rate was capped at 40 strokes.min^{-1} to ensure technically sound strokes were completed. There was a 5-min recovery period after each set, where RPE data were recorded.

Statistical Analysis

Mean, standard deviation (SD), and 90% confidence limits (CLs) were calculated for each testing and training variable. Percentage of maximum heart rate (%HRMAX) was calculated from each participant's highest value achieved in either of the two PRE performance trials. Statistical Package for Social Sciences (SPSS) software (Version 25, SPSS Inc., Illinois, United States) was used for statistical analyses. Linear mixed modeling was employed to determine differences in training method (HIIT and SIT) across the two 3-week interventions. The fixed effects factor was HIIT vs. SIT, and the random effects were the change in the dependent variables (2,000 m time and 4minTT power output) over time. The first testing block was analyzed independently to assess the rowing performance effects of SIT and HIIT following a single block of a specific training method, with a Bonferroni correction employed for all *post hoc* analyses. Sample size estimation using G*Power software (v3.1.9.4 *a priori* power analysis with ANOVA repeated measures, within-between interaction, $\alpha = 0.05$, $1 - \beta = 0.80$, Cohen's $d = 0.2$) indicated the study required 24 participants (Faul et al., 2007). An additional six participants were added to account for an assumed 25% dropout rate. Statistical significance was set at $p < 0.05$.

RESULTS

Of the 24 participants who completed the study, HIIT-SIT was comprised $n = 11$ and SIT-HIIT was comprised $n = 13$ participants (**Table 1**).

Two Blocks of High-Intensity Training

Table 2 displays changes in performance measures for the 2,000 m and 4minTT rowing tests. When compared to baseline, both HIIT-SIT and SIT-HIIT improved ($p = 0.01$) both 2,000 m and 4minTT performance (power output, distance covered in 4 min, and time to complete 2,000 m) after 9 weeks of the study. However, there was no significant difference in rowing performance between the training methods ($p = 0.62$). Changes in performance following the first 3-week training intervention for both HIIT-SIT and SIT-HIIT were significantly different to PRE values, but performance was not further improved following the second 3-week intervention, where the order of the training methods was reversed.

TABLE 1 | Mean body mass and 2,000 m rowing ergometer PB for heavyweight and lightweight athletes in HIIT-SIT and SIT-HIIT groups.

Variable	Group	Heavyweight men	Lightweight men	Heavyweight women	Lightweight women
Body mass (kg)	HIIT-SIT	90.8 ± 9.9	73.9 ± 0.2	75.5 ± 5.7	60.8 ± 0.2
	SIT-HIIT	97.8 ± 9.5	73.1 ± 2.1	67.7 ± 1.2	60.9 ± 0.0
2,000 m PB (s)	HIIT-SIT	375.2 ± 16.1	381.1 ± 7.6	433.9 ± 26.6	444.7 ± 0.4
	SIT-HIIT	373.5 ± 9.9	392.8 ± 12.6	444.2 ± 1.3	436.7 ± 0.0

Data are represented as mean ± SD.

TABLE 2 | HIIT-SIT and SIT-HIIT results for 2,000 m rowing ergometer performance (2,000 m) and incremental step test peak performance (4minTT) for PRE, MID, and POST.

Variable	Group	PRE	MID	POST	Δ PRE to MID	Δ MID to POST	Δ Overall
2,000 m finish	HIIT-SIT	411.5 ± 36.5	403.1 ± 35.0	401.0 ± 34.8	−8.4 ± 5.2*	−2.1 ± 5.5	−10.6 ± 7.8*
time (s)	SIT-HIIT	407.5 ± 28.2	401.5 ± 28.0	398.6 ± 28.0	−6.0 ± 3.1*	−2.9 ± 4.4	−9.0 ± 5.7*
2,000 m PO (W)	HIIT-SIT	334 ± 82	356 ± 86	361 ± 87	21 ± 13*	5 ± 15	27 ± 20*
	SIT-HIIT	339 ± 65	355 ± 68	363 ± 72	16 ± 8*	8 ± 11*	24 ± 15*
4 min TT	HIIT-SIT	1,162 ± 117	1,188 ± 108	1,198 ± 109	26 ± 17*	10 ± 18	36 ± 25*
distance (m)	SIT-HIIT	1,177 ± 80	1,197 ± 77	1,210 ± 84	20 ± 18	13 ± 23*	33 ± 27*
4 min TT PO (W)	HIIT-SIT	329 ± 90	353 ± 90	362 ± 93	24 ± 15*	9 ± 14	33 ± 21*
	SIT-HIIT	333 ± 67	348 ± 65	360 ± 73	14 ± 12	12 ± 22*	27 ± 23*

*PRE, MID, and POST data are represented as mean ± SD. Change data (Δ) are represented as mean ± 90% CL. *Significantly different from PRE ($p < 0.05$).*

Eight Sessions of High-Intensity Training: HIIT Vs. SIT

When data for the first 3-week intervention was analyzed as a single training block, both HIIT and SIT improved 2,000 m and 4minTT (**Table 2**). Eight sessions of HIIT resulted in a −2.0 ± 0.6% (mean ± 90%CL; $p = 0.01$) improvement in 2,000 m time and 2.6 ± 0.9% ($p = 0.01$) improvement in 4minTT distance. Similarly, eight sessions of SIT resulted in −1.5 ± 0.3% ($p = 0.01$) improvement in 2,000 m time, and 1.5 ± 0.3% ($p = 0.06$) improvement in 4minTT distance. There were no significant differences in either performance test when HIIT and SIT were compared for the first 3-week intervention ($p = 0.68$). Both HIIT and SIT training methods elicited improvements in power output of 10–15 W from the first to the eighth training session (**Figure 2A**).

HIIT sessions were associated with a lower mean session power output and higher %HRmax across all eight training sessions when compared with SIT (**Figures 2A**,**C**, respectively, $p < 0.05$). RPE was consistently lower during HIIT sessions, but only different from SIT for sessions 1, 2, 4, and 5 (**Figures 2B**, $p < 0.05$). Relative to session 1 of the corresponding training method, sessions 4–8 were completed with a greater power output for HIIT ($p < 0.05$), while sessions 3–8 were completed with a greater power output for SIT ($p < 0.05$).

Comparison of Consecutive Training Blocks

Table 3 shows the change in performance for 2,000 m and 4minTT measures when data were collapsed and analyzed for the first 3-week intervention vs. the second 3-week intervention, irrespective of the training intervention (HIIT or SIT). The greatest improvements in both 2,000 m and 4minTT were realized following the initial 3-week intervention ($p = 0.01$), with no further improvements occurring following another 3 weeks of training ($p = 0.75$).

Submaximal Performance

HIIT-SIT elicited marked reductions in HR at STEPs 4, 5, and 6 after 16 sessions ($p = 0.02$). In contrast, in SIT-HIIT only HR at STEP 6 of POST was reduced ($p = 0.07$). HIIT-SIT yielded a lower HR compared to SIT-HIIT ($p < 0.05$) after eight and 16 sessions. RPE was similar for both groups throughout the training interventions.

DISCUSSION

The major outcomes of this feasibility study were that both HIIT and SIT improved rowing performance (2,000 m time: 9.0–10.6 s and 4minTT power output: 27–33 W) after 16 sessions (**Table 2**). However, there was no significant difference in the magnitude of the improvements between HIIT and SIT training. Given this lack of difference between HIIT and SIT for any performance variable after both eight and 16 sessions, it appears both methods of training are viable options for coaches looking for short-term improvements in performance in highly trained rowers. The magnitude of performance improvement over 2,000 m (~10 s) compares very favorably with changes in performance following extended endurance training. This study is the first to demonstrate successive blocks of HIIT and SIT can improve rowing performance in national to elite-level rowers, with performance changes seemingly more dependent on the inclusion of high-intensity training (HIIT or SIT), than the specific nature of the intervals.

Investigations of HIIT in rowers have been largely confined to three studies. Driller et al. (2009) completed a randomized

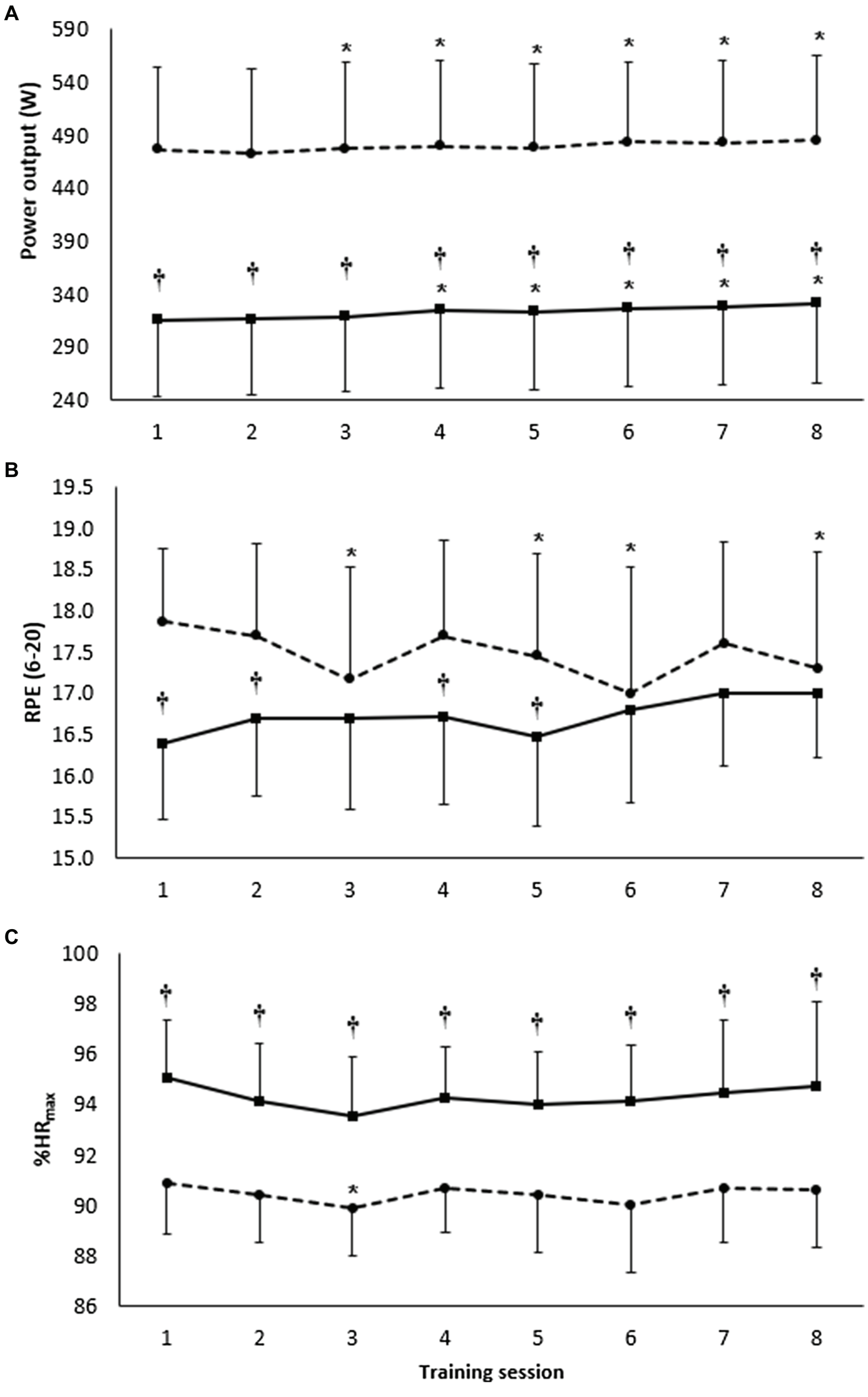

FIGURE 2 | Panel **A** shows mean power output (W), panel **B** shows rating of perceived exertion (RPE 6–20), and panel **C** shows heart rate as a percentage of maximum (%HRmax) for BLOCK1 training sessions. HIIT is represented by the solid line and SIT is represented by the dashed line. Data are displayed as mean ± SD. *Significantly different to session 1 ($p < 0.05$). †Significant between HIIT and SIT ($p < 0.05$).

cross-over design with 4 weeks of HIIT and control training balanced across two matched groups. Akca and Aras (2015) implemented a 4-week block of HIIT. Ní Chéilleachair et al. (2017) performed a straight 8-week block of high-intensity training. Regardless of study design and the work:rest ratio employed; these investigations demonstrated that HIIT improves rowing performance to a similar degree (1.3–1.8%). In the current study, our analysis of a single training block demonstrated

TABLE 3 | Change in performance measures following the first training block (BLOCK1) and the second training block (BLOCK2).

Variable	First 3-week block	Second 3-week block	Both 3-week blocks
Δ 2,000 m time (%)	−1.7 ± 0.3*	−0.6 ± 0.4†	−2.3 ± 0.5*
Δ 2,000 m power output (%)	5.5 ± 1.1*	2.0 ± 1.2†	7.6 ± 1.7*
Δ 4 minTT distance (%)	2.0 ± 0.5*	1.0 ± 0.6†	3.0 ± 0.8*
Δ 4 minTT power output (%)	6.2 ± 1.7*	3.1 ± 1.9†	9.4 ± 2.5*

*Values are shown as mean percentage change ±90% CL. *Significantly different to PRE ($p < 0.05$). †Significant between first and second 3-week blocks ($p < 0.05$).*

that HIIT and SIT yielded similar improvement (1.5–2.0%) after only eight sessions across 3 weeks. This outcome indicates that substantial improvements in performance can be realized in a shorter block of time than previous investigations. Importantly, a 3-week HIIT or SIT mesocycle is more viable for coaches to implement into a seasonal program than a longer 8-week block.

The first 3-week training intervention induced the greatest change in rowing performance regardless of training method (HIIT or SIT) with an additional 3-weeks of training yielding no further significant improvement in rowing performance. By session 4, both HIIT and SIT had already elicited higher average power output during the work intervals when compared with the first session of the respective training method. After the fifth session, there were no further substantial increases in power output for either training method. Our data indicate at least five high-intensity sessions may be required to induce a substantial change in rowing performance, and that beyond eight sessions there appears to be little additional improvement in rowing performance. Individual responses in the second 3-week block of training showed greater variation, with most rowers in both groups responding with either no further improvement, or a trivial improvement, in performance. Irrespective of the type of high-intensity training undertaken in the second block of training, athletes did not show deteriorations in performance. It is interesting to speculate on how best to periodize the inclusion of high intensity training in a typical competitive season. Our results appear to indicate that appropriate periodization of eight sessions of high-intensity training (HIIT or SIT) periodized once every three macrocycles (one macro cycle = 4 weeks) could promote incremental improvements in 2,000 m performance.

In this investigation the first 3-week training block was used to examine the performance benefits of eight sessions of HIIT compared with SIT when all other training was matched between groups at each training location. Our data showed that 2,000 m time improved for both HIIT-SIT and SIT-HIIT by 2.0 and 1.5%, respectively, (**Table 3**). Three other studies have been conducted in rowers where a variety of training methods were compared in a single training cycle (i.e., 4 weeks or 8–10 sessions). These investigations have yielded improvements in 2,000 m time of 5.7 s (1.4%), 5 s (1.2%), and 4 s (1%) with HIIT (2.5 min work with 3 min active recovery), supramaximal interval training (10 × 30 s max with 4 min active recovery), and SIT (4–6 × 60 s max with 2.5–5 min recovery), respectively (Driller et al., 2009; Akca and Aras, 2015; Stevens et al., 2015). These data are consistent with those from the present study and support the principle of training specificity (Hewson and Hopkins, 1996), confirming the notion that inclusion of HIIT, or SIT can improve 2,000 m rowing performance in as few as eight sessions in national-level rowers.

The submaximal responses to high-intensity training in rowing have largely been unreported in previous studies. While maximal performance benefits are often the primary indicator of success of a training intervention, such benefits are only realized after training induces the appropriate improvement in submaximal efficiency. While we were unable to complete a more in-depth metabolic analysis of our training due to COVID-19 restrictions, the results from the submaximal steps from our 7 × 4 testing protocol indicated HIIT-SIT reduced HR during STEP 6 after 16 sessions of high-intensity training. After only eight sessions HIIT-SIT showed a greater reduction in HR at STEP 4, 5, and 6 than SIT-HIIT. The combination of HIIT followed by SIT in the present investigation resulted in the greatest improvement in submaximal HR. Investigations in other sports (alpine skiers and soccer players) have also reported similar reductions in submaximal HR at a given workload following high-intensity training (Briel et al., 2010; Faude et al., 2014). Further research using a more detailed physiological assessment of the submaximal responses to HIIT and SIT is warranted. The next step will include a full randomized controlled trial to extend on the work of this study (Whitehead et al., 2014).

The sole outcome of this investigation was to determine the effect of concentrated blocks of high intensity training on maximal rowing performance. In achieving this outcome, it is worthy to consider the physiological and biochemical mechanisms underpinning the clear improvements in 2,000 m and 4 min "all-out" performances. Previous investigations utilizing work:rest and intensity domains similar to those used in this investigation reported changes in both intracellular and extracellular buffering capacity, heart remodeling and cardiac function, skeletal muscle oxidative capacity, submaximal oxygen efficiency, and the central nervous system (Weston et al., 1997; Shigenori, 2019; Callahan et al., 2021; Hu et al., 2021). Although we have no specific data to add to the underlying mechanisms, it appears that given the high baseline training status of the participants, coupled with the relatively short exposure time to the high intensity training regime, the major alteration in physiology and biochemistry that led to the positive changes in maximal rowing performances were biochemical rather than structural (i.e., heart remodeling) in nature. Rapid improvements in intra- and extra-cellular buffering capacities are likely responsible for the measured changes in maximal rowing performances reported in this study. Mechanistic studies typically involve moderately active participants rather than elite athletes, and further work in this area is required to provide greater understanding of mechanisms underpinning performance improvements with HIIT and SIT.

This study was conducted during the height of the COVID-19 pandemic. As a direct result we chose not to include a control group as the HIIT and SIT protocols were used as training motivation for athletes while conforming to local "social distancing" guidelines. This limitation has implications in quantifying the true effects of HIIT or SIT by accounting for the control group response. A similar protocol involving more traditional endurance training over 4 weeks induced improvements of 0.4–0.5% (Driller et al., 2009; Stevens et al., 2015). This limitation should be considered when evaluating the responses to HIIT or SIT in the present study, and future work could extend this using a more traditional randomized controlled trial design.

PRACTICAL APPLICATIONS

It appears that as few as eight sessions of high-intensity training (HIIT or SIT) can substantially improve rowing ergometer performance in elite rowers, and both HIIT and SIT are viable training options for coaches. Based on self-reported perceptual feedback, HIIT was better tolerated by the athletes and as such may be more favorable if only one style of high intensity training can be employed. Undertaking a second block of high-intensity training should be considered by coaches on a case-by-case basis, given the marked individual variability in responses.

CONCLUSION

A total of eight sessions of HIIT or SIT substantially improved 2,000 m rowing ergometer performance; however, 4minTT performance only improved after HIIT. There was no marked difference in the performance improvement between the training interventions. The greatest improvement in performance occurred following the first training block, and a second 3-week training block of HIIT or SIT did not result in further improvements in either 2,000 m or 4minTT performance. When selecting a training intervention, HIIT should be considered for an 8-session block while there is no difference between training styles across 16 sessions.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material; further inquiries can be directed to the corresponding author.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the University of Canberra Human Research Ethics Committee. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

KT and AR were responsible for all aspects of this manuscript. DP and JP were responsible for the development of the study protocol, data analysis, and manuscript revisions. All authors contributed to the article and approved the submitted version.

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Differences in Immune Response During Competition and Preparation Phase in Elite Rowers

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Background: Metabolic stress is high during training and competition of Olympic rowers, but there is a lack of biomedical markers allowing to quantify training load on the molecular level. We aimed to identify such markers applying a complex approach involving inflammatory and immunologic variables.

Methods: Eleven international elite male rowers (age 22.7 ± 2.4 yrs.; VO_2max 71 ± 5 ml·min^{-1}·kg^{-1}) of the German National Rowing team were monitored at competition phase (COMP) vs. preparation phase (PREP), representing high vs. low load. Perceived stress and recovery were assessed by a Recovery Stress Questionnaire for Athletes (*RESTQ-76 Sport*). Immune cell activation (dendritic cell (DC)/macrophage/monocytes/T-cells) was evaluated *via* fluorescent activated cell sorting. Cytokines, High-Mobility Group Protein B1 (HMGB1), cell-free DNA (cfDNA), creatine kinase (CK), uric acid (UA), and kynurenine (KYN) were measured in venous blood.

Results: Rowers experienced more general stress and less recovery during COMP, but sports-related stress and recovery did not differ from PREP. During COMP, DC/macrophage/monocyte and T-regulatory cells (T_{reg}-cell) increased ($p = 0.001$ and 0.010). HMGB1 and cfDNA increased in most athletes during COMP ($p = 0.001$ and 0.048), while CK, UA, and KYN remained unaltered ($p = 0.053$, 0.304, and 0.211). Pro-inflammatory cytokines IL-1β ($p = 0.002$), TNF-α ($p < 0.001$), and the chemokine IL-8 ($p = 0.001$) were elevated during COMP, while anti-inflammatory Il-10 was lower ($p = 0.002$).

Conclusion: COMP resulted in an increase in biomarkers reflecting tissue damage, with plausible evidence of immune cell activation that appeared to be compensated by anti-inflammatory mechanisms, such as T_{reg}-cell proliferation. We suggest an anti-inflammatory and immunological matrix approach to optimize training load quantification in elite athletes.

Keywords: rowing, inflammation, stress assessment, immune cells, recovery, load management

INTRODUCTION

In Olympic rowing, a race distance of 2000 m is covered within approximately 5.5–7.5 min, depending on sex, boat class, and environmental conditions and requires a high mechanical power output of 450 to 550 W (Steinacker et al., 1998). To prepare for rowing races, elite athletes spend about 1,128 (1104–1,200) h/year [median (min-max)] for training, corresponding to approximately 23.5 (23.0–25.0) h/week, mainly consisting out of rowing, unspecific endurance and strength training (Fiskerstrand and Seiler, 2004). Rowing training is associated with an outstanding metabolic demand (Winkert et al., 2021) and very different training intensity distributions in international rowing have been reported (Treff et al., 2017, 2021b).

In the light of the training-induced stress, monitoring of internal and external training load is a challenge for scientists, coaches, and athletes (Mäestu et al., 2005; Treff et al., 2021a).

Aside from non-invasive biomarkers like, e.g., resting heart rate, heart rate variability, or mood state, several blood borne variables have been applied to monitor internal training load and/or to diagnose training associated maladaptation (Steinacker et al., 2000; Plews et al., 2014; Hecksteden et al., 2016). These can be categorized into markers of metabolism (e.g., uric acid (UA) and blood lactate), the hormonal system (e.g., cortisol, testosterone, and leptin), and immune response. All of these indicators are known to respond in a highly individual way and due to their specific function in human physiology, and they provide just an incomplete assessment of the individual response to the complex process of acute/long-term training if seen in isolation (Hartmann and Mester, 2000; Podgórski et al., 2020).

Also for this reason, concepts involving inflammation due to cellular damage and metabolic and adrenergic stress inflammatory control gained importance, because they reflect acute and chronic impact of training (Pedersen and Hoffman-Goetz, 2000; Peake et al., 2017). Training, in such a concept, generates inflammatory messages and regeneration promote anti-inflammatory responses (Bay and Pedersen, 2020). Damage-associated molecular patterns (DAMPs) are released into circulation by damaged cells in response to strenuous exercise (Neubauer et al., 2013). DAMPs play a pivotal role for activation and maturation of dendritic cells (DCs), which are important antigen-presenting cells for early immune regulation, recruitment of macrophages, and furthermore T-cell signaling that translates the cellular message to the immunesystem (Brown et al., 2018). It has been shown that the amount of DC increased in rats in response to endurance training without affecting co-stimulatory molecules (CD80/CD86; Liao et al., 2006). Endurance training has also been reported to modulate DC development and to induce a shift toward a more matured state (Chiang et al., 2007). However, there is a lack of studies evaluating the usefulness of DC as an immunologic marker in elite athletes who are exposed to a high metabolic and overall stress. Moreover, the association between circulating and cellular immune variables, DAMPs, and seasonal changes in external training load have, to the best of our knowledge, never been evaluated in elite athletes.

To this end, we aimed to measure the concentration of circulating DAMPs, cytokines, and cell surface expression of cellular immune markers in highly trained male elite rowers at two different phases of a competitive season, specifically during competition phase (COMP; i.e., peak season) and preparation phase (PREP; i.e., low season) while also monitoring mood state. The additional assessment of neurotoxic kynurenine (KYN) should serve as a prospective training load and immune system susceptibility indicator. In doing so, we aimed to establish a basis of immunological and inflammatory variables as well as athletic-specific reference values, potentially serving as training stress markers to monitor training load in elite athletes.

MATERIALS AND METHODS

Patient and Public Involvement

It was not appropriate or possible to involve patients or the public in the design, or conduct, or reporting, or dissemination plans of our research, but the results are intended to support athletes and patients in load/stress management and monitoring.

Experimental Design and Participants

Eleven highly trained male elite scull rowers, all qualified for the German national team and with top results at international regattas (**Table 1**) agreed to participate in this study. Two distinct time points were defined, representing high and low competitive stress. The first time point was within the phase of world cup competitions in June, including high intensity training and augmented competitive stress, thereby representing COMP. The second time point was in early November, when rowers had started their preparation period, employing only low-intensity training without any competitions, therefore referred to as PREP. The average weekly training volume was similar between both time points, accumulating to approximately 1,400 min/week and 162 km of rowing. The latest preceding training session consisted of low-intensity endurance exercise and was completed the day before each blood drawing at 12:00 noon at the latest. No high intensity training and/or racing was conducted four days preceding the measurement, in order to minimize the effects of acute exercise in the severe domain. Measurements were made in the morning after getting up. Anthropometric data and performance characteristics of the participants are given in **Table 1**. Due to the elite status of the participants in terms of physiological characteristics and performance level, it was not possible to create a control group. It was also not possible to divide the existing group, because that would have meant that the control group would not participate in training and competitions. This is not feasible at the level of quasi-professional sport. The study was conducted according to the declaration of Helsinki and approved by the ethical board of the University of Ulm (#267/11). All participants gave informed written consent to participate in the study.

TABLE 1 | Anthropometric data and performance characteristics of study participants ($N = 11$, male).

ID	Age (years)	Weight Class M/LM	Standing height (cm)	Body mass (kg)	VO_{2max} (ml/kg/min)	T_{2k} (s)	Results in season 2011
R1	22	M	193	98.7	67	350.7	WCh 2nd; WC 1st
R2	22	M	194	90.4	71	354.9	WCh 2nd
R4	28	M	191	85.5	77	359.6	WC_{br} 1st
R5	22	M	188	86.6	69	356.5	WCh 2nd; WC 2nd
R6	21	M	194	85.2	71	358.8	WC_{br} 3rd
R7	20	M	195	94.6	69	351.3	WCh 2nd; WC 1st
R8	23	M	190	99.2	65	349.7	WCh 2nd; WC 1st
R9	25	M	199	87.7	75	357.6	WCh 2nd; WC 1st
Mean (M)	*22.9*		*193*	*91.0*	*71*	*354.9*	
R10	20	LM	*185*	74.3	79	374.8	WCh 4th
R11	25	LM	183	70.5	76	381.1	WCh 8th
R12	22	LM	188	73.0	71	374.2	WCh 4th
Mean (LM)	*22.3*		*185*	*72.6*	*75*	*376.7*	
Mean (total)	*22.7 ± 2.4*		*191 ± 4.7*	*86.0 ± 9.9*	*72 ± 4.4*	*360.8 ± 10.8*	

N = 11, male. LM = men, light weight class (≤ 72.5 kg pre-competition weight); M = men, open weight class; t_{2k} = duration of 2000 m rowing ergometer test (Concept 2, Type D); WCh, World Championships; WC, World Cup (Overall Standing); and WC_b = World Cup (best ranking at single event).

Recovery Stress Questionnaire for Athletes

To measure stress and recovery perception, the Recovery stress questionnaire for athletes (*RESTQ-76 Sport*) was applied. It covers three days preceding each measurement and has been described in detail elsewhere (Kallus and Kellmann, 2016). Briefly, the *RESTQ-76 Sport* is constructed in a modular way including 48 non-specific and 28 sport-specific items resulting in a comprehensive picture of an athlete's total stress and recovery. A Likert-type scale is used with values ranging from 0 (never) to 6 (always). The mean of each subtest can range from 0 to 6, with high scores in the stress-associated activity scales reflecting intense subjective strain, whereas high scores in the recovery-oriented items mirror sufficient recovery (Steinacker et al., 2000; Kallus and Kellmann, 2016).

Blood Sampling

Fasting venous blood was drawn at rest in the morning before breakfast at clinical standard conditions from the *vena brachialis*. Whole blood for flow cytometry was anticoagulated with ethylenediaminetetraacetic acid (EDTA) and stored at 4°C no longer than 30 h prior to fluorescent activated cell sorting (FACS) in order to evaluate immune cell status. Serum, respectively, EDTA-plasma was utilized to assess circulating molecular markers. After transportation at 4–8°C to the laboratory, samples were centrifuged at 2,500 g for 10 min to segregate cells. Supernatants were divided into aliquots to avoid repeated freeze thaw cycles and stored at minus 80°C until the final quantification of analytes.

Flow Cytometry

Surface markers of whole-blood leukocytes were determined by standard flow cytometric analyses using FACS Calibur and Cellquest software (BD).[1] Leukocytes were gated into lymphocytes, monocytes, and granulocytes by forward- and side-scatter analysis. Percent-positive cells were quantified *via* direct immunofluorescence staining using fluorescein isothiocyanate (FITC)-conjugated antibodies with phycoerythrin (PE)-conjugated antibodies. After binding of fluorescently labeled antibodies, expression densities of individual antigens were recorded. The expression density of the relevant antigens was calculated as the mean fluorescence intensity (MFI) according to the equation:

$$\begin{aligned} \text{MFI} = {} & \text{\%positives} \times \text{mean expression density of the relevant} \\ & \text{antigen} - \text{\%positives} \times \text{mean expression density} \\ & \text{of the respective isotype control} \end{aligned}$$

Subsequent monoclonal antibodies were determined separately on monocytes: antibodies directed against HLA-DR (clone L243, BD), CD83 (clone HB15a, Beckman Coulter), and CD123 (clone 9F5, BD). Lymphocytes were evaluated using antibodies directed against CD25 (clone M-A251, BD Biosciences) on its own and together with CD4 (cloneRPA-T4, BD Biosciences), CD2 (clone 39C1.5, Beckman Coulter) either together with CD80 (clone L307.4, Immunotech) or CD86 (clone B-T7; Diaclone). A mouse FITC-IgG1 antibody (clone X40) in conjunction with PE-conjugated IgG2a (clone X39, both from BD Biosciences) served as the isotype controls.

Plasma Biomarkers

ELISA

EDTA-plasma was deployed for the quantification of biomarkers using a highly sensitive and validated ELISA system (Immulite 1,000®).[2] The following Immulite 1,000® kits were used to quantify markers: IL-1β (#6602656), IL-6 (#6604071), IL-8 (#6604136), IL-10 (#6604004), TNF-α (#6602826), and ferritin (#6601889). HMGB1, serving as a marker for necrotic cells, was analyzed

[1]biosciences.com/

[2]https://www.siemens.com/

using an enzyme immunoassay from IBL-International (ST51011) according to the manufacturer's manual.

Spectrophotometry

Uric Acid

A colorimetric endpoint assay (Fluitest UA, Analyticon) was applied for the quantitative determination of UA in serum, where the color intensity is proportional to UA concentration and is analyzed photometrically at 546 nm using a calibrator sample.

Creatine Kinase

Circulating total CK in serum was determined using an *in vitro* test from Analyticon (CK NAc, Analyticon® Biotechnologies AG, Lichtenfels, Germany) according to the manufacturer's manual. Enzyme activity of CK is measured indirectly *via* NADPH amounts. The photometrically measured rate of NADPH formation is proportional to CK and was quantified at 354 nm.

Kynurenine

kynurenine was determined by the following protocol: 1000 µm of L-kynurenine sulfate salt (Sigma-Aldrich, Munich, Germany) was diluted 1:20 with 15% Trichloric acid (TCA) to a final concentration of 50 µm. This stock solution was further diluted with TCA to 25 µm, 12.5 µm, 6.25 µm, 3.125 µm, 1.56 µm, and 0.78 µm for standard curve determination. Aqua dest was used as blank solution. 150 µl serum sample was mixed with 100 µl of 30% TCA and centrifuged at 20,000 g for 10 min and 4°C. 150 µl of standard solutions and blank as well as 150 µl of the supernatant were pipetted into a 96-well plate in duplicate and incubated for 15 min at 65°C. 0.15 g of diaminobenzoic acid (DABA) was diluted in 10 ml of 100% acetic acid and 150 µl of this final solution was mixed with the samples for 5 min at room temperature. Fluorescence was measured with a plate reader and the concentration of samples was calculated by the slope of the linear regression line of the optical density from 492 nm minus 620 nm.

Circulating Cell-Free DNA Concentration Assay

Cell-free DNA (cfDNA) was determined as described before (Velders et al., 2014). In brief, the cfDNA concentrations in serum samples were directly analyzed with a fluorescent nuclear stain (SYBR Gold) without prior DNA extraction and amplification and a standard curve was generated by serial dilution of commercial salmon sperm DNA. 40 µl of SYBR Gold (1:10,000 dilution in PBS) was added to 10 µl of serum in 96-well plates and fluorescence was recorded using a spectrofluorometer with an excitation wavelength of 485 nm and emission wavelength of 535 nm.

Statistical Analysis

All data were tested on Gaussian distribution using the Shapiro–Wilk normality test. Pairwise two-tailed t-testing was used for all normally distributed data. Otherwise, a Wilcoxon matched-pairs signed rank test was used to determine statistical significance of differences. For KYN, one-way ANOVA was used to allow for an appropriate multi-group analysis. If significance was observed, Tukey's multiple comparisons post-hoc test was applied to assess differences between groups (GraphPad Prism, 9.1, San Diego, CA, United States). Statistical significance was established at $p \leq 0.05$.

RESULTS

High Load During Competition Phase Leads to Mental Stress

General stress, indicated by the subtests "Emotional Stress" (**Figure 1A**, $p < 0.001$), "Social Stress" (**Figure 1B**, $p = 0.001$), and "General Stress" (**Figure 1C**, $p = 0.006$), were significantly increased during COMP vs. low season. However, even though athletes experienced mental and physical stress, significantly higher scores for the subtests "Physical Recovery" (**Figure 1D**, $p = 0.007$), "Social Recovery" (**Figure 1E**, $p = 0.019$), and "Personal Accomplishment" (**Figure 1F**, $p = 0.014$) during COMP vs. PREP indicated compensatory mechanisms. What is more, despite high general stress loads at COMP, no other significant differences between competition vs. PREP were observed in any subtest representing sport-specific stress and recovery specified as "Injury" (**Figure 1G**, $p = 0.834$), "Being In Shape" (**Figure 1H**, $p = 0.161$), or "Self-Regulation" (**Figure 1I**, $p = 0.728$). This finding is further underlined by a distinct stability of subtests, such as "Conflicts/Pressure," "Lack of Energy," "Sleep Quality," or "Fatigue" (data not shown).

The DAMPs HMGB1 and cfDNA Are Increased During High and Low Physical Load

HMGB1 (**Figure 2A**, $p = 0.0012$) and cfDNA (**Figure 2C**, $p = 0.048$) reflect the elevated physical load of athletes at COMP at resting state and are increased vs. PREP, while the damage marker CK (**Figure 2B**, $p = 0.053$) and the metabolic stress marker UA **Figure 2D**, $p = 0.304$) remained largely unaltered.

Monocyte and Dendritic Cell Activation and Orchestration of Adaptive Immunity

The percentage of monocytes did not change from competition vs. PREP (**Figure 3A**, $p = 0.250$); however, the monocyte/macrophage cell surface marker HLA-DR increased (**Figure 3B**, $p = 0.001$), being a receptor on antigen-presenting cells that are involved in antigen presentation and T-cell priming. In concert with HLA-DR, also CD83 increased (**Figure 3C**, $p = 0.004$) – which is a molecule important for antigen presentation and DC maturation – as did CD123 (**Figure 3D**, $p < 0.001$), the alpha subunit of the IL-3 receptor that is expressed on plasmacytoid DC.

Antigen-presenting cells are activated during COMP to orchestrate the adaptive/cellular immune response, involving T-lymphocyte activation to eliminate or prevent pathogen growth. T-lymphocyte activation increased during low season, as indicated by the significant increases in CD2/CD80 (**Figure 3E**, $p = 0.006$) and CD2/CD86 (**Figure 3F**, $p = 0.010$) positive lymphocytes. However, at the same time, $CD25^+/CD4^+$ positive immunosuppressive T-regulatory cells increased, suggesting

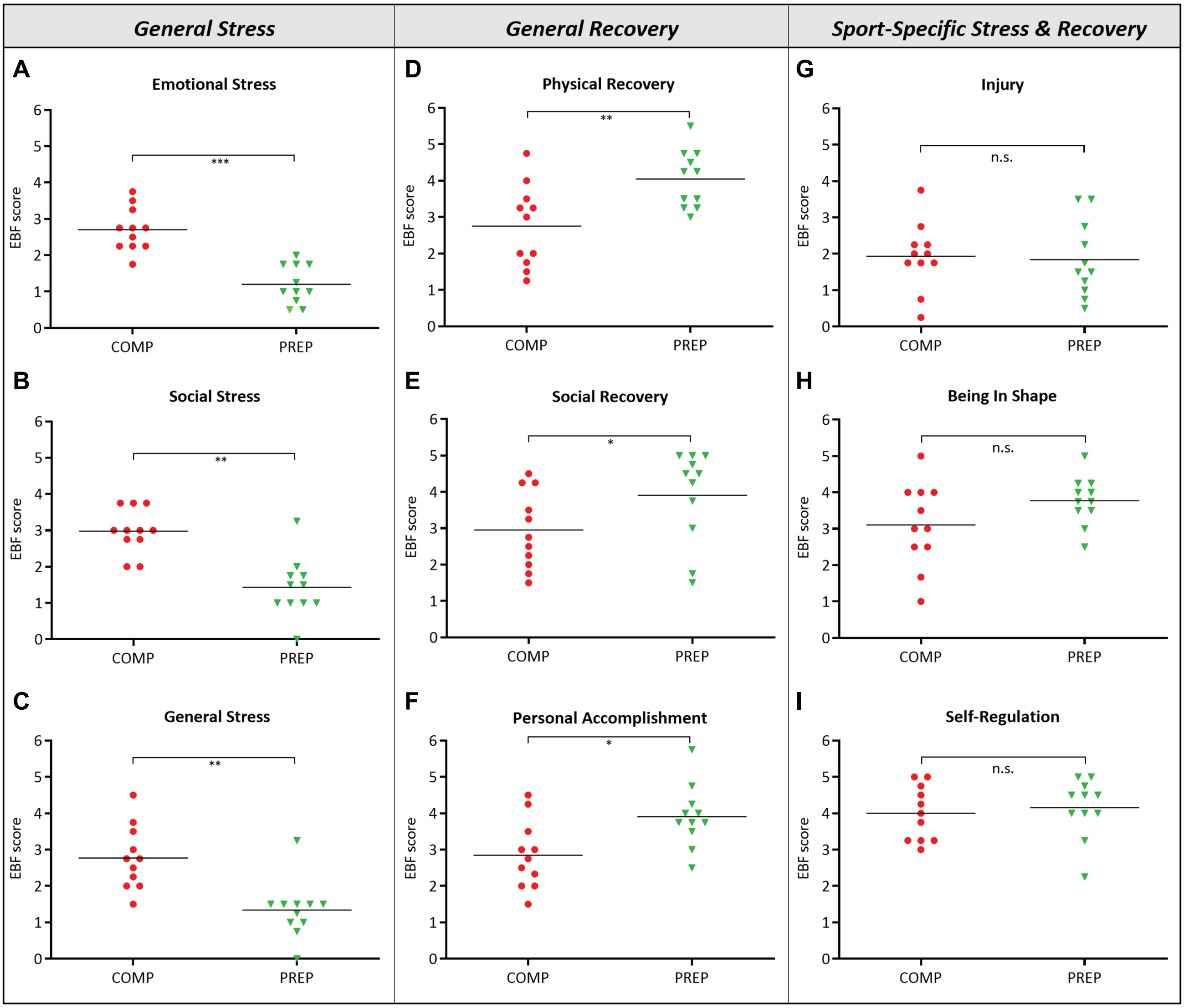

FIGURE 1 | High physical load during competition phase (COMP) in elite rowers induces perceived mental stress. **(A–C)** General stress, **(D–F)** general recovery, and **(G–I)** sport-specific stress and recovery scales and subscales from the RESTQ-Sport questionnaire surveyed during competition and PREP (RESTQ-Sport represents recalls of the last 3 days and answers can range from 0 (never) to 6 (always). $^{*}p \leq 0.05$, $^{**}p \leq 0.01$, $^{***}p \leq 0.001$, and n.s. = non-significant, $N = 11$.

prevention of autoimmune responses (**Figure 3G**, $p = 0.010$). Il-2R concentration sorted by sCD25^{+} did not differ between competition and PREP (**Figure 3H**, $p = 0.822$).

Serum KYN Levels Are Elevated in Patients Suspected to Suffer From Overtraining but Remain Unaltered in Elite Rowers

The comparison of KYN serum concentrations (μm) between patients assumed to suffer from overtraining syndrome (OTS), a group of healthy recreational athletes, and an age matched cohort of elite rowers showed that KYN levels between common recreational athletes and rowers at competition vs. PREP are not significantly different among each other, yet considerably different compared to OTS patients (**Figure 4**). Hence, even competitive world cup stress leads only to slight and non-significant increases of KYN in elite rowers at competition vs. PREP. It is worth to mention that the slight increase in the mean was mainly due to only one individual rower showing an aberrant KYN concentration either at competition or at PREP.

Circulating Pro-inflammatory Cytokine Concentrations Are Elevated During Competition vs. Preparation Phase

Serum concentrations of pro-inflammatory macrophage-derived cytokines IL-1β (**Figure 5A**, $p = 0.002$), TNF-α (**Figure 5B**, $p < 0.001$), and the chemokine IL-8 (**Figure 5C**, $p = 0.001$) are elevated at competition vs. PREP. In contrast, the anti-inflammatory cytokine IL-10 (**Figure 5D**, $p = 0.002$) is significantly

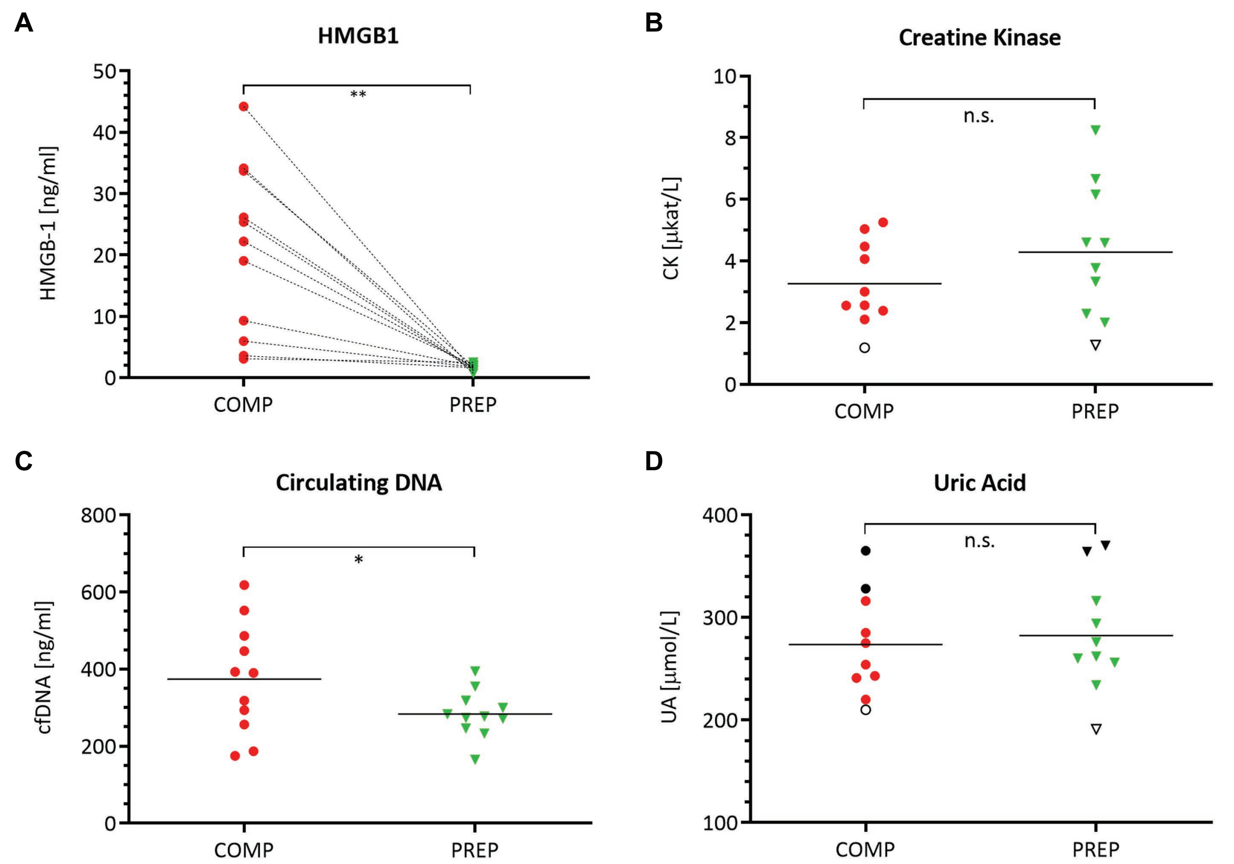

FIGURE 2 | Serum levels of damage-associated molecular pattern (DAMP) molecules **(A)** HMGB1, **(B)** creatine kinase (CK), **(C)** circulating cell-free DNA (cfDNA), and **(D)** uric acid (UA) during competition vs. PREP. $^{*}p \leq 0.05$, $^{**}p \leq 0.01$, and n.s. = non-significant, $n = 10$ or 11, respectively. HMBG1 is elevated in all athletes compared to low season. Notably, despite a generally large range of most analytes, UA shows a distinct individual pattern as indicated for three athletes mirroring the highest (black circles/triangles) and lowest (empty circle/triangle) UA levels during the course of the season. This also applies in part to CK with an unaltered lowest level of this analyte for a single individual.

downregulated at COMP and shows an increased expression level at PREP. The acute-phase protein Ferritin is lower at PREP (**Figure 5F**, $p < 0.050$). Noteworthy, the black dots in the upper region of the IL-6 (**Figure 5E**) and Ferritin (**Figure 5F**) graphs label two identical rowers at competition, respectively, PREP and indicate that this could be a sign for higher inflammatory stress in these particular athletes, whereas the cytokine/myokine IL-6 shows a nearly unaffected concentration (**Figure 5E**, $p = 0.870$).

DISCUSSION

The main results of our study are an increase of psychological and physiological stress in a group of elite rowers at competition vs. PREP, which is accompanied by an increased stimulation of the immunomodulatory response. This response is marked by an increase in damage-associated molecular patterns like cfDNA and HMGB1, and a DC activation indicating an immune response that stimulates the corresponding immune cascade of subsequent T-cell activation and cytokine release.

Athletes experience high psychological and physiological stress during their career, especially in competitive periods (Kellmann and Günther, 2000; Steinacker et al., 2000; Oblinger-Peters and Krenn, 2020). In detail, Steinacker and colleagues reported decreases of performance, gonadal and hypothalamic steroid hormones, and deterioration of psychological recovery during very high load training in elite rowers, thereby highlighting the interaction between mood state and metabolic stress (Steinacker et al., 2000). Our results also indicated an increase in general emotional and physiological stress during COMP in elite rowers, presumably leading to the observed alerted immune response.

Mechanistically, the intense cellular and metabolic stress apparently promote the release of DAMPs from cells into the blood stream, including HMBG1 and cfDNA. HMBG1, normally a DNA-binding protein in the nucleus, serves as a pro-inflammatory cytokine in the cytosol after cellular damage (Scaffidi et al., 2002; Castiglioni et al., 2011; Velders et al., 2014). The HMGB1 increase seen in our athletes with high training load was paralleled by a concomitant increase of cfDNA. This finding confirms similar release kinetics of both cfDNA and HMGB1 observed after short-term treadmill running (Beiter et al., 2011). When such damage

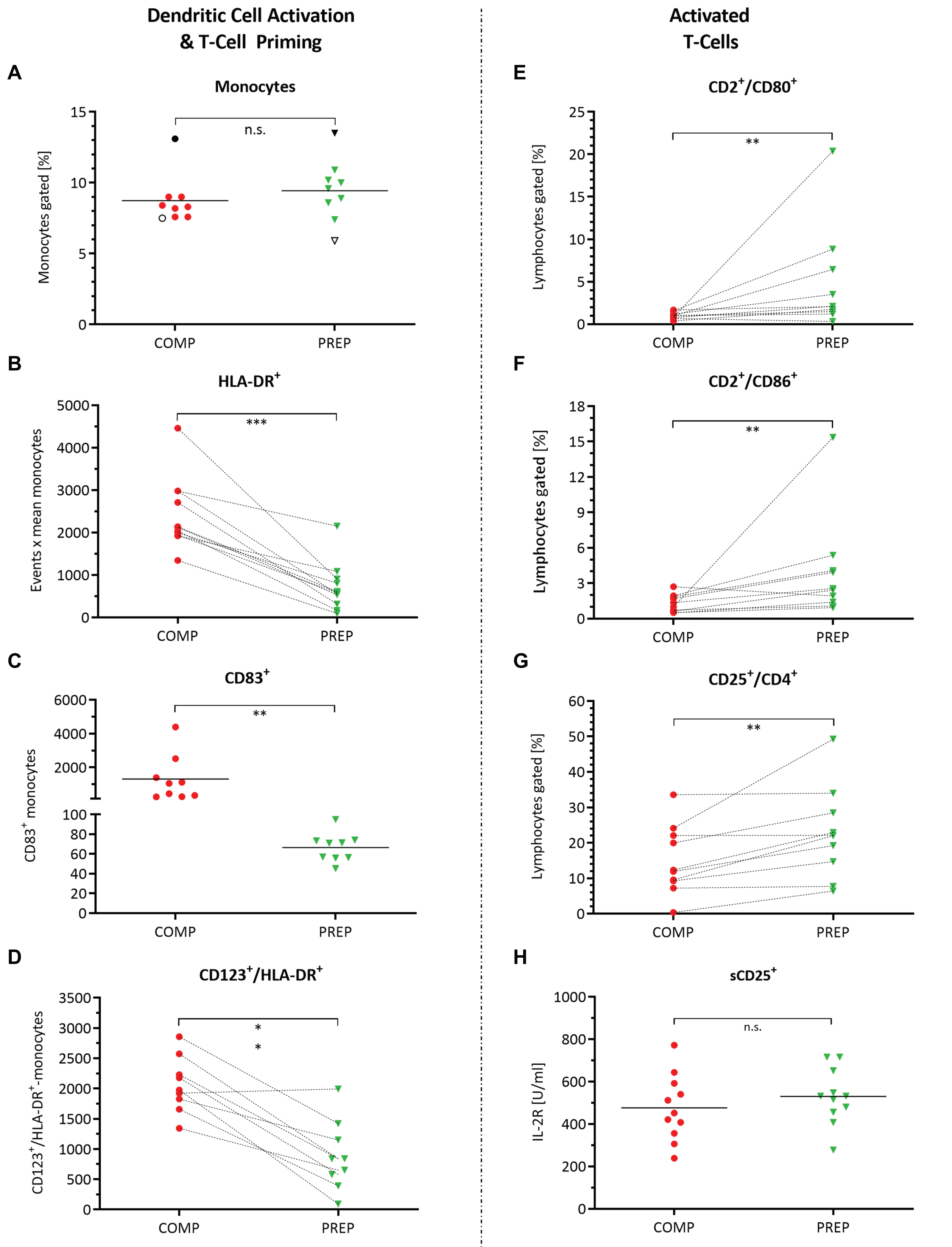

FIGURE 3 | Monocyte and dendritic cell activation and orchestration of adaptive immunity. Cell surface markers detected by fluorescence-activated cell sorting (FACS) quantified in whole-blood cell lysates during competition vs. PREP. $^*p \leq 0.05$, $^{**}p \leq 0.01$, $^{***}p \leq 0.001$, and n.s. = non-significant, $n = 9$, 10, or 11, respectively.

(Continued)

FIGURE 3 | **(A)** The percentage of monocytes did not differ between competition vs. PREP, whereas increased **(B)** monocyte/macrophage cell surface marker HLA-DR on MΦ detection in COMP indicates immune system stimulation by monocyte/macrophage activation. This is underlined by **(C)** higher measures of CD83⁺ during COMP, a molecule important for antigen presentation, and dendritic cell (DC) maturation and **(D)** CD123, the alpha subunit of the IL-3 receptor, expressed on plasmacytoid DC. Analysis of T-cell activation showed increased values during low season for **(E)** CD2⁺/CD80⁺ and **(F)** CD2⁺/CD86⁺ positive lymphocytes. However, at the same time, **(G)** CD25⁺/CD4⁺ positive immunosuppressive T-regulatory cells increase, suggesting prevention of autoimmune responses. **(H)** Il-2R concentration sorted by sCD25⁺ did not differ between phases.

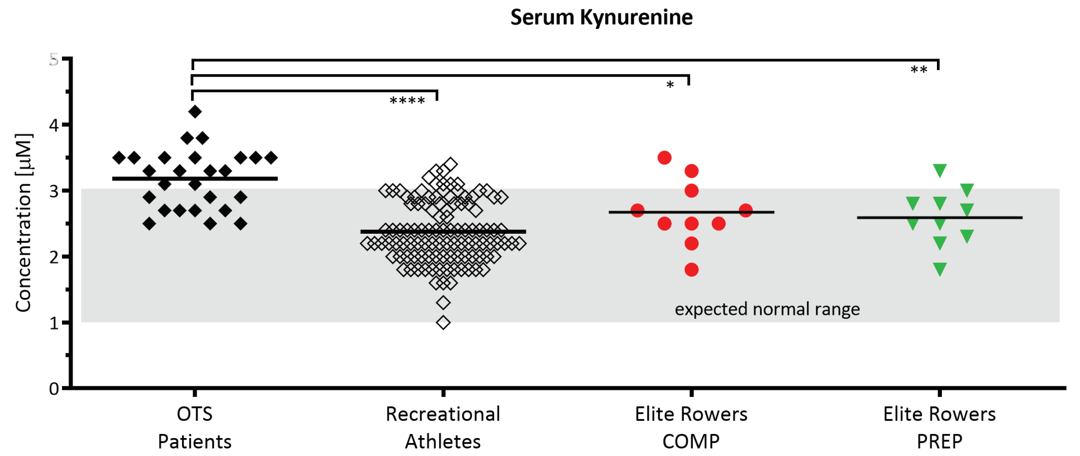

FIGURE 4 | Serum kynurenine (KYN) levels are elevated in patients suspected to suffer from overtraining but are unaltered in response to short periods of overload in elite rowers. Normal range of 1–3 µm according to Kaden et al. (Kaden et al., 2015). Comparison of KYN serum concentrations between patients assumed to suffer from overtraining syndrome (OTS, $n = 26$, black diamond), a group of healthy recreational athletes ($n = 108$, open diamond), and an age cohort of elite rowers during competition and PREP ($n = 10$, red circle vs. green triangle, respectively); $^{*}p \le 0.05$, $^{**}p \le 0.01$, and $^{****}p \le 0.0001$. The grayish rectangle marks the expected normal range of KYN in blood sera of healthy donors (Kaden et al., 2015).

and inflammation occur as a consequence of exercise, the released HMBG1 obviously induces the activation and maturation of DCs, a notion that is supported by the significant increases of CD83 and CD123, being indicators of DC activation and maturation (Bates et al., 2015; Feng et al., 2021).

The postulated immune response cascade is in line with other studies reporting highly increased immune response at phases of relatively high training load: Morgado and colleagues reported that after *in vitro* blood immune cell stimulation, DC cell numbers and production of IL-1β, IL-6, IL-12, TNF-α, and MIP-1β decreased in elite swimmers especially early in the season, when training volume increased substantially, potentially compromising the athletes' immune defense capacities over the whole season (Morgado et al., 2012). Furthermore, secretory patterns of cultured DCs of well-trained skiers and healthy controls revealed that concentrations of several pro-inflammatory cytokines (IFN-α, IL-31, and TNF-β) were higher in the athlete group exposed to training stress (Evstratova et al., 2016). In addition, two animal studies reported an effect of exercise training on rat dendritic cells: Firstly, Liao et al. reported that dendritic cell number increased after training, with no difference in co-stimulatory molecule (CD80 or CD86) expression (Liao et al., 2006), and Chiang et al. found that MHC II expression mixed leukocyte reaction and IL-12 production increased in DCs of exercise trained rats (Chiang et al., 2007). The fact that DC activation is, among other, triggered by cell-free molecules like HMBG1 after cellular damage underlines the potential application of DC activation when it comes to monitoring training-induced stress response.

DC activation in turn may induce further immunomodulatory response with the stimulation and activation of different T-cell and macrophage populations, and the subsequent release of inflammatory cytokines. The increase of pro-inflammatory cytokines IL-1ß, IL-8, and TNF-α observed in our elite rowers suggests an augmented stimulation of the immune system. Since CD25⁺/CD4⁺ expression decreased concomitantly, an increased susceptibility to infections is possible. On the other hand, an increased gating of lymphocytes positive for proteins CD80 and CD86 suggests an upregulated immune response capability at PREP. In general, DCs can activate all types of effector T-cells (T_{reg}, T-helper cells, or killer T-cells) and regulate activation and regulation of immune responses (Dieterlen et al., 2016). We did not observe a concomitant increased T-cell activation despite DC activation and T-cell priming COMP, which may be due to insufficient co-stimulatory signals to result in an increased percentage of activated T-cells, potentially indicating a more susceptible immune system.

The reason for this increased susceptibility after intense exercise, reflected in the "open window" theory, is still incompletely understood (Nielsen, 2003; Kakanis et al., 2010). Nielsen et al. examined the impact of a 6-min "all-out" ergometer rowing test on lymphocytes and natural killer (NK) cells. They reported increased NK cell activity and lymphocyte subsets during the test, but while two hours after the rowing test leucocyte and neutrophil numbers remained elevated, the lymphocyte count

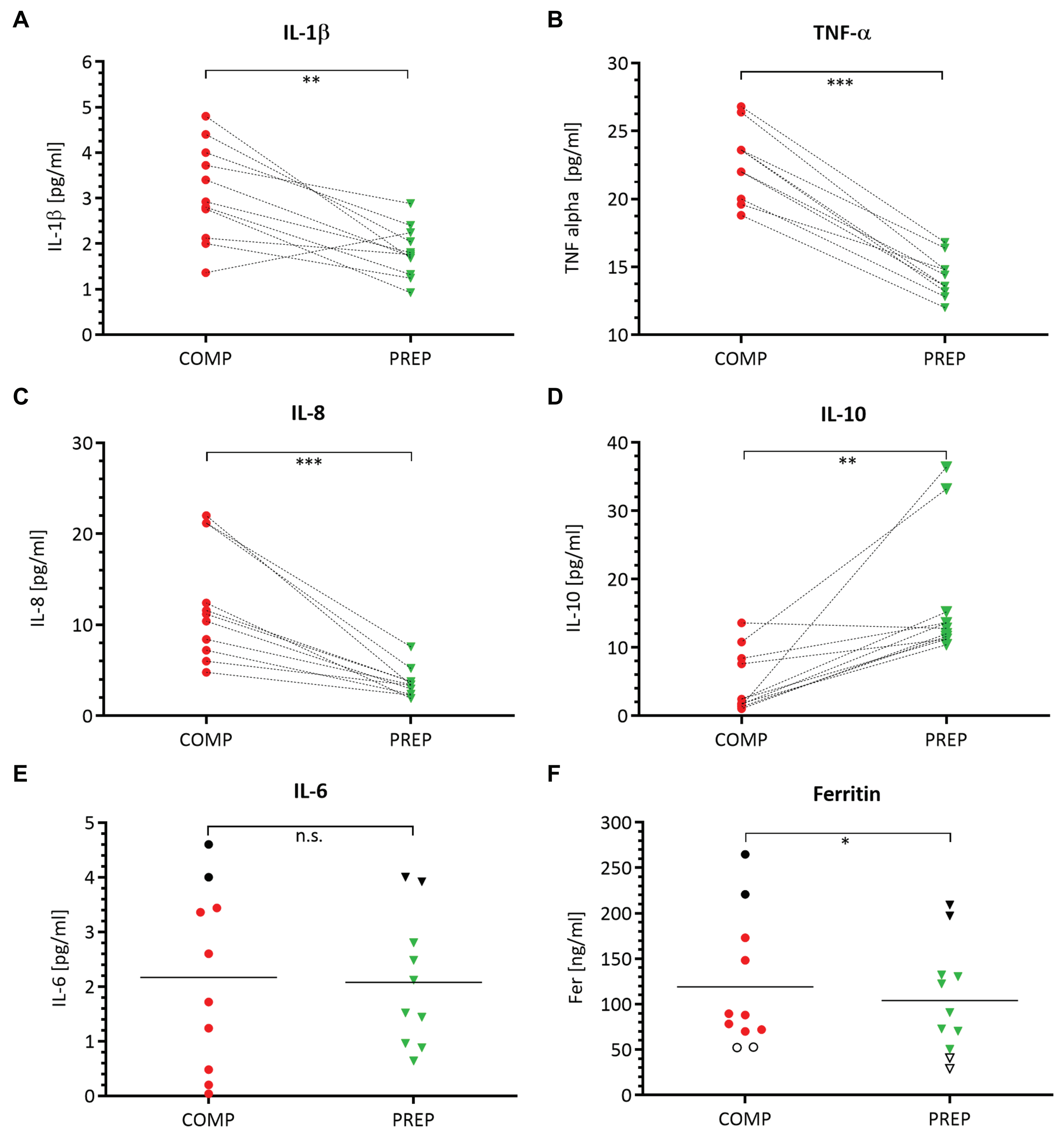

FIGURE 5 | Pro-inflammatory processes are prevailing at COMP, which is illustrated by a distinct cytokine pattern. Serum concentrations of pro-inflammatory cytokines IL-1β **(A)**, TNF-α **(B)**, chemokine IL-8 **(C)**, anti-inflammatory IL-10 **(D)**, acute-phase proteins IL-6 **(E)**, and ferritin **(F)** during competition vs. PREP. $^{*}p \leq 0.05$, $^{**}p \leq 0.01$, $^{***}p \leq 0.001$, and n.s. =non-significant $n = 10$ or 11, respectively.

decreased (Nielsen et al., 1996a,b). Apparently, this acute maximal rowing test did induce lymphocytosis but did not suppress the immune response during recovery, despite the previous involvement of large muscle mass during exercise in the severe intensity domain (Nielsen et al., 1996b), which is also in line with other studies (Nielsen, 2003). However, prolonged and regular intense endurance exercise has been reported to suppress total lymphocyte and NK cell counts as well as neutrophil phagocytic function, suggesting an increased immune system susceptibility during COMP (Kakanis et al., 2010).

Although previous findings associated pro-inflammatory cytokines IL-1ß and TNF-α with depressed mood, sleep disturbances, and stress (Main et al., 2009, 2010), no similar conclusion can be drawn from our data, because sleep and mood state were undisturbed. On the other hand, an overstimulation of the immune system due to sustained high training load may lead to increased susceptibility for pathogen invasion, a mechanism that may be summarized as the open window theory (Nielsen et al., 2016), which is also in line with the lacking T-cell activation mentioned before.

Deregulated or sustained inflammation leads to pathological conditions, such as chronic infection, inflammatory, and autoimmune diseases (Walsh et al., 2011). Also in rowers, acute inflammatory responses to training are associated with decreased aerobic performance (VO_2max and maximal aerobic power; Jürimäe et al., 2016). In line with that we previously showed that hepcidin and ferritin, both representing acute-phase proteins, are sensitive to initial increases in training load after seven days during a training camp (Zügel et al., 2019). Also, in the present study, we found slightly increased ferritin levels during COMP, which were not associated with significantly increased IL-6 levels. Conversely, this association was reported in a recent review (Larsuphrom and Latunde-Dada, 2021). This contrasting observation may be due to differences in training load assessment or the observed high inter-individual acute-phase reactions in our participants, which reduces the application as possible metabolic stress marker during a whole training season.

Practitioners in the field frequently assess CK or urea to monitor training load, which is also recommended by recent scientific studies and appears to be suitable to measure acute responses (Hecksteden et al., 2016). However, neither CK nor UA differed from competition vs. PREP in our study. In the light of these results, our immunologic approach suggests the promising prospect of better capturing especially cumulated training stress, which is probably at least as relevant for athletic decision making like measures of acute stress.

Another prospective indicator or pathway to monitor training load and immune system susceptibility may be the kynurenine pathway. Kynurenine is a downstream metabolite in the tryptophan metabolism and increased in diseases showing depression disorders (Schlittler et al., 2016). Endurance exercise is a possible treatment for such disorders and was proposed due to the increased metabolization of the neurotoxic kynurenine to its non-toxic form kynurenic acid by kynurenine aminotransferase (Schlittler et al., 2016; Strasser et al., 2016). According to our experience, both immune system and depressive disorders are common in overtrained athletes with concomitantly elevated kynurenine levels (**Figure 4**). The comparison of our elite rowing athletes' kynurenine concentrations with either athletes suffering from overtraining or healthy controls showed less abnormal levels in controls and rowers than in overtrained individuals. Finally, these data reveal an necessity for further research, as the normal range was defined by measurements in healthy controls (Kaden et al., 2015) and this range is possibly lower than in elite athletes who often present with abnormal blood and metabolic levels of inflammation and immune responses due to training (Steinacker et al., 1993; Bowen et al., 2011; Banfi et al., 2012).

Strengths and Limitations

Our study has some limitations worth indicating. The sample size is relatively small, thereby limiting the generalizability of our results. This is, however, an unavoidable problem when studying elite athletes, because an elite group is a small group per definition and furthermore, access and possibility to monitor them is confined. This limitation is scientifically outweighed by the fact that the results of this study are based on training and racing performances that only such an extreme group can realize.

Another limitation is that the data were obtained at only two time points, which is clearly related to the confined access and the relatively high volume of blood drawn per athlete. Notwithstanding, this study underlines the importance of longitudinal monitoring of elite athletes to establish individual normal values/ranges of immunological and inflammatory variables. This is a prerequisite to apply our results to diverse athlete populations and to help optimize athletic performance by improved load management.

Conclusion and Perspectives

Our data suggest that DAMPs like HMGB1, cfDNA, and particular cytokine matrices are promising markers allowing to monitor especially cumulated training stress in highly trained athletes, and in this respect, they potentially surpass the advantages of conventional indicators. This notion is supported by the concomitant alterations of these markers with training load and the plausibility of the proposed mechanisms. However, individual normal ranges need to be defined due to a substantially high inter-individual variability. In addition, molecular damage markers like mitochondrial DNA (mtDNA; Wenceslau et al., 2014) or heat shock proteins (HSPs; Foell et al., 2007; Wang et al., 2012) may qualify to further improve assessment of internal training load with the ultimate goal to differentiate between functional or non-functional overreaching and the overtraining syndrome, currently lacking validated diagnostic tests and biomarkers (Meeusen et al., 2013; Kreher, 2016). A graphical summary is provided as **Supplementary Material**.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the ethical board of the University of Ulm (#267/11). The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

DB, GT, MZ, US, and JS participated in the study design and contributed to data collection and data analysis. MS and DA contributed to sample analysis and experimental protocol evaluation. KW contributed to scientific discussion of the study and the manuscript. All authors contributed to the manuscript writing. All authors have read and approved the final version of the manuscript, and agreed with the order of presentation of the authors.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fphys.2021.803863/full#supplementary-material

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World and European Rowing Medallists Pace With Smaller Variation Than Their Competitors

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Purpose: To establish the relation between pacing pattern and performance, within sex, and number of crew members, at the very highest performance level in World class rowing.

Methods: Pacing profiles based on official 500 m split times in 106 A-finals with six contesting boat crews ($n = 636$ crews), in recent World (2017–2019) and European (2017–2021) championships, were analyzed. The coefficient of variation (CV) and sum of relative differences (SRD) of the split times, and normalized velocities in the four segments of the race, were compared between performance levels, that is, placement (1st–6th), and subgroups based on sex (female or male) and number of crew members (one, two, or four). Statistical tests and resulting p-values and effect sizes (Cohen's d) were used to assess differences between groups.

Results: The pacing profiles of the medallists had smaller variation than those of the non-podium finishers (CV = 1.72% vs. CV = 2.00%; $p = 4 \times 10^{-7}$, $d = 0.41$). Compared to the non-podium finishers, the medallists had lower normalized velocities in the first and second segments of the race, slightly higher in the third segment and higher in the fourth segment. Female crews paced somewhat more evenly than male crews. No significant differences were found in the evenness of pacing profiles between singles, doubles/pairs and quads/fours. Analyses of SRD were overall consistent with analyses of CV.

Conclusion: Medal winners in major rowing championships use a more even pacing strategy than their final competitors, which could imply that such a strategy is advantageous in rowing.

Keywords: pacing, rowing, strategy, race analysis, endurance, performance level, split times, hydrodynamics

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INTRODUCTION

An athlete's pacing pattern is widely recognized to have a substantial influence on the performance in endurance sports (Abbiss and Laursen, 2008; Tucker, 2009; Roelands et al., 2015; Casado et al., 2021). As the pacing pattern composed by the athlete directly influences the energy turnover rate and thereby performance, a variety of patterns (e.g., negative, all-out, positive, parabolic, and variable) exists. In endurance sports of short durations ($\lesssim$2 min), all-out and positive pacing profiles are advantageous and common, e.g., $\leq$800 m running (Tucker et al., 2006) and $\leq$ 200 m swimming (Menting et al., 2019). It has been suggested that for events lasting longer than 2 min, an even pacing strategy may be optimal to achieve the best time or highest mean power output (Abbiss and Laursen, 2008). In practice, this seems evident at least for relatively long durations ($\gtrsim$ 10 min), e.g., $\geq$5,000 m running (Tucker et al., 2006; Diaz et al., 2018). For events lasting approximately 2–10 min, the literature and applied practice seem less certain. Typically, various parabolic (U-, J-, or reverse J-shaped) pacing profiles are observed (Menting et al., 2019; Casado et al., 2021). Interestingly, several best times and world records are set with small variations in pace and relatively even profiles, e.g., 5,000 m speed skating ($\approx$6 min) (ISU, 2020) and 4,000 m track cycling ($\approx$4 min) (Tokyo Olympics, 2021). Moreover, in various sports, the more "calculated" even pacing pattern has occurred over the recent years, making the even pacing more even, cf. e.g., Foster et al. (2014) and Diaz et al. (2018). However, as stated by Casado et al. (2021), pacing profiles within sports differ as well as the type of competition (championship; finals vs. qualifications, goal to set best times) implying the need for study of pacing profiles in the sport specific content.

The finishing time in rowing is always more than at least 5 min in 2000 m events, that is, World Rowing's standard regatta distance, which is used in all major championships. The importance of viscous fluid (hydro- and aerodynamic) drag yields a highly non-linear relation between mechanical power output and velocity. Consequently, the energetic cost of an uneven pacing strategy may be higher than in sports where the total resistive force is less dominated by viscous drag, e.g., running (gravity), cross-country skiing (gravity and snow-ski-friction) or uphill cycling (gravity) in sufficiently steep slopes (van Druenen and Blocken, 2021). Therefore, an even pacing strategy seems the most obvious choice to optimize performance in rowing. In contrast, previous studies, that have used 500 m split times to assess various aspects of pacing strategies in rowing, agree that, typically, a reverse J-shaped pacing profile (fastest-slow-slow-fast) is applied in 2,000 m rowing (Garland, 2005; Brown et al., 2010; Muehlbauer et al., 2010; Muehlbauer and Melges, 2011). Interestingly, a fast-start approach is also found in long-distance rowing (Edwards et al., 2016).

However, it is unclear if rowers at the highest performance level will seek toward more even pacing strategies (flatten their reverse J), to further increase performance. The study by Brown et al. (2010) supports the hypothesis that there is a relation between performance level and pacing strategy. In contrast, Garland (2005) did not find any difference in pacing profiles between winners and the rest of the heat. Furthermore, the study by Muehlbauer and Melges (2011) confirmed that there are significant differences in pacing patterns in heats and finals. Thompson (2014) summarized that previous studies of pacing in rowing have found similar pacing profiles independent of finishing position. Notably, previous studies have proved differences in pacing profiles between performance levels in some sports, e.g., running (Hettinga et al., 2019), and insignificant differences in pacing between performance levels in other sports, e.g., 1,500 m swimming (Lara and Del Coso, 2021). Further, Losnegard et al. (2016) found that the pacing pattern depended on performance in cross-country skiing among males, but not among females.

Inspired by the previous studies of split times, we analyze pacing profiles, from recent World (2017–2019) and European (2017–2021) championships, in the present study. Official 2,000 m race times, as well as intermediate split times at each 500 m mark, are obtained from the website of the World Rowing Federation. In our study, we limit the analysis to A-finals only, in order to investigate the split time characteristics and pacing profiles at the very highest performance level and to limit tactical behaviors often seen in the qualifications. This obviously limits the number of events and boat crews, which we compensate for by assessing eight recent championships.

Our main objective was to establish the relation between rowing performance, in terms of the final placement, and the pacing strategy. Furthermore, we tried to establish whether or not the pacing strategy in the considered A-finals is a function of sex and/or the number of crew members in the boat class.

MATERIALS AND METHODS

Dataset and Inclusion Criteria

The analysis included some of the most contested boat classes in the World championships of 2017, 2018, and 2019 (W17–W19) and the European championships of 2017, 2018, 2019, 2020, and 2021 (E17–E21). The considered boat classes were the lightweight single sculls (LM1x, LW1x), the lightweight double sculls (LM2x, LW2x), the single sculls (M1x, W1x), the coxless pairs (M2-, W2-), the double sculls (M2x, W2x), the coxless fours (M4-, W4-), and the quadruple sculls (M4x, W4x). This includes all Olympic rowing classes, except M8+/W8+ which we did not include in the analysis due to several finals with less than six contesting crews.

Four criteria were applied to the dataset. (1) Only A-finals were considered to ensure that the contesting crews were at the highest performance level, that the athletes were highly motivated to go as fast as possible for the whole race distance, and that the winners were indeed World or European champions. (2) All 500 m segment times needed to be available on the website of the World Rowing Federation. (3) Only A-finals with six contesting boats were included. (4) Only A-finals with a difference in time between the 1st and 6th place smaller than 30 s were considered. Criteria (3) and (4) were applied to ensure comparable conditions between the different events and to avoid extreme outliers. In the rowing classes and events considered, a total of 106 finals (636 boats) fulfilled the criteria. A list of the rowing classes and events included in the analysis is provided in **Table 1**.

Pacing Profile Assessment

To assess the pacing profiles, analyses were made based on the time spent on each of the four 500 m segments. In the following, a segment time is denoted t_j; $j = 1, ..., 4$, where $j = 1$ is the first segment from 0 to 500 m, $j = 2$ is the second segment 500–1,000 m and so forth. Further, $\bar{t}$ is the arithmetic mean of the segment times. The pacing pattern was assessed through the standard deviation of the segment times, i.e., the square root of

TABLE 1 | Included A-finals; events and boat classes.

	E17	E18	E19	E20	E21	W17	W18	W19
LM1X	-	-	-	-	-	-	-	-
LM2X	-	-	-	-	-	-	-	-
LW1X	-	3	-	-	-	-	4	-
LW2X	-	-	-	-	-	-	-	-
M1X	-	-	-	-	-	-	-	-
M2-	-	4	-	-	-	-	-	-
M2X	-	-	-	2	-	-	-	-
M4-	-	-	-	-	-	-	-	-
M4X	-	-	-	-	-	-	-	-
W1X	-	-	-	-	-	-	-	-
W2-	-	-	-	-	-	4	-	-
W2X	-	-	-	-	-	-	-	-
W4-	3	-	-	-	-	-	-	-
W4X	-	-	-	-	-	-	-	-

Of the 112 possible A-finals, six are excluded for the following reasons (cf. criteria in text): 2) Not all 500 m split times were available; 3) Less than six boats in the final; 4) More than 30 s between 1st and 6th place. A cell with a - indicates that the A-final was included in the dataset.

the average of the squared deviations from the mean segment time,

$$t_{std} = \sqrt{\frac{1}{4}\sum_{j=1}^{n=4}\left(t_j - \bar{t}\right)^2}. \tag{1}$$

The coefficient of variation (CV) allows for comparisons of the relative variation for different mean segment times, hence, different race times,

$$CV = \frac{t_{std}}{\bar{t}}. \tag{2}$$

Consequently, if CV is large, the standard deviation of the segment times is relatively large compared to the mean of the segment times, indicating that the rower's average speed in the four segments varied relatively more than if CV is small. Note the importance of squaring of terms in Equation (1); if one split time is more different to the mean than the other split times, this split time can dominate the standard deviation (and CV) considerably. As an alternative to CV, we also analyzed the sum of the absolute differences of the split times and the mean split time, relative to the mean split time, here denoted SRD (sum of relative differences),

$$SRD = \frac{\sum_{j=1}^{n=4}|t_j - \bar{t}|}{\bar{t}}. \tag{3}$$

Furthermore, the normalized velocity for each 500 m segment, v_j, yields a comparison between the mean velocity of a 500 m segment, u_j, and the mean velocity of the full 2,000 m race distance, $\bar{u}$, which is equivalent to a comparison of the mean segment time, $\bar{t}$, and the time spent on a given segment, t_j,

$$v_j = \frac{u_j}{\bar{u}} = \frac{\frac{500\,\text{m}}{t_j}}{\frac{2000\,\text{m}}{\sum_{j=1}^{n=4} t_j}} = \frac{\frac{1}{4}\sum_{j=1}^{n=4} t_j}{t_j} = \frac{\bar{t}}{t_j}. \tag{4}$$

The normalized velocity yields a comparison of a crew's mean velocity in each 500 m segment compared to the same crew's mean velocity for the full 2,000 m race distance. Moreover, we use the relative race time, t_{rel}, of a crew to express the race time of that crew compared to the mean race time of all six crews in the final. This quantity may also be expressed in terms of the mean split times, as is done in the following,

$$t_{rel} = \frac{\bar{t}}{\frac{1}{6}\sum_{k=1}^{m=6}\bar{t}_k}, \tag{5}$$

with $\bar{t}_k$; $k = 1, ..., 6$, being the mean split times of the six crews in the final.

Statistical Analysis

Analyses and calculations were performed in Python (version 3.8.3). The statistical tests applied functions of the stats package of SciPy (version 1.7.0) and Pingouin (version 0.5.0). A $p \leq 0.05$ was considered statistically significant. Welch's t-test for the means of two populations (scipy.stats.ttest_ind) was used to compare two groups, e.g., CV of female crews vs. male crews. Comparisons were made with analysis of variance (ANOVA) methods using the statsmodels and Pingouin packages. The chi-square test of independence of variables in a contingency table (scipy.stats.chi2_contingency) was used to test the independence of the distribution of pacing profile types between different subgroups of the dataset (e.g., distribution among female crews vs. distribution among male crews).

RESULTS

Pacing Profile Characteristics

The coefficient of variation (CV) of the segment times is presented in **Figure 1** as a function of the relative race time, i.e., the race time of a crew compared to the mean race time in that final, cf. Equation (5). The CV (mean and standard deviation) per placement is provided in **Table 2**. Each group of medallists (1st, 2nd, 3rd place) had smaller mean CV than each group of non-podium finishers (4th, 5th, 6th place). The difference in mean CV (standard deviation) between the medallists, CV = 1.72% (0.60%), and the non-podium finishers, CV = 2.00% (0.78%), was significant ($p = 4 \times 10^{-7}$, $d = 0.41$), indicating less variation in the time spent on each of the four 500 m segments among the medallists compared to the non-podium finishers. The sum of the relative differences (SRD), Equation (3), is included in **Table 1**. Consistent results are found between CV and SRD; linear regression yielded $r = 0.98$ based on the $n = 636$ crews. Each group of medallists had smaller mean SRD than each group of non-podium finishers. The difference in mean SRD (standard deviation) between the medallists, SRD = 6.0% (2.1%), and the

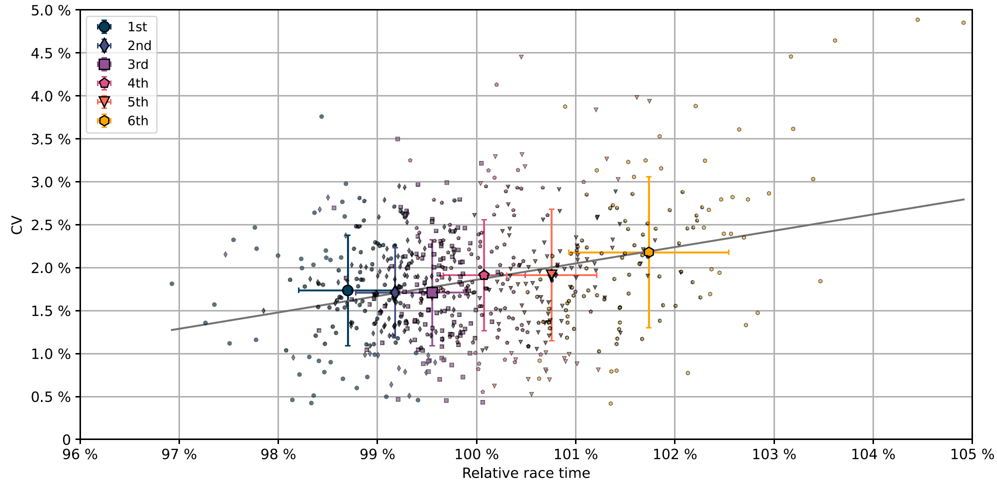

FIGURE 1 | The coefficient of variation (CV) of the split times as function of the relative race time, i.e., the race time of a crew compared to the mean race time in that final, c.f. Equation (5). The results include 636 boat crews from 106 A-finals. Different colors and markers are used for the six finishing placements; mean values per placement are presented with bigger markers; error bars indicate one standard deviation, cf. legend. Linear regression analysis yields intercept equal to −0.172 and slope equal to 0.190 (gray solid line); $r = 0.30$, $p = 5 \times 10^{-15}$, i.e., the slope of CV against relative race time is non-zero with $p = 5 \times 10^{-15}$.

TABLE 2 | Mean CV (standard deviation), mean SRD (standard deviation), Equation (3), and the mean standard deviation, t_{std}, of the four segment times, and mean normalized velocities in the four segments of the race, 0–500 m (v_1), 500–1,000 m (v_2), 1,000–1,500 m (v_3), and 1,500–2,000 m (v_4), as function of performance (final placement).

	CV [%]	SRD [%]	t_{std}	v_1 [%]	v_2 [%]	v_3 [%]	v_4 [%]
1st	1.73 (0.64)	6.0 (2.3)	1.73 s	102.3	99.0	98.7	100.2
2nd	1.71 (0.52)	6.1 (1.9)	1.71 s	102.1	98.8	98.6	100.7
3rd	1.71 (0.62)	6.0 (2.1)	1.72 s	102.0	98.8	98.6	100.6
4th	1.91 (0.65)	6.7 (2.3)	1.94 s	102.5	98.9	98.4	100.4
5th	1.91 (0.77)	6.6 (2.6)	1.95 s	102.7	99.2	98.6	99.7
6th	2.18 (0.88)	7.4 (3.0)	2.25 s	103.3	99.5	98.5	98.9

Results based on 106 A-finals.

non-podium finishers, SRD = 6.9% (2.6%), was significant ($p = 4 \times 10^{-6}$, $d = 0.37$).

Figure 2 illustrates the distribution, in terms of kernel density estimation, of CV per performance level. The distribution plots are cut at the maximum and minimum values of CV per placement. Dashed lines in **Figure 2** indicate the lower quartile (Q1), median (Q2), and upper quartile (Q3). Q1, Q2, and Q3 of all medallists are smaller than the corresponding values of all non-podium finishers.

The mean normalized velocity profiles are presented as function of performance in **Figure 3**; numerical values are provided in **Table 2**. The medallists had, in general, lower normalized velocities in the first two segments of the race, and higher in the third and fourth segments when compared with the non-podium finishers. The differences in means between the medallists (1st, 2nd, 3rd place) and the non-podium finishers (4th, 5th, 6th place) yielded ($p = 9 \times 10^{-9}$, $d = 0.46$), ($p = 4 \times 10^{-5}$, $d = 0.33$), ($p = 0.08$, $d = 0.14$) and ($p = 5 \times 10^{-9}$, $d = 0.47$) in, respectively, the first, second, third, and fourth segments.

The higher normalized velocities in the first two segments yielded a larger mean positive split time, $(t_3 + t_4) - (t_1 + t_2)$, among the non-podium finishers (4th: 2.57 s, 5th: 3.60 s, 6th: 5.46 s) compared to the medallists (1st: 2.39 s, 2nd: 1.56 s, 3rd: 1.59 s). Also, relative to each crew's mean 1,000 m time, $\frac{1}{2}(t_1 + t_2 + t_3 + t_4)$, a difference between the non-podium finishers (4th: 1.23%, 5th: 1.73%, 6th: 2.61%) and the medallists (1st: 1.19%, 2nd: 0.75%, 3rd: 0.78%) was found. The difference in mean relative 1,000 m split time between the medallists (0.91%) and non-podium finishers (1.86%) yielded $p = 3 \times 10^{-10}$, $d = 0.51$.

In **Table 3**, CV for five subgroups—female and male crews (sex), singles, doubles/pairs and quads/fours (number of crew members)—are presented. The mean CV was somewhat smaller for female crews (1.81%) than for male crews (1.91%). This difference yielded $p = 0.06$, $d = 0.15$. Accordingly, the mean SRD was smaller for female crews (6.3%) than for male crews (6.7%), with $p = 0.03$, $d = 0.18$. The mean CV and SRD were larger for single crews (CV = 1.91%, SRD = 6.6%) compared to doubles/pairs (CV = 1.83%, SRD = 6.4%) and quads/fours (CV = 1.85%, SRD = 6.4%). However, comparisons of the CV of these groups all yielded $p \geq 0.3$, $d \leq 0.11$; comparisons of the SRD all yielded $p \geq 0.5$, $d \leq 0.08$.

In **Figure 4**, the mean normalized velocity profiles of the five subgroups are presented; numerical values are provided in **Table 3**. The differences in the normalized velocities between female and male boat crews were all minor ($p \geq 0.1$, $d \leq 0.13$). Compared to doubles/pairs, singles had higher normalized velocity in the second segment ($p = 0.01$, $d = 0.26$) and lower normalized velocity in the fourth segment ($p = 0.03$, $d = 0.21$). Compared to quads/fours, singles had higher normalized velocity in the second ($p = 0.02$, $d = 0.24$) and third ($p = 9 \times 10^{-4}$,

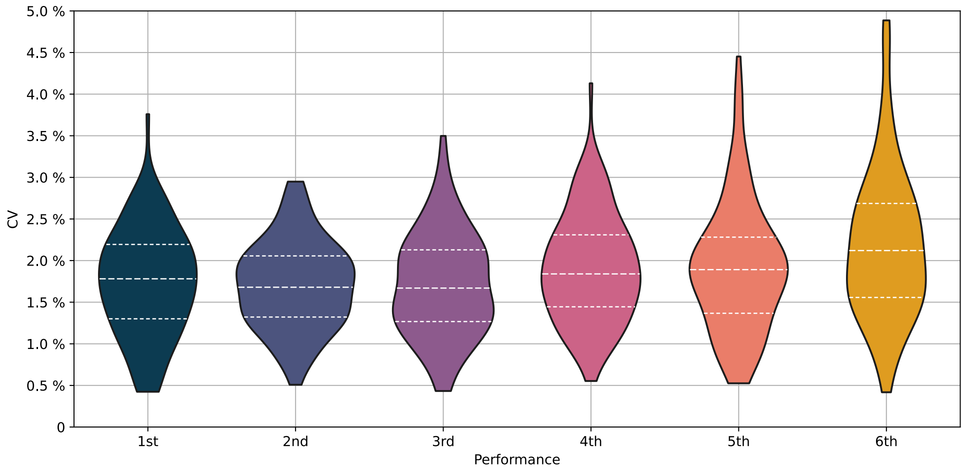

FIGURE 2 | The distribution (violin plots; kernel density estimation) of coefficient of variation (CV) of the split times as function of performance, i.e., placement. The results include 636 boat crews from 106 A-finals. The bottom and top of the violins represent the minimum and maximum values of CV per placement. Dashed lines are used to indicate the lower quartile (Q1), median (Q2), and upper quartile (Q3).

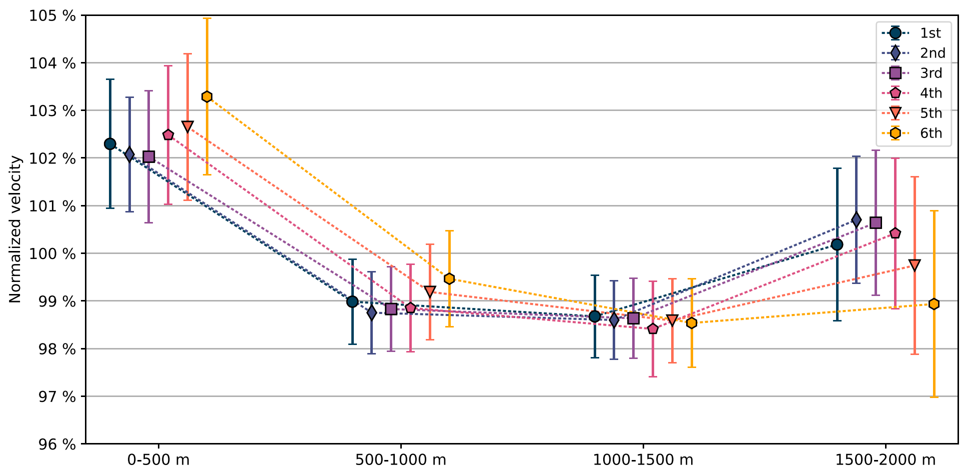

FIGURE 3 | Mean normalized velocities, i.e., the mean velocity in a 500 m segment compared to the mean velocity of the full 2,000 m race distance, Equation (4), in the four segments of the race for all crews sorted on performance, 1st to 6th place (in 106 A-finals). Error bars indicate one standard deviation.

TABLE 3 | Mean CV (standard deviation), mean SRD (standard deviation), Equation (3), and the mean standard deviation, t_{std}, of the four segment times, and mean normalized velocities in the four segments of the race, 0–500 m (v_1), 500–1,000 m (v_2), 1,000–1,500 m (v_3), and 1,500–2,000 m (v_4), for all boat crews, for female crews, for male crews, for singles, for doubles/pairs, and for quads/fours.

	n	CV (%)	SRD (%)	t_{std}	v_1 (%)	v_2 (%)	v_3 (%)	v_4 (%)
All crews	636	1.86 (0.71)	6.5 (2.4)	1.88 s	102.5	99.0	98.6	100.1
Female crews	312	1.81 (0.70)	6.3 (2.4)	1.92 s	102.4	99.0	98.6	100.1
Male crews	324	1.91 (0.71)	6.7 (2.5)	1.85 s	102.6	98.0	98.5	100.1
Singles	180	1.91 (0.75)	6.6 (2.6)	2.08 s	102.5	99.2	98.7	99.8
Doubles/pairs	270	1.83 (0.70)	6.4 (2.4)	1.86 s	102.4	98.9	98.6	100.1
Quads/fours	186	1.85 (0.67)	6.4 (2.3)	1.72 s	102.5	99.0	98.4	100.4

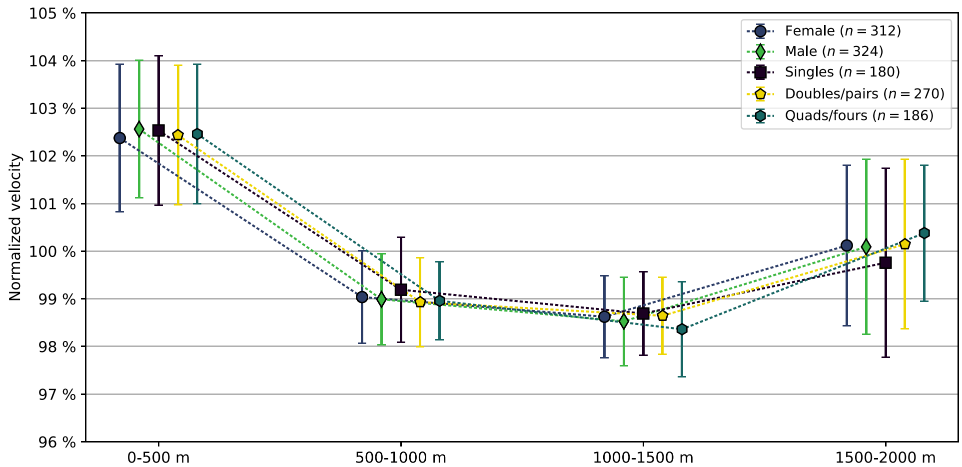

FIGURE 4 | Mean normalized velocities, i.e., the mean velocity in a 500 m segment compared to the mean velocity of the full 2,000 m race distance, Equation (4), in the four segments of the race for all female and male boat crews, as well as the three groups of crew members (singles: 1 crew member, doubles/pairs: 2 crew members, quads/fours: 4 crew members). Error bars indicate one standard deviation.

TABLE 4 | Pacing profile classification of the 636 considered boat crews.

Abbreviations	Profile	Criterion	*n*
r-J	Reverse J-shaped	$t_1 < t_4$ and $t_4 < \min(t_2, t_3)$	303 (48%)
J	J-shaped	$t_4 < t_1$ and $t_1 < \min(t_2, t_3)$	117 (18%)
FS	Fast start and fade	$t_1 < t_2$ and $t_2 < \min(t_3, t_4)$	169 (27%)
else	All other combinations	different to the above	47 (7%)

The pacing profile of a crew is classified based on the split times in the four segments of the race, t_1 (0 to 500 m), t_2 (500–1,000 m), t_3 (1,000–1,500 m) and t_4 (1,500–2,000 m).

$d = 0.35$) segments, and lower normalized velocity in the fourth segment ($p = 7 \times 10^{-4}$, $d = 0.36$). Doubles/pairs had higher normalized velocity than quads/fours in the third segment ($p = 0.001$, $d = 0.32$).

In **Table 4**, we categorize the velocity profiles in terms of three commonly found pacing profiles in rowing; the reverse J-shaped (fastest-slow-slow-fast), normal J-shaped (fast-slow-slow-fastest) and a positive pacing profile here denoted fast start and fade (fastest-fast-slow-slow). All but 47 crews fell into one of these three categories (93%). For 497 of 636 crews (78%), the first 500 m segment was the fastest of the four 500 m segments. Illustrations of the categorized pacing profiles, based on the normalized velocities (mean values and upper and lower quartiles) in each group, are presented in **Figure 5**.

Pacing profiles sorted on performance are presented in **Table 5**. The resulting *p*-values from chi-squared tests of independence are provided in **Table 6**. The difference in distribution of pacing profiles between some of the placements were significant, in particular for the last place which had a distribution that was different to all other placements ($p \leq 0.03$). The difference in distribution of pacing profiles of all medallists combined [r-J: 163 (51%), J: 71 (22%), FS: 59 (19%), else: 25 (8%)] and the non-podium finishers combined [r-J: 140 (44%), J: 46 (14%), FS: 110 (35%), else: 22 (7%)] yielded $p = 5 \times 10^{-5}$.

The pacing profiles of the five subgroups presented in **Figure 4** and **Table 3** are provided in **Table 7**. Chi-square tests of independence yielded no significant difference in the pacing profile distributions between female and male crews ($p = 0.5$). The difference between singles and doubles/pairs was also insignificant ($p = 0.2$), as was the difference between doubles/pairs and quads/fours ($p = 0.4$). The difference in profiles between singles and quads/fours yielded $p = 0.03$.

Segment Performance

In **Figure 6**, the fastest crews in each of the four segments of the race are presented in terms of the final placement. In 225.5 of the 424 considered segments (53%), the fastest crew was also the winner of the race[1]. The winner particularly dominated the two mid-race sections; in 68 of the considered finals (64%), the fastest boat from 500 m to 1,000 m was also the winner of the race, and in 66 finals (62%), the fastest boat from 1,000 m to 1,500 m was the winner.

Figure 7 is a supplement to **Figure 6** and presents the position of the winners at 1,000 m and 1,500 m into the race. In 77 finals (73%), the leading crew at 1,000 m won the race, and in 84 finals (79%), the leading crew at 1,500 m won the race.

DISCUSSION

This study provides novel information on how rowers in A-finals of World and European championships apply their pacing strategy. 106 finals were considered, in which all

[1] In one event (W19 W4x), both the first and second place had the equal fastest time at the 500 m mark.

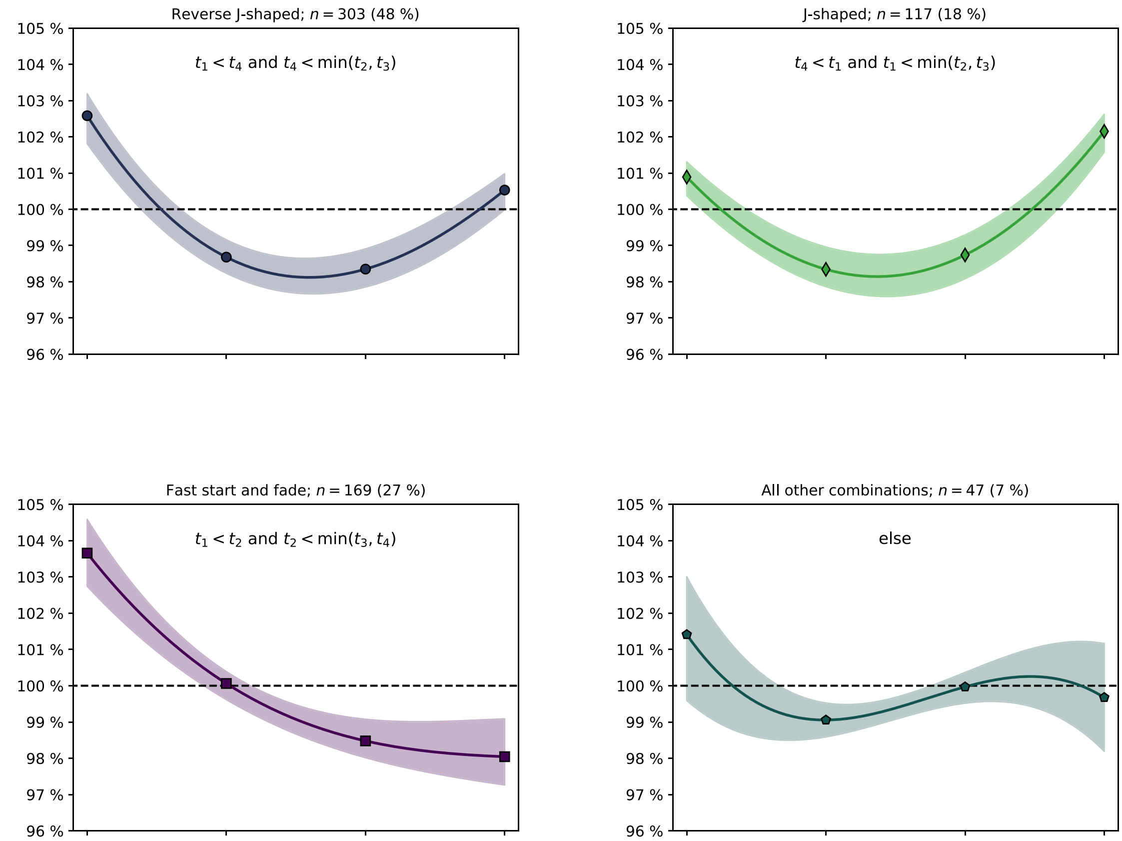

FIGURE 5 | Illustrations of pacing profiles for the crews that fit into the reverse J-shaped **(upper left)**, standard J-shaped **(upper right)** and fast start and fade **(lower left)** pacing profile groups (all other combinations group; **lower right**), cf. **Table 4**. Markers: Mean normalized velocities in the four segments of the race. Solid line: Third order polynomial fit based on the four mean values. The shaded area is bordered by third order polynomial fits based on the lower (Q1) and upper (Q3) quartiles of the normalized velocities in the four segments of the race.

TABLE 5 | Pacing profile as function of final placement of the 636 considered boat crews.

Abb.	1st	2nd	3rd	4th	5th	6th
r-J	46 (43%)	63 (59%)	54 (51%)	54 (51%)	47 (44%)	39 (37%)
J	19 (18%)	26 (25%)	26 (25%)	19 (18%)	19 (18%)	8 (8%)
FS	32 (30%)	11 (10%)	16 (15%)	23 (22%)	37 (35%)	50 (47%)
else	9 (8%)	6 (6%)	10 (9%)	10 (9%)	3 (3%)	9 (8%)

*Profiles and criteria for the abbreviations are provided in **Table 4**.*

TABLE 6 | *p*-values from chi-squared tests of independence comparing the distribution of the pacing profiles between the different final placements, cf. **Table 5**.

	1st	2nd	3rd	4th	5th	6th
1st	-	0.002	0.07	0.5	0.3	0.03
2nd	0.002	-	0.5	0.07	3×10^{-4}	8×10^{-9}
3rd	0.07	0.5	-	0.5	0.003	2×10^{-6}
4th	0.5	0.07	0.5	-	0.06	7×10^{-4}
5th	0.3	3×10^{-4}	0.003	0.06	-	0.02
6th	0.03	8×10^{-9}	2×10^{-6}	7×10^{-4}	0.02	-

had six competing boat crews. We used the coefficient of variation (CV) of the 500 m intermediate times to quantify the evenness of the pacing profiles. Analyses of an additional pacing variation parameter, the sum of the relative differences (SRD) of the 500 m split times, were overall consistent with analyses of the CV. We did not find significant differences in the CV of female vs. male crews—although females paced somewhat more evenly than men and had smaller SRD ($p = 0.03$, $d = 0.18$)—or in the CV of various crew members (singles vs. doubles/pairs vs. quads/fours), cf. **Table 3**. However, more even pacing profiles were evident for the medallists compared to that of the 4th–6th places, implying that the pacing pattern discriminates athletes at the highest performance level in World class rowing, cf. **Figures 1**, **2** and **Table 2**.

The mean pacing profile of all crews, in the subgroups (sex, crew members), and for all placements except the last, followed a reverse J-shape, cf. **Figures 3**, **4** and **Tables 2**, **3**. In 78% of the

TABLE 7 | Pacing profiles of various subgroups.

Abb.	Female	Male	1x	2x/2-	4x/4-
r-J	140 (45%)	163 (50%)	76 (42%)	126 (47%)	101 (54%)
J	60 (19%)	57 (18%)	28 (16%)	55 (20%)	34 (18%)
FS	86 (28%)	83 (26%)	59 (33%)	71 (26%)	39 (21%)
else	26 (8%)	21 (6%)	17 (9%)	18 (7%)	12 (6%)

*Profiles and criteria for the abbreviations are provided in **Table 4**.*

crews, the first 500 m segment was the fastest of all four 500 m segments. These findings are in line with studies of previous rowing events (Garland, 2005; Brown et al., 2010; Muehlbauer et al., 2010; Muehlbauer and Melges, 2011). Moreover, segment analyses revealed the winner's dominance in the relatively slower mid-race sections, cf. **Figure 6**. Notably, for the winners, being the fastest crew in the last segment was considerably less common compared with the three other segments, and in 79% of the finals, the winner was also leading at the 1,500 m mark, cf. **Figure 7**. This is consistent with A-finals of previous World championships (2003–2007) and Olympic games (2004, 2008), studied by Brown et al. (2010), who found that 78% of winners were placed first at the 1,500 m mark. We note the lack of drafting benefits in rowing, which is an important difference between rowing and several other mass start sports, where the outcome often comes down to a so-called endspurt phenomenon, e.g., 1,500 m running (Casado et al., 2021). Consequently, there seems to be limited good reasons for saving energy for an endspurt (Tucker, 2009), a likely reason why the regular J-shaped pacing profile, often seen in other endurance sports of similar duration, does not seem to be that common in rowing, cf. **Figure 5** and **Table 4**. Interestingly, in a recent rundown of the regattas at the 2021 Tokyo Olympics, Kleshnev (2021) showed that the mean pacing profile was J-shaped. Kleshnev (2021) also noted that the Tokyo Olympics was the second fastest of 28 World regattas since 1993, and the pacing profiles were characterized as "much more even" than previous events.

From a pure mechanical point of view, our main finding that performance depends on the evenness of the pacing profile, seems very likely. Considering the streamlined vessels and the mean velocities—which ranged from 4.1 m/ s to 6.0 m/ s in the considered events—the resistance force on the boat and crew, F, should be dominated by viscous forces that can be approximated as (Faltinsen, 2005),

$$F = \frac{1}{2}\rho C S u^2. \tag{6}$$

Here ρ is the fluid density, u is the velocity, C is a dimensionless coefficient and S is a characteristic surface area, e.g., the friction forces along the wet hull are expressed with a friction coefficient, C_f, and wet hull surface, S_w. Alternatively, if pressure forces dominate—for instance the aerodynamic drag forces on the rower's upper body—the expression may be written in terms of a form drag coefficient, C_d, and the projected frontal area, A. In either case, Equation (6) predicts that these viscous drag forces are proportional to velocity squared, $F \propto u^2$. Consequently, the power (P; the rate at which a force does work), needed to overcome the total resisting force in rowing, is approximately proportional to velocity cubed, $P \propto u^3$. More refined models and experimental investigations support these assumptions, e.g., $P \propto u^{3.2}$ (di Prampero et al., 1971), $P \propto u^{2.95}$ (di Prampero, 1986), $P \propto u^{2.8}$ (Affeld et al., 1988), $P \propto u^{2.7}$ (Hofmijster et al., 2007), and $P \propto u^{2.92}$ (Hill and Fahrig, 2009). Arguments have been made that the exponent is somewhat smaller if a model of actual rowing is considered (Shephard, 1998; Hill and Fahrig, 2009). Nevertheless, a highly non-linear relation between power and velocity is obtained. Consequently, for a given mean power output, the mean velocity is maximized when rowing at a constant velocity, i.e., constant power (even pacing strategy), assuming similar conditions over the course of the race. This is impossible for two obvious reasons; 1) initially, the boat must be accelerated from rest; 2) intracyclic velocity variations are inevitable consequences of the propulsive mechanisms of rowing. However, these effects may be treated separately from changes to the mean stroke velocity during the greatest part of the race. Typically, the initial acceleration phase of a 2,000 m regatta is limited to the very start of the race, increasing the time spent on the first 50 m of the race by 1–4 s compared to the mean 50 m split time, but not affecting later 50 m split times (Thompson, 2014, Figure 11.1). Moreover, the intracyclic velocity variations may be treated as representing an additional resistance component—which requires an additional power output—compared to traveling the boat constantly at the mean stroke velocity (Hofmijster et al., 2018), with an associated increase in the net mechanical power of 2–10% (Nigg, 1984; Sanderson and Martindale, 1986; Hofmijster et al., 2007; Hill and Fahrig, 2009; de Brouwer et al., 2013).

A reason why relatively fast starts (despite the initial acceleration phase) are common in rowing, may be due to the fact that rowing regattas are lane-based mass start events with both mental and hydrodynamic arguments for leading, not following. Since the crews are faced backwards, being upstream of competitors is a visual advantage. Therefore, a lead may give a sense of control with positive mental feedback which could influence performance (Schiphof-Godart et al., 2018). Clear favorites that are likely winners in many race scenarios may enjoy the confidence in taking an early lead to have visual control of the race. This may explain why the winners had slightly larger CV, relatively faster starts and more often applied the fast-start and fade pacing strategy, compared to the other medallists, cf. **Figures 1–3**, and **Tables 2**, **5**, **6**. In addition to mental aspects, there are also hydrodynamic arguments for uneven pacing. Incident waves from the competitors' boats may yield both a larger resistance force and make it more challenging to row effectively for a crew downstream. The risk of incident waves from competing boats may be estimated by considering the Kelvin angle, that is, the angle between the boundary of the wave system and course of a vessel (Faltinsen, 2005). Assuming deep water conditions, the Kelvin angle is $\arcsin \frac{1}{3} \approx 19^\circ$. If the lane width is 12.5 m and the boats are placed in the center of their lanes, the course direction distance from the wave propagation of

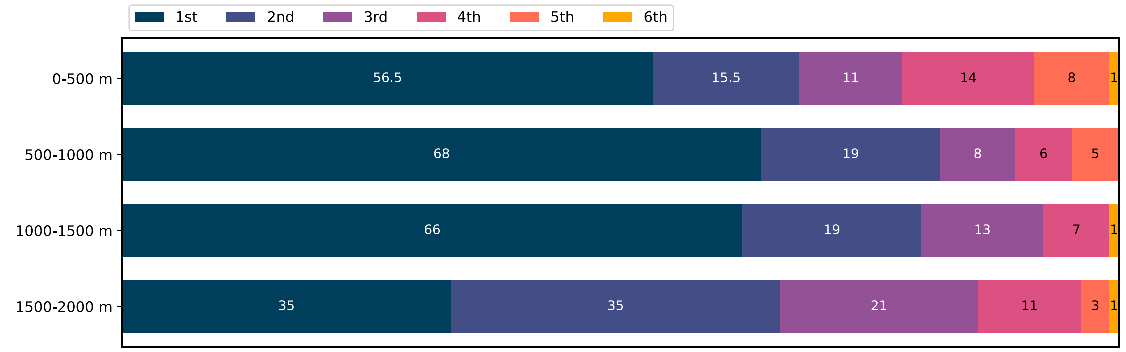

FIGURE 6 | Segment winners sorted on race performance: the number of 1st, 2nd, 3rd, 4th, 5th, and 6th place finishers that are the fastest boat crew in each of the four 500 *m* segments. 106 A-finals considered. Total number of segment wins: 1st place 225.5 (53%), 2nd place 88.5 (21%), 3rd place 53 (13%), 4th place 38 (9%), 5th place 16 (4%), 6th place 3 (1%).

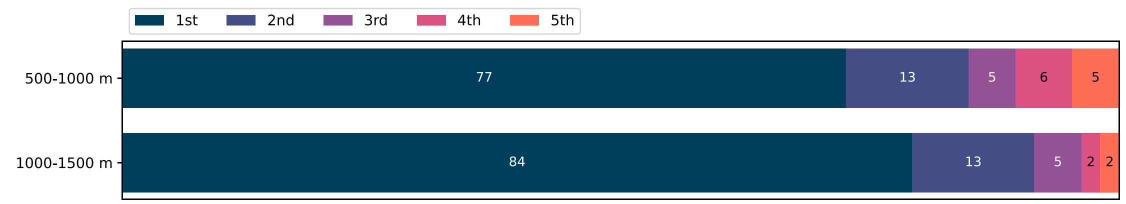

FIGURE 7 | The number of race winners that are placed at the 1st, 2nd, 3rd, 4th, and 5th at 1,000 m and 1,500 m in the 106 considered A-finals. The position of the winning crew at 500 m is equal to the top bar of **Figure 6** (at 2,000 m all winners are placed first).

the upstream boat to the stern of the downstream boat, must be less than 35 m to avoid incident waves from the upstream boat on the downstream boat. This distance is reduced if the upstream crew position the boat closer to the line of buoys. Consequently, if competitors apply a very fast start, incident waves is a risk worth noting if applying a more conservative pacing strategy. However, in general, the smallest risk of incident waves from competing boats throughout the race is achieved by going as fast as possible for the whole race distance, not just the start.

CONCLUSION

Medal winners in major rowing championships pace with smaller variation than their competitors. This may imply that a more even pacing profile, than what is typically applied by non-podium finishers, is advantageous in rowing.

DATA AVAILABILITY STATEMENT

The dataset supporting the conclusions of this article will be made available by the corresponding author, without undue reservation.

ETHICS STATEMENT

Ethical review and approval or written informed consent were not required for the study on human participants in accordance with the local legislation and institutional requirements.

AUTHOR CONTRIBUTIONS

FM collected and analyzed the data. Both authors contributed to the design of the study, wrote the manuscript, and approved the submitted version.

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Initial Evaluation of the Concept-2 Rowing Ergometer's Accuracy Using a Motorized Test Rig

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Introduction: The Concept 2 (C2) rowing ergometer is used worldwide for home-based training, official competitions, and performance assessment in sports and science. Previous studies reported a disparate underestimation of mechanical power output positively related to an unclearly defined stroke variability. The aim of this study was to quantify the accuracy of the C2 while controlling for the potentially influencing variables of the rowing stroke by using a test rig for air-braked rowing ergometers and thus excluding biological variability.

Methods: A unique motorized test rig for rowing ergometers was employed. Accuracy was assessed as the difference in mechanical power output between C2 and a reference system during steady (i.e., minimal variations of stroke power within a series of 50 spacemark, no -strokes) and unsteady simulated rowing (i.e., persistent variations during measurement series) while manipulating the stroke variables shape, force, or rate.

Results: During steady simulated rowing, differences between C2 and the reference system ranged 2.9–4.3%. Differences were not significantly affected by stroke shapes ($P = 0.153$), but by stroke rates ranging 22–28 min^{-1} ($P < 0.001$). During unsteady simulated rowing with alterations of stroke force and rate, mean differences of 2.5–3.9% were similar as during steady simulated rowing, but the random error increased up to 18-fold. C2 underestimated mechanical power output of the first five strokes by 10–70%. Their exclusion reduced mean differences to 0.2–1.9%.

Conclusion: Due to the enormous underestimation of the start strokes, the nominal accuracy of the C2 depends on the total number of strokes considered. It ranges 0.2–1.9%, once the flywheel has been sufficiently accelerated. Inaccuracy increases with uneven rowing, but the stroke shape has a marginal impact. Hence, rowers should row as even as possible and prefer higher stroke rates to optimize C2 readings. We recommend external reference systems for scientific and high-performance assessments, especially for short tests designs where the start strokes will have a major impact.

Keywords: automated testing, indoor rowing, validity, power output, home-based training

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INTRODUCTION

Ergometer training is a common type of training in many outdoor endurance sports, because it provides a highly controllable workout regardless of weather conditions. The SARS-CoV-2 pandemic has furthermore increased the relevance of indoor and home-based training among athletes and recreational athletes and thus of ergometers (Kim et al., 2020; Pedersen et al., 2021). In the sport of rowing, ergometer training is so widely accepted that the World Rowing Federation hosts official world indoor championships on the indoor rowing machine from Concept 2 (C2, Concept 2, Morrisville, VT, USA). The C2 was actually designed as a training device, but is also used by training centers and rowing federations around the world (Smith and Hopkins, 2012) for performance testing to reduce the influence of environmental conditions, which are difficult to control and greatly affect on-water performance (Kleshnev, 2009; Smith and Hopkins, 2011; Malcata and Hopkins, 2014).

The C2 is an air-braked ergometer and resistance is created by a flywheel that becomes accelerated via a handle that is attached to a chain. During each rowing cycle, the rower pulls the handlebar with the coordinated muscle force of legs, trunk and arms, while moving backward on a sliding seat (i.e., drive phase), thereby accelerating the flywheel. Subsequently, the direction of movement is reversed and the rower moves forward to the starting position (i.e., recovery phase). During this phase the flywheel decelerates due to the resistance of the circulated air, but it does not stop immediately. That is due to the rotating mass of the flywheel and the energy stored. This phenomenon is similar to the momentum of an already accelerated rowing boat. It is worth highlighting that the principle of such an air dampened ergometer is substantially different to mechanically braked ergometers, where an external brake controller determines resistance. In an air-damped ergometer such as the C2, it is the rower who determines resistance via stroke force, rate, and length and thereby also the accuracy of the targeted mechanical output.

According to Van Holst (2014), the actual mechanical power output per rowing cycle, usually the key measure of performance (Soper and Hume, 2004), is calculated by the display-computer of the C2, based on measurements of angular velocity (which is used to calculate acceleration and deceleration of the flywheel), the mass of the flywheel, and a constant factor. This approach differs substantially from the physical definition of mechanical power as work per time. Considering the special calculation and the fact that the C2 is employed worldwide for performance measurements of rowers, it is surprising that there is limited and incomplete information about the quality criteria and particularly validity of the C2.

Two validation studies compared the mechanical power output of the C2 vs. a criterion measure (i.e., external force- and displacement-sensors) during rowing. Lormes et al. (1993) postulated a systematic underestimation of approximately 14 W (6.8%) of the C2 (Model C) and Boyas et al. (2006) reported a systematic underestimation of approximately 25 W (7.4%) (Model D). The latter study showed in fact differences in the error's magnitude between novice and trained rowers due to stroke-to-stroke variability. This has been reported by others, too (Smith and Spinks, 1995). Hence, a systematic error is questionable and accurate validation requires the integration of stroke-to-stroke variability.

The stroke-to-stroke variability within a rowing cycle mentioned here may arise from different variables: (i) The shape of the force vs. displacement curves during drive phase may vary due to different anthropometrical portions and/or sequencing of the lower and upper body, resulting in triangular up to rectangular shapes (Kleshnev, 2000). This shape determines where the force peaks during the stroke, i.e., relatively at the front, mid, or end of the stroke. (ii) The ratio of drive (i.e., when the rower pulls and moves backwards) to recovery phase (i.e., when the rower moves forward and does not apply force to the handle) (drive:recovery) varies between rowers. (iii) The consistency of the generated force varies, depending on pacing strategy, ability, and fitness of the rower. (iv) Finally, the consistency of the drive:recovery ratio and/or stroke rate may vary to a lower or higher degree.

However, the unknown impact of these variables and their variability on the calculation of the C2's mechanical power output can almost not be studied in human rowers since these variables cannot be controlled precisely. We therefore developed a unique test rig for rowing ergometers (Mentz et al., 2020), allowing to control all of the aforementioned variables during simulated rowing and providing a robust criterion measure. Using this test rig, it was possible to evaluate the validity of the C2's mechanical power output and to quantify the effects of manipulations of stroke shape, -frequency (via the drive:recovery ratio), -force, and irregularities in these variables. The aim of this study was the first-time quantification of the C2's accuracy while controlling for the potentially influencing variables of the rowing stroke by using a test rig for air-braked rowing ergometers and thus excluding biological variability.

MATERIALS AND METHODS

The test setup consisted out of a custom-made test rig for air-braked rowing ergometers and a commercially available C2 rowing ergometer with the manufacturer's PM5 performance monitor (Concept 2, Morrisville, USA). All trials were conducted in a laboratory (18.0–23.1°C, 40–60% relative humidity, 940–967 hPa air pressure). The drag factor, a C2-specific variable that influences the behavior of the flywheel, was set to 145, corresponding to the standard value of the German Rowing Federation (Schwarzrock et al., 2017). This setting was also applied during human ergometer rowing, when those strokes were recorded that are now reproduced by the test bench [see Mentz et al. (2020) for details].

Test Rig and Criterion Measure

The test rig for air-braked rowing ergometers (see **Supplementary Figure 1**) has been described elsewhere (Mentz et al., 2020). In short, the rig enables highly reliable rowing strokes [coefficient of variation (CV) < 1%] that are very similar to those of German elite rowers in terms of stroke shape, force, and mechanical power output. The test rig mounts the front part of the C2 without modifying it in any way and a controlled motor moves a sledge that is connected to the ergometer's chain. The chain is equipped with a 100 Hz load cell (U9C, 2 kN, HBM, Darmstadt, Germany) to measure stroke force. A 100 Hz odometer (Limes L120/B1, Kübler, Villingen-Schwenningen, Germany) captures the displacement of the chain. These sensors allow for the exact calculation of mechanical work, which—divided by the duration of the rowing cycle—allows to calculate mechanical power output of the reference system (P_{REF}). A custom MATLAB algorithm (Matlab R2018b, The Mathworks, Inc., Natick, MA, USA) was applied to calculate P_{REF}.

Rowing Ergometer

A previously unused C2 indoor rower (Model D, Concept 2, Morrisville, USA) with a PM5 monitor was applied for all tests. Mechanical power output of the C2 (P_{C2}) was logged using a third-party app (FLOAT, Ergstick Lmt, Cambridge, UK). According to the manufacturer's information, the FLOAT-App reads the numbers from the PM5 without any manipulation, thereby mirroring the displayed accuracy of 1 W without decimals.

Test Design

To obtain the main outcome measure, i.e., the difference in mechanical power output between REF and C2 (ΔP_{REF-C2}), a series of experiments (specified below) were conducted on the test rig and data for REF and C2 were logged simultaneously. All strokes (i.e., drive phases) applied during the experiments were based on strokes that had originally been recorded during ergometer testing in German national and international elite rowers with an external reference system (Treff et al., 2017, 2018b). These profiles were subsequently implemented via torque control. Due to the principle of torque control, the first strokes are shorter, while force is higher. This is related to the high inertia of the flywheel at the start, when it gets accelerated from stand still. In that situation, maximum torque (which is defined in the input torque control) is reached after a shorter displacement or travel. Of note, this finely mimics behavior and biomechanical limitations of human rowers. For more details regarding the functionality of the test rig please see (Mentz et al., 2020).

Experiments

The experiments (**Figure 1**; **Supplementary Table 1**) were divided into steady and unsteady simulated rowing. Steady rowing was used to evaluate the impact of (i) stroke shape ($STEADY_{SHAPE}$) and (ii) drive:recovery ratio expressed as stroke rate ($STEADY_{RATE}$) in measurement series with minimum stroke-to-stroke variability. Unsteady rowing was applied to evaluate the impact of persistent fluctuations in (iii) force ($UNSTEADY_{FORCE}$) and (iv) stroke rate ($UNSTEADY_{RATE}$) in measurement series with high stroke-to-stroke variability.

i. **$STEADY_{SHAPE}$**: To evaluate the impact of different force vs. displacement curve shapes on ΔP_{REF-C2}, series of 50 strokes each with either a front-, mid-, or end-emphasized profile were completed 10 times. The location of the peak torque relative to the distance was at 45, 51, and 57% of stroke length, respectively (**Figure 1A**). The stroke rate was set to 27 min $^{-1}$.

ii. **$STEADY_{RATE}$**: To evaluate the impact of different *drive:recovery* ratios on ΔP_{REF-C2}, four measurement series where conducted, where the recovery phase lasted 1.6, 1.4, 1.2, or 1.1 s while the drive phase always lasted 1.1 s (**Figure 1B**). This resulted in drive:recovery rations of 0.69, 0.79, 0.91, and 1.00 and stroke frequencies of 22, 24, 26, and 28 min^{-1}, respectively. A mid-emphasized stroke was used for this experiment and each series of 50 strokes was completed twice.

iii. **$UNSTEADY_{FORCE}$**: To evaluate the impact of an unsteady force application on ΔP_{REF-C2}, the magnitude of force between strokes within measurement series was modified by alternating the input torque curve of the mid-emphasized profile within two different measurement series, each consisting of 50 strokes completed 10 times. Duration of the recovery phase was kept constant at 1.1 s during each series.

   a. Alternating (ALT): The peak-torques of 14.5 or 15.5 Nm were alternated stroke by stroke (**Figure 1C**).
   b. Random (RND): The peak-torques of 14.5 and 15.0 Nm were randomly varied between the strokes (**Figure 1D**). These peak-torques were chosen to generate a coefficient of variation for stroke-to-stroke variability of 2–5%, corresponding to a stroke-to-stroke variability obtained in human elite rowers (Mentz et al., 2018; Treff et al., 2018a).

iv. **$UNSTEADY_{RATE}$:** To assess the effect of permanent changes in the drive:recovery ratio (stroke rate) on ΔP_{REF-C2}, the duration of the recovery phases was alternated within three measurement series, while stroke duration and peak torque during the drive phase were clamped. Each series consisted out of 50 mid-emphasized strokes (**Figures 1E,F**) and was completed 10 times.

   a. High variation (HV): The recovery duration of 1.07 s and 1.66 s was alternated stroke by stroke, resulting in stroke rates of 22 and 28 min^{-1} (**Figure 1E**).
   b. Low variation (LV): The recovery durations of 1.2 and 1.3 s were alternated randomly, resulting in stroke rates of 29 and 30 min^{-1}, thereby simulating a human variation (**Figure 1F**).

Data Analysis and Statistics

The force, displacement, and time data of the test rig were logged using a custom code in Labview 2019 (National Instruments, Texas, Austin, USA) and stroke by stroke mechanical power output was calculated using a custom algorithm in MATLAB (Matlab r2018b, The Mathworks, Inc., Natick, MA, USA). Arithmetic mean, standard deviation, and CV of P_{REF} and P_{C2} were calculated for each trial using SPSS 26 (IBM, Armonk, NY, USA). Accuracy was calculated for each trial as absolute and relative mean difference [100 x ((P_{REF} – P_{C2}) / P_{REF})]. ΔP_{REF-C2} between tests was statistically analyzed using a mixed model with fixed effects being *stroke number* (stroke) and *type*. *Type* was defined in $STEADY_{SHAPE}$ (i) as front-, mid-, or end-emphasized stroke shape, in $STEADY_{RATE}$ (ii) as a stroke rate of 22, 24, 26, or 28 min^{-1}, and for $UNSTEADY_{FORCE}$ (iii) as alternating (ALT) or random variation (RND) in stroke force within a measurement

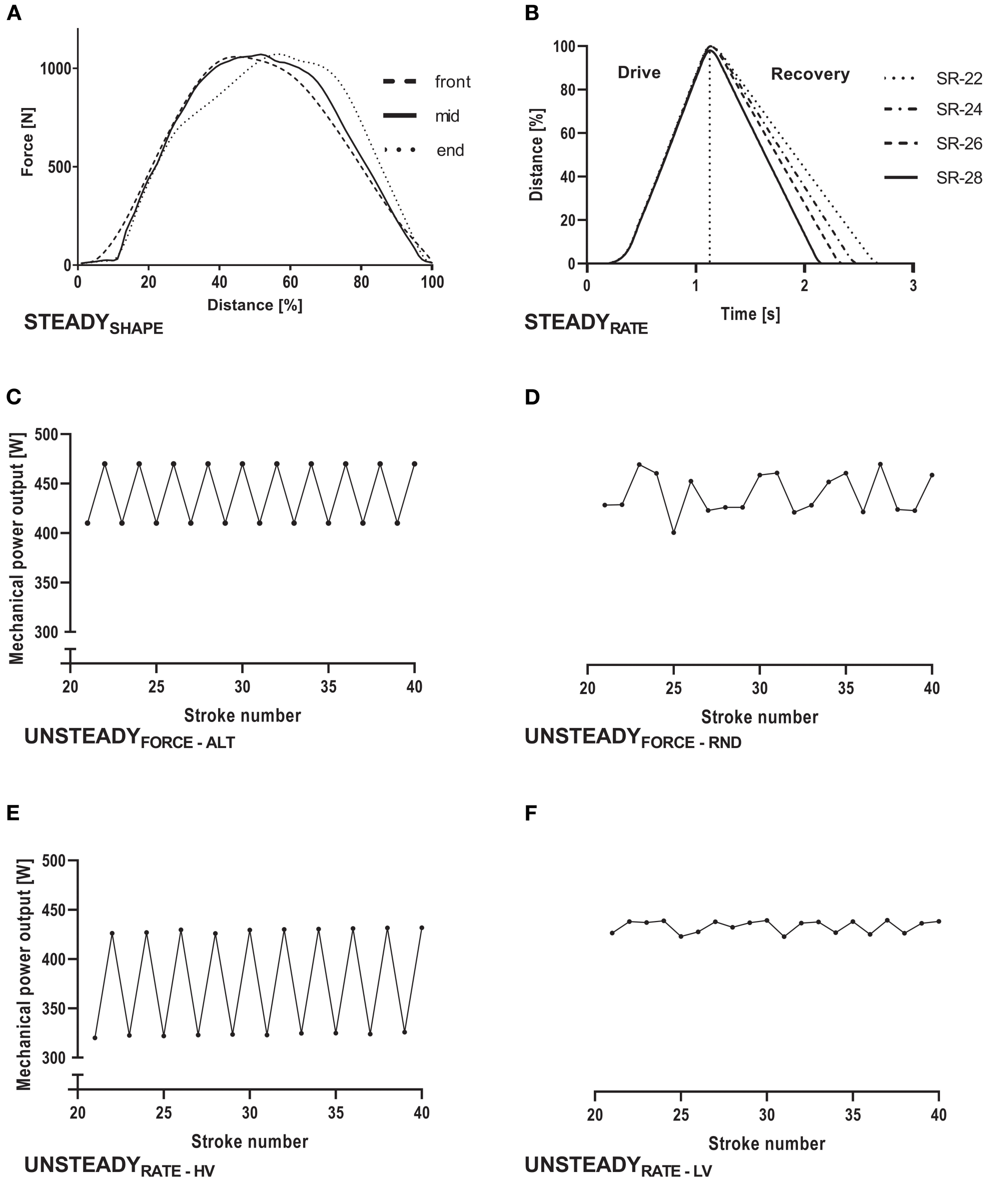

FIGURE 1 | Schematic overview of the experimental design to evaluate differences in mechanical power output between the reference system of a test rig for air-braked rowing ergometers and the Concept 2 Indoor Rower's PM5 Monitor. In **(A,B)** the influence of stroke shape and stroke rate was tested during steady simulated rowing, i.e., stroke-to-stroke variability was as low as possible during each measurement series. **(A)** Shows three different stroke shapes (front-, mid- and end-emphasized) that were applied, while **(B)** visualizes four different stroke rates (SR) of 22, 24, 26 and 28 min^{-1}. **(C–F)** depict the mechanical power output (detailed excerpt of strokes 20–40) during unsteady experiments, where stroke-to-stroke variability was experimentally augmented by regular [ALT, **(C)**] or random manipulations of stroke force [RND, **(D)**]. Finally, stroke rate was manipulated highly and regularly [HV, **(E)**] or slightly and randomly [LV, **(F)**], while force was kept constant.

series; for $UNSTEADY_{RATE}$ (iv) as high or low variation (HV and LV, respectively) in recovery duration within each measurement series. The interaction effect of *stroke***type* was also tested. A graphic visualizing the statistical approach can be found in the supplements (see **Supplementary Figure 2**). The same model was applied for absolute (i.e., Watt) and relative (i.e., percentage) differences. The mixed model was implemented in SAS (SAS institute, Cary, NC, USA), applying the proc mixed procedure. The level of significance was set to $P < 0.05$ and Bonferroni tests were used for *post-hoc* testing. Effect sizes (partial eta squared η^2) were considered as small ($\geq 0.01 < 0.06$), medium ($\geq 0.06 < 0.14$), or large (≥ 0.14) (Cohen, 1988).

Due to the previously reported underestimation in mechanical power output of the C2 system during the starting strokes, which in some way was expected to mitigate the impact of the experimental manipulation, we calculated results not only for *all*

TABLE 1 | Mean differences in mechanical power output between the reference system of a test rig for air-braked rowing ergometers and the Concept 2 Indoor Rower's PM5 Monitor during steady simulated rowing.

Data	Variable	i. $STEADY_{SHAPE}$			ii. $STEADY_{RATE}$			
		front	mid	end	SR-22	SR-24	SR-26	SR-28
	P_{REF}, W	432 ± 7	435 ± 4	445 ± 4	329 ± 9	370 ± 7	400 ± 5	450 ± 5
$Strokes_{1-50}$	ΔP_{REF-C2}, W	12.9 ± 51.4	13.3 ± 50.5	13.9 ± 51.4	15.1 ± 42.7	15.2 ± 47.4	15.4 ± 49.0	15.6 ± 52.6
	ΔP_{REF-C2}, %	2.9 ± 11.1	3.0 ± 11.1	3.1 ± 11.1	4.3 ± 11.2**	3.9 ± 11.6*	3.8 ± 11.8	3.6 ± 12.3
$Strokes_{6-50}$	ΔP_{REF-C2}, W	1.9 ± 1.8	2.3 ± 1.8	2.7 ± 1.8	6.3 ± 1.5	5.2 ± 1.7	4.6 ± 2.0	3.6 ± 2.0
	ΔP_{REF-C2}, %	0.5 ± 0.4	0.5 ± 0.5	0.6 ± 0.4	1.9 ± 0.5++	1.4 ± 0.5##	1.1 ± 0.5	0.8 ± 0.5

*Data are arithmetic mean ± standard deviation. ΔP_{REF-C2}: differences in mechanical power output between the reference system of a test rig for air braked rowing ergometers (REF) and the Concept 2 Indoor Rower's PM5 monitor (C2); $Strokes_{1-50}$: all strokes are analyzed; $Strokes_{6-50}$: first five strokes are excluded from analysis; front, mid, and end indicate the location of peak force relative to stroke length; SR: stroke rate (min^{-1}); **indicates highly significant difference to SF 24, 26, 28 min^{-1} ($P < 0.001$); *indicates significant difference to SR 28 min^{-1} ($P < 0.05$); ++indicates highly significant difference to SR 24, 26, 28 min^{-1} ($P < 0.001$); ##indicates highly significant difference to SR 28 min^{-1} ($P < 0.001$).*

TABLE 2 | Mean differences in mechanical power output between the reference system of a test rig for air-braked rowing ergometers and the Concept 2 Indoor Rower's PM5 Monitor during unsteady simulated rowing.

Data	Variable	iii. $UNSTEADY_{FORCE}$		iv. $UNSTEADY_{RATE}$	
		a: ALT	b: RND	a: HV	b: LV
	P_{REF}, W	444 ± 31	447 ± 22	380 ± 52	438 ± 10
$Strokes_{1-50}$	ΔP_{REF-C2}, W	13.7 ± 58.5	12.7 ± 53.4	19.8 ± 57.6**	13.1 ± 52.9
	ΔP_{REF-C2}, %	2.5 ± 13.2	2.6 ± 11.9	3.9 ± 15.0**	2.8 ± 11.3
$Strokes_{6-50}$	ΔP_{REF-C2}, W	3.1 ± 36.2	2.4 ± 22.3	9.8 ± 35.9**	1.6 ± 4.4
	ΔP_{REF-C2}, %	0.2 ± 8.2*	0.3 ± 5	1.3 ± 9.4**	0.4 ± 1.0

*Data are arithmetic mean ± standard deviation. ΔP_{REF-C2}: differences in mechanical power output between the reference system of a test rig for air braked rowing ergometers (REF) and the Concept 2 Indoor Rower's PM5 monitor (C2); $Strokes_{1-50}$: all strokes are analyzed; $Strokes_{6-50}$: first five strokes are excluded from analysis; ALT and RND indicate regularly and random alternation of stroke force, respectively; HV and LV indicate high regularly and random low alternation of stroke rate, respectively. **indicates highly significant difference to LV ($P < 0.001$). *indicates significant difference to RND ($P < 0.05$).*

strokes (i.e., $strokes_{1-50}$) but also exclusively for strokes 6–50 (i.e. exclusion of start strokes; $strokes_{6-50}$). For $strokes_{6-50}$, the same mixed model approach described above was applied.

Due to the impact of the start strokes, these were also excluded for the Bland-Altman plots (Bland and Altman, 1986), in order to analyze bias and limits of agreement (i.e., random error) without the influence of the starting strokes. If ΔP_{REF-C2} indicated a magnitude dependence, the Bland-Altman plots were modified with linear regression analysis and regression based limits of agreement (LoA), as suggested by Bland and Altman (Bland and Altman, 1999).

RESULTS

Impact of Shape and Stroke Rate During Steady Rowing

Tables 1, **3** indicate that different shapes did not lead to significant differences of ΔP_{REF-C2} ($P = 0.153$). Differences ranged 12.9–13.9 W (2.9–3.1%) for front, mid, and end emphasized stroke shapes.

On the other hand, differences ranged 15.1–15.6 W (4.3–3.6%) for the four different stroke rates, where a longer duration of the recovery phase for a given drive phase was associated with highly significant differences of ΔP_{REF-C2} ($P < 0.001$). The different drive:recovery ratios (i.e., different stroke frequencies) had a medium or large effect on ΔP_{REF-C2} for $strokes_{1-50}$ and $strokes_{6-50}$. In addition, a large interaction effect was found when all strokes were included. I.e., the stroke rates ranging between 22 and 28 min^{-1} were associated with different ΔP_{REF-C2}, noteworthy for absolute and percentage differences ($P < 0.001$). It is worth mentioning that also the analysis without starting strokes was associated with a large (albeit not significant) interaction effect for stroke rate ($P = 0.23$). Accordingly, **Figure 2A** indicates almost no visible differences between stroke shapes, but **Figure 2B** clearly shows larger differences to zero and larger differences between strokes caused by manipulations of stroke rate.

Impact of Force and Stroke Rate Alterations During Non-steady Rowing

The results of the unsteady rowing experiments (iii)–(iv) are shown in **Table 2**. For continued systematic or random alterations in force generation (i.e., $UNSTEADY_{FORCE}$), the mean differences of the mechanical power output ranged 12.7–13.7 W (2.5–2.6%), i.e., systematic and random alterations had a similar, not significantly different effect on P_{REF-C2}. High or low variations of the stroke rate ($UNSTEADY_{RATE}$), in contrast, caused significant differences of 19.8 W (3.9%) or 13.1 W (2.8%).

TABLE 3 | *P*-values and effect sizes for fixed effects (stroke, type and the interaction of stroke*type) of differences in mechanical power output between the reference system of a test rig for air-braked rowing ergometers and the Concept 2 Indoor Rower's PM5 Monitor within steady and unsteady experiments.

Effect	i. $STEADY_{SHAPE}$		ii. $STEADY_{RATE}$		iii. $UNSTEADY_{FORCE}$		iv. $UNSTEADY_{RATE}$	
	P	η^2	P	η^2	P	η^2	P	η^2
$Strokes_{1-50}$	<0.001	0.98	<0.001	0.99	<0.001	0.99	<0.001	0.97
$Type_{1-50}$	0.1534	0.00	<0.001	0.11	0.6331	0.00	<0.001	0.07
$Strokes_{1-50}$*Type	0.6053	0.07	<0.001	0.80	<0.001	0.95	<0.001	0.83
$Strokes_{6-50}$	<0.001	0.16	<0.001	0.53	<0.001	0.97	<0.001	0.84
$Type_{6-50}$	0.0609	0.00	<0.001	0.32	0.0204	0.02	<0.001	0.06
$Strokes_{6-50}$*Type	0.2541	0.08	0.2311	0.46	<0.001	0.97	<0.001	0.84

$Strokes_{1-50}$ all strokes are analyzed; $Strokes_{6-50}$ first five strokes are excluded from analysis; $STEADY_{SHAPE}$: P-Values and effect sizes for fixed effects between front-, mid- and end-emphasized stroke shapes; $STEADY_{RATE}$: P-Values and effect sizes for fixed effects between stroke rates of 22, 24, 26 and 28 min^{-1}. $UNSTEADY_{FORCE}$: P-Values and effect sizes for fixed effects between regularly high and randomly low alternation in stroke force. $UNSTEADY_{RATE}$: P-values and effect sizes for fixed effects between high regularly and low randomly alternation in stroke rate; significance level was set to $P < 0.05$.

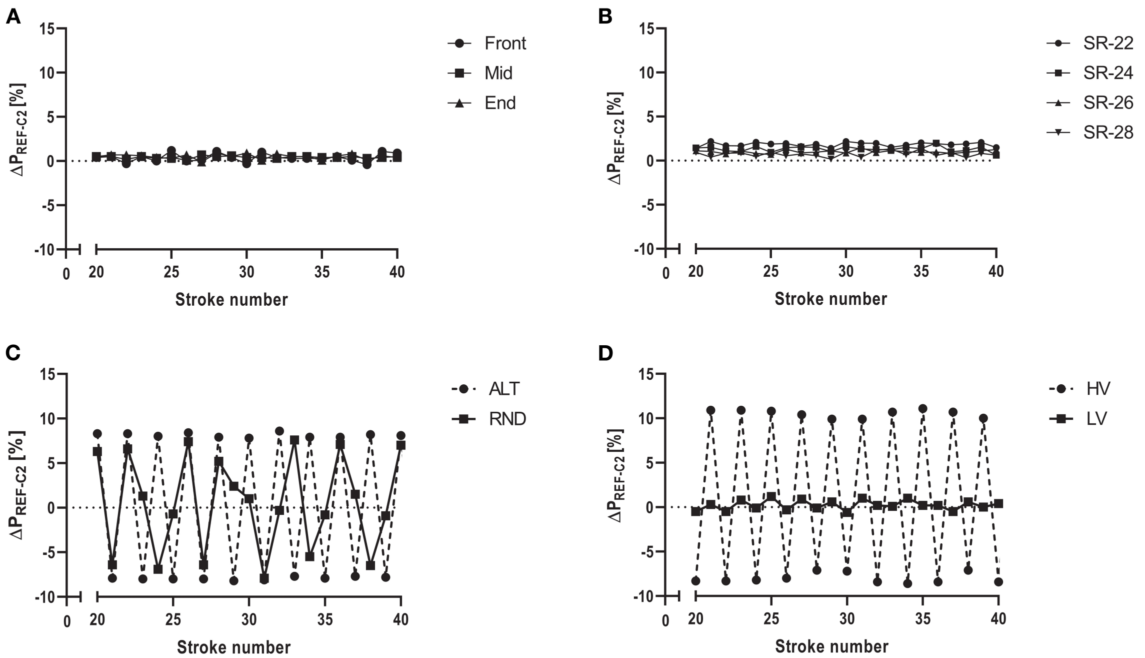

FIGURE 2 | Differences in mechanical power output between the reference system of a test rig for air-braked rowing ergometers and the Concept 2 Indoor Rower's PM5 Monitor (ΔP_{REF-C2} [%]). **(A–D)** show arithmetic mean of 10 repeated measurement series for strokes 20–40 **(A)** Different stroke shapes, i.e., front-, mid- and end-emphasized strokes during steady rowing. **(B)** Four different stroke rates, corresponding to 22, 24, 26, and 28 min^{-1} during steady rowing. **(C)** Persistent variations in stroke force within the measurement series either by regular (ALT) or random (RND) alterations causing unsteady rowing. **(D)** Persistent regular or random variations in stroke rate within measurement series causing either high (HV) or low variations (LV).

It is worth mentioning that the interaction effects of the experiments (iii)–(iv) (i.e., those employing unsteady simulated rowing) remained highly significant and were accompanied by (very) large effect sizes even when start strokes were excluded.

Figure 2C illustrates details of continuous alterations of force ($UNSTEADY_{FORCE}$), where ΔP_{REF-C2} ranged from −48.2 W (−12.1%) to 49.4 W (10.6%) during ALT and from −39 W (−9.8%) to 43 W (9.1%) during RND. **Figure 2D** shows details of continuous alterations of stroke rate ($UNSTEADY_{RATE}$), where ΔP_{REF-C2} ranged −25.5 to 45 W (−8 to 11%).

Start Strokes Largely Affect Overall Accuracy

The analysis without starting strokes revealed a substantial reduction of the mean P_{REF-C2} of 81–85% for $STEADY_{SHAPE}$ and 58–71% for $STEADY_{RATE}$, respectively (**Figure 3**; **Table 1**). Exclusion of the starting strokes reduced the difference during persistent alterations of force ($UNSTEADY_{FORCE}$) by 77–81% and by 51–86% when stroke rate was persistently altered ($UNSTEADY_{RATE}$) (**Table 2**).

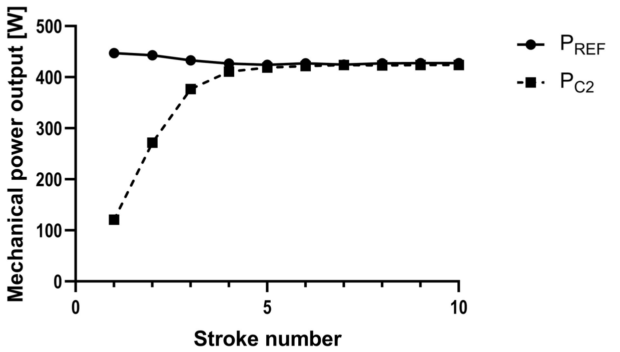

FIGURE 3 | Mechanical power output measured by a reference system of a test rig (P_{REF}) and calculated by the Concept 2 Indoor Rower's PM5 Monitor (P_{C2}) for the starting strokes (1–10), when the flywheel is accelerated from standstill. Exemplary data from one measurement with steady rowing strokes (using mid-emphasized strokes).

The Bland-Altman plots in **Figure 4** (please see **Supplementary Figure 3** for further details) provide an overview of the experiments with out start strokes, that is the "pure" effect of the manipulations. Systematic bias ranged 0.5–1.9% during steady tests (i–ii) with limits of agreement ranging −0.4–2.9%. The bias during unsteady tests (iii–iv) was mostly magnitude-dependent and limits of agreement ranged −27.5 to 23.3%, depending on the particular experiment and mechanical power output.

DISCUSSION

The results of this study indicate that the measurement error of the C2 ranges 2.5–4.3% during 50-stroke measurement series, depending on alterations of stroke rate and force, while manipulations of the stroke shape revealed a minor influence. In addition, we found a large underestimation of mechanical power output within the first five strokes when the flywheel was accelerated from standstill. If these strokes were excluded, the error range was reduced to 0.2–1.9%. The random error of measurement increased considerably during unsteady simulated rowing, augmenting the measurement error by up to ∼10% for a single stroke. This caused an obvious magnitude dependence of P_{REF-C2}.

Inconsistency Is Linked to Inaccuracy

With very steady rowing strokes within the measurement series (i.e., during $STEADY_{SHAPE}$ and $STEADY_{RATE}$), inaccuracy of the C2 ranged 2.9–3.1% for differently shaped strokes and 3.6–4.3% for different stroke frequencies. Noteworthy, inaccuracy was markedly reduced (up to 6-fold) when ignoring the starting strokes. At the same time, the magnitude of these errors, the narrow limits of agreement as well as their direction (**Figure 4**) indicate a moderate and systematic error [i.e., consistent bias or offset of the data read from the ergometer (Paton and Hopkins, 2001)] for the stroke shapes, with limits of agreement ranging −0.4–1.4%. The higher errors found for the manipulation of stroke rate reduced gradually (4.3→3.6%) from longer to shorter recovery phases, i.e., the closer the drive:recovery ratio approximated 1, the smaller the error became.

During unsteady rowing, the errors from stroke to stroke were markedly amplified (**Figures 2C,D**; **Table 2**), but the mean P_{REF-C2} was similar compared to steady rowing tests as long as alterations were not extreme. Noteworthy, the random error [i.e., noise, fluctuations around constant bias (Paton and Hopkins, 2001)] increased considerably in each unsteady rowing experiment, as indicated by the very high standard deviations (**Table 2**) and considerably wider limits of agreement (**Figure 4**). In addition, and in contrast to the evenly applied strokes, this error was magnitude dependent. That was the case both with changing stroke force and with large variations in stroke rate (**Figures 4E–H**).

When the fluctuations in stroke rate increased (i.e., experiment $UNSTEADY_{RATE}$ with high variation) an augmentation of the mean difference from 13.1 to 19.8 W ($P < 0.001$, **Table 2**) occurred. Hence, the in accuracy of the C2 ergometer is positively associated with stroke to stroke inconsistency. Boyas and colleagues already reported in 2006 a higher accuracy of the C2 in trained rowers (Boyas et al., 2006), who performed with a higher stroke to stroke "consistency" than untrained rowers (Smith and Spinks, 1995). Our results add the information that inconsistency in the drive:recovery ratio has a higher impact in accuracy than variations in stroke force and they also demonstrate a magnitude dependence associated with inconsistency.

The highest degree of inconsistency during all our experiments was observed during the start strokes (**Figure 3**). Consequently, the exclusion of the first five strokes reduced the mean error substantially, from 2.9–4.3% to 0.5–1.9% during steady simulated rowing experiments and to 0.2–1.3% during unsteady rowing.

Vice versa, the positive association between consistency and accuracy of the power calculation also became evident in the C2's relatively small underestimation of the mechanical power output of only ∼13–17 W found in our study during steady simulated rowing. This range is considerably smaller than 14–25 W reported previously in human rowers (Lormes et al., 1993; Boyas et al., 2006). The main reason is likely that our test rig's reliability is much higher than human reliability. The rig has a coefficient of variation of ∼0.75% (Mentz et al., 2020), which is much lower (i.e., higher reliability) than variations of 4–5% obtained in elite rowers (Mentz et al., 2018; Treff et al., 2018a) during steady rowing tests. Of note, when the first five strokes were excluded, the mean difference was markedly reduced to 2–7 W, indicating a huge impact of the first five strokes on the mean of a measurements series as long as 50 strokes.

Underlying Mechanisms

Based on the present data, inaccuracy of the C2 is associated with inconsistency in stroke rate and stroke force. This result is attributable to the measurement principle of the C2 where angular velocity (ω) is the only variable directly measured. This measure also provides the basis for the definition of drive and recovery and therefore each rowing cycle duration. Mechanical

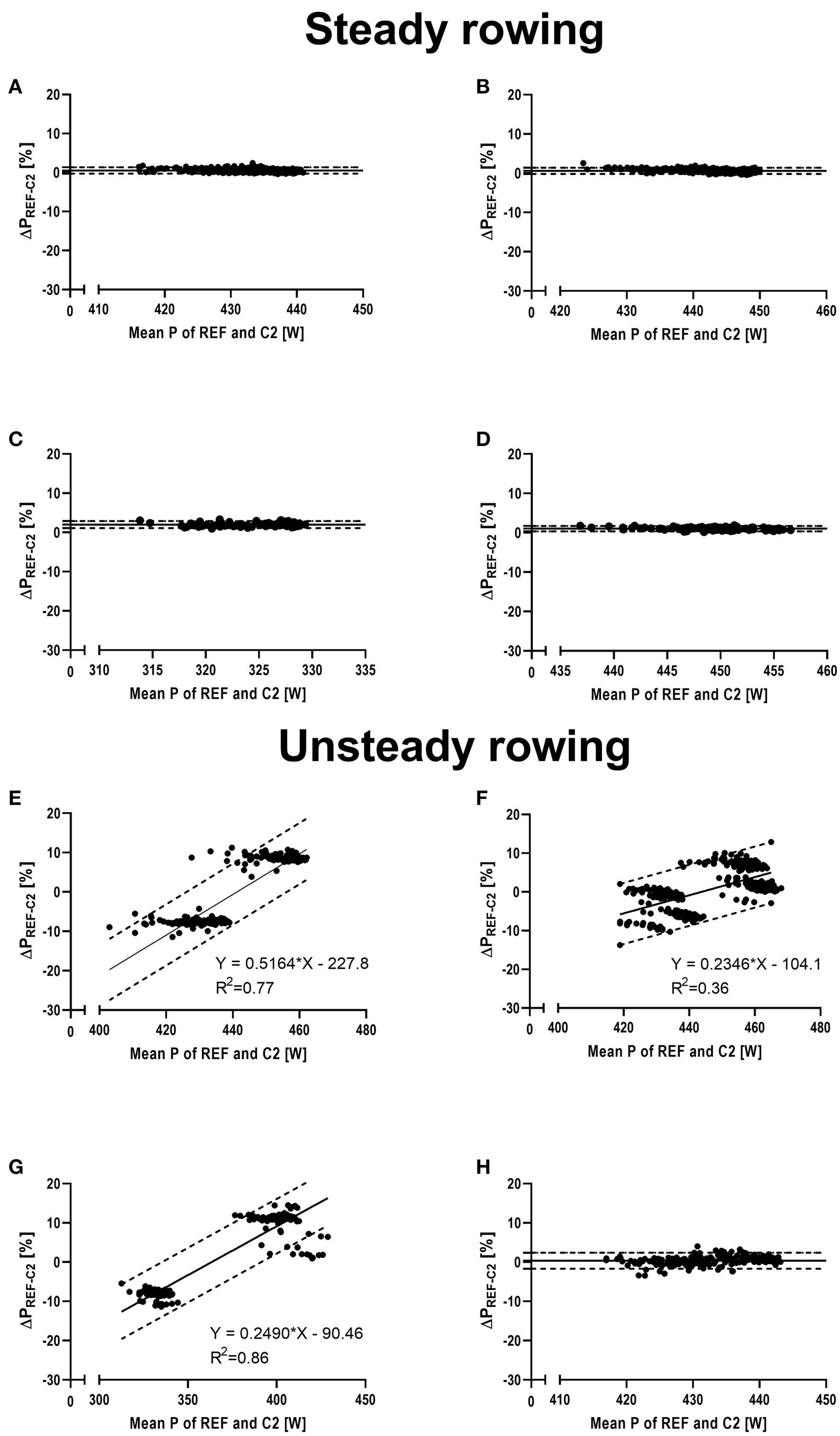

FIGURE 4 | Bland-Altman plots visualizing the percentage differences in mechanical power output between the reference system of a test rig for air-braked rowing ergometers and the Concept 2 Indoor Rower's PM5 Monitor, shown on the y-axis (ΔP [%]). The x-axis shows the mean mechanical power output (P) of both measurement systems. Solid line indicates mean difference and broken dotted lines indicate 95% limits of agreement or, in case of magnitude dependent differences, linear regression analysis and regression-based limits of agreement, respectively. **(A)** Steady rowing with mid-emphasized strokes (mid); **(B)** steady rowing with end-emphasized strokes (end); **(C)** steady rowing with a stroke rate of 22 min^{-1} (SR-22); **(D)** steady rowing with a stroke rate of 28 min^{-1} (SR-28); **(E)** unsteady rowing with high regularly alternating stroke force (ALT); **(F)** unsteady rowing with low randomly alternating stroke force (RND); **(G)** unsteady rowing with high regularly alternations in stroke rate (HV); **(H)** unsteady rowing with low randomly alternations in stroke rate (LV).

power is then calculated by including the so-called drag factor that describes the difference of deceleration and acceleration of the previous rowing cycle and is used as an approximation for the current drive (Van Holst, 2014). This calculation differs substantially from the REF system, which employs a force and displacement sensor to measure all the variables included in the physical definition of mechanical power directly, namely stroke *work* (i.e., *force* times *displacement)* per *time*. In other words, the REF system measures the mechanical power applied to the chain by the rower, whereas the C2 measures the impact of the rower's power output on the behavior of the flywheel. It is noteworthy that both approaches ignore the work of the rower during the recovery phase, when no force is applied to the handle and thus no acceleration of the flywheel occurs (Lindenthaler et al., 2018).

The particularly extreme behavior of the flywheel during the starting strokes allows to gain deeper understanding of our results: Since there is no previous recovery period and therefore no drag factor at stroke #1, the PM5 assumes a default value, which likely contributes to the relatively high error. Furthermore, the first few strokes are different from the subsequent ones, because the flywheel has to be accelerated from standstill. Such acceleration of the mass requires a relatively high amount of energy and a considerable amount of this energy is stored in the flywheel, which therefore continues to rotate even if the rower does not pull the handle while moving himself forward on the ergometer. Of note, this energy is not captured by the PM5. Finally, the difference between acceleration and deceleration is higher the first strokes than between subsequent ones. This causes the substantial underestimation of P_{C2} during the start (personal communication with Peter Dreissigacker, CEO Concept 2) and also supports the results of our study and especially the higher differences observed during unsteady rowing.

The stroke shape does obviously not influence the ratio of acceleration and deceleration substantially ($STEADY_{SHAPE}$ **Table 1**; **Figures 2A**, **4A,B**) and therefore the effect of the different shapes on ΔP_{REF-C2} is small. But, similar to the start strokes, the C2 underestimates mechanical power output when the deceleration is high relative to the acceleration, which is the case when recovery phases are relatively long during steady rowing ($STEADY_{RATE}$), This causes a strong decrease of rotational velocity during the recovery phase. Consequently, ΔP_{REF-C2} is high when the drive:recovery ratio is low (e.g., 0.69, stroke rate 22 min^{-1}) and decreases when the ratio approaches 1 (stroke rate 28 min^{-1}). The same effect and additional fluctuations of the flywheel's deceleration and acceleration between consecutive strokes during unsteady rowing in experiments iii and iv demonstrate an extreme miscalculation (**Figures 2C,D**) on a stroke to stroke level, which, however, almost balances out on average.

It is noteworthy, that the C2 aims to mirror the relationship between mechanical power output and boat speed (personal communication with Peter Dreissigacker, CEO Concept 2). At the start of a race the rower generates substantial power to accelerate the boat from standstill, but the boat speed is relatively low, because of the inertia due to the boat's and the rower's mass and due to the resistance of the water. The same occurs in the C2 that directly links power to pace and therefore estimates a low speed as a consequence of the huge underestimation of the first strokes. So, in this context, a weakness turns out to be a strength, because if mechanical power output was calculated "correctly" (i.e., *work* per *time*), the high mechanical power output at the start would result in an implausible high speed.

Practical Implications

Our results suggest that rowing as evenly as possible in regard to stroke force and stroke rate will result in less underestimation and thus "better" results on the C2 for a given mechanical power output. This is the case when rowing with high stroke rates and might partly explain—beside dominating biomechanical and physiological reasons—why many rowers prefer high stroke rates in ergometer competitions, at least according to our own observations. In addition, a high number of strokes also ensures that the underestimation of the starting strokes becomes less influential.

On the other hand, when rowing with low stroke rates during training or testing for basic endurance performance like the 6-km test, different drive:recovery ratios will clearly contribute to differences between or within rowers to a small degree. Based on our results and even when excluding the start strokes, the mean difference of 1.9% declines to 1.4% due to a slight alteration in drive:recovery corresponding to a stroke rate of 22 or $24 \cdot min^{-1}$ for a given drive phase (**Table 1**). Consequently, a pace of e.g., 1:45.0 min 500 m^{-1} (302.3 W) will increase to 1:45.2 min 500 m^{-1} (300.8 W) cumulating to a difference of 2.4 s during over a virtual 6,000 m distance (i.e., from 21:00.0 min to 21:02.4 min)—notably for the identical drive phase. When testing performance at low stroke rates, we therefore recommend to keep drag factor and stroke rate fixed between tests and between rowers. However, the modification of the C2 with an external reference system would be ideal (Treff et al., 2018b).

Due to the huge underestimation of the first strokes such a reference system seems to be indispensable when aiming to capture start strokes or conducting tests of short duration (e.g., 20-s all out testing). Noteworthy, it is likely that such tests will become more relevant with the possible shortening of the race distance to 1,500 m at the 2028 Olympic Games. Likewise, such a reference system is appropriate whenever the recording of physically exact performance is necessary in scientific contexts. Finally, we recommend paying close attention to always stopping the flywheel before ergometer performance tests to avoid further inaccuracies.

Limitations

Our study has some limitations worth mentioning. First of all, even though the test rig produces very reliable rowing strokes (CV < 1%), there is still some variability left influencing the results to some extent. In addition, we were not able to generate high stroke frequencies, thereby limiting the transferability of our results for frequencies above ∼33 min^{-1} actually applied in ergometer racing. Finally, we conducted all testing on the same ergometer and it remains unclear to which extent our results can be transferred to other C2 ergometers. This is an area for future research just like the evaluation of other types of ergometers that become increasingly popular.

CONCLUSION

The error of the C2 ranges 2.5–4.3% if all strokes of a 50-stroke series are included, but it is considerably reduced to 0.2–1.9% once the flywheel has been sufficiently accelerated. Uneven rowing is the main reason for increased inaccuracy. Hence, rowers should row as even as possible and prefer higher stroke rates to minimize underestimation of their performance. Since there is currently no option to exclude the enormously underestimated start strokes, the nominal accuracy of the C2 depends on the total number of strokes considered. We recommend to apply external reference systems for scientific and high-performance assessments of rowers, especially for short tests designs where the start strokes have a major impact.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

GT developed the research question and study design, conducted data analysis and interpretation, drafted and revised the manuscript. LM developed the study design, collected the data, analyzed and interpreted the data, drafted and revised the manuscript. BM designed, conducted, and interpreted the statistical analysis. KW analyzed data and reviewed the manuscript. TE developed the research question and study design and supported data collection. JS analyzed and interpreted the data and reviewed the manuscript. All authors have read, approved the final version of the manuscript, and agree with the order of presentation of the authors.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fspor.2021.801617/full#supplementary-material

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ORIGINAL RESEARCH
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The Effect of Hyperoxia on Central and Peripheral Factors of Arm Flexor Muscles Fatigue Following Maximal Ergometer Rowing in Men

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Purpose: This study evaluates the effect of hyperoxia on cerebral oxygenation and neuromuscular fatigue mechanisms of the elbow flexor muscles following ergometer rowing.

Methods: In 11 competitive male rowers (age, 30 ± 4 years), we measured near-infrared spectroscopy determined frontal lobe oxygenation (ScO_2) and transcranial Doppler ultrasound determined middle cerebral artery mean flow velocity (MCA V_{mean}) combined with maximal voluntary force (MVC), peak resting twitch force (P_{tw}) and cortical voluntary activation (VA_{TMS}) of the elbow flexor muscles using electrical motor point and magnetic motor cortex stimulation, respectively, before, during, and immediately after 2,000 m all-out effort on rowing ergometer with normoxia and hyperoxia (30% O_2).

Results: Arterial hemoglobin O_2 saturation was reduced to 92.5 ± 0.2% during exercise with normoxia but maintained at 98.9 ± 0.2% with hyperoxia. The MCA V_{mean} increased by 38% ($p < 0.05$) with hyperoxia, while only marginally increased with normoxia. Similarly, ScO_2 was not affected with hyperoxia but decreased by 7.0 ± 4.8% from rest ($p = 0.04$) with normoxia. The MVC and P_{tw} were reduced (7 ± 3% and 31 ± 9%, respectively, $p = 0.014$), while VA_{TMS} was not affected by the rowing effort in normoxia. With hyperoxia, the deficit in MVC and P_{tw} was attenuated, while VA_{TMS} was unchanged.

Conclusion: These data indicate that even though hyperoxia restores frontal lobe oxygenation the resultant attenuation of arm muscle fatigue following maximal rowing is peripherally rather than centrally mediated.

Keywords: rowing, cerebral oxygenation, hyperoxia, maximal voluntary contraction, transcranial magnetic stimulation

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INTRODUCTION

Maximal rowing provokes disturbance to systemic and intramuscular homeostasis (Volianitis and Secher, 2009; Volianitis et al., 2018) that exacerbates pulmonary diffusion limitations and reduces arterial hemoglobin oxygen saturation (SaO_2) to below 88% (Nielsen et al., 1998). Such pronounced arterial hypoxemia, combined with the hyperventilation-induced reduction in $PaCO_2$ by 8–10 mm Hg (Volianitis et al., 2008) and dependent cerebral blood blow (CBF), compromises oxygen cerebral delivery and reduces cerebral mitochondrial oxygen tension by more than 10 mm Hg (Nybo and Rasmussen, 2007) that can impair motor performance (Rasmussen et al., 2007). Conversely, when cerebral oxygenation is enhanced with oxygen supplementation rowing performance is improved (Nielsen et al., 1999), suggesting that the performance improvement may be attributed to attenuation of "central fatigue" (Gandevia, 2001), that is, enhanced volitional motor output to locomotor muscles (Nybo and Rasmussen, 2007). Alternatively, the ergogenic effect may stem from enhanced force-generating capacity of the exercising muscles due to processes at, or distal to, the neuromuscular junction (i.e., attenuation of "peripheral fatigue"; Allen et al., 2008), secondary to enhanced arterial oxygen content (CaO_2) and hence oxygen delivery to muscles (Amann et al., 2006a). Oxygen supplementation attenuates the rate of development of peripheral fatigue provoked both by high intensity whole body exercise (Amann et al., 2006b; Romer et al., 2006; Dominelli et al., 2017) and isolated muscle exercise (Katayama et al., 2007), indicating that the effect is independent of possible attenuation of fatiguing metabolites, secondary to a hyperoxia-induced increase in maximal exercise capacity and, thus, changes in relative work intensity.

The contribution of both central and peripheral fatigue mechanisms is considered when attempting to explain performance fatigability, albeit implications for performance should be approached with caution, as the translation of fatigue mechanisms to human whole body performance is not straightforward (Enoka and Duchateau, 2016). The contribution of central and peripheral mechanisms to neuromuscular fatigue depends on the tested muscle group (Enoka et al., 2011) as shown for the upper and lower limbs (Vernillo et al., 2018), for example, 2 min MVCs result in central fatigue of the lower limbs, but not of the upper limbs indicating that fatigue mechanisms may be regulated differently and limb specific. The functional significance of such differential contribution of central activation to the force production of different muscle groups can be appreciated with the leg "strength paradox," that is, the strength deficit of a bilateral leg effort, typically 15–20%, compared to the strength expected from the sum of the separate unilateral leg efforts, as observed in rowers (Secher, 1975).

Rowing is unique in using both arms and legs in a synchronous manner (i.e., bilateral leg extension and arm flexion), as opposed to most sports and daily life where the limbs are used alternatively as in, for example, walking and running. The training adaptation of such synchronous movement is reflected in attenuation of the strength deficit of bilateral leg effort in rowers. Indeed, in the very best trained rowers the bilateral leg strength may even surpass the sum of the strength of each leg (Secher, 1975). The comparison between unilateral vs. bilateral leg efforts allows for investigation of differences in muscle mass-related fatigability, as suggested by Rossman et al. (2012) and Koral et al. (2020). In contrast to leg efforts, there is no "strength paradox" when using the arms, that is, the strength measured during simultaneous use of both arms corresponds to the sum of the strength of each arm determined separately (Secher et al., 1988). Taken together, the seemingly differential central motor activation to upper and lower limbs suggests that the legs may be more prone to develop force deficit than the arms in circumstances where central motor activation is challenged, as in maximal rowing. In support, leg strength deficit following maximal rowing has been attributed to supraspinal origin (Husmann et al., 2017). However, data on arm neuromuscular activation following rowing are lacking.

This study evaluated the contribution of central and peripheral factors to elbow flexors fatigue following maximal rowing. Considering the different contribution of centrally and peripherally located fatigue mechanisms of upper and lower limbs (Vernillo et al., 2018), we hypothesized that central factors would be less prevalent compared to peripheral factors in the arms following maximal ergometer rowing. In addition, considering the marked arterial desaturation developed during rowing, a second aim of this study was to evaluate the effect of oxygen supplementation on central vs. peripheral factors of elbow flexor muscle fatigue. A second hypothesis was that oxygen supplementation would attenuate central fatigue by enhancing cerebral oxygenation. Maximal voluntary contraction (MVC), transcranial magnetic stimulation (TMS) of the motor cortex, and electrical stimulation of the motor point (MP) were applied for evaluation of central and peripheral factors of elbow flexor muscles fatigue. Also, CBF, cerebral (ScO_2) and muscle oxygenation (SmO_2) evaluations were applied as factors associated with rowing fatigability.

MATERIALS AND METHODS

Participants

Eleven healthy males (mean ± SD age, 30 ± 4 yrs.; height, 1.80 ± 0.03 m; weight, 75.0 ± 3.1 kg), following written informed consent, volunteered to the study as approved by the Ethics Committee of Copenhagen (KF 01287471) and conformed to the Declaration of Helsinki. Sample size calculation was based on changes in cortical voluntary activation following maximal dynamic exercise (Δ VA_{TMS}, −13%; Rasmussen et al., 2010) and the typical error for the measurement of elbow flexion MVC (ICC, 0.992; Allen et al., 1995) with power of 0.80 and an α of 0.05. All subjects were recruited from a local rowing club and were well familiarized with maximal ergometer rowing as they had been competing for several years at national/international level (one was a current World champion and two others were members of the national team).

Experimental Design

Each subject completed one familiarization and two experimental trials. During the familiarization trial, subjects practiced maximal voluntary isometric elbow flexion with and without TMS and electrical stimulation. "All-out" 2,000 m rowing on a wind-braked ergometer (Concept II, Morrisville, VT, United States) was performed with normoxia [inspiratory O_2 fraction (FIO_2), 0.21] and hyperoxia (FIO_2, 0.30), in a pseudo-randomized counter-balanced order, in two experimental trials separated by 1–2 weeks at the same time of day under consistent laboratory conditions (temperature 22 ± 1°C, humidity 50 ± 10%, barometric pressure 757 ± 4 mmHg). While the conditions were not blinded, the participants were naive to the purpose of the study and unaware of the experimental hypotheses. The subjects refrained from strenuous exercise, alcohol, and caffeine for 24 h prior the investigations and reported to the laboratory after an 8 h overnight fast. On each trial, the subjects rowed for about 20 min on the ergometer with an individually chosen pre-race warm-up that were accustomed. Then, submaximal and maximal contractions (60–100% MVC) were performed to allow estimation of resting twitch for the calculation of VA_{TMS}, and the stimulation intensities for MP and TMS were determined (for details see the Neuromuscular Evaluation section). Then, the subjects performed two 4-s MVCs, separated by 2 min of rest, while still seated on the rowing ergometer. If the difference between these MVCs was >5%, a third MVC was performed. The largest MVC was taken to represent control muscle strength. For all MVCs subjects were encouraged to apply maximal effort and to try to maintain the same intensity throughout the 4-s period. Hyperoxic air was humidified in a Douglas bag and delivered to the subjects through a two-way low-resistance T valve (model 2,700, Hans Rudolph, Kansas City, MO, United States) for 5 min prior to and during rowing. Breath-by-breath O_2 consumption (VO_2) and ventilation (VE) were measured with an online gas analyzer (CPX/D, Medical Graphics, St. Paul, MN, United States) and data averaged over 30 s. During rowing, the subjects were verbally encouraged to perform maximally.

Blood samples were drawn anaerobically from a catheter (20 gauge; 1.1 mm) inserted in the radial artery of the non-dominant arm (left, for all subjects) three times at rest, once after 500, 1,000, 1,500 m of rowing and immediately after exercise in heparinized syringes and analyzed immediately for blood gas variables (ABL 725; Radiometer, Copenhagen, Denmark).

Cerebral Perfusion

Transcranial Doppler ultrasound (2 MHz probe; Multidop X; DWL, Sipplingen, Germany) determined middle cerebral artery mean flow velocity (MCA V_{mean}) as an index of CBF, since changes in MCA V_{mean} reflect those of CBF during dynamic exercise (Secher et al., 2008). The MCA V_{mean} was the mean velocity of the time-averaged maximal velocity over the cardiac cycle derived from the envelope of the maximum frequencies of the Doppler spectra. The MCA was located by insonation through the temporal ultrasound window and the position with the highest signal to noise ratio (depth 48–60 mm) was marked. The probe was fixed to a headband with adhesive sonography gel and data sampled at 100 Hz (Chart v5.2 and PowerLab; ADInstruments, Bella Vista, NSW, Australia).

Cerebral and Muscle Oxygenation

ScO_2 and SmO_2 were evaluated using near-infrared spectroscopy (NIRS; INVOS 5100C, Somanetics, Troy, MI, United States). For ScO_2, the optode (3 and 4 cm emitter detector separation, wavelength 730 and 808 nm) was placed over either the right or left prefrontal cortical area, in randomized order, between Fp1 and F3, or Fp2 and F4, according to the landmarks of the 10–20 system (Perrey, 2008) to avoid influence from the frontal and sagittal sinus and ipsilateral to the Doppler probe. This area of the brain is not directly involved in the neural control of movement, but deoxygenation of the prefrontal cortex has been associated with termination of exercise during both controlled and self-paced exercise (Nielsen et al., 1999; Amann et al., 2007; Seifert et al., 2009; Subudhi et al., 2009).

For SmO_2 the optode was positioned on the vastus lateralis muscle of the left leg at the midpoint between the anterior superior iliac spine and the superior part of the fibula. Hair on the leg was removed for maximal optode contact and the same position of the probe was used in both trials. We considered that reductions in SmO_2 and ScO_2 together with cerebral perfusion would be indicative of peripheral and central fatigue, respectively.

Neuromuscular Evaluation

Neuromuscular evaluation was performed after the warm-up and immediately after the rowing trials (**Figure 1**). The transition time from the end of the rowing to the start of the neuromuscular evaluation was less than 10 s. It was important to minimize this transition time because neuromuscular fatigue is strongly influenced by recovery, as all parameters recover almost linearly within 1 min (Vernillo et al., 2018). With this consideration, the subjects' right arm was swiftly attached to a custom designed arm-bar equipped with a calibrated strain gauge dynamometer (14-bit A/D conversion) while they were still seated on the ergometer. The shoulder and elbow of the subjects were flexed at 90° with the forearm vertical and fully supinated. The dynamometer's position was adjusted in direct line with the applied force and secured at the wrist. The neuromuscular evaluation included two 4-s MVCs for determination of (averaged) elbow flexors strength, with one TMS and one motor point (MP) stimulation superimposed on each MVC, followed by another resting MP stimulation 2 s after each MVC to obtain peak potentiated twitch force (P_{tw}). Electromyographic (EMG) activity was recorded with pairs of self-adhesive surface (10-mm recording diameter) electrodes (Cleartrace, 1700-030, Conmed, Utica, NY, United States) placed over the muscle belly and tendons of biceps brachii, brachioradialis, and long head of triceps brachii muscles, in bipolar configuration with a 30-mm interelectrode distance and the reference on the medial epicondyle of the humerus. Low impedance (<5 kΩ, controlled by a digital meter) between electrodes was achieved by shaving and gently abrading the skin and then cleaning it with isopropyl alcohol. The positions of EMG electrodes were marked with indelible ink to ensure consistent placement. The EMG signal was amplified (×1,000), filtered (25–1,000 Hz), digitized, and sampled (at 5 kHz) to a computer using CED Micro1401 and Spike2 software (Cambridge Electronic Design, Cambridge, United Kingdom). The EMG activity was quantified as the

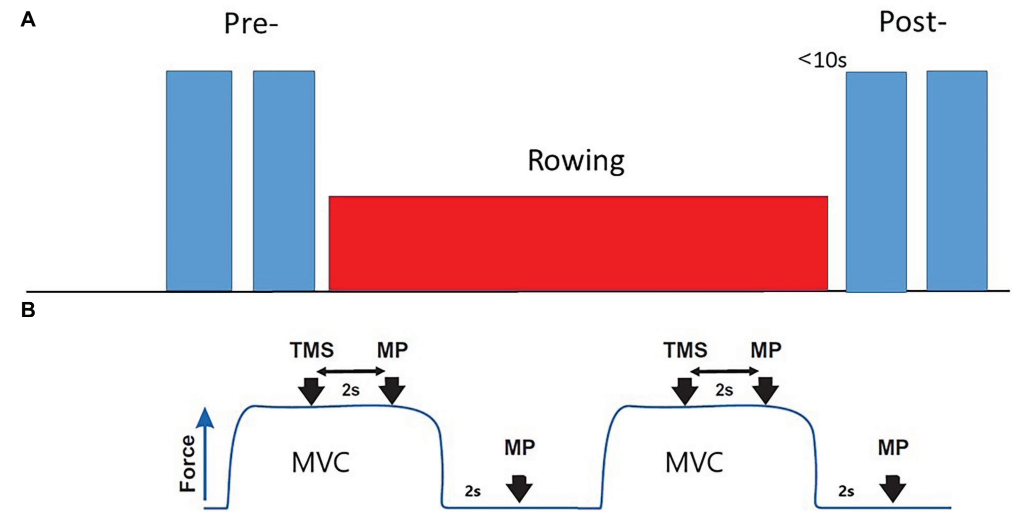

FIGURE 1 | Neuromuscular evaluation protocol. **(A)** Pre- baseline evaluation; Post-, After rowing (less than 10 s) evaluation. **(B)** Each evaluation included two 4 s MVCs. One TMS and one MP stimulation, interspersed by 2 s, followed by a resting MP stimulation 2 s after the end of contraction, were applied with each MVC.

root-mean-square value and expressed relative to the activity obtained during the control MVC.

Brachial Plexus Stimulation

Before the voluntary contractions, the size of the resting maximal compound muscle action potential (Mmax) was determined with surface EMG and used as a reference for the size of the EMG responses evoked by TMS. While the subjects were at rest single electrical stimuli of 100-μs duration were delivered to the brachial plexus *via* a cathode in the supraclavicular fossa (Erb's point) and an anode on the acromion. The electrical current was gradually increased until the M-wave (i.e., Mmax) of the biceps brachii no longer increased. A supramaximal stimulation current (i.e., 20% higher than that required to elicit Mmax) was used for the remainder of the experiment. The supramaximal stimulus intensitys was 136 ± 52 mA.

Transcranial Magnetic Stimulation

Single magnetic pulses to the motor cortex were delivered with a circular coil (13.5 cm outside diameter; Magstim 200, The Magstim Co. Ltd., Whitland, Wales, United Kingdom) with its center placed at the vertex, and thus evoked motor potentials (MEPs) in the biceps brachii. The vertex was determined by marking the intersection of the measured halfway points from nasion to inion and from tragus to tragus. The optimal coil position was the site where the largest MEP was elicited, and it was marked on the scalp for consistent positioning throughout the protocol. The direction of the current flow in the coil was clockwise on the left motor cortex (postero-anterior intracranial current flow) to activate preferentially the muscles on the contralateral side. The TMS intensity was determined from a stimulus–response curve constituted of four brief consecutive contractions at 50, 60, 70, and 80% maximal stimulator output, in randomized order. The selected stimulus intensity was the lowest intensity eliciting maximal MEP amplitudes (>50% Mmax) in m. biceps brachii (with little or no response, usually <10–15% of Mmax, in the antagonist m. triceps brachii) during brief voluntary contractions at 20% MVC. The TMS was always delivered once the voluntary contraction reached the intended force level and the force had stabilized.

Electrical Stimulation

For electrical stimulation of the biceps muscle, surface electrodes (Cleartrace, Conmed) were placed on each of the MPs approximately halfway from the coracoid process to the lateral epicondyle of the humerus (Park et al., 2007). A computer triggered a double 1 ms electrical stimulus at constant current (inter-stimuli interval: 10 ms, DS7A Digitimer, Hertfordshire, United Kingdom). The maximal resting twitch was determined by stepwise increases in the stimulus intensity until elbow flexor twitch force failed to increase, despite an increase in stimulus intensity. Stimulation intensity was set 10–20% above the level required to produce a resting twitch of maximal amplitude and it was 122 ± 32 mA.

Cortical Voluntary Activation (VA_{TMS})

Cortical voluntary activation was quantified by the force responses. Using magnetic cortical stimulation any increment in elbow flexion force evoked during an MVC (superimposed twitch) was expressed as a fraction of the amplitude of the maximal response evoked by the same stimulus in the relaxed muscle. The resting twitch was estimated by linear interpolation of the TMS induced muscle twitches obtained at 60, 80, and 100% of MVC and was identified as the y-intercept of the regression corresponding to the value at which voluntary force would be zero (**Figure 2**; Todd et al., 2003):

$$\text{Voluntary activation}(\%) = \left(\frac{1-\text{superimposed twitch}}{\text{estimated resting twitch}}\right) \times 100$$

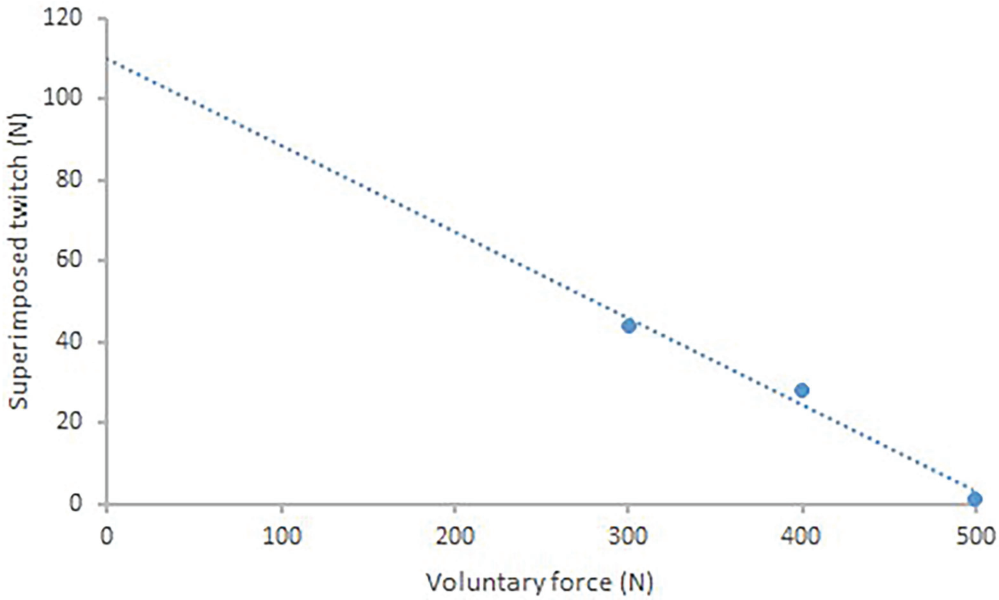

FIGURE 2 | Single subject data showing linear regression between the amplitude of the TMS superimposed twitch and voluntary force ($r = 0.99$). The *y*-intercept (114.5N) is taken as the estimated amplitude of the resting twitch.

TABLE 1 | Cerebral, cardiovascular, and respiratory variables at rest and over the last 30s of rowing with normal and hyperoxic air.

	21% O_2		30% O_2	
	Rest	**Rowing**	**Rest**	**Rowing**
HR, beats min^{-1}	71 ± 5	181 ± 2*	68 ± 2	178 ± 2*
MAP, mmHg	96 ± 2	104 ± 4*	94 ± 2	109 ± 3*
VE, L min^{-1}	13 ± 1	168 ± 3*	13 ± 1	172 ± 5*
VO_2, L min^{-1}	0.4 ± 0.0	4.7 ± 0.2*	0.4 ± 0.0	5.2 ± 0.2*
PaO_2, mmHg	103 ± 2	94 ± 2*	164 ± 3	161 ± 5†
$PaCO_2$, mmHg	39 ± 1	29 ± 1*	39 ± 1	31 ± 1*
SaO_2, %	98.3 ± 0.2	92.5 ± 0.2*	99.4 ± 0.1	98.9 ± 0.2†
MCA V_{mean}, cm s^{-1}	52.3 ± 8.2	54.7 ± 7.6	44.7 ± 4.0	61.7 ± 7.7*†
ScO_2, %	67.3 ± 8.2	60.3 ± 5.4*	66.6 ± 3.6	67.7 ± 5.4†
SmO_2, %	63.5 ± 7.3	41.2 ± 2.0*	64.9 ± 3.6	48.0 ± 3.4*†

*HR, heart rate; MAP, mean arterial pressure; VE, ventilation; VO_2, oxygen uptake; PaO_2, arterial oxygen tension; $PaCO_2$, arterial carbon dioxide tension; MCA V_{mean}, middle cerebral artery mean blood flow velocity; SaO_2, arterial oxygen saturation; ScO_2 frontal lobe oxygen saturation; SmO_2, oxygenation of the vastus lateralis muscle; Values are mean ± SD, N = 11. *Difference compared with rest. †Difference compared with normoxia ($p < 0.05$).*

Data points were excluded ($n = 5.4\%$) when the regression of the estimated twitch was $r^2 < 0.85$.

The reliability of the TMS protocol for the determination of voluntary activation and estimated resting twitch (ICC < 0.85) is comparable to values derived from motor nerve stimulation (Sidhu et al., 2009).

Statistics

Assumptions of sphericity (Mauchly test) and normality (Shapiro–Wilk test) were tested for all dependent variables. If the assumption of sphericity was violated, the corrected value for non-sphericity with Greenhouse–Geisser epsilon was reported. Values are presented as mean ± SD.

A two-way analysis of variance (ANOVA) with repeated measures (time × trial) was used to reveal significant interactions between conditions and the Tukey *post hoc* test for paired data was used to locate differences. F-ratios were considered statistically significant at $p < 0.05$ level and analysis was performed using SPSS Statistics 24 (IBM, Armonk, NY, United States). Descriptive statistics in the text include mean percentage change for each dependent variable, while the reported *p* values are based on statistical comparison using absolute values.

RESULTS

In normoxia, the subjects completed the ergometer row in 6 min 56 ± 5 s and hyperoxia had no significant effect compared to normoxia (6 min 54 ± 4 s, 0.5% improvement). Yet, VO_2 was 10.6% higher during the hyperoxic compared with the normoxic trial ($p < 0.01$, **Table 1**). Also, the reduction of SaO_2 observed during the normoxic trial was prevented during the hyperoxic trial ($p < 0.01$, **Table 1**).

Cerebrovascular Variables

There was a significant interaction [$F_{(1, 12)} = 5.9$, $p < 0.01$] between trials and time for MCA V_{mean} and ScO_2. During the normoxic trial MCA V_{mean}, after a 4.6% increase by 1,000 m, plateaued until the end of the trial and returned to baseline after exercise (**Figure 3; Table 1**). During the hyperoxic trial, MCA V_{mean} increased from rest until 1,500 m of rowing (38% higher, $p < 0.01$), then plateaued until the end and also returned to resting level after exercise.

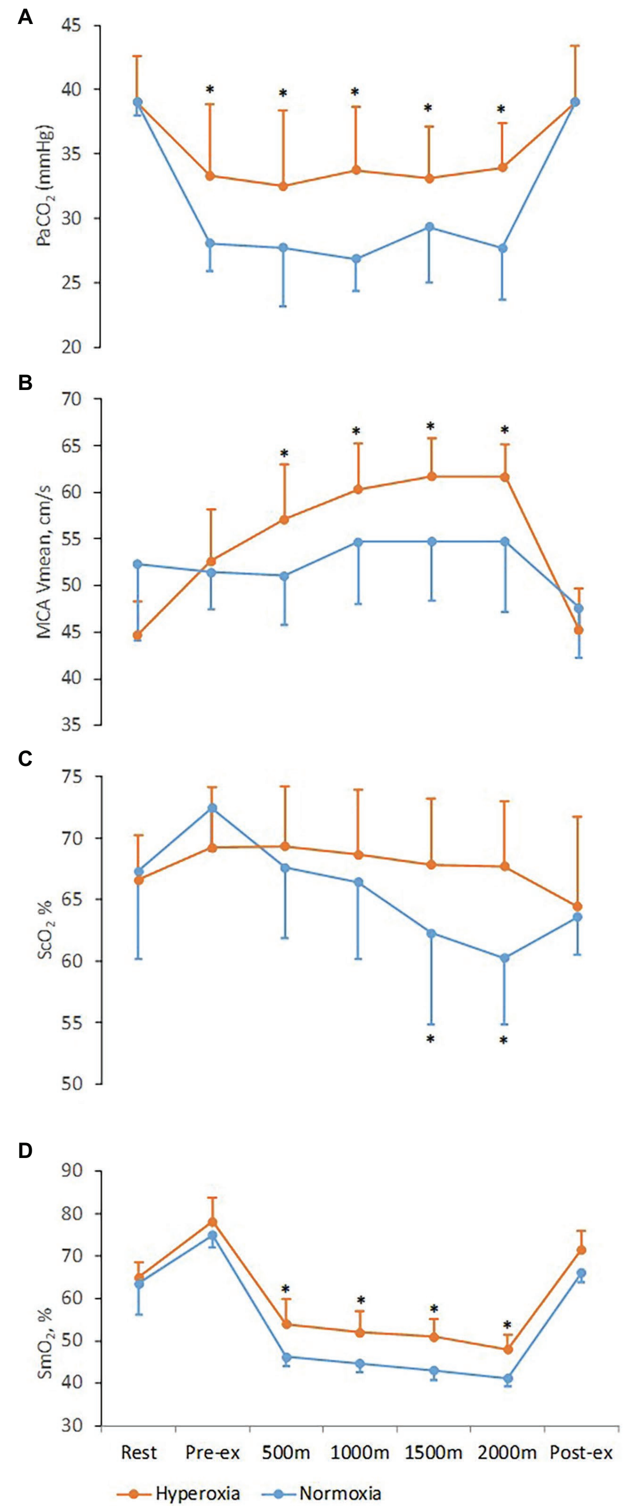

FIGURE 3 | Respiratory, cerebrovascular, and muscle variables at rest and during 2,000 m all-out ergometer rowing with normoxia and hyperoxia. Pre-ex and post-ex values are obtained after the warm-up and 15 min into the recovery, respectively. **(A)** $PaCO_2$, arterial carbon dioxide tension; **(B)** MCA V_{mean}, middle cerebral artery mean blood flow velocity; **(C)** ScO_2, frontal lobe oxygen saturation; **(D)** SmO_2, oxygenation of the vastus lateralis muscle. Values are means ± SD; *Difference between normoxic and hyperoxic trials ($N = 11$, $p < 0.05$).

The ScO_2 decreased by 7.0 ± 4.8% ($p < 0.01$) during the normoxic trial, while it was maintained at resting level during the hyperoxic trial (**Figure 3; Table 1**).

Muscle Oxygenation

There was interaction [$F_{(1, 12)} = 5.4$, $p < 0.01$] between trials and time for SmO_2. During the normoxic trial, SmO_2 was reduced by 26.9 ± 2.8% by the first 500 m compared to rest ($p < 0.001$) and then continued to a nadir of 35.0 ± 2.1% decrease at the end of the row ($p < 0.01$). During the hyperoxic trial, the reduction in SmO_2 was attenuated to 16.8 ± 3.0% ($p < 0.01$) by the first 500 m and to a nadir of 26.1 ± 2.4% ($p < 0.01$) compared to rest at the end of the 2,000 m row (**Figure 3**; **Table 1**), indicating a ~ 25% improvement of SmO_2 compared to the normoxic trial ($p = 0.03$).

Neuromuscular Function

There was no significant difference in the MVC prior to the normoxic and hyperoxic trials (502 ± 15 N). There was an interaction [$F_{(1, 6)} = 6.9$, $p < 0.01$] between trials and time for MVC. Following the normoxic trial, there was a reduction in MVC during elbow flexion (7 ± 3%, $p = 0.014$) but following the hyperoxic trial the reduction was not significant (4 ± 3%, $p = 0.06$, **Figure 4A**).

Electrical Stimulation

There was an interaction [$F_{(1, 2)} = 19.9$, $p < 0.01$] between trials and time for (P_{tw}). The force evoked with direct stimulation of the motor point (P_{tw}) in biceps brachii at rest immediately after MVC was reduced by 31 ± 9% following the normoxic rowing trial (pre: 140 ± 14 N; post: 95 ± 12 N, $p = 0.005$, **Figure 4B**). In contrast, after the hyperoxic rowing trial, there was only a ~ 13 ± 4% reduction from the resting value in P_{tw} (pre: 148 ± 14 N; post: 128 ± 12 N) that was not statistically significant [$F_{(1, 6)} = 1.2$, $p = 0.21$] and indicative of ~58% attenuation of the deficit observed in the normoxic trial ($p < 0.05$). P_{tw} values before the normoxic and hyperoxic trials were similar ($p = 0.52$).

Transcranial Magnetic Stimulation

The additional force evoked with superimposed twitch on MVC was not different after rowing in normoxia. Similarly, the size of the superimposed twitch was not different before and after rowing in hyperoxia. VA_{TMS} was not changed after the normoxic trial [pre- 99.0 ± 1.3%; post- 98.6 ± 1.4%; $F_{(1, 6)} = 1.6$, $p = 0.84$] or the hyperoxic trial (pre 98.0 ± 1.0%; post 98.5 ± 1.2%, $p = 0.88$, **Figure 4C**).

DISCUSSION

This study evaluated the effect of oxygen supplementation on central and peripheral fatigue of elbow flexor muscles following maximal ergometer rowing in trained male rowers. Maximal rowing in normoxia compromised cerebral and leg muscle oxygenation and reduced arm strength that was associated with reduced force generated with direct electrical

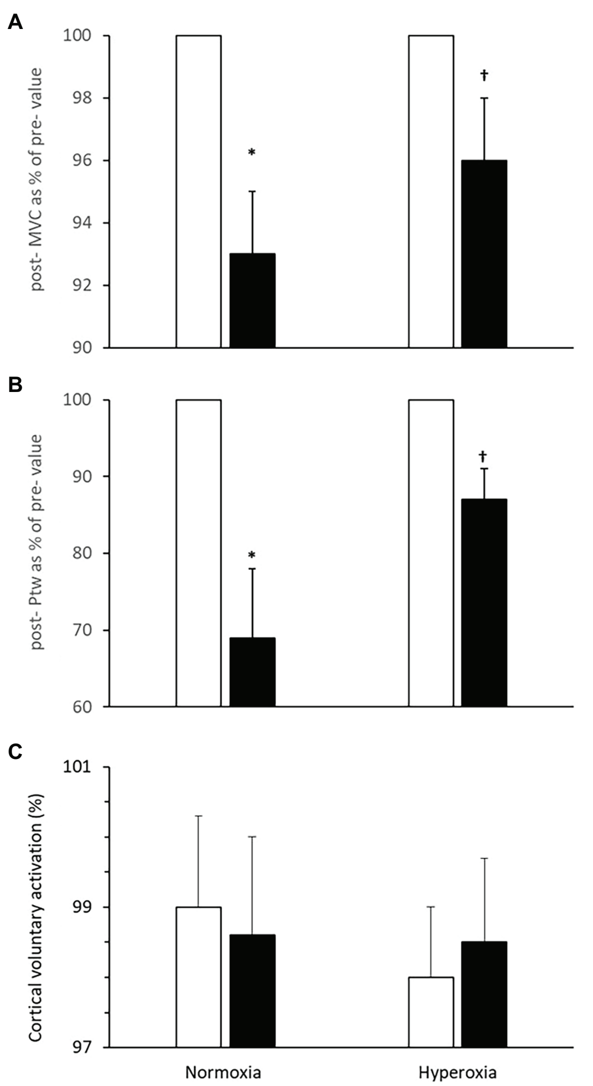

FIGURE 4 | Neuromuscular function pre- (open bars) and immediately post- (closed bars) 2,000 m all-out rowing. **(A)** Maximal voluntary contraction (MVC) of the arm flexor muscles; **(B)** potentiated twitch force (P_{tw}); and **(C)** cortical voluntary activation. Values are means ± SD, post-values in **(A,B)** are expressed as % of pre-values; *Different from pre-value; †Different from respective value in normoxia ($N = 11$, $p < 0.05$).

stimulation but unaltered force generated with transcranial magnetic stimulation. Supplementation with 30% oxygen in inspired air enhanced arterial oxygen delivery, maintained cerebral oxygenation at resting level and attenuated leg muscle deoxygenation. In addition, hyperoxia attenuated the deficit in arm flexion MVC and force produced with direct electrical stimulation following the normoxic trial, while there was no effect on the force produced with transcranial magnetic stimulation. These findings demonstrate that oxygen supplementation restores cerebral oxygenation and that the attenuation of the arm strength deficit following maximal rowing is associated with peripheral rather than central fatigue mechanisms.

The present finding that arm muscle fatigue following rowing is mainly of peripheral origin is in contrast with the study by Husmann et al. (2017) that evaluated the knee extensors fatigue in elite rowers after intense rowing. Even though Husmann et al. (2017) used peripheral nerve stimulation to assess central fatigue, which provides different information from the cortical stimulation used in the present study (Todd et al., 2004), nevertheless, both methods assess whether the voluntary drive to the muscle is suboptimal for generation of maximal force. Husmann et al. (2017) observed impaired voluntary drive indicating central fatigue with no significant change in indices of peripheral fatigue. A possible explanation for this discrepancy may be offered by the unique synchronous movement pattern of the limbs during rowing. It seems that there is a central constraint that prevents recruitment of the leg muscles during the two-legged exercise inherent to rowing, while the arm muscles are not constrained by such central activation mechanism, and thus, arm muscle fatigue is likely of peripheral origin. Furthermore, such differential fatigue origin for the arms and the legs indicates that leg muscle performance is determined to a large extend by central mechanisms and, combined with the consideration that the largest amount of work during rowing is by far performed by the large leg muscles, it likely explains why an increase in SaO_2, SmO_2, and VO_2max (Nielsen et al., 1998) does not necessarily increase the amount of work performed.

In agreement with the present findings, studies on exercise-induced fatigue that used self-paced whole body exercise of similar duration with the present study (Amann et al., 2006a; Thomas et al., 2015; 5 and 4 km cycling time trials, respectively) suggest that the contribution of central vs. peripheral fatigue is shifted peripherally in short exercise trials (~6 min). In contrast, the observation that the contribution of central vs. peripheral fatigue is shifted centrally with increasing severity of arterial hypoxemia (Amann et al., 2007) suggests central fatigue following maximal rowing (Nielsen et al., 1999). Furthermore, the association of central fatigue with inhibition of slow muscle fiber recruitment (Rasmussen et al., 2007) that are abundant in rowers (Volianitis et al., 2020) supports a contribution of central fatigue to rowing performance. A possible explanation of our finding of a primarily peripheral contribution to arm muscle fatigue may be that exercise-induced fatigue is primarily central below 70–75% SaO_2 (Amann et al., 2007), while in our study SaO_2 was attenuated only to 92.5% during rowing in normoxia.

Oxygen supplementation prevented the moderate arterial desaturation (~7%) and maintained SaO_2 at resting levels. Consequently, peripheral arm fatigue was reduced by more than half, in agreement with the effect of hyperoxia on quadriceps fatigue (Amann et al., 2006b; Romer et al., 2006). However, besides the effect on peripheral muscle fatigue oxygen supplementation increased VO_2max by ~11% in agreement with previous rowing studies (Peltonen et al., 1995; Nielsen et al., 1999; Volianitis et al., 2008), which is suggestive of central (i.e., cardiovascular) rather than peripheral (i.e., muscular) limitation to rowing performance, albeit work output performed was not increased significantly. Presumably, the restoration of ScO_2 would attenuate the motor activation limitations associated with cerebral deoxygenation (Rasmussen et al., 2007; i.e., one possible factor of central fatigue) providing support to the notion of central origin to rowing fatigability. On the other hand, the level of cerebral deoxygenation in the present study is small compared with other studies (González-Alonso et al., 2004) suggesting that the subjects could tolerate even higher degree of cerebral deoxygenation. This consideration is supported by that the TMS evaluation did not confirm our presumption of central fatigue in normoxia, and therefore, there was no significant deficit in central motor activation that could be attenuated with oxygen supplementation. It should also be acknowledged that since women exhibit different fatigue characteristics than men (f.x. less fatigable when sustaining a contraction at the same relative intensity; Hicks et al., 2001), our findings on male rowers may not be applicable to the same extent in female rowers.

The O_2 supplementation also increased MCA V_{mean} by ~13% compared to normoxia, a response that can be explained by the higher $PaCO_2$ (~2 mmHg) during the hyperoxic trial. However, this elevated MCA V_{mean} did not enhance rowing performance by increasing cerebral oxygen delivery, as has been shown also for incremental cycling performance (Smith et al., 2012). Taken together, these findings support the postulate that increasing cerebral oxygen delivery above what is required to maintain cerebral metabolism has little to no positive effect on performance, as expressed by Smith (2016).

The elevation of SmO_2 with O_2 supplementation is concomitant with the attenuation of the decline of electrically twitch-evoked force after MVC, suggesting that muscle oxygenation is associated with the attenuation of peripheral fatigue in the hyperoxic trial. Abolishment of the ScO_2 deoxygenation, while only partial recovery of SmO_2 deoxygenation, with O_2 supplementation is in agreement with suggestions that hyperoxia has a larger effect on attenuating the decrease in cerebral rather than muscle oxygenation (Nielsen et al., 1999; Oussaidene et al., 2013). The MVC was reduced following rowing with normoxia but not significantly so with hyperoxia. However, since a MVC is the sum of the motor systems performance including the efficacy of the central nervous system and of the contractile apparatus (Gandevia, 2001), MVC does not allow for separation between central and peripheral (muscle) fatigue.

Strengths and Limitations

The strength of the present study is the use of an externally valid whole body dynamic exercise model to evaluate neuromuscular fatigue of a muscle group, combined with evaluation of cerebral and muscle oxygenation values providing an integrative depiction of rowing performance and fatigability. The participants are all competitive rowers at national/international level ensuring that the contribution of the muscle group evaluated (arm) to the whole body skilled performance is valid and thus enhance generalization of the findings.

The limitations inherent to evaluations of fatigue post-exercise also apply to our study. The need for a quick measurement post-fatigue is somehow incompatible with the necessity to perform several contractions to provide a reliable evaluation of MVCs or evoked contractions. The elusive nature of fatigue is affected critically by the rapid recovery of most fatigue indices and thus our findings should be interpreted in a relative context applicable to intra-subject comparisons with similar evaluation delay, rather than absolute values and comparisons across subjects or studies. Also, it has to be recognized that the locus of neuromuscular fatigue of a muscle group does not necessarily translate to fatigability in rowing performance.

CONCLUSIONS AND PERSPECTIVES

In conclusion, the evaluations of ScO_2, SmO_2, MCA, and VO_2 during rowing support a central component to fatigability in agreement with the study by Husmann et al. (2017). Yet, evaluation by electrical and transcranial magnetic stimulation of the elbow flexors indicate peripheral fatigue that is attenuated with O_2 supplementation. Overall, even though evaluation of some fatigability indices point to a central limitation of rowing performance, that seems not to be the case for the arm muscles.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Ethics Committee of Copenhagen (KF 01287471). The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

SV, PR, NP, and NS contributed to the study design, data collection and analysis, and manuscript writing. All authors have read and approved the final version of the manuscript and agreed with the order of presentation of the authors.

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Changing Oar Rotation Axis Position Increases Catch Angle During Indoor and In-Field Para-Rowing: A Randomized Crossover Trial Verified by a Repeated Measurement Trial

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A long rowing stroke length is crucial for adequate rowing performance. Therefore, the relocation of the oar from traditional "in front" (NORM) to "behind the rotation axis" (GATE) may increase (para) rowing performance. Thus, 15 able-bodied rowers (21.4 ± 3.6 years; 187 ± 8 cm; 85.4 ± 8.2 kg) completed indoor TANK rowing 2 min TimeTrials (2 min-TT) of GATE and NORM in a randomized order. Additionally, one elite Paralympic oarsman (37 years, 185 cm, 67 kg) performed a multiple single case in-field BOAT testing (24x2min-TT of GATE and NORM in a randomized order). GATE revealed significantly larger catch angles during TANK (+97.1 ± 120.4%; $p = 0.001$, SMD = 0.84) and BOAT (+11.9 ± 3.2%; $p < 0.021$; SMD = 2.69; Tau-U = 0.70) compared to NORM. While total stroke length, rowing power, and work per stroke increased in GATE during TANK ($p < 0.010$, SMD > 0.634), no such significant changes of these performance parameters between GATE and NORM were observed during BOAT ($p > 0.021$; SMD < 0.58; Tau-U < 0.29). Rowing economy-related parameters (power or speed per oxygen uptake) and boat speed also showed no significant differences between GATE und NORM during BOAT ($p > 0.61$; SMD < 0.31; Tau-U < 0.19). The shape of the force–angle curve (position of peak force and ratio between average and maximal force) remained unaffected from GATE during both TANK ($p > 0.73$, SMD < 0.1) and BOAT ($p > 0.63$; SMD < 0.60; Tau-U < 0.27). In conclusion, GATE shifted the entire rowing stroke towards the catch (+6.6 ± 1.8°) without notably affecting relevant performance parameters during BOAT. Particularly during crew rowing, the minimization of detrimental boat movements for perfect synchrony should be aimed for. Accordingly, the combined application of GATE and NORM (for different athletes in crew boats) may be beneficial for rowing synchronization.

Keywords: gearing, multiple testing, Paralympic, single case, biomechanics, spinal cord injury

INTRODUCTION

Para-rowing is a competitive and recreational sportive activity that gained growing worldwide popularity (Lewis, 2011). Para-rowing was firstly introduced to the Paralympics at the 2008 Beijing Games. Para-rowing programs allow and encourage sports participation by individuals with functional, intellectual, or visual disabilities. According to the elite-standard para-rowing classification regulations of the World Rowing Association, three categories of para-rowing exist (FISA, 2017): Legs, trunk, and arms (LTA), trunk and arms (TA), and arms and shoulders (AS) rowing. LTA rowing is similar to able-bodied rowing using a sliding seat and having no movement restrictions. The AS category (e.g., *PR1 Single Sculls*) of para-rowing is characterized by motions of the AS for propulsion (FISA, 2017). Athletes within this category have minimal or no trunk and leg function and thus require additional stability by a fixed seat back, to which the torso of the AS rower is strapped across the thoracic region (Cutler et al., 2017). Due to these restrictions, the rowing stroke length of TA and AS rowing is significantly shorter compared to conventional LTA rowing (Cutler et al., 2017). A long rowing stroke length, however, is crucial for adequate rowing performance (Baudouin and Hawkins, 2004; Kleshnev, 2016). In this regard, large oar angles in the frontal reversal of the rowing motion (catch) have been shown to increase propulsion through enhanced utilization of the hydrodynamic lift (Baudouin and Hawkins, 2004).

The stroke length can be modified by moving the rotation axis of the oars (in relation to the boat; Dudhia, 2007; Kleshnev, 2016). A displacement of the rotation axis inwards (toward the center of the boat) generates an increased catch angle (Kleshnev, 2016). Accordingly, the displacement of the oar from in front of the rotation axis (NORM) to behind of the rotation axis (GATE) may result in larger catch angles (**Figure 1**). Subsequently, these larger catch angles could produce longer overall stroke length, which may increase the resulting rowing power.

Against this background, the present study aimed to analyze these hypotheses. By employing biomechanical measurements during indoor tank (Trompeter et al., 2019) and in-field *PR1 single scull* (FISA, 2017) rowing, we examined whether GATE vs. NORM resulted in higher rowing power and boat speeds. Since access to participants in competitive sports, and especially in para-sports, is heavily limited, an alternative research setup was chosen. First, a proof-of-concept trial was completed with able-bodied participants (indoor rowing tank measurements), in order to test, whether the displacement of the oar from in front of the rotation axis to behind results in larger catch angles. Subsequently, these results were re-examined in a repeated single case study design with multiple testing (Parker et al., 2011; Lee and Cherney, 2018) of one elite Paralympic oarsman (in-field boat measurements). Thereby, the proof-of-concept data were used for power estimation of the repeated single case measurements. Our findings might deliver new insights into the biomechanical setup of para-rowing and biomechanical optimization of para-sport setups.

MATERIALS AND METHODS

Proof-of-Concept Testing—Indoor Rowing Tank Measurements

Participants

In accordance with previous para-rowing studies (Cutler et al., 2017), able-bodied athletes were enrolled in a para-rowing setup (described in the following section). Assuming large effect sizes ($\eta_p^2 = 0.14$; $f = 0.41$) and high correlations ($r = 0.70$) between measurements (Cohen, 1988), a previously conducted power analysis ($\alpha = 0.05$, study power (1-β-error) = 0.95, g*Power, Version 3.1.9.6) revealed a sample size of $n = 15$. Therefore, 15 experienced male rowers (21.4 ± 3.6 years; 187 ± 8 cm; 85.4 ± 8.2 kg, >5 years of rowing experience) volunteered in this proof-of-concept testing. Inclusion criteria were (I) at least 18 years of age and (II) no health complaints and other disease conditions. Before testing, all participants refrained from any strenuous exercise for 48 h. All participants of the proof-of-concept testing and single case repeated measurements signed an informed consent after receiving relevant study information. The proof-of-concept testing and single case repeated measurements study protocol complied with the Declaration of Helsinki, has been approved by the ethics committee of the German Sport University Cologne (172/2018), and fulfilled the international ethical standards (Harriss and Atkinson, 2015).

Design

The proof-of-concept testing part was conducted as a randomized controlled crossover trial employing an indoor rowing tank. The indoor rowing tank is considered a well-established indoor testing approach that properly simulates an open-water situation (Trompeter et al., 2019). Thereby, rowers sit in a fixed rowing position with 2 (scull) oars, surrounded by a channel of water (Trompeter et al., 2019). After a standardized 15-min warm up (rowing at low intensity/heart rate, which corresponds to a blood lactate concentration < 2 mmol/L), two 2-min time trials (5 min rest in between) were completed in a randomized order, with a standard oarlock (**Figures 1A**,**C**; NORM; *Concept 2*, Morrisville, United States) and a modified oarlock [**Figures 1B**,**D**; GATE; *Institut für Forschung und Entwicklung von Sportgeräten* (FES), Berlin, Germany]. Both 2-min time trials were performed at maximum intensity with a fixed stroke rate of 34 spm. The last min of each 2-min time trial was included for further analysis. To simulate the (no leg) rowing motion of para-athletes, the legs and trunk were fixed with straps. A familiarization session (20 min tank rowing at low intensity/heart rate, which corresponds to a blood lactate concentration < 2 mmol/L and several short burst at high intensity) was completed 1 week prior to testing.

Data Collection

A radio telemetry system (*BioRowTel System*, Biorow, Berkshire, Great Britain) was used for data acquisition (25 Hz sampling frequency) during tank rowing. The force applied to the oar-handle was measured using a strain gauged transducer attached to the oar shaft (*BioRowTel System*, Biorow, Berkshire, Great Britain,

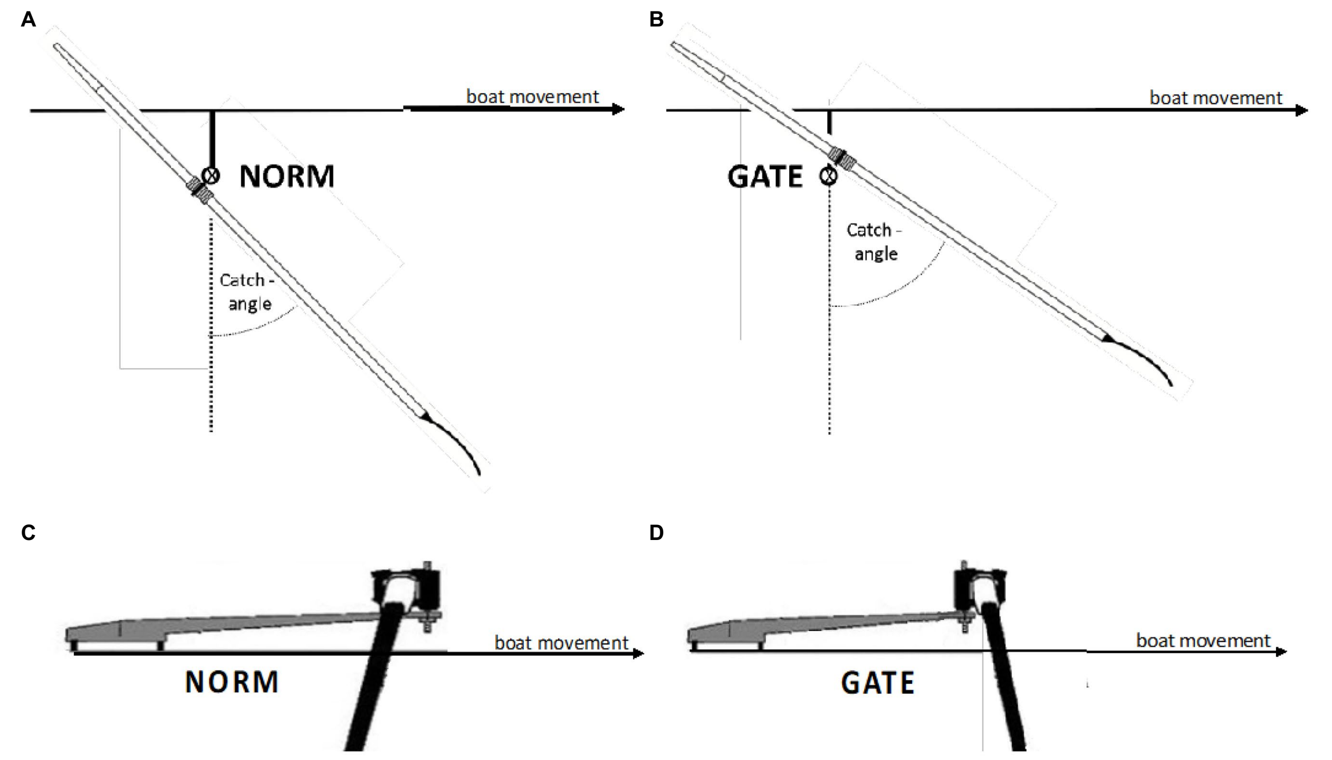

FIGURE 1 | Schematic representation of the standard setup (**A,C**; NORM) and the modified version (**B,D**; GATE).

accuracy ± 0.5%). Each oar was dynamically calibrated before each session using a precision load cell. The oar angles in horizontal and vertical dimensions were measured using conductive plastic potentiometers (*BioRowTel System*, Biorow, Berkshire, Great Britain, accuracy ±0.1%). Total rowing angle (angle; ±0.1%), catch angle (±0.1%), stroke rate (rate; ±0.1%), rowing power (P_{row}; ±0.5%), and work per stroke (WPS; ±0.5%) were determined (Kleshnev, 2016; Held et al., 2019) accordingly. To quantify the shape of the force–displacement curve, the position of peak force ($Peak_{Position}$; ±0.1%) and the ratio between average and maximal force ($Ratio_{mean-max}$) were determined (Kleshnev, 2016).

Statistics

Data are presented as mean ± SD. After verifying normal distribution and variance homogeneity, pairwise comparisons (pairwise *t*-test) between NORM and GATE were performed for each output parameter (P_{row}, WPS, total angle, catch angle, stroke rate, $Peak_{Position}$, and $Ratio_{mean-max}$). For pairwise effect size comparison, standard mean differences (SMD) were additionally calculated as between mode differences divided by the pooled standard deviations of both modes (trivial: $SMD < |0.2|$, small: $|0.2| \leq SMD < |0.5|$, moderate: $|0.5| \leq SMD < |0.8|$, large $SMD \geq |0.8|$; Cohen, 1988).

Single Case Repeated Measurements—In-Field Boat Measurements

Participant

One elite Paralympic oarsman (37 years, 185 cm, 67 kg; 8 years Olympic rowing experience) was tested in a single case (n-of-1) design using repeated in-field rowing (boat) measurements. This elite athlete took part in several Paralympic, World, and European championships. Due to a clinically motor complete spinal cord injury (T6), this athlete was classified in the AS classification.

Design

A multiple (repeated) testing design was then used for the (n-of-1) in-field boat trial. Therefore, the data obtained from the indoor rowing tank were used for the sample size estimation of this in-field boat measurements. Based on indoor rowing tank measurements (P_{row}; **Table 1**), an estimation of the necessary measurement repetitions ($\alpha = 0.10$; study power (1-β-error) = 0.95; effect size SMD = 0.855; no baseline drift) required a number of samples/measurements of $n = 21$ (Percha et al., 2019). In conclusion, in-field boat measurements in the *PR1 single scull* mode were repeated 24 times (12× GATE; 12× NORM). These 24 measurement trials were spread over six testing days. Between each of the six testing days, 1 week of training (alternating between GATE and NORM, for 5 sessions) was conducted. On each testing day, four 2-min time trials (with 5 min rest in between) were completed in randomized order, two with GATE and two with NORM. Both 2-min time trials were performed at maximum intensity with a fixed stroke rate of 34 spm. The last minute of each 2-min time trial was included into further analysis. Similar to the indoor tank measurements, a standardized 10-min warm up (as described above) was performed prior to each in-field measurement. In order to control the circadian effects on performance, all measurements were conducted at similar times of day. All in-field measurements were carried out in the participant's own (accustomed) *PR1 single scull* para-boat.

Data Collection

In addition to the indoor rowing measurement setup, the average boat speed (v_{boat}) was determined by a 10 Hz-GPS (*BioRowTel Systems*, Biorow, Berkshire, Great Britain, accuracy $\pm 0.1\,m\,s^{-1}$) during in-field boat measurements. Furthermore, oxygen uptake (VO_2) data were collected with a breath-by-breath spiroergometric system (*Metamax 3b*, Cortex Biophysics, Leipzig, Germany) during field rowing. The technical error of measurement of the device is reported to be less than 2% (Macfarlane and Wong, 2012). The spiroergometric system was calibrated prior to each test following the manufacturer's recommendations. Objective exhaustion were verified for each in-field boat measurement trials following the criteria by Midgley et al. (2007). In-field rowing efficiency was determined as rowing power per oxygen uptake (P_{VO2}) and boat speed per oxygen uptake (v_{VO2}).

Statistics

All single case repeated measurement data are presented as mean ± SD. Normal distribution of all output variables was verified using Shapiro–Wilk tests, and variance homogeneity was visually verified *via* plotting residuals. Repeated measures analysis of variances (rANOVA) were conducted to examine "mode" differences (GATE vs. NORM) for the respective outcome measures (P_{row}, WPS, total angle, catch angle, stroke rate, $Peak_{Position}$ and $Ratio_{mean-max}$, P_{VO2}, and V_{VO2}) during in-field boat measurements. Effect sizes for rANOVA were given as partial eta squared (η_p^2), with values ≥ 0.01, ≥ 0.06, and ≥ 0.14 indicating small, moderate, and large effect sizes, respectively (Cohen, 1988). In case of significant rANOVA effects, Bonferroni *post-hoc* tests were subsequently computed. Further, for pairwise effect size comparison, SMD were calculated (Cohen, 1988). The multiple testing outcome measures of the in-field boat measurements were visually analyzed using percentage of non-overlapping data (PND), percentage exceeding the median (PEM), percentage exceeding the trend (PET), non-overlap of all pairs (NAP), percentage all non-overlapping data (PAND), mean difference between both conditions (MD), trend difference 400 between both conditions (Δtrend), and SMD (Horner et al., 2005; Kratochwill et al., 2010). Furthermore, Tau-U effect sizes (Parker et al., 2011; Lee and Cherney, 2018) were calculated to complement visual analysis using the "scan" package for R (Wilbert and Lueke, 2021). Tau-U is a non-parametric effect size analysis that examines non-overlap between phases (Parker et al., 2011; Lee and Cherney, 2018) and corrects for undesirable baseline trends (Vannest and Ninci, 2015). Tau-U effect size scores ≥ 0.01, ≥ 0.20, ≥ 0.60, and ≥ 0.80 indicate small, moderate, large effects, and very large effects, respectively (Vannest and Ninci, 2015). All statistical analyses (for the proof-of-concept testing and single case repeated measurements) were conducted using R (version 4.0.5) and RStudio (version 1.4.1106) software.

TABLE 1 | Output parameter of the proof-of-concept testing (indoor rowing tank measurements).

	NORM	GATE	p	SMD
Stroke rate (spm)	34.3 ± 2.8	34.2 ± 3.4	0.980	−0.032
P_{row} (W)	101 ± 44	146 ± 60	0.006	0.855
WPS (J)	177 ± 82	261 ± 121	0.010	0.813
Angle (°)	44.8 ± 9.4	52.4 ± 14.1	0.010	0.634
Catch angle (°)	9.4 ± 7.3	18.0 ± 12.5	0.001	0.840
$Peak_{Position}$ (%)	39.5 ± 5.6	40.1 ± 7.2	0.730	0.093
$Ratio_{mean-max}$ (%)	48.2 ± 5.0	48.1 ± 4.9	0.914	−0.020

P_{row}: rowing power; WPS: work per stroke; Angle: total rowing angle; Catch angle; $Peak_{Position}$: position of peak force; $Ratio_{mean-max}$: ratio between average and maximal force. In addition, the Bonferroni t-test results (p value) and pairwise effect sizes (SMD) are displayed.

RESULTS

Indoor Rowing Tank Measurements

Stroke rate and shape of force–angle curve ($Peak_{Position}$, $Ratio_{mean-max}$) revealed no significant differences ($p \geq 0.730$; SMD ≤ 0.09; **Table 1**) during indoor tank rowing measurements. In contrast, rowing power (P_{row} +55.8 ± 57.3%; **Figure 2A**), work per stroke (WPS +59.7 ± 67.2%; **Figure 2B**), total angle (+19.9 ± 23.9; **Figures 2C, 3A**), and catch angle (+97.1 ± 120.4%; **Figures 2D, 3B**) increased significantly ($p \leq 0.010$; SMD ≥ 0.63; **Table 1**) from NORM to GATE, during indoor tank rowing.

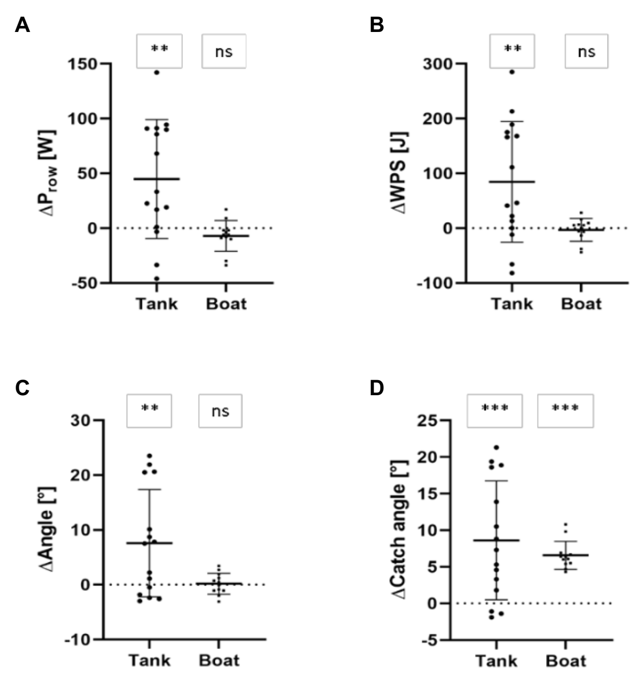

FIGURE 2 | Change scores of rowing power (ΔP_{row}; **A**), work per stroke (ΔWPS; **B**), total rowing angle (ΔAngle; **C**) and catch angle (ΔCatch angle; **D**) during indoor rowing tank and in-field boat measurements. Note: ***$p < 0.001$; **$p < 0.01$; ns = not significant ($p > 0.05$).

In-Field Boat Measurements

During in-field measurements (**Table 1**) the rANOVA revealed no statistically significant mode × time interactions ($p \geq 0.066$; $\eta_p^2 \leq 0.60$; **Table 2**) for all output parameters [rate, v_{boat}, P_{row} (**Figure 2A**), WPS (**Figure 2B**), Angle (**Figure 2C**), shape of force–angle curve ($Peak_{Position}$, $Ratio_{mean-max}$), power per oxygen uptake (P_{VO2}), and boat speed per oxygen uptake (V_{VO2})] except of catch angle ($p \leq 0.001$; $\eta_p^2 = 0.81$; **Table 2**). *Post-hoc* tests revealed statistically significant ($p = 0.021$; SMD = 2.70) larger catch angle (+11.9 ± 3.2%) for GATE compared to NORM during all in-field measurement trials (**Figure 2C**).

Percentage of non-overlapping data (PND), percentage exceeding the median (PEM), percentage exceeding the trend (PET), non-overlap of all pairs (NAP), and percentage all non-overlapping data (PAND) ranged between 0 and 83.3% (**Table 2**) for stroke rate, boat speed (v_{boat}), rowing power (P_{row}; **Figure 4A**), work per stroke (WPS, **Figure 4B**), total angle (**Figure 4C**), $Peak_{Position}$, $Ratio_{mean-max}$, and rowing economy (P_{VO2}: power per oxygen uptake; V_{VO2}: boat speed per oxygen uptake). In addition, rate, v_{boat}, P_{row}, WPS, Angle, $Peak_{Position}$, $Ratio_{mean-max}$, P_{VO2}, and V_{VO2} showed only trivial to moderate SMD and small to moderate Tau-U effect sizes (**Table 2**). In contrast, catch angle (**Figure 4D**) revealed percentage of non-overlapping data (PND), percentage exceeding the median (PEM), percentage exceeding the trend (PET), non-overlap of all pairs (NAP), and percentage all non-overlapping data (PAND) ≥ 83.3% (**Table 2**). In addition, large SMD and Tau-U effect sizes revealed increased catch angles (**Table 2**) during GATE compared to NORM during in-field boat measurements.

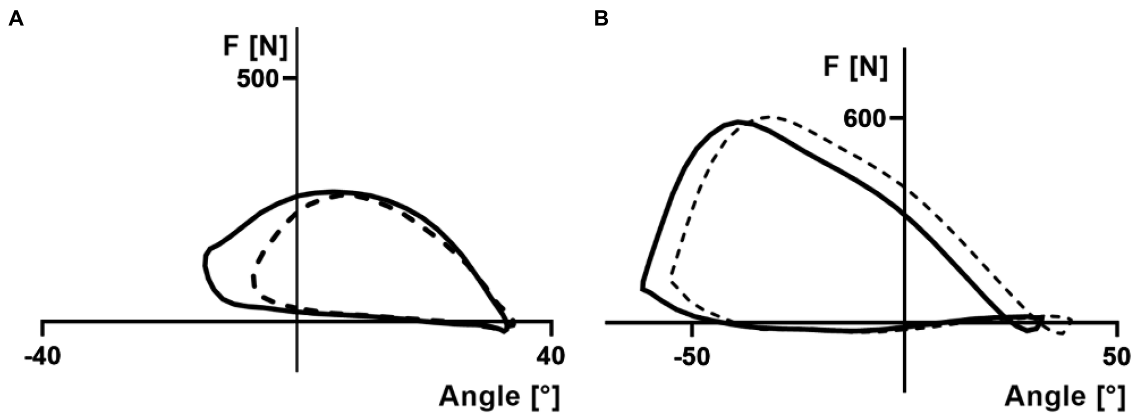

FIGURE 3 | Representation of the average handle force (F) as a function of rowing angle during proof-of-concept (**A**; indoor rowing tank measurements) and single case repeated measurement (**B**; in-field boat measurements) and indoor rowing tank measurements **(B)**. GATE is displayed in solid lines and NORM in dashed lines.

TABLE 2 | Output parameter and overlapping indices of the single case repeated measurements (in-field rowing measurements).

	Stroke rate (spm)	v_{boat} (m s^{-1})	P_{row} (W)	WPS (J)	Angle (°)	Catch angle (°)	$Peak_{Position}$ (%)	$Ratio_{mean-max}$ (%)	P_{VO2} (W min^{-1} L^{-1})	v_{VO2} (m s^{-1} min^{-1} L^{-1})
NORM	33.9 ± 1.0	3.23 ± 0.21	303 ± 13	537 ± 21	94.3 ± 1.7	55.2 ± 1.9	24.9 ± 1.9	51.3 ± 1.8	117 ± 9	1.26 ± 0.14
GATE	33.3 ± 1.1	3.17 ± 0.17	296 ± 11	534 ± 21	94.5 ± 1.8	61.8 ± 2.9	23.9 ± 0.9	52.2 ± 1.9	116 ± 9	1.24 ± 0.12
p	0.955	0.997	0.999	0.990	0.066	0.001	0.063	0.134	0.614	0.786
η_p^2	0.091	0.028	0.017	0.047	0.599	0.810	0.603	0.525	0.269	0.192
SMD	−0.571	−0.314	−0.581	−0.143	0.114	2.692	−0.673	0.486	−0.111	−0.160
PND	0.00	8.33	0.00	8.33	8.33	83.33	0.00	8.33	8.33	8.33
PEM	25.00	16.67	33.33	41.67	50.00	100.00	25.00	75.00	33.33	41.67
PET	0.00	75.00	41.67	83.33	75.00	100.00	66.67	25.00	58.33	75.00
NAP	30.56	36.81	34.38	47.22	48.96	98.61	31.25	66.67	44.44	47.92
PAND	25.00	37.50	37.50	41.67	50.00	91.67	33.33	66.67	41.67	50.00
Tau-U	−0.29	−0.19	−0.23	−0.04	−0.02	0.70	−0.27	0.24	−0.08	−0.03
MD	−0.59	−0.06	−7.08	−3.02	0.17	6.58	−0.01	0.01	−1.04	−0.01
Δtrend	0.05	0.02	0.49	−0.06	−0.06	0.19	0.00	0.00	1.46	0.02
SMD	−0.58	−0.29	−0.51	−0.14	0.09	3.40	−0.51	0.50	−0.11	−0.05

Rate: stroke rate; v_{boat}: boat speed; P_{row}: rowing power; WPS: work per stroke; Angle: total rowing angle; Catch angle; $Peak_{Position}$: position of peak force; $Ratio_{mean-max}$: ratio between average and maximal force; P_{VO2}: rowing power per oxygen uptake; v_{VO2}: boat speed per oxygen uptake; mode × time rANOVA interaction (p) and effect size (η_p^2) are displayed separately for each rowing condition; PND: percentage of non-overlapping data; PEM: percentage exceeding the median; PET: percentage exceeding the trend; NAP: non-overlap of all pairs; PAND: percentage all non-overlapping data; Tau-U: Tau-U effect size; MD: mean difference between both conditions; Δtrend: trend difference between both conditions; SMD: standardized mean difference.

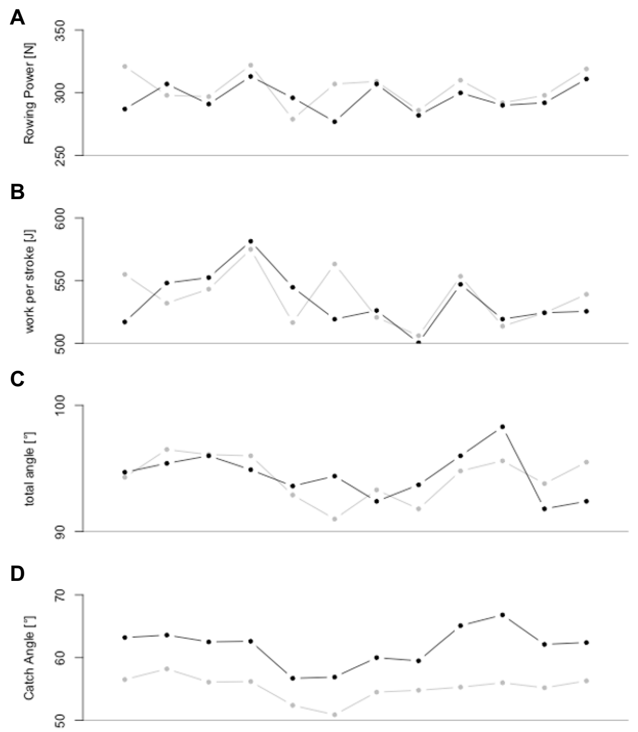

FIGURE 4 | Rowing power **(A)**, work per stroke **(B)**, total angle **(C)**, and catch angle **(D)** data (means) for both NORM (grey) and GATE (black) during in-field boat measurement of the elite para-rower.

DISCUSSION

To the best of our knowledge, this is the first study that comparatively examined different (para) boat setups during indoor tank rowing and in-field rowing including a single subject approach. We first conducted a randomized crossover testing as an initial proof-of-concept study with able-bodied participants (indoor rowing tank measurements) with a subsequent verification *via* multiple single case testing of an elite Paralympic oarsman (in-field boat measurements). Our key findings indicate that the displacement of the oar from in front of the rotation axis (NORM) to behind the rotation axis (GATE) resulted in significantly larger catch angles during both indoor tank and in-field *PR1 single scull* rowing. While total stroke length, rowing power, and work per stroke increased in GATE during indoor tank rowing, no such significant changes of these performance parameters between GATE and NORM were observed during the in-field boat condition. Rowing economy-related parameters (power or speed per oxygen uptake) and boat speed also showed no significant differences between GATE und NORM during in-field rowing. Interestingly, the shape of the force–angle curve (position of peak force and ratio between average and maximal force) remained unaffected from GATE during both indoor rowing tank and in-field boat measurements.

The observed rowing angle changes after modifying the oar-boat setups are in line with previous scientific research findings in rowing (Kleshnev, 2016; Held et al., 2019). In contrast to the current study, however, previous rowing angle changes were merely induced by changes of the gearing ratio between inner and outer lever of the oar (Held et al., 2019). Our study was the first that showed the effect of the displacement of the rotation axis on the rowing angle. The results indicate that GATE (compared to NORM) enables larger catch angles during both indoor tank and in-field rowing, but larger total stroke lengths were only observed during indoor tank rowing. Based on enhanced utilization of the hydrodynamic lift (Baudouin and Hawkins, 2004), larger catch angles are considered favorable for the rowing performance (Baudouin and Hawkins, 2004; Kleshnev, 2016). The observed differences between indoor tank and in-field rowing might result from the following factors: By fixing the legs and hips during indoor tank rowing, the able-bodied athletes could use an arm, shoulder, and despite fixation partly trunk movement for propulsion. In contrast, the *PR1 single scull* para-athlete could only use the arms and shoulders for propulsion. Correspondingly, the indoor tank rowing setup may allow a large increments of stroke length. In addition, according to the elite-standard Para-Rowing Classification Regulations of the World Rowing Association, the used indoor rowing tank setup seems to be more suitable as trunk and arms (TA) and the *PR1 Single Scull* of the para-athlete as arms and shoulders (AS) rowing (FISA, 2017).

The shape of the force–angle curve (Kleshnev, 2016) was characterized by the position of the peak (in relation to the stroke length; $Peak_{Position}$) and the ratio of peak force to average force ($Ratio_{mean-max}$). GATE showed no effect on these two parameters ($Peak_{Position}$ and $Ratio_{mean-max}$) for both indoor tank and in-field rowing. Accordingly, the in-field rowing results showed that GATE shifted the entire rowing stroke by $6.6 \pm 1.8°$ toward the catch position without affecting other parameters like total stroke length, rowing power, work per stroke, rowing economy (power or boat speed per oxygen uptake) and shape of force–angle curve. In general, the goal in competitive rowing is to cover a 2000 m race distance in the shortest amount of time. Accordingly, each rower or rowing crew aims at maximizing power output and minimizing power losses to achieve maximum average boat velocity. During crew rowing, it is the collective performance of the crew that affects the movements of the boat (Wing and Woodburn, 1995; Hill, 2002; Baudouin and Hawkins, 2004). Particularly for crew rowing, the coaching literature (O'Brien, 2011) and also scientific research (Wing and Woodburn, 1995; Baudouin and Hawkins, 2004; Cuijpers et al., 2017) suggest to minimize detrimental boat movements for perfect synchrony. Improved synchrony in the crew boat can be achieved by adjusting the rowing angles (total stroke length and catch angle) of each oarsman. Accordingly, our results enable to increase the crew boat synchronicity by matching the catch angles using GATE or NORM for different athletes in crew boats. Therefore, the combination of GATE and NORM enables a broader range of rowing angles enabling a better exploration for synchronized kinematics of the entire rowing crew, aiming at minimizing detrimental boat movements. For this purpose, GATE and NORM were already used in a crew boat at the 2019 World Rowing Championships.

Apart from the able-bodied participants, only one elite Paralympic oarsman was examined. However, the number of elite athletes and para-athletes in particular is very limited. Nevertheless, the combination of proof-of-concept (indoor rowing tank) and multiple single case (in-field boat) testing allows statistically relevant conclusions despite the small sample size. Furthermore, the results show that findings from able-bodied athletes measured in a para-setup are only partially transferable to the para-athlete. Therefore, the chosen research design (randomized crossover testing as proof-of-concept and subsequent verification *via* multiple single case testing) can also serve as a template for further research in the para-sport field.

In conclusion, the displacement of the oar from in front of the rotation axis (NORM) to behind the rotation axis (GATE) resulted in significant and meaningful larger catch angles during indoor tank and in-field *PR1 single scull* rowing. While total stroke length, rowing power and work per stroke increased in GATE only during tank rowing, no meaningful changes of these performance parameters between GATE and NORM were observable during in-field boat measurements. Therefore, GATE shifted the entire rowing stroke toward the catch position without affecting other parameters, such as total stroke length, rowing power, work per stroke, rowing economy (power or boat speed per oxygen uptake), and shape of force–angle curve. Since synchrony in the crew boat can be improved by adjusting the rowing angles of each crew member, the combination of GATE and NORM in crew boats seems reasonable to enhance synchronization which is essential for optimal propulsion.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Ethics committee, German Sport University Cologne. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

SH, LR, and LD contributed to the conception and design of the study. SH led the intervention and wrote the first draft of the manuscript. SH and LR performed the statistical analysis. SH, LR, PW, and LD wrote sections of the manuscript. PW copyedited the draft for content, language, and format and organized the submission and revision/resubmission process. All authors contributed to the article and approved the submitted version.

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Estimation of Cerebral Hemodynamics and Oxygenation During Various Intensities of Rowing Exercise: An NIRS Study

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Purpose: This study aimed to investigate changes in cerebral hemodynamics and oxygenation at moderate, heavy, maximal and supramaximal intensities of rowing exercise. It also examined whether these changes reflect alterations in sensation of effort and mood. We also aimed to examine the effects of peak pulmonary oxygen consumption ($\dot{V}O_{2peak}$) on cerebral oxygenation.

Methods: Eleven rowers, consisting out of six athletes and five recreational rowers [two female; age, 27 ± 9 years; height, 171 ± 7 cm, body mass, 67 ± 9 kg; $\dot{V}O_{2peak}$, 53.5 ± 6.5 mL min^{-1} kg^{-1}] rowed a 13-min session separated by 10 and 3 min, at 70 ($Ex_{70\%}$) and 80% of $\dot{V}O_{2peak}$ ($Ex_{80\%}$), respectively, on a rowing ergometer, followed by three sessions of 1-min supramaximal exercise (ExSp). After a warm-up at 60% of $\dot{V}O_{2peak}$ (ExM), seven male rowers performed a 2,000 m all-out test (Ex_{2000}). Cardiovascular and respiratory variables were measured. Cerebral oxygenation was investigated by near-infrared time-resolved spectroscopy (TRS) to measure cerebral hemoglobin oxygen saturation (ScO_2) and total hemoglobin concentration ([HbT]) in the prefrontal cortex (PFC) quantitatively. We estimated the relative changes from rest in cerebral metabolic rate for oxygen ($rCMRO_2$) using TRS at all intensities. During $Ex_{70\%}$ and $Ex_{80\%}$, ratings of perceived exertion (RPE) were monitored, and alteration of the subject's mood was evaluated using a questionnaire of Positive-and-Negative-Affect-Schedule after $Ex_{70\%}$ and $Ex_{80\%}$.

Results: When exercise intensity changed from $Ex_{70\%}$ to $Ex_{80\%}$, the sense of effort increased while ScO_2 decreased. [HbT] remained unchanged. After $Ex_{70\%}$ and $Ex_{80\%}$, a negative mood state was less prominent compared to rest and was accompanied by increases in both ScO_2 and [HbT]. At termination of Ex_{2000}, ScO_2 decreased by 23% compared to rest. Changes in ScO_2 correlated with $\dot{V}O_{2peak}$ only during Ex_{2000} (r = −0.86; p = 0.01). $rCMRO_2$ did not decrease at any intensities.

Conclusion: Our results suggest that alterations in the sense of effort are associated with oxygenation in the PFC, while positive changes in mood status are associated with cerebral perfusion and oxygen metabolism estimated by TRS. At exhaustion, the cerebral metabolic rate for oxygen is maintained despite a decrease in ScO_2.

Keywords: prefrontal cortex (PFC), cerebral blood volume (CBV), cerebral blood flow (CBF), cerebral metabolic rate for oxygen ($CMRO_2$), effort, exhaustion, central fatigue, training

INTRODUCTION

Rowing involves the large muscles and in total a high muscle mass of the entire body. Both strength and endurance are mandatory for achieving optimal competitive performance. In competitive rowing, the high-intensity work rate requires high metabolic demand, and all metabolic pathways are mobilized. In addition to the development of muscle hypertrophy with predominantly slow-twitch (or type I) fibers and the notable maximal oxygen uptake ($\dot{V}O_{2max}$) (Larsson and Forsberg, 1980; Secher, 1993), elite rowers become exhausted because of extremely low levels of blood pH and arterial hypoxemia at the end of the competition (Nielsen et al., 1998, 1999). It has been suggested that the ability of the central nervous system to recruit motoneurons becomes limited during maximal-intensity rowing exercise, a limitation in the ability of the central nervous system to recruit motoneurons has been suggested (Roth et al., 1993; Volianitis et al., 2020). This limitation in recruiting slow-twitch fibers has been supposed to be due to the central fatigue mechanism (Secher et al., 2008; Taylor et al., 2016). Because of extreme fatigue induced by competitive rowing, alterations in cerebral blood flow (CBF) and oxygen metabolism, including the cerebral metabolic rate for oxygen ($CMRO_2$), have been explored from the perspective of central fatigue (Nielsen et al., 1999; Volianitis et al., 2020). Previous studies have investigated the association between fatigue or exhaustion induced by maximal-intensity rowing exercise by measuring oxygenation of the prefrontal cortex (PFC) using near-infrared spectroscopy (NIRS) and the cerebral metabolic ratio, which is the oxygen-to-glucose index determined by arterial-to-internal jugular venous differences in the entire brain (Secher et al., 2008; Volianitis et al., 2020). Because of its practical utility, a large number of studies focused on oxygenation changes in the PFC during exercise (Herold et al., 2018; De Wachter et al., 2021). Furthermore, several studies using NIRS have investigated oxygenation in the PFC during rowing exercise (Nielsen et al., 1999, 2001; Faull et al., 2015). Although the PFC may not directly contribute to the neuronal control of movement, it is associated with various features of affective processing (Davidson, 2003), cognitive function (Fernandes et al., 2018), and mood status (Monroe et al., 2020) evoked by exercise. Cerebral oxygenation decreased before motor performance failure when exhaustion was elicited by maximal cycling exercise (Rupp and Perrey, 2008). Accordingly, the sense of effort and exhaustion evoked by high-intensity rowing exercise was reflected in the oxygenation in the PFC.

During training sessions for rowers, high-intensity training and repetitive sessions involving supramaximal intensity are mandatory (Treff et al., 2017); however, endurance training is often performed at low to moderate intensity (Nybo et al., 2014). When selecting exercise intensity during training sessions, the ratings of perceived exertion (RPE) and feelings experienced during exercise sessions are crucial indicators, because they are mirrored by physiological variables such as the heart rate (HR) and pulmonary oxygen consumption ($\dot{V}O_2$), especially during steady-state continuous exercise. In addition to recognizing fatigue, it is important to know how rowers feel at different training intensities when examining these changes in sensations accompanying changes in the regional CBF and $CMRO_2$. Because positron emission tomography (PET) cannot be used to measure regional CBF and/or $CMRO_2$ during rowing ergometer exercise, we used NIRS to investigate cerebral oxygenation during rowing exercise and to estimate $CMRO_2$, according to other methods involving NIRS (Brown et al., 2003; Roche-Labarbe et al., 2010).

Recently, near-infrared time-resolved spectroscopy (TRS) has enabled the in-depth measurement of absolute values of cerebral tissue oxygenation (Ohmae et al., 2006; Torricelli et al., 2014; Auger et al., 2016). Although the continuous-wave NIRS system is conventional and commercially available, it can only detect changes in oxygenated- and deoxygenated-hemoglobin concentrations in cerebral tissue because it is based on the modified Beer-Lambert law. TRS can continuously and simultaneously measure the absolute values of cerebral hemoglobin oxygen saturation (ScO_2) and cerebral blood volume (CBV). ScO_2 can be calculated by the ratio of oxyhemoglobin ([HbO]) and total hemoglobin ([HbT]) concentrations in the brain tissue, where [HbT] is the sum of [HbO] and deoxyhemoglobin concentration in the brain tissue ([HbR]) (Ijichi et al., 2005; Roche-Labarbe et al., 2010). Using [HbT], CBV is calculated using the molecular weight of hemoglobin, brain tissue density, and hemoglobin concentration of blood (HGB) (Kretschmann et al., 1986; Roche-Labarbe et al., 2010). Furthermore, we explored changes in $CMRO_2$, not absolute values, by estimating the relationship between CBF and CBV reported by previous studies using PET and NIRS (Takahashi et al., 1999; Brown et al., 2003; Roche-Labarbe et al., 2010).

With a notable workload and maximal effort for competition, the physiological aspect of rowing demonstrates a unique challenge to the human capacity, including cerebral perfusion and metabolism (Volianitis and Secher, 2009). However, little is known about altered sensations of effort and fatigue caused by rowing exercise and brain metabolism associations. Therefore, this study aimed to investigate changes in oxygenation in the PFC during various exercise intensities used during regular training sessions for rowing in conjunction with cardiovascular and respiratory variables. To address this issue, we observed a session of rowing exercise consisting of two different intensities of constant-load exercise, that is, 70% ($Ex_{70\%}$) and 80% of $\dot{V}O_{2peak}$ ($Ex_{80\%}$), which were related to the heavy-intensity domain between the first (VT1) and the second ventilatory threshold (VT2) (Cerezuela-Espejo et al., 2018; Jamnick et al., 2020). Considering the actual rowing training session, supramaximal exercise (ExSp), which surpasses peak $\dot{V}O_2$ ($\dot{V}O_{2peak}$) for a short duration, was also observed. Furthermore, we studied maximal exercise represented by the 2,000-m competition simulation (Ex_{2000}) followed by moderate-intensity exercise (ExM), 60% of $\dot{V}O_{2peak}$, which corresponds to the intensity below VT1. To investigate the impact of the oxidative capacity on the extent of potential alterations in cerebral oxygenation, we investigated both moderately and highly trained rowers.

MATERIALS AND METHODS

Participants

Eleven club-level rowers (two females, median age, 23 years; age range, 20–45 years) participated in this study. Characteristics of participants are shown in **Table 1**. Six male rowers were fit and performed competitive training of more than 6 h per week. Five rowers had retired or suspended their involvement in national-level competitions but continued to participate in recreational-level competitions and performed physical training fewer than 2 h per week. They had 2–23 years of rowing training and were familiar with Concept2 rowing ergometer (Concept2, Morrisville, United States) training and maximal rowing. None of the participants had a personal history of physical or psychiatric illness or substance abuse, and none was using any medications. The participants were advised to maintain an appropriate diet including carbohydrates and to stay well-hydrated. Additionally, they were instructed to avoid rigorous exercise, alcohol, and drugs during the 24 h preceding the experiments. All participants provided written informed consent after a detailed explanation of the study. The study protocol was designed in accordance with the guidelines of the national government and the 2008 revision of the Declaration of Helsinki. The protocol was approved by the Ethics Committee of the Faculty of Sociology, Aomori University (no. 03-2021).

Experimental Design

All participants completed an incremental test using the Concept2 ergometer until volitional exhaustion before the main experimental sessions. Within the 2 weeks after the incremental tests, the participants performed two experimental trials within a range of 4 weeks. The study protocol consisted of four sessions with five variations in exercise intensity and duration (**Figure 1**). During the first trial, participants performed a total of 13 min of exercise on a rowing ergometer at two different exercise intensities. After a 20-min period of recovery, they started three bouts of 1-min ExSp. On the second trial, seven male participants (five competitive and two recreational rowers) performed an Ex_{2000} simulating an on-water competition following a 2,000-m warmup session at 60% of $\dot{V}O_{2peak}$. During the experimental protocol, the HR and respiratory variables were measured. NIRS signals were explored on the forehead to investigate oxygenation in the PFC throughout the four experimental sessions. During each session, measurements were initiated 2 min before the start of exercise while the participants rested in the exercising position on the ergometer. At the dual-intensities of constant load exercise, the RPE (6–20 scale) (Borg, 1970) and mood alterations were evaluated using a questionnaire (Positive and Negative Affect Schedule (PANAS)] (Watson et al., 1988).

Rowing Ergometer Incremental Test

As previously described (Jensen et al., 2021), seven 2-min incremental step tests were performed continuously without a break on a wind resistance-braked rowing ergometer (Model D, Concept2, Morrisville, United States) to determine $\dot{V}O_{2peak}$, and target power output (PO) for each experimental session. Before exercise started, rowers were equipped with the instruments and sat quietly for 1 min on the rowing ergometer before starting the exercise. The Concept2 rowing ergometer was equipped with a PM5-monitor, which allows the calculation of the PO averaged over 1 min. Respiratory variables were measured using an online gas analyzer (Quark CPET; Cosmed, Rome, Italy) in the breath-by-breath mode, and $\dot{V}O_2$, CO_2 production ($\dot{V}CO_2$), minute ventilation ($\dot{V}_E$), breathing frequency (R_f), end-tidal CO_2 ($P_{ET}CO_2$), and respiratory exchange ratio (RER) were continuously measured. HR was recorded using a Sport tester Polar 725X (Polar Electro Oy, Kempele, Finland). All data were averaged at 15-s intervals. $\dot{V}O_{2peak}$ was defined as the maximum 15-s average $\dot{V}O_2$. The maximal PO (MPO) was determined as the average power at the last completed step plus 25% of the starting step multiplied by the percentage of the 2 min completed during the last step (Jensen et al., 2021). The linear relationship between PO and $\dot{V}O_2$ was determined and used to identify the target PO during different exercise intensities for the protocol. The first and second ventilatory thresholds (VT1 and VT2, respectively) were determined by a visual analysis. The VT1 was determined using the following criteria: the first increase in both the ventilatory equivalent of oxygen ($\dot{V}_E/\dot{V}O_2$) and end-tidal pressure of oxygen ($P_{ET}O_2$) with no concomitant increase in the ventilatory equivalent of carbon dioxide ($\dot{V}_E/\dot{V}CO_2$) during the incremental test. The VT2 was determined using the following criteria: the first increase in both the $\dot{V}_E/\dot{V}O_2$ and $\dot{V}_E/\dot{V}CO_2$ and a decrease in $P_{ET}CO_2$ (Cerezuela-Espejo et al., 2018).

Main Experimental Sessions

Dual-Stage Constant-Load Rowing Exercise

The exercise session consisted of a constant load of 10-min of $Ex_{70\%}$, followed by a 3-min of $Ex_{80\%}$ (**Figure 1A**). PO for $Ex_{70\%}$ corresponded to 70% $\dot{V}O_{2peak}$, which was determined using the linear relationship between PO and $\dot{V}O_2$ obtained during the incremental test described. Because VT1 was determined as 69 ± 6% using the data obtained data during the incremental test, 70% $\dot{V}O_{2peak}$ was determined to be the $Ex_{70\%}$. PO for $Ex_{80\%}$ corresponded to 80% $\dot{V}O_{2peak}$ because VT2 was determined to be 85 ± 5%. Cardiovascular and respiratory gas exchange variables and oxygenation in the PFC were measured throughout the exercise session. NIRS values and cardiorespiratory data were averaged at the last 15 s of rest, $Ex_{70\%}$, $Ex_{80\%}$ and 3 min after the exercise was terminated. To determine the cardiac output (CO),

TABLE 1 | Demographic, physiological characteristics of the participants.

Participant ID	Performance level	Sex	Age (years)	Height (cm)	Body mass (kg)	Rowing experience (years)	Involvement in 2,000 m all-out test
1	C	M	20	179	65	2	+
2	C	M	22	171	70	4	+
3	C	M	23	173	65	7	+
4	C	M	22	180	74	7	
5	C	M	33	172	72	16	+
6	C	M	22	170	75	6	+
7	R	W	22	156	47	4	
8	R	W	23	164	56	5	
9	R	M	24	170	66	5	
10	R	M	45	170	68	23	+
11	R	M	44	180	80	23	+
Median (Total, *n* = 11)			23	171	68	6	
Median (competitive rowers, *n* = 6)			24	173	71	5	
Median (recreational rowers, *n* = 5)			22	170	66	5	

C, competitive rowers; R, recreational rowers; W, women; M, men; +, participant who participated in 2,000-m maximal rowing.

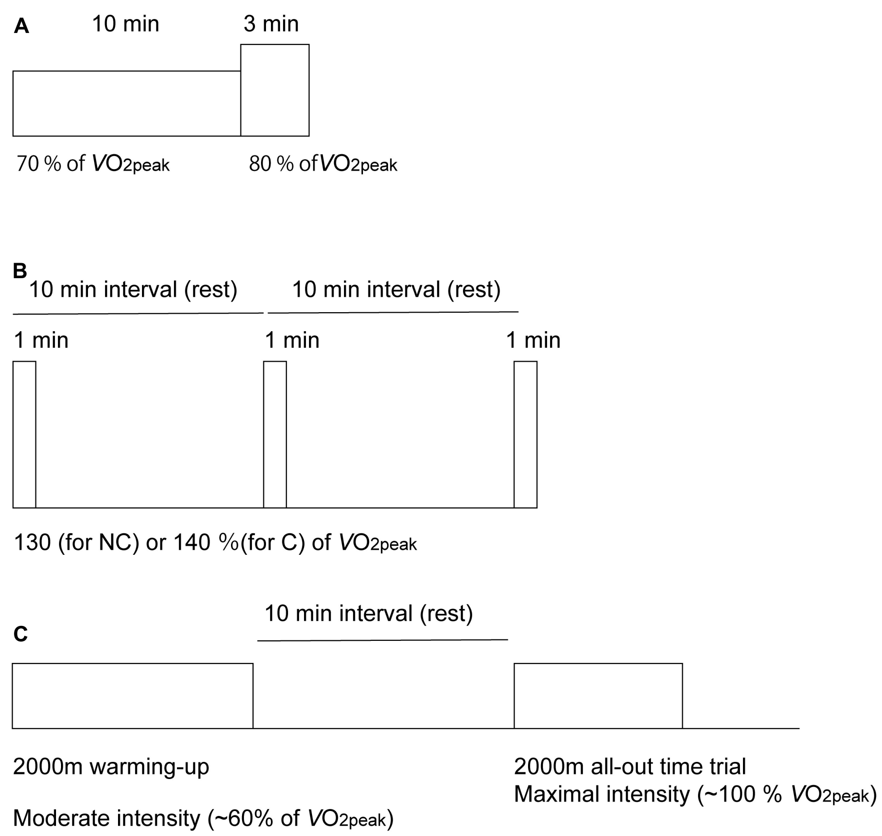

FIGURE 1 | Diagram of the experimental protocol used for the acquisition of cerebral oxygenation using near-infrared time-resolved spectroscopy during the dual-intensities of constant-load exercise consisting of 10 min of rowing exercise at 70% of peak oxygen consumption ($\dot{V}O_{2peak}$), followed by 3-min of rowing exercise at 80% of $\dot{V}O_{2peak}$ **(A)**, three sessions of 1-min of supramaximal-intensity rowing exercise **(B)** and a 2,000-m maximal row (all-out time trial) simulating an on-water competition after a 2,000-m warm-up session **(C)**. Exercise intensities are normalized as the percentages of peak pulmonary oxygen consumption ($\dot{V}O_{2peak}$). During supramaximal intensity **(B)**, intensities were determined as 130% $\dot{V}O_{2peak}$ for the non-competing rowers (NC) and as 140% $\dot{V}O_{2peak}$ for the competitive rowers **(C)** group.

data were averaged at the last 30 s of rest, $Ex_{70\%}$, $Ex_{80\%}$ and 3 min after the exercise was terminated; fluctuations derived from body movement and respiration during rowing were considered. RPE was monitored at 10 min and 13 min after the exercise started. Ten minutes before exercise initiation and 3 min after the exercise was terminated, the mood of the participants was evaluated using the PANAS questionnaire.

Supramaximal Rowing Exercise

After 20 min of rest after the dual-staged constant-load rowing ergometer exercise, rowers performed three sessions of 1-min of ExSp, during which the intensity exceeded 130% $\dot{V}O_{2peak}$ for recreational rowers and 140% $\dot{V}O_{2peak}$ for competitive rowers (**Figure 1B**). ExSp started with a 10-min interval so that rowers had enough time to recover between the sessions. Cardiovascular and respiratory gas exchange variables and oxygenation in the PFC were measured throughout the exercise session. NIRS data and cardiorespiratory data were averaged at the last 15 s of rest before the exercise started as the baseline for each ExSp. Cardiorespiratory data were averaged at the last 15 s of the 1-min ExSp. NIRS data were collected when these values attained the nadir after the termination of the exercise.

2,000 m All-Out Row Following a Warmup Session

Seven male rowers (five competitive and two recreational rowers) were included. The rowers performed their routine programs before the Ex_{2000} time trial. A 2,000-m warm-up rowing session, during which exercise intensity was targeted at approximately 60% $\dot{V}O_{2peak}$ (ExM), was included. This intensity corresponded to the level below VT1. After a 10-min rest, the rowers started Ex_{2000} and were encouraged to develop maximal effort. Cardiovascular variables, respiratory gas exchange variables, and oxygenation in the PFC were measured throughout the exercise session (during the warmup and all-out rows). NIRS values and cardiorespiratory data were averaged at the last 15 s of rest before the exercise started as the baseline and at the last 15 s of ExM and Ex_{2000} as the termination of exercise. Measurements of cardiovascular and respiratory gas exchange variables and NIRS values were continued until 2 min after ExM was terminated. NIRS measurements were continued until 4 min after Ex_{2000} was terminated, whereas measurements of cardiovascular and respiratory gas exchange variables were completed immediately after the exercise was terminated.

Cardiovascular and Respiratory Gas Exchange Measurements

CO, systolic blood pressure (SBP), and diastolic blood pressure (DBP) were measured with an impedance cardiograph (Physio Flow Enduro, Manatec Biomedical, Paris, France) only for the dual-staged constant-load rowing exercise, $Ex_{70\%}$, and $Ex_{80\%}$. Measured data were averaged and indicated at 5-s intervals. As the diastolic period is reduced disproportionately more than the systolic period, mean blood pressure (MBP) is calculated as follows: MBP = DBP + Fs * (SBP–DBP), where Fs denotes the duration of arterial systole as a fraction of the cardiac cycle (Rogers and Oosthuyse, 2000). As Physio Flow Enduro provides the left ventricular ejection time (LVET) but not the pre-ejection period (PEP), it does not indicate the duration of arterial systole, which is the sum of LVET and PEP. Accordingly, we estimated MBP using the LVET as a fraction of the cardiac cycle. For the other two sessions including Ex_{2000} and ExSp, CO measurements were not applied because the signals were unstable because of artifacts introduced by body movement. HR was measured using the Sport tester Polar 725X (Polar Electro Oy, Kempele, Finland). Respiratory gas exchange variables were measured throughout all four sessions with the breath-by-breath mode using an online gas analyzer (Quark CPET, Cosmed) as described previously. All data were averaged at 15-s intervals. During the exercise sessions, except for Ex_{2000}, measurements were begun 2 min before the exercise started and continued 5 min after the exercises were completed. During Ex_{2000}, measurements of respiratory gas exchange measurements were stopped immediately after the session was completed.

Near-Infrared Spectroscopy Measurements

We used a portable three-wavelength TRS system (tNIRS; Hamamatsu Photonics K.K., Hamamatsu, Japan) to quantitatively measure changes in PFC oxygenation. The TRS system uses a time-correlated single-photon counting technique for detection. The precise methodology has been previously described (Ijichi et al., 2005; Torricelli et al., 2014; Lange and Tachtsidis, 2019). Briefly, the system consists of three-picosecond light pulsers with different wavelengths (755, 816, and 850 nm), with a 100-ps duration at a repetition frequency of 5 MHz as the pulse light source, a photon-counting head for single-photon detection, and signal-processing circuits for time-resolved measurements. The light emission and detection optodes were positioned on the forehead just below the hairline with a 30-mm interoptode distance. Based on our previous study (Hiura et al., 2018), the location probes were allocated using the International EEG 10–20 system for electrode placement (Klem et al., 1999). The optodes were placed over the left and right sides of the forehead between Fp1 and F3, and between Fp2 and F4 to maximize the probability of photon transmission through the lateral portions of Brodmann areas 9 and 46 (Okamoto et al., 2004). The optodes were fixed with black-colored rubber to prevent stray light from reaching the detector. The covered optodes were firmly adhered to the skin with transparent tape. Furthermore, to prevent movement, the participant wore a cap with an opaque cloth attached. The photons passed through the scalp, skull, and frontal lobe to a depth of several centimeters, with only a minimal influence on skin blood flow. The TRS method provided absolute values of cerebral HbO and HbR. ScO_2, HbT, and CBV were calculated as follows:

$$ScO_2\,(\%) = \frac{[HbO]}{[HbO] + [HbR]} \quad (1)$$

$$[HbT] = [HbO] + [HbR] \quad (2)$$

$$CBV\,(mL/100\,g) = \frac{HbT \times MW_{Hb}}{HGB \times D_{bt}} \quad (3)$$

where [HbO], [HbR], and [HbT] indicate the concentrations of oxyhemoglobin, deoxyhemoglobin and total hemoglobin in the brain tissue (μM), respectively, obtained using TRS, MW_{Hb} is the molecular weight of hemoglobin (64,500), HGB is the blood hemoglobin concentration (g/dL), and Dbt is the brain tissue density (1.05 g/mL) (Ijichi et al., 2005; Ishii et al., 2014).

To estimate relative $CMRO_2$ ($rCMRO_2$) using TRS, we used the following equation:

$$CMRO_2 = CBF \times 1.39 \times HGB \times (SaO_2 - SvO_2)$$

where SaO_2 is arterial hemoglobin and SvO_2 is venous hemoglobin.

ScO_2 was calculated using the following equation (Watzman et al., 2000):

$$ScO_2 = \alpha SaO_2 + \beta SvO_2, \text{ with } \alpha + \beta = 1$$

where α and β are constants.

Using these formulas and applying SaO_2 and ScO_2, we obtained the following:

$$CMRO_2 = CBF \times 1.39 \times HGB \times \frac{SaO_2 - ScO_2}{\beta}$$

Because we assumed a constant power-law relationship among changes in CBF and CBV (Roche-Labarbe et al., 2010) and considered the reference status (e.g., at rest), relative changes in $CMRO_2$ ($rCMRO_2$) were calculated as follows:

$$rCMRO_2 = \frac{CMRO_2}{CMRO_{2\ rest}} = \frac{HGB}{HGB_{rest}} \times \left(\frac{CBV}{CBV_{rest}}\right)^{\gamma} \times \left(\frac{SaO_2 - ScO_2}{SaO_{2\ rest} - ScO_{2\ rest}}\right)$$

with γ = 2.6 (Grubb et al., 1974; Brown et al., 2003) and the subscript "rest" indicated the baseline values.

Because arterial and venous blood samplings were not available in the present study, we assumed that changes in HGB and SaO_2 would be identical to the results of previous studies with similar exercise protocol (Nielsen et al., 1998; Nielsen, 2003; González-Alonso et al., 2004). We assumed that HGB would increase by 5, 6, 7, and 10% with ExM, $Ex_{70\%}$, $Ex_{80\%}$, and Ex_{2000}, respectively, while the influence of the short duration of ExSp would be negligible. We assumed SaO_2 to be 98% for the baseline; however, we assumed it to be 97, 96, 95, and 92% for ExM, $Ex_{70\%}$, $Ex_{80\%}$, and Ex_{2000}, respectively. For ExSp, SaO_2 was assumed to be 97%. Although the HGB values for five participants were examined within 1 week of the main study, we referred to these values only to clarify whether [HbT] was attributed as an outlier. As shown in the aforementioned formula, individual HGB was not necessary to estimate $rCMRO_2$ and relative changes in CBV (i.e., the ratio of CBV to CBV_{rest} [rCBV]).

To evaluate the effect of different types of exercise intensities on cerebral oxygenation and hemodynamics, relative changes in ScO_2 (ΔScO_2) and [HbT] (ΔHbT), $rCMRO_2$, and rCBV were measured at the end of exercise and at 2–4 min after exercise termination. Values obtained at the last 15 s of exercise were defined as the effect at the end of exercise and compared with those at rest for all sessions. Values obtained at 3 min after the exercise was terminated were used as the effect after exercise termination for $Ex_{70\%}$, $Ex_{80\%}$ and ExSp and compared with those at rest. For the dual-stage constant-load rowing exercise, the effect of at the end of $Ex_{80\%}$ was regarded as the sum of $Ex_{70\%}$ and $Ex_{80\%}$ ($Ex_{70\%} + Ex_{80\%}$). For ExM and Ex_{2000}, values obtained at approximately 2 and 4 min after the exercise was terminated were used, respectively, as the effect after exercise termination compared with those at rest. These time points corresponded to the 20th and 50th percentiles of the total elapsed time of ExM and Ex_{2000}, respectively, considering the inter-individual differences.

When significant changes in ScO_2 or [HbT] for any exercise session were identified, we examined whether ΔScO_2 and ΔHbT were correlated with relative $\dot{V}O_{2peak}$, $\dot{V}O_{2peak}$, and MPO.

Statistics

Data were analyzed using GraphPad Prism 9 (GraphPad Software, Inc, San Diego, CA, United States) and SPSS version 25 (IBM, Armonk, NY, United States). The average data are expressed as the arithmetic mean ± standard deviation, unless otherwise stated. Normal Gaussian distribution of normality was performed using the Shapiro-Wilk test. To calculate differences between groups, a *t*-test was performed after testing the normality of distribution using the Shapiro-Wilk test. To evaluate differences between time points for the examined variables throughout each exercise session, a one-way repeated-measures analysis of variance (ANOVA) with Turkey's honestly significant difference *post hoc* procedure was performed. For NIRS variables, one-way repeated-measures ANOVA with Tukey's HSD *post hoc* procedure was performed to evaluate the difference between rest, during exercise, and after exercise. The magnitude of the difference was assessed by the effect sizes (Cohen's d; d or partial eta squared; η^2) and defined as small (≥0.2 to < 0.5), medium (≥0.5 to <0.8), and large (≥0.8) for d, and small (≥0.01 to < 0.06), medium (≥ 0.06 to < 0.14), and large (≥0.14) for η^2 (Cohen, 1988). Pearson's correlation coefficients were used to assess relationships between two variables of interest.

RESULTS

As training years, status, body size, age and sex differed among rowers, $\dot{V}O_{2peak}$ and relative $\dot{V}O_{2peak}$ ranged from 2.3 to 4.8 L min^{-1} (3.6 ± 0.7) and from 43 to 65 mL min^{-1} kg^{-1}, respectively. Because the NIRS data of two rowers were not completely available throughout the exercise sessions because of artifacts probably caused by sweat and head movement, we applied data obtained from the left forehead for nine rowers and from the right forehead for two rowers. An evaluation of the NIRS data obtained from the right PFC of two rowers indicated similarities in the NIRS trends when both sides were available.

Dual-Staged Constant-Load Rowing Exercise

Table 2 contains a summary of cardiovascular and respiratory variables at the baseline, $Ex_{70\%}$, $Ex_{80\%}$, and 3 min after exercise termination. Cardiovascular and respiratory variables (except for HR, CO, $\dot{V}_E$, $\dot{V}CO_2$, and RER) increased at the end of $Ex_{70\%}$ and $Ex_{80\%}$ and returned to the baseline levels. A summary of NIRS variables during the session are shown in **Table 3**. The magnitude of changes in ScO_2 and [HbT] were large compared with other NIRS variables. Changes in ScO_2 and [HbT] throughout the exercise session are presented with those in $P_{ET}CO_2$ and relative $\dot{V}O_{2peak}$ in **Figure 2**.

During $Ex_{70\%}$, the PO was 147 ± 34 W, corresponding to 56 ± 5% MPO and relative $\dot{V}O_2$ increased to 67 ± 6 of $\dot{V}O_{2peak}$. RPE recorded at 10 min during the exercise session was 12 ± 1.6 arbitrary units (a.u.). [ScO_2] began to decrease at the onset of $Ex_{70\%}$ and had significantly lower values than that at rest from 2 to 8 min when analyzed throughout the session. [HbT] gradually increased during $Ex_{70\%}$ and was significantly higher than that at rest after 6 min when the exercise was started.

During $Ex_{80\%}$, PO was 187 ± 48 W, corresponding to 70 ± 4% of MPO, and relative $\dot{V}O_2$ increased to 79 ± 6 of $\dot{V}O_{2peak}$, with further increases in CO and MBP compared with $Ex_{70\%}$. RPE increased to 13 ± 1.6 a.u. compared with the end of $Ex_{70\%}$ ($p < 0.001$). The manipulation of exercise intensity evoked significant increases in all cardiovascular and respiratory variables except for $P_{ET}CO_2$ at the end of $Ex_{80\%}$ compared with $Ex_{70\%}$. [ScO_2] began to decrease again at the onset of $Ex_{70\%}$, and it reached its nadir at the end of $Ex_{80\%}$. [HbT] increased from that at rest during $Ex_{80\%}$, but it did not increase further compared with $Ex_{70\%}$.

After exercise termination, MBP, R_f, $\dot{V}O_2$, and $P_{ET}CO_2$ returned to the same level as those at rest, but other cardiovascular and respiratory variables increased compared to the values at rest values. [ScO_2] sharply increased after exercise termination, attaining the highest value at 5 min after exercise termination. [ScO_2] increased to 66.6 ± 4.0%, without a significant difference compared to that at rest. [HbT] had a peak of 79.4 ± 11.9 μM at 1 min after exercise termination; then, it gradually decreased, staying at a higher level than that at rest

TABLE 2 | Cardiovascular and respiratory variables in response to 10-min of 70% $\dot{V}O_{2peak}$-intenity followed by 3-min of 80% $\dot{V}O_{2peak}$-intenity rowing ergometer exercises.

	Rest	$Ex_{70\%}$	$Ex_{80\%}$	Post-3 min
Heart rate (beats min^{-1})	78 ± 11	156 ± 14***	167 ± 15***, ††	104 ± 13**
MBP (mmHg)	90 ± 6	102 ± 5***	107 ± 5***, ††	90 ± 7
Cardiac output (l min^{-1})	5.8 ± 0.9	15.0 ± 2.6***	18.1 ± 3.3***, ††	8.2 ± 1.1**
$\dot{V}_E$ (l min^{-1})	13 ± 2	73 ± 20***	88 ± 21***, ††	22 ± 7**
R_f (breaths min^{-1})	19 ± 4	45 ± 10***	49 ± 10***	24 ± 8
$\dot{V}O_2$ (l min^{-1})	0.4 ± 0.1	2.5 ± 0.6***	2.9 ± 0.6***, ††	0.5 ± 0.1
Relative $\dot{V}O_2$ (ml min^{-1} kg^{-1})	6.5 ± 1.4	37.4 ± 5.1***	41.2 ± 5.7†	7.7 ± 1.7
$P_{ET}CO_2$ (mmHg)	35 ± 3.0	42 ± 4.8**	40 ± 5.1*	36 ± 4.2
$\dot{V}CO_2$ (l min^{-1})	0.4 ± 0.1	2.5 ± 0.6***	2.9 ± 0.7***, ††	0.6 ± 0.2**
RER	0.84 ± 0.07	0.99 ± 0.03**	1.06 ± 0.03***, ††	1.20 ± 0.07***

*Values are expressed as mean ± standard deviation. (N = 11) at baseline (Rest), at the end of 10-min of constant-load exercise at 70% of peak oxygen consumption ($\dot{V}O_{2peak}$; $Ex_{70\%}$), and during 3-min of constant-load exercise at 80%$\dot{V}O_{2peak}$ ($Ex_{80\%}$), and at 3 min after exercise termination (Post-3 min). Data were averaged over 15 s for each time point. MBP, mean blood pressure;$\dot{V}_E$, minute ventilation; R_f, breathing frequency;$\dot{V}O_2$, pulmonary oxygen consumption; $P_{ET}CO_2$, end-tidal carbon dioxide,$\dot{V}CO_2$, CO_2 production; RER, respiratory exchange ratio. Significant difference compared to rest: *P < 0.05, **P < 0.01, ***P < 0.001. Significant difference compared to $Ex_{70\%}$: †P < 0.05, ††P < 0.001.*

TABLE 3 | Changes in near-infrared spectroscopy signals in response to 10-min of 70% $\dot{V}O_{2peak}$-intenity followed by 3-min of 80% $\dot{V}O_{2peak}$-intenity rowing ergometer exercises.

	Rest	$Ex_{70\%}$	$ExH_{80\%}$	Post-3 min	Effect sizes (η^2-partial)
ScO_2 (%)	64.4 ± 4.0	62.0 ± 3.8	60.2 ± 4.0**, ††	66.5 ± 4.3*, ††,§§	0.872
HbT (μM)	70.4 ± 9.3	76.5 ± 11.2**	77.5 ± 11.7**	78.9 ± 11.4**, ††,§§	0.881
O_2Hb (μM)	43.1 ± 8.8	45.4 ± 9.6	44.9 ± 9.1	49.5 ± 11.5*, †,§	0.576
HHb (μM)	25.1 ± 4.4	29.2 ± 4.9**	30.9 ± 5.7**, ††	26.6 ± 5.1††,§§	0.803

*Values are expressed as mean ± standard deviation. (N = 11) at baseline (Rest), at the end of 10-min of constant-load exercise at 70% of peak oxygen consumption ($\dot{V}O_{2peak}$; $Ex_{70\%}$), during 3-min of constant-load exercise at 80%$\dot{V}O_{2peak}$ ($Ex_{80\%}$), and at 3 min after exercise termination (Post-3 min). Data were averaged over 15 s for each time point. ScO_2, cerebral hemoglobin oxygen saturation; HbT, total hemoglobin concentration in the brain tissue; HBO, oxyhemoglobin concentration in the brain tissue; HHb, deoxyhemoglobin concentration in the brain tissue. Significant difference compared to rest: *P < 0.05, **P < 0.01. Significant difference compared to $Ex_{70\%}$: †P < 0.05, ††P < 0.01. Significant difference compared to $Ex_{80\%}$: § P < 0.05, §§ P < 0.01.*

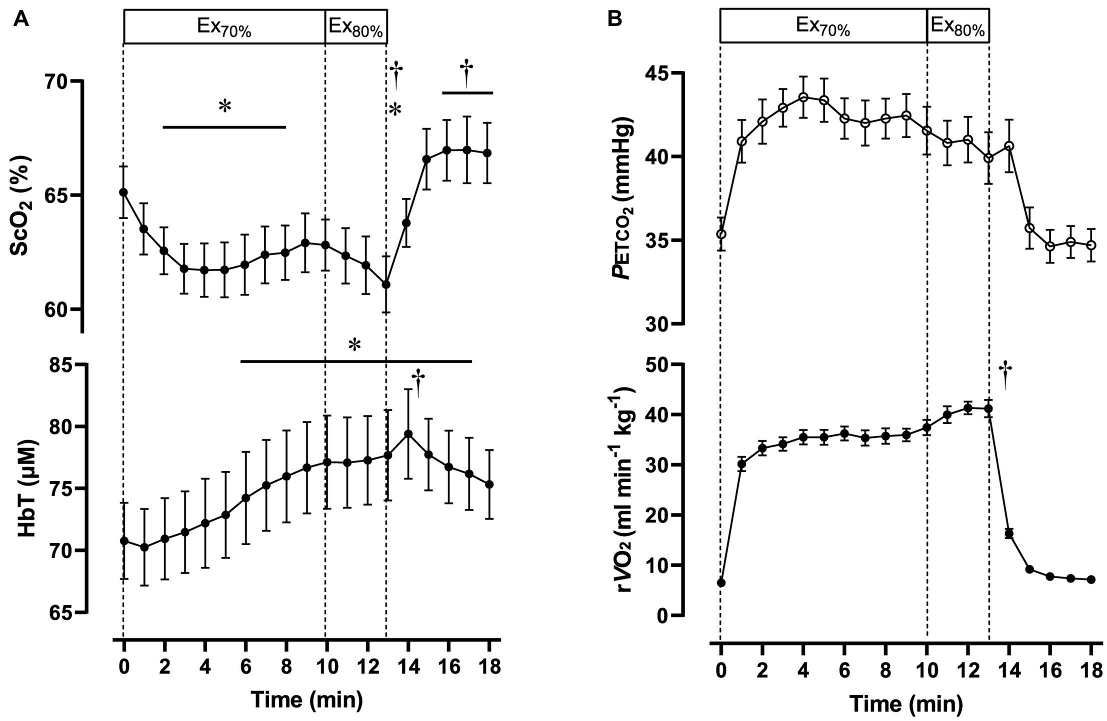

FIGURE 2 | Cerebral oxygenation variables obtained using near-infrared spectroscopy for the prefrontal cortex **(A)** and respiratory variables **(B)** during the dual-stage constant-load rowing exercise for 10-min at 70% of peak oxygen consumption ($\dot{V}O_{2peak}$) followed by 3-min of rowing ergometer exercises at 80% of $\dot{V}O_{2peak}$. Solid lines indicate baseline (0 min) and at the end of $Ex_{70\%}$ (10 min) and $Ex_{80\%}$ (13 min) exercise. Data were averaged over 15 s for each time point. $Ex_{70\%}$, exercise at 70% of $\dot{V}O_{2peak}$; $Ex_{80\%}$, exercise at 80% of $\dot{V}O_{2peak}$; ScO_2, cerebral hemoglobin oxygen saturation; HbT, total hemoglobin concentration in the brain tissue; $r\dot{V}O_2$, relative pulmonary oxygen consumption; $P_{ET}CO_2$, end-tidal carbon dioxide. Significant difference compared to baseline; $^*P < 0.05$. Significant difference compared to the end of exercise at 70% of $\dot{V}O_{2peak}$ (10 min); $^†P < 0.05$. Statistical differences between each timepoint were determined using a one-way analysis of variance for repeated measures and Turkey's *post hoc* multiple comparisons test.

until 5 min after exercise termination. The PANAS negative score changed significantly from 17 ± 5.1, at rest, to 13 ± 5.6 a.u., after $Ex_{80\%}$ ($p < 0.01$), while the PANAS positive score did not change significantly (from 29 ± 4.9 to 30 ± 6.4 a.u.; $p = 0.13$).

Supramaximal Rowing Exercise

Three sessions of ExSp evoked volitional exhaustion during each session. For three repetitions, PO values were 359 ± 135 W, 357 ± 115 W, and 352 ± 116 W, corresponding to 132 ± 24, 133 ± 11, and 131 ± 13% of MPO, respectively. There was no significant difference in PO among the three sessions [$F(2, 125) = 0.20$, $p = 0.70$]. **Table 4** contains a summary of cardiovascular and respiratory variables at the baseline and end of each bout. With 10-min intervals, the baseline values at each ExSp for HR, $\dot{V}O_2$, and $\dot{V}CO_2$ were identical, while respiratory variables were changed as sessions accumulated. During each ExSp session, the relative $\dot{V}O_2$ increased to 81 ± 14, 84 ± 8, and 83 ± 10% of $\dot{V}O_{2peak}$, respectively. $P_{ET}CO_2$ significantly differed from baseline during the first and third sessions, and it decreased at the end of the second and third sessions compared with that of the first session. The trends of the variables measured using NIRS are shown in **Table 5**. Changes in [ScO_2] and [HbT] throughout the three sessions are presented with those of $P_{ET}CO_2$ and relative $\dot{V}O_{2peak}$ in **Figure 3**. The baseline values at each ExSp for the NIRS samples were identical. [ScO_2] continued to decrease during each session and reached its nadir at 105, 15, and 30 s after exercise termination. [HbT] had its nadir exactly at the termination of each session and significantly decreased only during the first and second sessions compared with the baseline values. The magnitude of changes in [ScO_2] was larger than that of [HbT] throughout the session.

Warmup and 2,000-m All-Out Row

Table 6 contains a summary of cardiovascular and respiratory variables at the baseline and at the end of ExM and Ex_{2000}. A summary of NIRS variables during the session are shown in **Table 7**. Changes in ScO_2 and [HbT] throughout the exercise session are presented with those in $P_{ET}CO_2$ and relative $\dot{V}O_2$ in **Figure 4**. For both ExM and Ex_{2000}, individual total elapsed times were normalized to the scale of 100% because inter-individual differences were apparent.

For ExM, PO was 127 ± 18 W during 564 ± 27 s, corresponding to 45 ± 7% MPO. At the end of ExM, the values of the cardiovascular and ventilatory variables (except for RER) increased. Relative $\dot{V}O_2$ increased to 61 ± 5% of $\dot{V}O_{2peak}$. $\dot{V}O_{2peak}$ and $P_{ET}CO_2$ remained at the same level, but not during the initial phase. [ScO_2] significantly decreased compared to that at rest to 61.3 ± 3.5% from 20 to 30% to the normalized scale;

TABLE 4 | Cardiovascular and ventilatory variables in response to three sessions of 1-min of supramaximal-intensity rowing exercise.

	First		Second		Third	
	Pre-Ex1	Ex1	Pre-Ex2	Ex2	Pre-Ex3	Ex3
Heart rate (beats min^{-1})	102 ± 16	164 ± 20	111 ± 13**	170 ± 12	116 ± 12***	170 ± 11
$\dot{V}_E$ (breaths min^{-1})	22 ± 9	110 ± 22	28 ± 9	109 ± 26	32 ± 9**	119 ± 33*
R_f (breaths min^{-1})	21 ± 4	61 ± 16	25 ± 6	69 ± 15	27 ± 6**	75 ± 13$
$\dot{V}O_{2peak}$ (l min^{-1})	0.5 ± 0.2	2.9 ± 0.8	0.6 ± 0.1	3.0 ± 0.6	0.6 ± 0.2	3.0 ± 0.7
Relative $\dot{V}O_2$ (ml min^{-1} kg^{-1})	6 ± 0.8	43 ± 9	8 ± 1.3	45 ± 6	7 ± 1.4	44 ± 7
$P_{ET}CO_2$ (mmHg)	32 ± 3	36 ± 6	30 ± 3	29 ± 6$$	26 ± 3**, ††	26 ± 5$$
$\dot{V}CO_2$ (l min^{-1})	0.6 ± 0.2	3.1 ± 0.7	0.7 ± 0.2	2.6 ± 0.5$$	0.7 ± 0.2	2.6 ± 0.6$
RER	1.05 ± 0.13	1.01 ± 0.13	1.10 ± 0.13	0.91 ± 0.12	1.03 ± 0.14	0.91 ± 0.08

*Values are expressed as mean ± standard deviation. (N = 11) at baseline of the first session (Pre-Ex1), the end of the first session (Ex1), at baseline of the second session (Pre-Ex2), at the end of the second session (Ex2), at baseline of the third session (Pre-Ex3), and the end of the third session (Ex3). Data were averaged over 15 s for each time point. V_E, minute ventilation; R_f, breathing frequency;$\dot{V}O_2$, pulmonary oxygen consumption; $P_{ET}CO_2$, end-tidal carbon dioxide,$\dot{V}CO_2$, carbon dioxide production; RER, respiratory exchange ratio. At Ex1, Ex2, and Ex3, all variables, except for $P_{ET}CO_2$ and RER significantly changed compared with the corresponding baselines (P < 0.01). Significant difference compared to Pre-Ex1 for Pre-Ex2 and/or Pre-Ex3: *P < 0.05, **P < 0.01, ***P < 0.001. Significant difference compared to Pre-Ex2 at Pre-Ex3: ††P < 0.01. Significant difference compared to Ex1 at Ex2 and/or Ex3: $P < 0.05, $$P < 0.01.*

TABLE 5 | Changes in near-infrared spectroscopy signals in response to three bouts of 1-min supramaximal-intensity rowing ergometer exercises.

	First			Second			Third		
	Pre-Ex1	Ex1	ES (d)	Pre-Ex2	Ex2	ES (d)	Pre-Ex3	Ex3	ES (d)
ScO_2 (%)	66.8 ± 3.9	62.5 ± 3.9**	1.19	66.0 ± 4.0	62.5 ± 4.2**	0.89	66.8 ± 4.6	62.5 ± 3.6**	1.08
HbT (μM)	74.2 ± 11.6	72.4 ± 10.9**	0.17	74.8 ± 11.3	72.6 ± 10.6**	0.21	76.5 ± 13.0	74.1 ± 11.1	0.21
HbO (μM)	49.7 ± 9.6	45.8 ± 9.2***	0.40	49.7 ± 9.6	45.8 ± 9.2**	0.44	51.5 ± 11.7	46.7 ± 7.3*	0.49
HbR (μM)	24.4 ± 3.4	28.1 ± 5.3**	0.85	24.4 ± 3.4	28.1 ± 5.3**	0.81	25.0 ± 2.4	28.0 ± 4.7*	0.76

*Values are expressed as mean ± standard deviation. (N = 11) at baseline of the first session (Pre-Ex1), at the end of the first session (Ex1), at baseline of the second session (Pre-Ex2), at the end of the second session (Ex2), at baseline of the third (Pre-Ex3), and at the end of the third session (Ex3). Data were averaged over 15 s for each time point. ScO_2, cerebral hemoglobin oxygen saturation; HbT, total hemoglobin concentration in the brain tissue; HBO, oxyhemoglobin concentration in the brain tissue; HHb, deoxyhemoglobin concentration in the brain tissue; ES(d), effect sizes (Cohen's d). For Ex1, Ex2, and Ex3, these time points differed among ScO_2, HbT, HbO, and HbR because data were demonstrated at time points when the largest changes were observed. For ScO_2, values at 105, 15 and 30 s after exercise termination of Ex1, Ex2, and Ex3, respectively. For HbT, values at 0 s after exercise termination of all conditions. For HbO, values at 0 s for Ex1 and Ex2 and 30 s after exercise termination of Ex1 and Ex2,and at 30 s after exercise termination. For HbR, values at 120, 90, and 45 s after exercise termination of for Ex1, Ex2, and Ex3, respectively. Significant difference compared to Pre-Ex1 for Ex1, compared to Pre-Ex2 for Ex2, and compared to Pre-Ex3 for Ex3 *P < 0.05, **P < 0.01, ***P < 0.001.*

then, it continued to increase, attaining the highest value of 66.1 ± 3.5% at the end of the session. [HbT] gradually increased and attained the highest value of 78.7 ± 14.1 μM at 110% of the normalized scale. The magnitude of the changes was similar among NIRS variables.

For Ex_{2000}, PO was 262 ± 39 W during 445 ± 26 s, corresponding to 91 ± 4% MPO. At the end of Ex_{2000}, the cardiovascular and ventilatory variables except for RER and $P_{ET}CO_2$ increased. Relative $\dot{V}O_2$ increased to 95 ± 9% of $\dot{V}O_{2peak}$. HR and $P_{ET}CO_2$ significantly increased at baseline during Ex_{2000} as a result of the warmup procedures, but the other variables were similar. Changes in [ScO_2] and [HbT] throughout the session are presented with those of $P_{ET}CO_2$ and relative $\dot{V}O_2$ in **Figure 5**. [ScO_2] decreased immediately after the exercise started and reached its nadir of 49.2 ± 3.0% at the termination of exercise; then it began to increase to the same level as that at baseline at 130% of the normalized scale. [HbT] stayed at the same level during Ex_{2000} and began to increase after the termination of exercise, and significantly increased compared to the rest at 120% of the normalized scale thereafter. When comparing the baseline variables of ExM and Ex_{2000}, only [HbT] had a significantly higher value. The magnitude of the changes in NIRS variables of Ex_{2000} was larger than that of ExM.

Relative Changes in Cerebral Oxygenation and Estimation of rCBV and $rCMRO_2$

At the End of Exercise

The ΔScO_2 and ΔHbT (**Figure 6A**) and estimated rCBV and $rCMRO_2$ (**Figure 6B**), comparing baseline values with values at the end of the five intensities of rowing exercise are presented in **Figure 6**. Because there were no significant differences among ΔScO_2 [$F(1.87, 18.67) = 0.35$; $p = 0.70$] and ΔHbT [$F(1.91, 19.10) = 0.18$; $p = 0.83$] at the end of three sessions of ExSp or for rCBV and rCMRO2, these values obtained during the first session were used as the effect of ExSp. The ΔScO_2 was −23.0 ± 2.9% at the end of Ex_{2000}, and it was significantly greater than all the other intensities; however, the ΔScO_2 were similar among ExM, $Ex_{70\%}$, $Ex_{70\%}$ + $Ex_{80\%}$, and ExSp. The ΔHbT were 8.3 ± 4.6, 8.8 ± 4.8, and 9.7 ± 4.8% during ExM, $Ex_{70\%}$ and $Ex_{70\%}$ + $Ex_{80\%}$, respectively. The ΔHbT at the end

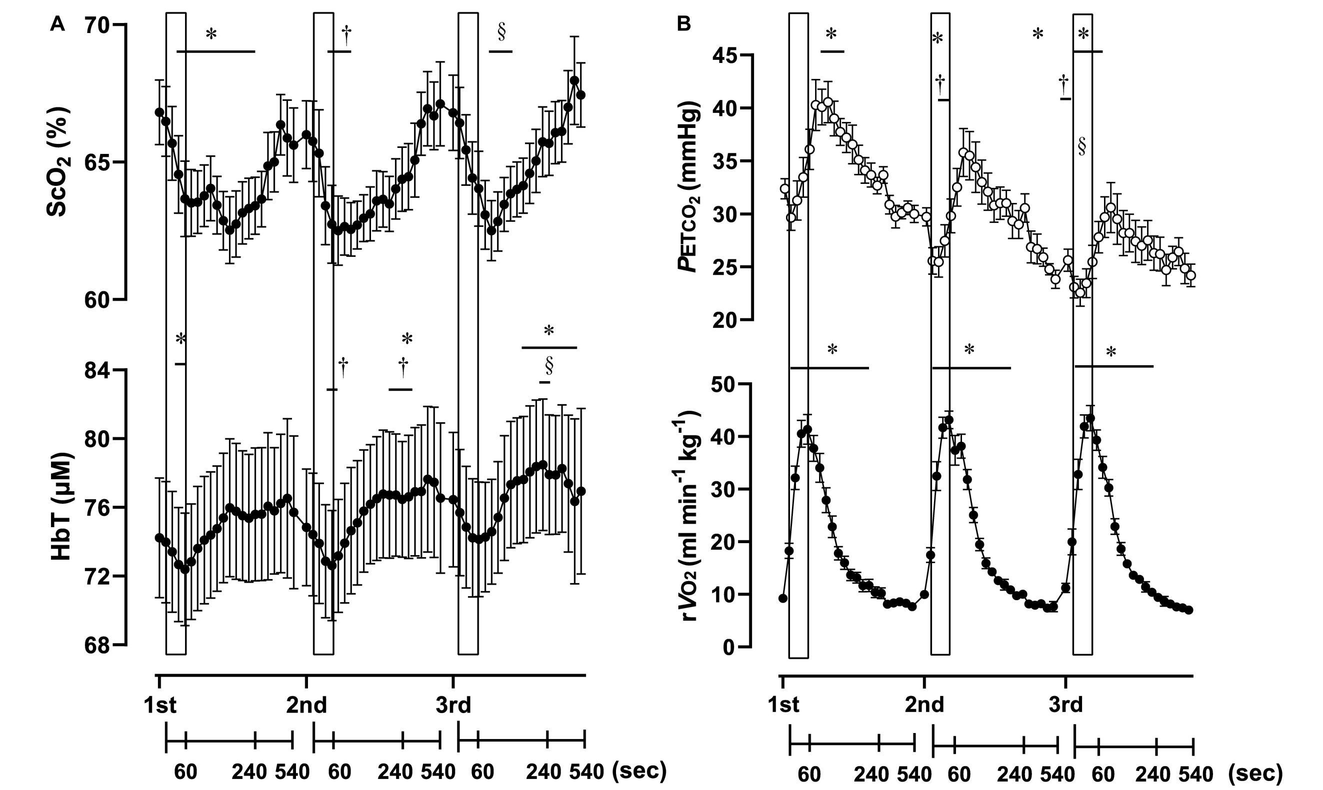

FIGURE 3 | Cerebral oxygenation variables obtained using near-infrared spectroscopy for the prefrontal cortex **(A)** and respiratory variables **(B)** of three sessions of 1-min of supramaximal rowing exercise. Each exercise bout started with a 10-min interval. Data are plotted with samplings of 15 s for 4 min from the start, and then with samplings of 60 s from 5 to 9 min for graphical representation. Solid rectangles representing 1-min sessions are placed at the time when exercise was started. ScO_2, cerebral hemoglobin oxygen saturation; HbT, total hemoglobin concentration in the brain tissue; $r\dot{V}O_2$, relative pulmonary oxygen consumption; $P_{ET}CO_2$, end-tidal carbon dioxide. Significant difference compare to baseline of the first exercise session; $^*P < 0.05$. Significant difference compared to baseline of second exercise session; $^\dagger P < 0.05$. Significant difference compared to baseline of the third exercise session; $^\S P < 0.05$. Statistical differences between each timepoint were determined using a one-way analysis of variance for repeated measures and Turkey's *post hoc* multiple comparisons test.

TABLE 6 | Cardiovascular and ventilatory variables in response to 2,000 m moderate-intensity (warming up) followed by 2,000 m maximal rowing ergometer exercises.

	2,000 m moderate-intensity rowing		2,000 m maximal rowing	
	Rest	**Ex terminated**	**Rest**	**Ex terminated**
Heart rate (beats min^{-1})	92 ± 5	143 ± 15***	109 ± 13†	183 ± 16***
$\dot{V}_E$ (breaths min^{-1})	22 ± 4	64 ± 5***	22 ± 4	144 ± 13***
R_f (breaths min^{-1})	21 ± 7	37 ± 4***	25 ± 5	62 ± 7***
$\dot{V}O_{2peak}$ (l min^{-1})	0.8 ± 0.1	2.0 ± 0.2***	0.7 ± 0.1	4.0 ± 0.6***
Relative $\dot{V}O_2$ (ml min^{-1} kg^{-1})	11 ± 2	34 ± 5***	10 ± 2	51 ± 7***
$P_{ET}CO_2$ (mmHg)	39 ± 2	43 ± 3***	38 ± 4	33 ± 2**
$\dot{V}CO_2$ (l min^{-1})	0.8 ± 0.1	2.0 ± 0.2***	0.7 ± 0.1	4.0 ± 0.7***
RER	0.94 ± 0.12	0.95 ± 0.01	1.00 ± 0.16	1.10 ± 0.05*

Values are expressed as mean ± standard deviation. N = 7 at baseline (Rest) and at exercise termination (Ex terminated). Data were averaged over 15 s for each time point. $\dot{V}_E$, minute ventilation; R_f, breathing frequency; $\dot{V}O_{2peak}$, pulmonary oxygen consumption; $P_{ET}CO_2$, end-tidal carbon dioxide, $\dot{V}CO_2$, carbon dioxide production; RER, respiratory exchange ratio. Significant difference compared to Rest: $^*P < 0.05$, $^{**}P < 0.01$, $^{***}P < 0.001$. Significant difference compared to Rest of 2,000-m moderate-intensity rowing exercise: $^\dagger P < 0.01$.

of ExM, $Ex_{70\%}$, and $Ex_{70\%} + Ex_{80\%}$ were significantly greater than those of Ex_{2000} and ExSp. The estimated rCBV values at the end of each exercise intensity were 1.03 ± 0.04, 1.02 ± 0.05, 1.03 ± 0.04, 0.92 ± 0.04, and 0.98 ± 0.02 for ExM, $Ex_{70\%}$, $Ex_{70\%} + Ex_{80\%}$, Ex_{2000}, and ExSp, respectively. For Ex_{2000}, the rCBV was significantly lower than that of the other intensities. The rCBV of $Ex_{70\%} + Ex_{80\%}$ was significantly higher than that of $Ex_{70\%}$ and ExSp. The estimated $rCMRO_2$ values at the end of each exercise intensity were 1.06 ± 0.12, 1.06 ± 0.12, 1.17 ± 0.14, 1.02 ± 0.09, and 1.00 ± 0.04 for ExM, $Ex_{70\%}$, $Ex_{70\%} + Ex_{80\%}$, Ex_{2000}, and

TABLE 7 | Summary of NIRS data in response to 2,000 m moderate intensity (warming up) followed by 2,000 m maximal rowing ergometer exercises.

	2,000 m moderate-intensity rowing			
	Rest	**100% of elapsed time**	**120% of elapsed time (post exercise)**	**ES (η^2-partial)**
ScO_2 (%)	63.7 ± 3.5	63.6 ± 3.3	66.1 ± 3.5**, †	0.860
HbT (μM)	71.2 ± 13.1	76.6 ± 14.9**	76.4 ± 14.4**	0.825
HbO (μM)	44.7 ± 8.6	48.5 ± 9.8*	50.0 ± 10.6**	0.827
HbR (μM)	26.5 ± 4.9	28.1 ± 5.7*	26.4 ± 4.3†	0.668
	2,000 m maximal rowing			
	Rest	**100% of elapsed time**	**120% of elapsed time (post exercise)**	**ES (η^2-partial)**
ScO_2 (%)	64.5 ± 4.0	49.2 ± 3.3***	56.9 ± 3.0**, ††	0.996
HbT (μM)	75.2 ± 13.5§	76.0 ± 15.9	83.2 ± 15.9**, ††	0.951
HbO (μM)	48.7 ± 9.3	37.6 ± 8.0***	47.6 ± 9.8††	0.970
HbR (μM)	26.6 ± 4.9	38.6 ± 7.7***	35.7 ± 6.6**, †	0.942

*Values are expressed as mean ± standard deviation. N = 7 at baseline (Rest), at 100% and at 120% of total elapsed time (post exercise). Individual total elapsed times were normalized to the scale of 100% because of inter-individual differences. Es, effect size; ScO_2, cerebral hemoglobin oxygen saturation; HbT, total hemoglobin concentration in the brain tissue; HBO, oxyhemoglobin concentration in the brain tissue; HHb, deoxyhemoglobin concentration in the brain tissue. Significant difference compared to Rest: *P < 0.05, **P < 0.01, ***P < 0.001. Significant difference compared to 100% of total elapsed time: †P < 0.05, ††P < 0.001. Significant difference compared to Rest in 2,000-m moderate-intensity rowing: § P < 0.05.*

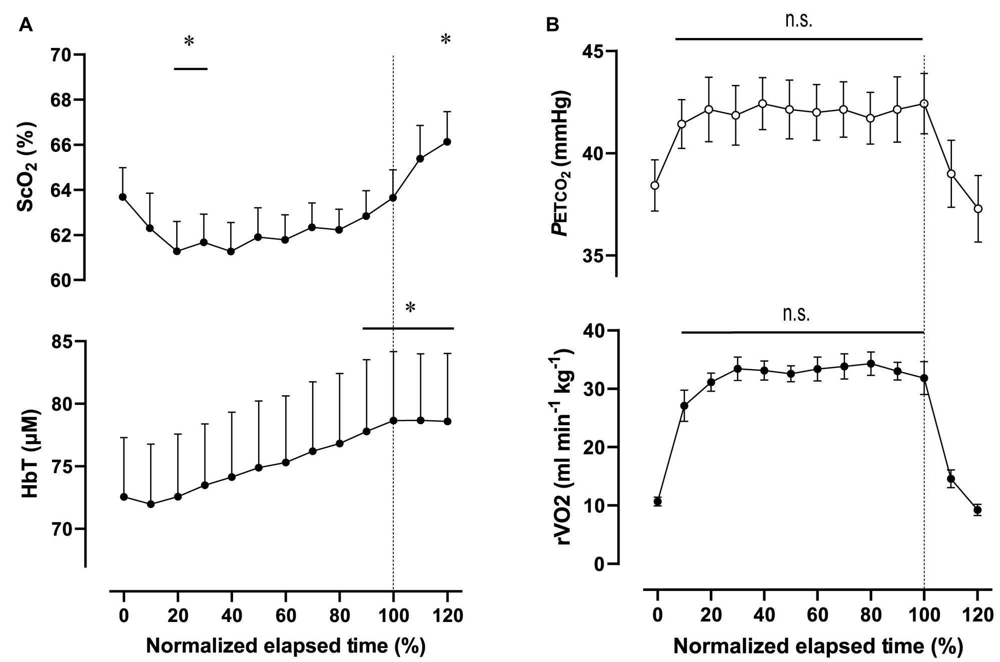

FIGURE 4 | Cerebral oxygenation variables from near-infrared spectroscopy obtained in the prefrontal cortex **(A)** and respiratory variables **(B)** during the 2,000-m warm-up row (moderate-intensity exercise). Individual total elapsed times were normalized to the scale of 100% because of inter-individual differences. Solid lines represent the time point for 100% of total elapsed time (the end of exercise). ScO_2, cerebral hemoglobin oxygen saturation; HbT, total hemoglobin concentration in the brain tissue; $r\dot{V}O_2$, relative pulmonary oxygen consumption; $P_{ET}CO_2$, end-tidal carbon dioxide. Significant difference compared to baseline; *$P < 0.05$. Significant difference compared to 100% of total elapsed time (the end of exercise); $P > 0.05$ was not significant (n.s.). Statistical differences between each timepoint were determined using a one-way analysis of variance for repeated measures and Turkey's *post hoc* multiple comparisons test.

ExSp, respectively. For $Ex_{70\%} + Ex_{80\%}$, the $rCMRO_2$ values were significantly higher than those of $Ex_{70\%}$, and ExSp.

After Termination of Exercise

The ΔScO_2 and ΔHbT observed after four sessions of different exercise intensities are presented in **Figure 6C**. Because there were not significant differences among ΔScO_2 [$F(1.84, 18.40) = 2.42$; $p = 0.12$], ΔHbT [$F(1.26, 12.53) = 0.75$; $p = 0.43$] after three sessions of ExSp, we used these values obtained after the first session of ExSp. The ΔScO_2 were 4.3 ± 2.3, 2.1 ± 4.5, −3.7 ± 3.7, and −4.3 ± 3.5% after ExM, $Ex_{70\%} + Ex_{80\%}$, Ex_{2000}, and ExSp, respectively. The ΔScO_2 after ExM and $Ex_{70\%}$ +

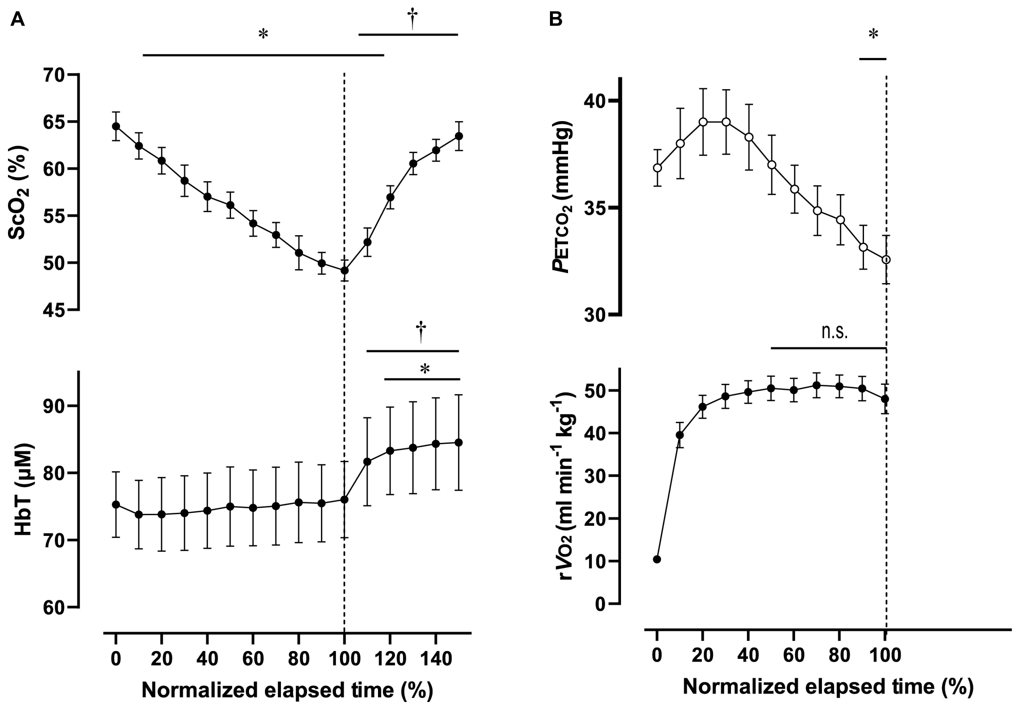

FIGURE 5 | Cerebral oxygenation variables from near-infrared spectroscopy obtained in the prefrontal cortex **(A)** and respiratory variables **(B)** during the 2,000-m all-out row (maximal-intensity exercise). Individual total elapsed times were normalized to the scale of 100% because of inter-individual differences. Solid lines represent time point for 100% of total elapsed time (the end of exercise). ScO_2, cerebral hemoglobin oxygen saturation; HbT, total hemoglobin concentration in the brain tissue; $r\dot{V}O_2$, relative pulmonary oxygen consumption; $P_{ET}CO_2$, end-tidal carbon dioxide. Significant difference compared to baseline; $^*P < 0.05$. $P > 0.05$ was not significant (n.s.). Significant difference compared to 100% of elapsed time (the end of exercise); $^†P < 0.05$. Statistical differences between each timepoint were determined using a one-way analysis of variance for repeated measures and Turkey's *post hoc* multiple comparisons test.

$Ex_{80\%}$ were significantly greater than those after Ex_{2000} and ExSp. ΔHbT were 8.4 ± 3.9, 11.5 ± 5.2, 9.6 ± 3.8, and 1.3 ± 1.8% after ExM, $Ex_{70\%} + Ex_{80\%}$, Ex_{2000}, and ExSp, respectively. The ΔHbT was significantly less after ExSp than after all other intensities.

Effect of Oxidative Capacity

When the ScO_2 and [HbT] significantly changed compared to rest, the ΔScO_2 correlated with $\dot{V}O_{2peak}$ at the end of Ex_{2000} ($r = -0.86$; $p = 0.01$). For other exercise intensities, the ΔScO_2 and ΔHbT were not correlated with MPO nor with $\dot{V}O_{2peak}$ (**Supplementary Tables 1**, **2**).

DISCUSSION

There were several main findings of this study that investigated cerebral oxygenation in the PFC during various types of exercise intensities during rowing and examined the association between altered sensations and cerebral oxygenation during exercise at 70 and 80% of $\dot{V}O_{2peak}$. First, quantitative measurements using TRS demonstrated a significant decrease in [ScO_2], but not in [HbT] in accordance with the alteration of the sense of effort (indexed from RPE) when a higher intensity of exercise was added during 13 min of dual-stage constant-load rowing exercise consisting of 67 and 79% $\dot{V}O_{2peak}$. Second, the 13 min of dual-stage constant-load rowing exercise induced a decrease in the negative affect of mood status (indexed by PANAS) accompanied by increases in both [ScO_2] and [HbT] in the PFC after exercise termination. Third, exhaustion evoked by the 2,000-m all-out row induced a distinct decrease of 23% in ScO_2, whereas exhaustion evoked by the 2,000-m all-out row and 1-min of ExSp induced declines in [HbT]. Fourth, exercise-induced changes in ScO_2 correlated with $\dot{V}O_{2peak}$ at the 2,000-m all-out row. Finally, the estimated rCBV and $rCMRO_2$ derived from quantitative values obtained by TRS demonstrated how they changed in accordance with exercise intensity.

Alterations in the Sensation of Effort and Cerebral Oxygenation Induced by High-Intensity Rowing

During the dual-stage constant-load rowing exercise at $Ex_{70\%}$ and $Ex_{80\%}$, the RPE changed from 12 to 13. In accordance with this alteration in the sensation of effort, accompanied by distinct changes in HR (156–167 bpm), CO (15.0–18.1 L min^{-1}), MBP (101–109 mmHg), and respiratory variables, ScO_2 significantly decreased from 62.0 ± 3.8 to 60.2 ± 4.0%. As exercise intensity is determined by physiological variables, with HR being most used for a typical exercise prescription, oxygenation in the PFC detects changes in exercise intensity during rowing. Because the medial PFC is involved in both executive control and the emotional salience network in conjunction with many

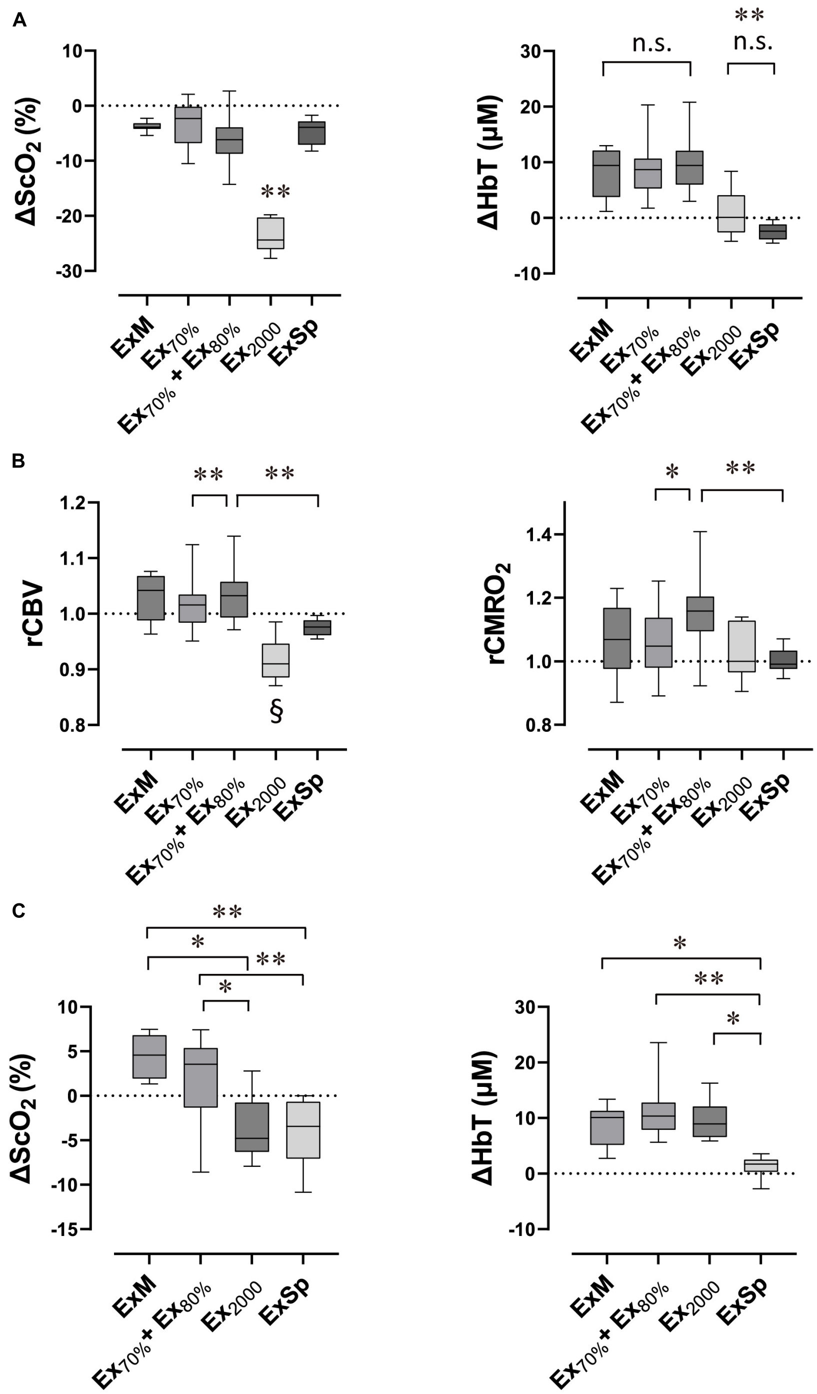

FIGURE 6 | Box plots show the extent of changes in variables compared with the baseline in response to exercise performed with various intensities ($N = 11$ for $Ex_{70\%}$, $Ex_{70\%} + Ex_{80\%}$ and ExSp; $N = 7$ for ExM and Ex_{2000}). Lower and upper box boundaries represent the 25th and 75th percentiles, respectively. Lines inside the box represent the median. Lower and upper error lines represent 10th and 90th percentiles, respectively. Relative changes in cerebral oxygenation at the end of exercise **(A)**, estimated relative changes in rCBV and $rCMRO_2$ at the end of exercise **(B),** and relative changes in cerebral oxygenation after exercise termination **(C)**. ΔScO_2, relative changes in cerebral hemoglobin oxygen saturation; ΔHbT, relative changes in total hemoglobin concentration in the brain tissue; rCBV, estimated relative changes in cerebral blood flow; $rCMRO_2$, estimated cerebral metabolic rates for oxygen; ExM, moderate-intensity exercise (2,000 m warmup row); $Ex_{70\%}$, exercise at 70% of $\dot{V}O_{2peak}$; $E_{70\%} + Ex_{80\%}$, exercise at 70% of $\dot{V}O_{2peak}$ followed by exercise at 80% of $\dot{V}O_{2peak}$; Ex_{2000}, maximal exercise (2,000 m all-out row); ExSp, three sessions of supramaximal intensity exercise. **(A)** ΔScO_2 evoked by Ex_{2000} was significantly different from those evoked by the other four intensities (**$P < 0.01$), and ΔHbT evoked by Ex_{2000} and ExSp were significantly different from those evoked by the other three intensities (**$P < 0.01$). Variables were not significantly different between Ex_{2000} and ExSp or among ExM, $Ex_{70\%}$, and $ExH_{70\%} + ExH_{80\%}$ (n.s. $P > 0.05$ was not significant [n.s.]). **(B,C)** rCBV evoked by Ex_{2000} was significantly different from those evoked by other four intensities (§$P < 0.05$). Pair-wised significant differences are indicated (*$P < 0.05$ and **$P < 0.01$). Statistical differences between variables were analyzed with a one-way analysis of variance and Turkey's *post hoc* multiple comparisons test.

other brain regions, such as the insular and anterior cingulate cortex, oxygenation in the PFC would be a surrogate for observing interoception caused by rowing exercise (Craig, 2009). Additionally, the PFC has been explored in NIRS studies that investigated the underlying mechanism of the pacing strategy related to an experimental model of time-to-exhaustion (De Wachter et al., 2021). From the perspective of the regulation of endurance exercise in the brain, the PFC has a key role in brain regions such as the anterior cingulate cortex and premotor area cortex, which integrate afferent and efferent information mandatory for executive function for endurance exercise (Robertson and Marino, 2016).

The finding that [HbT] did not change between $Ex_{70\%}$ and $Ex_{80\%}$ but did increase from the baseline by 8.6 and 10.0%, respectively, demonstrated the CBF stability. The combination of ScO_2 and [HbT] estimated the difference in $rCMRO_2$ between $Ex_{70\%}$ and $Ex_{80\%}$ (**Figure 6**). Increased $CMRO_2$ with $Ex_{80\%}$ despite unchanged CBF because of higher-intensity exercise would indicate fluctuation in neurovascular coupling, during which an increase in the metabolic demand of neurons during activity would induce a further increase in the CBF (Attwell et al., 2010). A previous study using NIRS demonstrated a cerebral oxygenation threshold of 87% for $\dot{V}O_{2max}$, corresponding to VT2, whereby oxygenation in the PFC decreased during the incremental exercise test to exhaustion (Rupp and Perrey, 2008). During our study, the finding that ScO_2 decreased as [HbT] stayed at the same level when intensity changed from $Ex_{70\%}$ to $Ex_{80\%}$ (from 67 to 79% of $\dot{V}O_{2peak}$) seemed compatible with the oxygenation threshold advocated by the previous study. We speculated that this difference in the threshold would be attributable to the study population and protocol.

After the combined sessions of $Ex_{70\%}$ and $Ex_{80\%}$, both ScO_2 and [HbT] significantly increased 3 min after exercise termination compared with the baseline. [HbT] notably increased by 12.1%, where ScO_2 increased by 3.3% (**Table 3** and **Figure 6**). We speculated that this increase in [HbT] would allow an increase in CBF, thus surpassing the change in HGB. A reason for the possible increase in CBF is that a significant increase in CO was identified 3 min after exercise termination. Since a single session of exercise improves mood and reduces subjective symptoms of anxiety in healthy non-anxious adults (Petruzzello et al., 1991; Smith, 2013), we measured the alterations in the mood status before and after the dual-stage constant-load rowing exercise to identify whether these alterations might be reflected in the oxygenation in the PFC. There was a significant decrease in the negative PANAS scores, but the positive scores remained at the same level. In addition to the possible increase in CBF, this small increase in ScO_2 could be linked to an increase in $CMRO_2$. Accordingly, it was speculated that these positive changes in CBF and $CMRO_2$ in the PFC might be possibly associated with alterations in mood. Although the results of our study could not identify neurophysiological mechanisms of the beneficial effects on mood that are evoked by exercise, these changes might trigger consecutive procedures in the network existing in the large regions of the brain that are associated with the development of post-exercise antidepressive effects.

Exhaustion Evoked by Maximal Rowing and Cerebral Oxygenation

With exhaustion caused by the 2,000 m all-out row, the SaO_2 may decrease below 85% (Nielsen et al., 1998). This systemic deterioration in oxygen delivery is critical for ScO_2 (Nielsen et al., 1999). Our results are in line with those of previous studies that investigated maximal exercise to exhaustion. However, the extent of decrease of 23% in ScO_2 was greater than that reported by previous studies (17%) (Nielsen et al., 1999). Although we could not determine actual changes in the CBF, the estimated $rCMRO_2$ was retained as the baseline value because of the balance between systemic arterial desaturation and decreased ScO_2.

To evaluate another type of maximal effort to develop exhaustion, we included ExSp. In contrast to other exercise intensities, during ExSp, [HbT] decreased immediately after exercise was started. Because the duration and intensity of ExSp (1 min at 130 or 140% of $\dot{V}O_{2peak}$) were different from those of other exercise sessions, the extent of changes in ScO_2 and in [HbT] were smaller than those during other sessions. When considering the three sessions of ExSp as a block, [HbT] tended to increase as the sessions were repeated. Additionally, in contrast to HbT, $P_{ET}CO_2$ declined with repetitive sessions at supramaximal intensity. CO_2 has an influences on regional CBF and CBV (Ito et al., 2003), and a decrease of 6 mmHg from the baseline value of the first session to that of third session in ExSp would induce a decreased of 7.8% in the CBV. Although, [HbT] did not change between the baseline of the first and the third bout, CBV may decrease by 9% because of the approximately 10% increase in HGB, similar to that observed with Ex_{2000}. Accordingly, this finding may indicate that the cerebrovascular response to CO_2 is applicable to these intermittent repetitive exercise sessions.

During Ex_{2000} and ExSp, with increasing intensity or an accumulated load, a severe sensation occurred, but the rowers endured it with exertion. Thereafter, PO decreased with fatigue and, eventually, stop exercising. During the present study, these phenomena at exhaustion were interpreted as peripheral fatigue (Noakes et al., 2005), which is explained by a catastrophic failure of homeostasis leading to skeletal muscle dysfunctions, and also as central fatigue, which refers to all the processes implicated in motoneuronal activation that can be modulated at the spinal and/or supraspinal levels (Gandevia, 2001). Central fatigue is a theoretical explanation of where afferent information of the body is integrated into brain areas, networks, and efferent pathway to stop movement. According to NIRS and functional imaging, such as PET and functional magnetic resonance imaging studies, the PFC may be intimately involved in the capacity to tolerate high levels of physical exertion and possibly in the determination of exercise termination (Robertson and Marino, 2016).

Effects of Heterogeneous Characteristics of Rowers

To identify changes in cerebral oxygenation, we investigated all participants as a group despite the heterogeneous characteristics. Because the participants of this study were consisted of two groups of six competitive and five recreational rowers, there was a large difference of $\dot{V}O_{2peak}$ (from 43 to 65 mL min^{-1} kg^{-1})

among the participants. However, as the groups were not equally balanced regarding sex and age, we did not analyze the data by comparing the two groups. Accordingly, we analyzed whether ΔScO_2 and ΔHbT were associate $\dot{V}O_{2peak}$. To evaluate Ex_{2000}, we investigated rowers only if they tolerated maximal exercise. Consequently, our observations seem to be limited to cases of true exhaustion. If the maximum sensation of effort was attained among rowers at the end of Ex_{2000}, then the oxidative capacity was correlated with ΔScO_2. Because we investigated only seven rowers, further investigations are required to determine whether the oxidative capacity affects changes in oxygenation in the PFC.

Estimation of Cerebral Metabolic Rate for Oxygen Resulting From Rowing Exercise

At exhaustion evoked by maximal exercise, the decrease in ScO_2 oxygenation was likely caused by the decreased regional CBF combined with the increased $CMRO_2$ (Nielsen et al., 1999; González-Alonso et al., 2004). To clarify this uncoupling between the oxygen supply and demand, we attempted to estimate $CMRO_2$. However, we could not explore the absolute values of $CMRO_2$ because the CBF could not be determined by CBV, which is assessed by TRS. An advantage of TRS is that theoretically quantitative measures of [HbT] can be converted to CBV using the molecular weight of hemoglobin (64,500 g/Mol) and brain tissue density (1.05 g/mL) if the individual HGB was measured during exercise. A previous study applied simultaneous measurements of TRS and PET and demonstrated that a good correlation coefficient was obtained between TRS-derived CBV and PET-derived CBV, and that the absolute CBV levels found with TRS were lower than those found with PET (Ohmae et al., 2006). Given that CBV could be correctly assessed by TRS, and that arterial and blood sampling could determine SaO_2, which was substituted by the values reported during this study (Nielsen et al., 1998; Nielsen, 2003; González-Alonso et al., 2004), $CMRO_2$ was not available if the association between CBF and CBV was not correct. Using PET, the association between the CBF and CBV has been investigated, but not sufficiently (Grubb et al., 1974). During a previous PET study, changes in the CBF during hypercapnia and hypocapnia were greater than those in CBV. Therefore, the CBV and CBF might change in a common direction, at least as a result of physiological stimulation.

Limitations

It is worth mentioning that small sample size, possible selection bias, and several methodological limitations in this study do not allow to draw generalizable conclusions. Limitations included the lack of a measurements of individual blood lactate during the incremental exercise test that could clearly define the boundaries of exercise intensities by the first lactate threshold (LT1) and second lactate threshold (LT2). Because we used 70 and 80% of $\dot{V}O_{2peak}$ as $Ex_{70\%}$ and $Ex_{80\%}$ and referred to VT1 and VT2, it is not impossible to interpret that these two intensity domains during this study correspond to above LT1 and between LT1 and LT2, respectively. Because of the heterogeneous background of the participants, 70% of $\dot{V}O_{2peak}$ was slightly lower than the VT1 for the recreational rowers, while 80% of $\dot{V}O_{2peak}$ was lower than the VT2 for all of the participants. Caution is warranted when interpreting the discrimination of $Ex_{70\%}$ and $Ex_{80\%}$, because inter-subject variance in ScO_2 was large in response to the exercise of the same intensity. Additionally, because the present study used the impedance cardiograph (Physio Flow) to measure CO during rowing exercise in $Ex_{70\%}$ and $Ex_{80\%}$ rowing exercise, CO seemed low considering a near-linear relationship with an approximately 6.1 slope between CO and $\dot{V}O_2$ (Astrand et al., 1964). However, our results are compatible with those of a recent study of stroke volume (SV) measured using a pulse contour analysis to determine waveform of arterial pressure during constant-load rowing exercise corresponding to 130 and 160 beats min^{-1} (Sejersen et al., 2021). This underestimation would be attributable to physiological characteristics of submaximal-intensity rowing which induces large fluctuations in SV while breathing similar to that occurring with a Valsalva-like maneuver, using a rowing cycle (24–26 min^{-1} during the present study) (Sejersen et al., 2021). Consequently, because prompt changes in central venous pressure and arterial blood pressure would induce rapid oscillation of systemic vascular resistance, CO might be underestimated by 5 s using impedance cardiography. The low fitness levels of athletes involved in the present study were considered and did not indicate that similar results would be obtained for highly trained athletes. The NIRS device was limited by artifacts caused by head movement and sweat during prolonged exercise, especially in high-intensity exercise. We carefully observed and removed errors caused by artifacts; consequently, NIRS data were observed in the right PFC of only two rowers. Because the physiological interpretation of the laterality of NIRS variables during a similar protocol of exercise has not been reported, further studies are required to examine the laterality effect. To detect the precise location in PFC, additional research involving magnetic resonance imaging should be performed to clarify the optimal area for NIRS data collection. Another limitation was that arterial blood sampling was not performed to measure HGB and SaO_2, which is mandatory to detect CBV and calculate $CMRO_2$ using the estimated CBF as well. Hence, further research including arterial blood sampling may validate and complement our results. Finally, regarding the accuracy of the determination of the association between CBF and CBV, additional studies involving simultaneous measurements of cerebral hemodynamics with PET and TRS are needed.

In summary, alterations in the sense of effort were paralleled by changes in PFC oxygenation, and positive changes in mood status were associated with cerebral perfusion and oxygen metabolism estimated by TRS. At exhaustion, with a possible decrease in CBF, a decrease in ScO_2 could be attributed to the maintenance of $rCMRO_2$. Oxidative capacity of rowers correlated with changes in ScO_2 when exhaustion was evoked by the 2,000-m all-out row. TRS potentially measures $CMRO_2$ if the correct association between CBV and CBF is determined by further multidisciplinary investigations. As recent reviews suggested that aspects of CBF and oxygen metabolism at exhaustive rowing remain unresolved (Volianitis et al., 2020; Treff et al., 2021), real-time measures of cerebral perfusion and metabolism during high-intensity and maximal rowing should be obtainable with future developments.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author/s.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Ethics Committee of the Faculty of Sociology, Aomori University. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

MH designed this study based on the previous researches collaborated with KT and YS. KT prepared physiological measurements. HS and AF prepared and evaluated psychological assessment. MH performed the research and data collection. MH and YS analyzed and interpreted the data. MH wrote the manuscript with the assistance of YS and YK. YK supervised the whole program. All authors critically reviewed and approved the manuscript prior to submission.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fphys.2022.828357/full#supplementary-material

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BRIEF RESEARCH REPORT
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Is the Most Commonly Used Strategy for the First 1,500 m of a 2,000 m Rowing Ergometer Race the Most Appropriate?

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This study investigated time-courses of physiological and psychological parameters of rowers during the first 1,500 m of a simulated race on a rowing ergometer using different pacing strategies. This provided a picture of the physiological and psychological state of the rowers at the start of the last 500 m of their race. Investigated strategies corresponded either to a degressive (*degr*), a progressive (*prog*), or a stable (*stab*) power output over the traveled distance. Thirteen French rowers (4 oarswomen and 9 oarsmen) of national and ex-international levels volunteered to participate. Handle force and velocity, oxygen uptake, heart rate, blood lactate concentration, and peripheral oxygen saturation were measured during the trials. Power output, generated energy [by O_2 consumption (E_{oxi}) and blood lactate accumulation ($E_{non-oxi}$)] and efficiency were computed. Rowers also rated their perceived exertion (*RPE*) and protocol preference. In the explored strategies, no significant differences were found for E_{oxi}. Final blood lactate concentration ($[La]_{blood}$) and *RPE* were similar for all strategies. However, the increase in $[La]_{blood}$ and *RPE* occurred sooner for *degr* than for *stab* and *prog*. Therefore, the time spent at higher $[La]_{blood}$ and *RPE* was longer for *degr* than for *stab* and *prog*. According to the questionnaire, *degr* was the least preferred protocol. While during 2000 m races, the first 1500 m are usually and empirically often conducted in a *degr* way, the present results indicate that this strategy was the least preferred by the rowers and led to a higher time spent at high $[La]_{blood}$ and RPE.

Keywords: physiology, oxygen uptake, lactate, pacing, race, performance, human

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1. INTRODUCTION

The Olympic distance of rowing races is 2,000 m. The races typically last between 5'30" and 7'30" according to the boat, sex, and weight category of the rowers (World Rowing - 2020 Olympic Games Regatta, 2021). In that context, rowers use all available energetic pathways to fulfill the huge energy requirement of this type of event. Hence, elevated oxygen uptake and blood lactate accumulation have been observed during and in response to rowing races (Hagerman et al., 1978; Secher, 1993; Steinacker, 1993; de Campos Mello et al., 2009). Previous studies have shown that 70–85% and 15–30% of energy demand are provided by the oxidative and non-oxidative pathways, respectively, (Hagerman et al., 1978; Roth, 1983; Messonnier et al., 1997; Russell et al., 1998; de Campos Mello et al., 2009).

During races, rowers adopt a strategy that can be retrospectively investigated from the time-course of speed (Garland, 2005). Like in any other racing sport, the presence of opponents changes the strategy (Hettinga et al., 2017). Rowers partly adjust/adapt the speed of the boat, their performance and their pacing strategy (Edwards et al., 2016) to the stakes of the race (qualifications or finals) (Chu et al., 2021). Muehlbauer et al. (2010) and Chu et al. (2021) found that the most observed strategy at the international level corresponds to a parabolic profile of speed: fast start in the first 500 m, slight deceleration in the second and third 500 m, and final acceleration in the last 500 m [keeping in mind that power output increases non-linearly with the velocity (with the cube of the velocity at constant speed)]. However, it is not known whether this strategy corresponds to an optimum in terms of psychological and/or energy management. Studying 228 crews of the Boat Race (Oxford-Cambridge), Edwards et al. (2016) observed that 81% of the teams in the lead after the first quartile of the race won the duel. Whether the winners were advantaged (i) by their leadership position, allowing them to adapt to variations in pace of their opponents, (ii) by their greater physical abilities and their management during the race, or (iii) by a combination of these possibilities, the question remains open. Note that the distance of the Boat Race (6,800 m) is not the Olympic distance. Contrary to this strategy of a fast first 500 m, some rowers adopt a more constant pacing strategy. If with this strategy, the rowers are not first at the beginning of the race and do not benefit from the potential advantage of being in the lead (Murray et al., 2016) and having a visual on their opponents, they may still manage to win the race. Although the velocity pattern was still U-shaped (Garland, 2005), these crews raced with speed changes of less amplitude. These findings put forward the question whether a more even pacing strategy, or a progressive strategy, is associated with higher performance in rowing races and should be considered by elite rowers and their coaches. The literature on middle-distance events (3–7 min) in other sports is not consensual either on this point. If certain retrospective analyzes (Foster et al., 1993) or optimization models (van Ingen Schenau et al., 1990) tend to show that a more even pacing strategy would be more efficient to achieve better performance, other studies, observing that winners were those whose speed varied the most in races (Mytton et al., 2015; Taylor et al., 2016), do not confirm this standpoint.

The present study aimed to investigate the individual physiological and psychological responses of rowers to different pacing strategies over the first 1,500 m of a race. This investigation allowed to assess the physiological and psychological state the rowers at each step of the 1,500 m and especially at the start the final and determinant 500 m. The initial hypothesis is that a non-degressive effort could be more optimal from a physiological and psychological point of view.

2. METHODS

2.1. Subjects

Thirteen French rowers of national and ex-international levels volunteered to participate in the study. The group included 4 oarswomen and 9 oarsmen. Their height, age, and weight were (mean ± SD) 178 ± 9 cm, 22 ± 4 yo, and 73 ± 10 kg, respectively. The rowers had 10 ± 4 years of experience in rowing and performed 6±2 training sessions per week. Although less marked in women (Chu et al., 2021), both sexes adopt on average a parabolic (U-shaped) curve of speed during the races (Garland, 2005; Chu et al., 2021). This gives support to include both sexes in the same study. The experiments were based on the 2000 m time trial performed within the same rowing season. The study was approved by the local ethics committee and conducted in agreement with the declaration of Helsinki. Before giving their written informed consent, subjects were advised of the objectives, all risks, possible discomforts, and potential benefits of the experiment.

2.2. Protocols

All tests were conducted on a wind resistance braked rowing ergometer (Concept II model C, Morrisville, VT, USA). Performing the experiments on a stationary ergometer facilitated monitoring of the different measured parameters. The participants were accustomed to the use of the apparatus. The computer of the ergometer continuously displayed power output, stroke rate and distance traveled.

Each athlete performed three trials, except for one who performed only two because of an injury. A summary of the protocols and measured parameters is available in **Figure 1A**. The protocol consisted in performing a 1,500 m on rowing ergometer in three different conditions at least 48 h apart (excepted once where only 24 h separated two consecutive trials). The three visits were carried out as far as possible, at a similar time of the day, in the same prandial state, and in the same energetic status (diet). The order in which the conditions were carried out was randomly assigned.

Each trial consisted of performing 1,500 m on rowing ergometer divided in three 500 m with a degressive (*degr*), progressive (*prog*), and stable (*stab*) profile/design in terms of mechanical power output performed during the test. Every 500 m was associated with a target power output determined as follows for each athlete and strategy:

$$\text{For } degr: P_{500} = 107\% P_{ref};\ P_{1000} = P_{ref};\ P_{1500} = 93\% P_{ref}.$$
$$\text{For } prog: P_{500} = 93\% P_{ref};\ P_{1000} = P_{ref};\ P_{1500} = 107\% P_{ref}.$$
$$\text{For } stab: P_{500} = P_{1000} = P_{1500} = P_{ref}.$$

where $P_{ref} = 97.5\%$ of the mean power output sustained during the best 2,000 m all-out performance test of the season. P_{500}, P_{1000}, and P_{1500} correspond to the target power output of the first, second and third 500 m.

At the beginning of each visit, a hyperemic cream was applied to the earlobe for arterialization of the capillary blood. The athletes then performed a self-paced warm-up on land (flexibility), on a cycling ergometer, on a rowing ergometer, or a combination of these possibilities. On rowing ergometer, the warm-up included accelerations and peak strokes. The rowers self-selected their drag factor (identical drag factor for all tests/visits for a given athlete). Subjects were then equipped with the measuring instruments for the following parameters: gas exchanges, heart rate and peripheral oxygen saturation (see **Supplementary Materials** for details). The hyperemic cream was

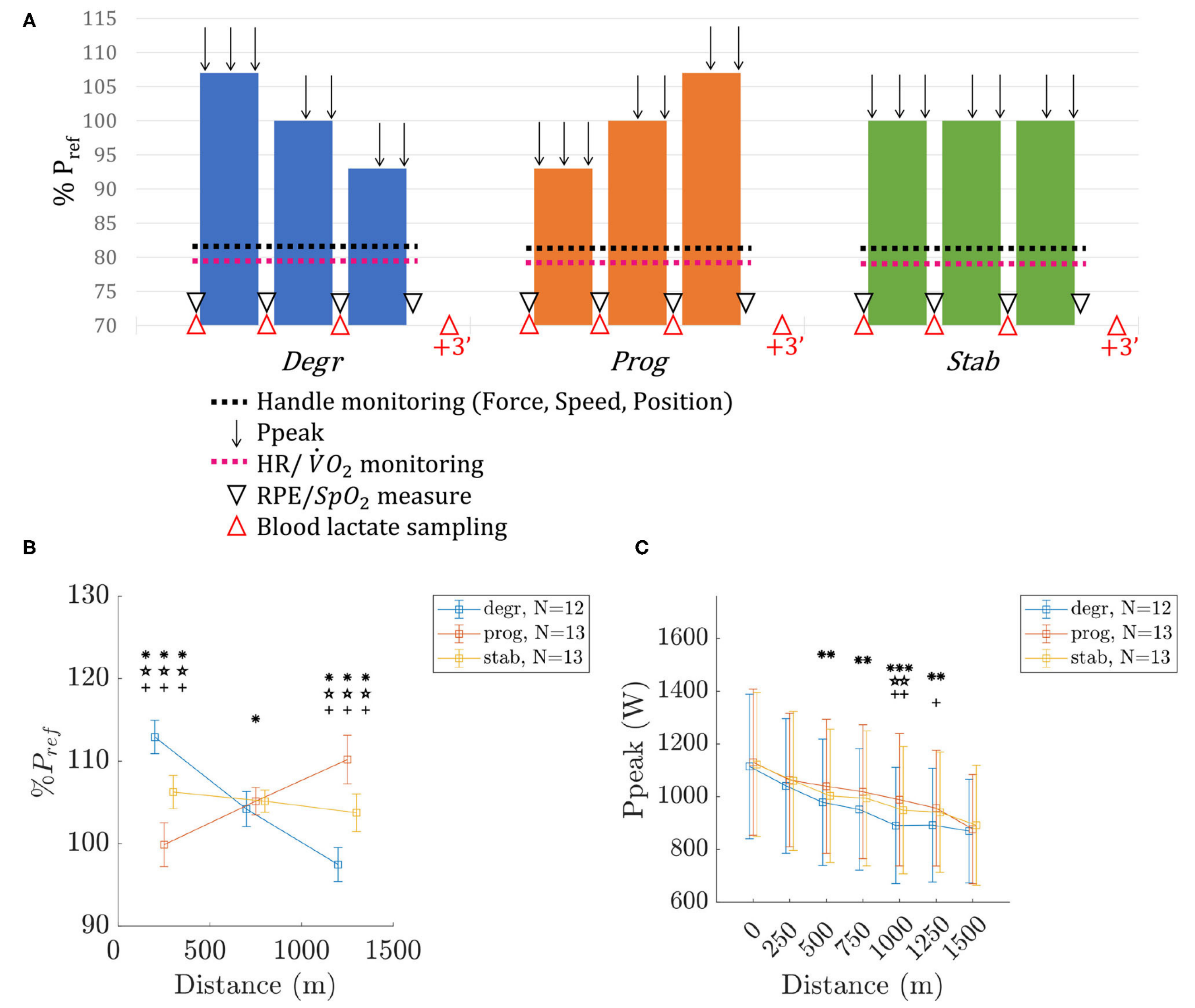

FIGURE 1 | Protocol design **(A)**, mean power on each 500 m **(B)** and *Ppeak* time-courses **(C)**. Values are mean ± SD. The symbols ∗, ⋆, and + indicate a significant difference between *degr-prog*, *prog-stab*, and *stab-degr*, respectively. The number of symbols (one, two, or three) indicate the *p*-value (< 0.05, < 0.01, and < 0.001, respectively).

removed from their earlobe and a blood lactate sample was taken to measure the pre-trial blood lactate concentration.

For the first 500 m, subjects were instructed to reach the target power output (typically in 3–5 strokes) as quickly as possible. Once stabilized at the target power output, the rowers had to perform one maximal stroke (typically the fifth or sixth stroke) to determine *Ppeak*. Then rowers turned back to the target power. Right at 250 m and just before reaching 500 m, the athletes performed a maximal stroke to determine *Ppeak*, then returning to the target power output or stopped, respectively. The same procedure was repeated thereafter for the second and third 500 m. A total of 7 *Ppeak* were thus performed during the 1,500 m trial. A rest period between two consecutive 500 m exercise bouts allowed to take a blood lactate sample at the earlobe and the recording of the rate of perceived exertion (RPE, 1–10 scale). The duration of the rest periods was strictly limited to the time necessary for the measurements (15 ± 4 s). A post-trial blood lactate sample was taken 3 min after exercise completion.

2.3. Measurements

Detailed protocols for the measurements of the mechanical (force, velocity, and power output), physiological [oxygen uptake ($\dot{V}O_2$), time-constant of the $\dot{V}O_2$ response during the first 500 m (τ), $\dot{V}O_2$ at steady state ($\dot{V}O_2SS$), oxidative contribution to energy supply (E_{oxi}), heart rate (HR), heart rate at steady state (HRSS), blood lactate concentration ($[La]_{blood}$), non-oxidative glycolytic contribution to energy supply ($E_{non-oxi}$), lactate area under the curve (AUC_{La}), peripheral oxygen saturation

(SpO_2), and efficiency (ϵ)] and psychological [rating of perceived exertion (RPE), RPE area under the curve (AUC_{RPE}) and grading of protocols by athletes] parameters are available in **Supplementary Materials**.

2.4. Statistical Analysis

Trials for which the measuring device was defective were removed from the statistical analyses. The size of each data group will be specified (N). The subject who performed only two of the three conditions was included in the one-to-one comparisons of the two conducted trials. All data processing and statistical analyses were performed on MATLAB. Means ($\pm$ standard deviation) were calculated by standard methods. On the graphs, the solid squares represent the means and the error bars represent the standard deviations. In the box plots, the segments delimit the first quartile, the median and, the third quartile. The hollow circles correspond to the individual results. The Kolmogorov–Smirnov test was used to refute the assumption of normality. The paired-Wilcoxon rank test was then used to compare the groups two by two. The statistical significance threshold was set at p-value < 0.05. On the figures, the symbols $*$, $\star$, and $+$ indicate a significant difference between *degr-prog*, *prog-stab*, and *stab-degr*, respectively. The number of symbols (one, two, or three) indicate the *p*-value (< 0.05, < 0.01, and < 0.001, respectively). The effect size was evaluated through a rank-biserial correlation. Numerical values of *p*-values and rank-biserial correlation are available in the **Supplementary Materials**.

3. RESULTS

3.1. Power Outputs

The mean power output for each 500 m and the different protocols are available in **Figure 1B**. The average variations between two consecutive 500 m bouts were $-7.1 \pm 0.1\%$, $+5.1 \pm 0.2\%$, $-1.2 \pm 0.1\%$ for *degr*, *prog*, *stab*, respectively. Although the variation for *prog* was below the targeted value (+7%), there still was a significant difference when compared to the other protocols and therefore the results can be analyzed considering that the protocols have been respected. In accordance, time duration to complete the 1,500 m trials (removing the stopping times for data collection) were similar among trials: 305 ± 31 s, 304 ± 29 s, 304 ± 31 s for *degr*, *prog*, and *stab*, respectively.

The time-courses of *Ppeak* are available in **Figure 1C**. Initial and final *Ppeak* did not differ significantly between protocols. However, *Ppeak* in *degr* was lower than in *prog* between 500 and 1,250 m and than in *stab* between 1,000 and 1,250 m. *Ppeak* in *stab* was also lower at 1,000 m than *Ppeak* in *prog*.

3.2. Physiological Measurements

3.2.1. Oxygen Uptake

Results drawn from $\dot{V}O_2$ are reported in **Figure 2**. The time constant τ (**Figure 2A**) was significantly lower in *degr* than in *prog*. τ in *stab* did not significantly differ from the other conditions (**Figure 2A**). $\dot{V}O_2SS$ was lower in the 2nd and 3rd 500 m for *degr* than in *stab* and *prog* (**Figure 2B**). E_{oxi} for each 500 m bout was not different between conditions (**Figure 2C**).

3.2.2. Heart Rate

The *HRSS* (**Figure 2D**) was lower in the last 500 m for *degr* than in *stab* and *prog*.

3.2.3. Blood Lactate Concentrations

Results drawn from $[La]_{blood}$ are reported in **Figure 3**. Initial and final values of $[La]_{blood}$ were similar for all conditions (**Figure 3A**). However, after the first 500 m, $[La]_{blood}$ was higher for *degr* than for *stab* and *prog*, while no difference was observed between the two latter conditions. At 1,000 m, $[La]_{blood}$ were higher in *degr*, lower in *prog* and in between in *stab*.

AUC_{La} (**Figure 3B**) was significantly greater for *degr* than for the two other conditions. A higher AUC_{La} corresponds to a longer time spent at higher $[La]_{blood}$.

$E_{non-oxi}$ (**Figure 3C**) was higher on the first 500 m for *degr* than for *prog* and *stab*. On the second 500 m, $E_{non-oxi}$ was higher for *degr* than for *prog* with no significant difference with *stab*. Finally, for the last 500 m bout including the first 3 min of recovery, $E_{non-oxi}$ was greater for *prog* than for the other conditions.

3.2.4. Blood Oxygen Saturation

No significant differences were observed in time-courses of SpO_2 between the different conditions (**Figure 3D**).

3.2.5. Efficiency

Efficiencies were $25 \pm 8\%$, $25 \pm 8\%$, and $26 \pm 2\%$ for *degr*, *stab*, and *prog*, respectively. These values are coherent with the literature (Fukunaga et al., 1986).

3.3. Psychological Variables

RPE (**Figure 4A**) was similar at the end of the 1,500 m trials in the three conditions. However, RPE was lower in *prog* than in *degr* at 500 m and than in *stab* at 1000 m.

AUC_{RPE} (**Figure 4B**) was significantly greater for *degr* than for the two other conditions. AUC_{RPE} also was greater for *stab* than for *prog*.

The grading of conditions by athletes (**Figure 4C**), reported that *stab* and *prog* conditions were preferred than *degr*, with no difference between the two first.

4. DISCUSSION

This study aimed to investigate the physiological and psychological responses to three pacing strategies on the first 1,500 m of a rowing race. Research has already been done in imposing a strategy to rowers on ergometer (Lander et al., 2009) but not in the range of power developed by the athletes during 2000 m races. The three strategies used in the present study (*degr*, *stab*, and *prog*) were equivalent in terms of performance, meaning that power output, time to travel the distance and thus work were similar in the three conditions. Contrary to our initial hypothesis, most parameters of interest measured during the 1,500 m trials (*Ppeak*, $[La]_{blood}$ and RPE) were not different at exercise completion between the three strategies. On the other hand, time-courses of several parameters were different between trials so that *Ppeak* was lower and $[La]_{blood}$ and RPE were higher

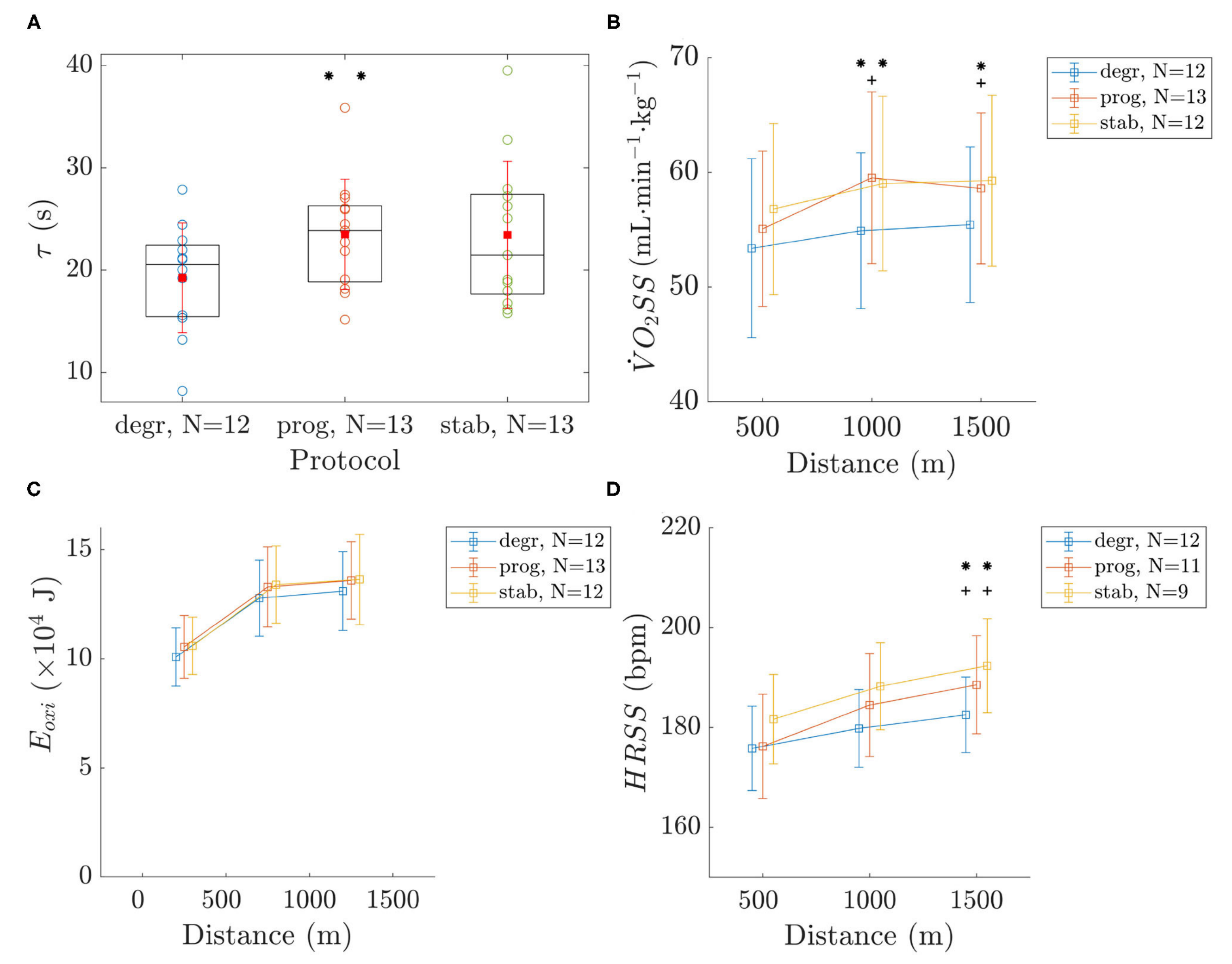

FIGURE 2 | τ (time constant of the primary response of the oxygen uptake on the first 500 m) **(A)**, $\dot{V}O_2SS$ **(B)**, E_{oxi} **(C)**, and *HRSS* **(D)**. Values are mean ± SD. The symbols ∗ and + indicate a significant difference between *degr-prog* and *stab-degr*, respectively. The number of symbols (one or two) indicate the *p*-value (< 0.05 and < 0.01, respectively).

in *degr* compared to *stab* and *prog* during and after the second 500 m. Finally, athletes clearly disliked the *degr* protocol.

4.1. Muscle Function

From a mechanical point of view, the 1,500 m trials were tiring (as illustrated by the decrease of *Ppeak* throughout the trials) but not in the same way according to the trials. Indeed, while initial and final *Ppeak* were similar, *Ppeak* in *degr* was lower than in *prog* between 500 and 1,250 m and than in *stab* between 1,000 and 1,250 m. It is interesting to note, that the difference between the trials are the most apparent on the middle 500 m while this is the period where the power output was similar between trials. This suggests that muscle function at 1,000 m is still under the dependence of what has been done during the first 500 m (*vide infra*).

4.2. Physiological Responses

Pacing strategies affected physiological responses. Interestingly, and similarly to what has already been described for muscle function, the discrepancies between the strategies were most often apparent during and after the second 500 m, while the power output was similar in the different conditions.

The first surprising result was that during the second 500 m, $\dot{V}O_2SS$ was lower in *degr* than in *stab* and *prog* while the power output were the same in the three conditions. There is very few probabilities that this result is a type I error insofar as $\dot{V}O_2SS$ during the first 500 m in *degr* was also significantly ($p < 0.05$) lower than $\dot{V}O_2SS$ during the third 500 m in *prog* (data not shown). The present study does not allow to find a definite explanation for this result. However, taking into account (i) that the lower $\dot{V}O_2SS$ in *degr* were accompanied by higher $[La]_{blood}$, (ii) that higher $[La]_{blood}$ are associated with lower pH

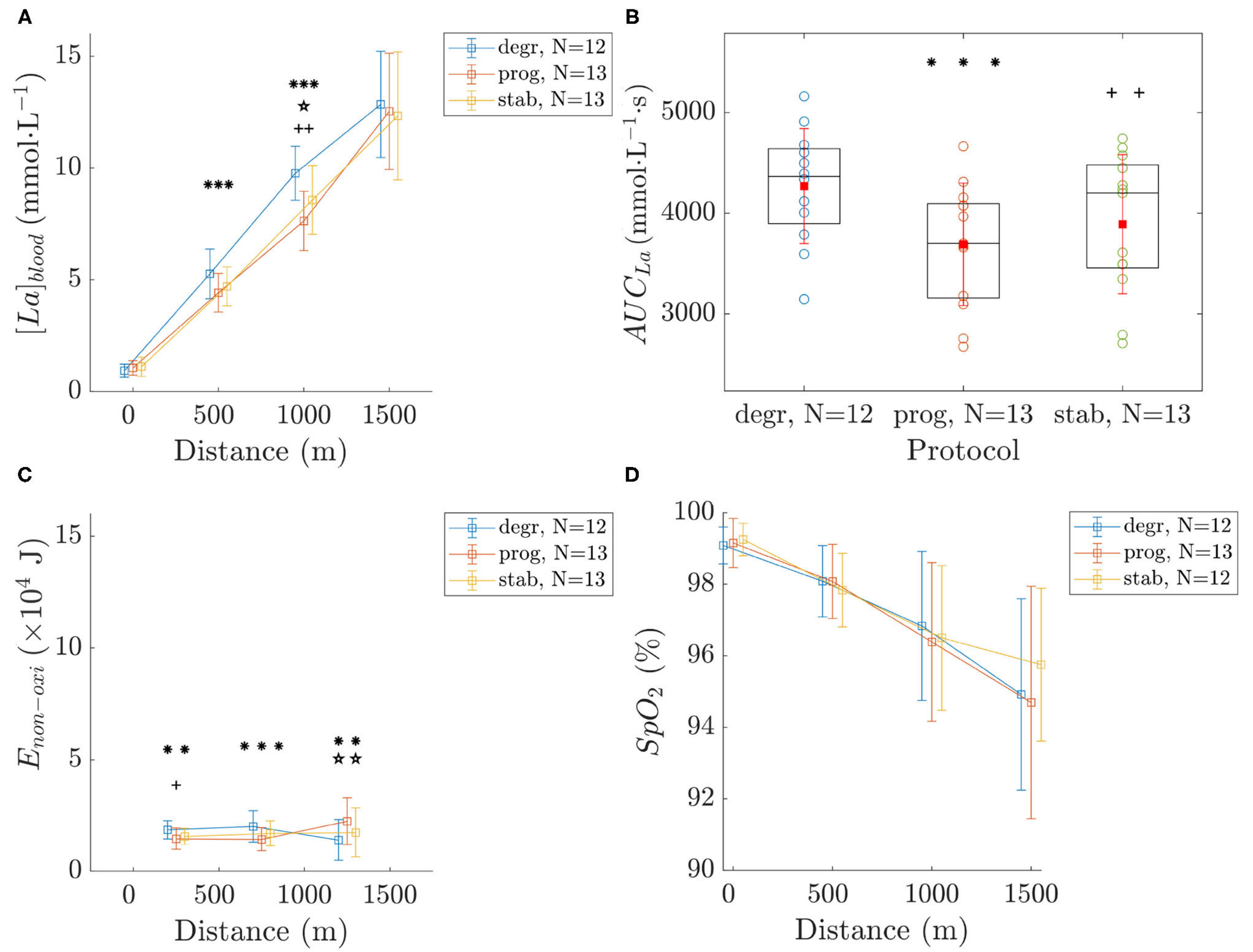

FIGURE 3 | $[La]_{blood}$ **(A)**, AUC_{La} **(B)**, $E_{non-oxi}$ **(C)**, and SpO_2 **(D)**. Values are mean ± SD. The symbols $*$, $\star$, and + indicate a significant difference between *degr-prog*, *prog-stab*, and *stab-degr*, respectively. The number of symbols (one, two, or three) indicate the *p*-value (< 0.05, < 0.01, and < 0.001, respectively).

(acidosis) (Stewart, 1983), and (iii) that acidosis inhibits oxidative phosphorylation *in vivo* (Jubrias et al., 2003), one cannot exclude that the lower $\dot{V}O_2SS$ observed in the present study at 1,000 m is the result of a lower muscle pH. However, further studies are necessary to confirm/infirm this speculation/hypothesis.

Taken into account τ and $\dot{V}O_2SS$, it resulted that oxidative energies were similar among conditions. These results are similar to those obtained by Hettinga et al. (2007) on 1,500 m cycling time trials conducted with three strategies similar to the ones used here, suggesting that pacing strategies have no significant impacts on the overall contribution of oxidative metabolism in energy supply.

During the first 500 m, $[La]_{blood}$ increased faster in *degr* than in *prog*. This result indicates that the higher power output was not compensated by the faster increase in $\dot{V}O_2$ (i.e., the lower τ) in *degr*, resulting in higher $[La]_{blood}$. The increase of the differences in $[La]_{blood}$ between the conditions after the second 500 m, while the power outputs were similar in the three conditions, may be explained by the delay of muscle lactate to reach the blood. At that point, it is tempting to link the time-course of $[La]_{blood}$ with those of *Ppeak* since *Ppeak* curves mirror those of $[La]_{blood}$. In a previous study, Hogan et al. (1995) observed that an increase in $[La]_{blood}$ induced a decrease of force production (muscle studied *in situ*). However, a causative link between elevated $[La]_{blood}$ and low *Ppeak* is highly speculative, highly controversial, and unlikely in the present case.

In the present study, AUC_{La} was higher in *degr* than in *stab*, this later being itself higher than in *prog*. This latter result illustrates that the athletes spent a longer time at higher $[La]_{blood}$ in *degr* than in *prog* and *stab*.

4.3. Psychological Responses

Results for RPE were reminiscent with those for $[La]_{blood}$. This is consistent with the association between $[La]_{blood}$ and the perception of an effort (Borg et al., 1987). Moreover, AUC_{RPE} was higher in *degr* than in *prog* and *stab*, indicating that athletes spent a longer time at higher RPE in *degr* than in the two other conditions.

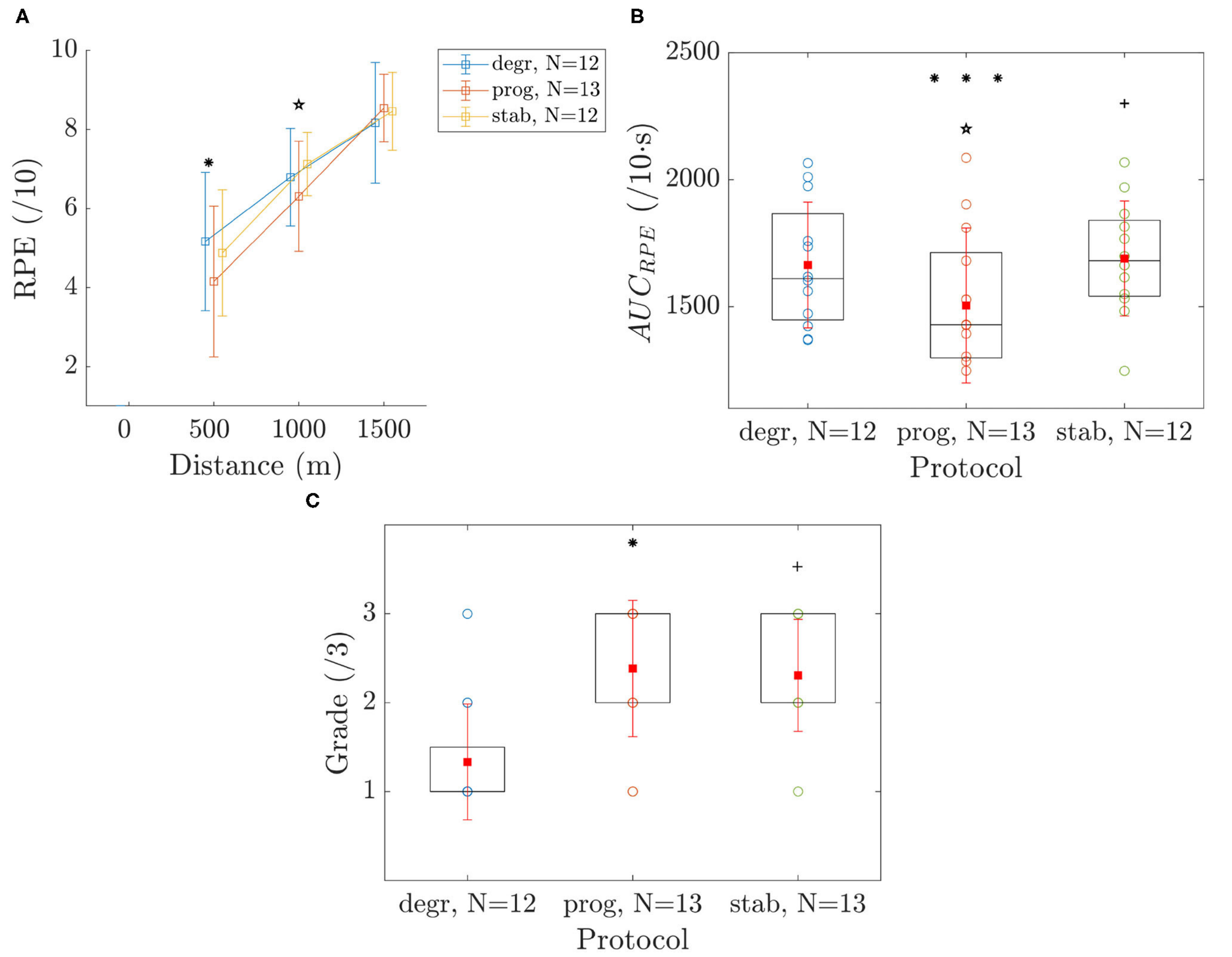

FIGURE 4 | RPE **(A)**, AUC_{RPE} **(B)**, and grading of protocol **(C)**. Values are mean ± SD. The symbols ∗, ⋆, and + indicate a significant difference between *degr-prog*, *prog-stab*, and *stab-degr*, respectively. The number of symbols (one, two, or three) indicate the *p*-value (< 0.05, < 0.01, and < 0.001, respectively).

If it is difficult to infer whether there is a link between the RPE profile during the trials and the rating of conditions by the athletes, one may nevertheless report that for the athletes, the worse strategy was *degr*. At least, *degr* was the strategy they disliked the most. This result is relatively surprising since this is the most often strategy observed during the first 1,500 m of races (Garland, 2005; Muehlbauer et al., 2010; Chu et al., 2021). Four possible explanations may account for the discrepancy between the personal rating of the rowers and what they actually do during races, and one cannot exclude that the explanation lies in a combination of the following possibilities.

First, starting the race in the lead offers a certain psychological advantage. This situation gives (i) athletes confidence and (ii) a visual control on their opponents, allowing them to adapt and modulate their effort according to possible catching up of the other competitors. The poor rating of the *degr* strategy in the present study might then be explained by the absence of opposition and visual on this opposition.

Second, *degr* strategy could be advantageous for the boat speed from a mechanical point of view. This could be investigated through a mechanical model taking into account (i) the propulsive power generated by the athletes and (ii) the resistive properties of the (considered) boat. One of the resistive terms, namely the added mass, is proportional to the acceleration of the boat (Cabrera et al., 2006; Formaggia et al., 2009). Therefore, in a *degr* strategy, the initial added mass term would be of great magnitude at the beginning of the race. During the following deceleration, this added mass term would result in a propulsive contribution for the boat. However, such a model needs to be further investigated in order to determine and quantify the benefit, if it exists.

Third, there may be a physiological reason to perform higher power outputs at the beginning. As fatigue develops during the race, it may become more and more difficult to perform high power outputs. In other words, the high level of power outputs, generated in the early phase of a race in a *degr* scenario, might be impossible to produce later, especially during the last 500 m of a race, even if a more "energy-sparing" strategy (e.g., *prog*) was used at the beginning of the race. In accordance with this possibility, one may note that in the present study, the mean increase in power output in (*prog*) was of only +5.1 ± 0.2% instead of the required 7%. Indeed, it was difficult for some athletes to increase the power output in the final 500 m of the *prog* condition.

Last, this strategy may be the simplest for the athletes, insofar as the other strategies (*prog* or *stab*) would require rowers to know precisely their physical abilities and their energy reserve at any time of the race. Therefore, starting stronger and letting the deceleration be dictated by the occurrence of fatigue may ensure the athletes to provide a maximum effort, whereas starting with less power output could result in finishing the race without having used all energetic reserves. In favor of this last argument, Hoffmann et al. (2014) have shown that energy management on a 2000 m ergometer race was improved in the presence of a "rowing avatar" that indicated them the pace to follow during the simulated race.

To conclude, a contradiction exists between athletes' preferences and field observations. To understand this contradiction, it would be interesting/necessary to include a "performance" trial in a future study. Indeed, it would be of great interest to quantify the maximum effort achievable in each strategy configuration to be able to conclude on the most optimal strategy (*vide infra* 4.4 for additional words in that regards).

4.4. Limitations and Perspectives

We are aware that this study has limitations. One first criticism may lie on the fact that rowers were stopped at each 500 m. Because we intended to measure time-course of parameters during the different trials and because it is highly difficult to perform some measurements during physical activity (e.g., $[La]_{blood}$), we choose to stop the athletes every 500 m. A second criticism may lie on the fact that athletes did not perform a complete 2000 m. This choice is justified by several aspects. First of all, none of the athletes accepted to perform three all-out 2,000 m rowing exercises. Second, the type of effort required in the present study was not usual for the rowers. They had to follow strategies they do not necessarily apply during races. Most of the rowers of the present study would have been unable to travel an extra 500 m. Retrospectively, not having pushed the distance to 2,000 m was reasonable since some athletes were in trouble or even did not succeed to respect precisely the imposed power outputs, attesting of the exhaustion of the rowers. Along the same line, one may note that $[La]_{blood}$ measured at the end of the 1,500 m trials were approaching the levels found after a 2,000 m race (Hagerman et al., 1978; Nielsen et al., 2002). Another limitation is that under none of the conditions performed in the present study did the rowers complete a self-paced 1,500 m. An interesting study (Lander et al., 2009) suggested that a self-paced trial might have been a more effective strategy than any of the other conditions proposed. Therefore, it cannot be excluded that the crews that adopt a more even (but still U-shaped) pace and win the race are those that are able to ignore their opponents and to race at their own pace. Despite the limitations mentioned above, we believe that our results are still of great interest in understanding the influence of pacing strategy on a 2,000 m rowing event. Our results underline the intra-trial differences in the time-course of psychological and physiological variables for different strategies on the first 1,500 m of a race.

5. CONCLUSION

Contrary to our initial hypothesis, While *Ppeak*, E_{oxi}, $[La]_{blood}$ and RPE were similar at the start and at the end of the different conditions, time-courses of several of these parameters were different. It resulted that (i) *Ppeak* was lower and (ii) $[La]_{blood}$ and RPE were higher in *degr* than in *prog* and *stab* especially in the middle 500 m while the power outputs were the same between trials. These results indicate (i) that the alterations of muscle function and physiological responses are delayed compared to the actual power output performed and (ii) that determination of the time-course of parameters during exercise brings more insights than just pre- and post-exercise measurements. Athletes retrospectively disliked the *degr* strategy the most, which is surprising since it is the one to most often used in competition during the first 1,500 m. This contradiction might be explained by the fact that using a degr strategy could be more efficient in terms of performance either from a positioning with respect to competitors, mechanical, physiologically achievable effort, or tactical implementation. Further studies are necessary.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Comité d'Éthique de la Recherche de l'Université Savoie Mont Blanc. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

LM, PS, CC, and BM designed and conducted this study. MB was in charge of the experimental set-up design. LM, BH, MB, CC, and AB conducted the experiments. AB and LM wrote the first draft of the article and analyzed data. All authors critically reviewed the draft and approved the final version.

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SUPPLEMENTARY MATERIAL

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Is the Energy Cost of Rowing a Determinant Factor of Performance in Elite Oarsmen?

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In elite oarsmen, the rowing ergometer is a valuable tool for both training and studying rowing performance determinants. However, the energy cost of rowing, often reported as a determinant of performance, has never been described for ergometer rowing. Therefore, this study aimed to characterize the energy cost of ergometer rowing (ECR) in elite oarsmen, its contribution to 2,000 m performance, and its determinants. This study was conducted on 21 elite oarsmen from the French national team. It included an incremental exercise test up to exhaustion and an all-out performance test over 2,000 m, both conducted on a rowing ergometer. Gas exchange analysis was performed to calculate oxygen uptake and substrate utilization rate. Whole blood lactate concentrations during the incremental test were obtained from the earlobe. During the incremental test, ECR displayed a significant linear increase up to a plateau that reached a mean rowing speed of 5.23 ± 0.02 m·s^{-1}. The ECR values at 300, 350, and 400 W were positively correlated with performance expressed as the time required to perform the 2,000 m distance on the rowing ergometer. The same ECR values were found to be significantly related to fat oxidation (expressed in percentage of total energy supply) and blood lactate concentrations. This study provides the first description of ECR and of its relationship to exercise intensity on the rowing ergometer in elite oarsmen. ECR appeared to be a factor of performance and interestingly was related to energy supply from fat and blood lactate concentrations.

Keywords: rowing, energy cost, ergometer rowing, fat oxidation, elite performance

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INTRODUCTION

The official Olympic distance of rowing races is 2,000 m, lasting between 5:45 and 7:20 (min:s) depending on the boat and the crew. The determinants of performance for this type of event are numerous (Ingham et al., 2002), but the most simplified model, meaning the model with the lowest number of parameters, for predicting performance (expressed in m·s^{-1}), relies on the ratio between power production (J·s^{-1}) and the energetic cost of the task (J·m^{-1}) (di Prampero et al., 1971).

In the case of rowing, power production, the numerator in the abovementioned ratio, has been extensively studied and has been a focus for improvement *via* training. Power production depends mainly on energetic and physiological factors (Hagerman et al., 1978; Secher, 1993; Steinacker and Secher, 1993; Maetsu et al., 2005; Izquierdo-Gabarren et al., 2010)3). In that regard, elevated maximal oxygen uptake ($\dot{V}O_{2max}$, up to 6.9 L·min^{-1}) (Nielsen and Christensen, 2020), power output associated with $\dot{V}O_{2max}$ ($\dot{W}_{VO2max}$, ∼550 W), and blood lactate concentrations (∼16 mmol·L^{-1}) have been reported in rowers during or in response to performance events (Secher, 1993; Nielsen et al., 2002; Nielsen and Christensen, 2020)). Consequently, an elevated maximal oxygen uptake seems to be a prerequisite for successful rowing (Secher, 1993). Similarly, the later the blood lactate accumulation occurs during an incremental rowing test (∼9–15 mmol·L^{-1} posttest), the better the performance (Messonnier et al., 1997). It is also noteworthy that open-class elite rowers are characterized by large body dimensions (height > 190 cm and body weight > 90 kg) (Cosgrove et al., 1999; Ingham et al., 2002).

On the contrary, to the best of our knowledge, the importance of the energy cost of rowing, the denominator in the performance predicting ratio, for 2,000 m performance has rarely been considered, neither in recreational nor in elite rowers. Previously, the energy cost of rowing has been described for on-water rowing (two-oared racing shell with coxswain) (di Prampero et al., 1971). In this study, the energy cost was modeled from the mechanical power required to maintain a given speed against estimated resistance. The absence of oxygen uptake measurement due to inherent constraints of environmental conditions prevented the authors from considering the cost of rowing as a determinant of performance.

Extensively used for training, rowing ergometers are also valuable tools for athlete testing (Lamb, 1989). In fact, rowing ergometer exercise accurately simulates the metabolic demand of on-water rowing and allows rigorous measurement of physiological and metabolic parameters (Lamb, 1989; Rossi et al., 2015; Bourdin et al., 2017). For this reason, elite athletes carry out performance tests, as well as $\dot{V}_{O2max}$ and lactate threshold determination, using the rowing ergometer. These assessments constitute important parts of the selection process and the annual evaluation routine for elite rowers (Maetsu et al., 2005). Another advantage of this device is that it can provide other useful evaluation parameters, including pace. Thus, interest arose to assess the energy cost of ergometer rowing (ECR), its changes with pace, and its links with performance. Furthermore, the importance of the metabolic source of energy (carbohydrates and fat) on the energy cost of rowing has not been paid attention so far. However, such knowledge is of great importance for the choice of training modalities, insofar as these modalities determine specific improvements for each of the metabolic pathways involved (Gibala et al., 2006). For the French rowing team, the training program is separated into three intensity zones (i.e., moderate for zone 1, heavy for zone 2, and severe for zone 3) separated by the lactate thresholds 1 and 2 (Beneke et al., 2003; Messonnier et al., 2005a). A high training volume is performed at the upper limit of the first zone (Messonnier et al., 2005a), which is systematically higher (∼75%$\dot{W}_{VO2max}$) than exercise-intensity corresponding to the maximal fat oxidation rate (Fat_{max}; ∼45–55%$\dot{W}_{VO2max}$) (Brooks and Trimmer, 1996; Rømer et al., 2020). The neglect of low-intensity training is questionable as fat oxidation capacities could be important even for performance during high-intensity exercise (Messonnier et al., 2005b) and metabolic flexibility (San-Millán and Brooks, 2018).

The aim of this study was to (i) describe theECR in French elite rowers, (ii) better understand ECR determinants, and (iii) explore ECR contribution to 2,000 m performance. Specifically, we hypothesized that the ECR and its determinants can play a significant role in ergometer rowing performance.

MATERIALS AND METHODS

Participants

Twenty-one heavyweight male rowers of international level, including two Olympic gold medalists, participated in this study. Data were collected during the annual testing procedure of the athlete. Data obtained between December 2017 and December 2019 were included. This study has been approved by the local ethics (CERUSMB, n° EOFPA-2017) committee and was performed in accordance with the Declaration of Helsinki.

Devices

A wind-resistance braked rowing ergometer (Concept II model D, fixed, Morrisville, VT, USA) was used for all the tests. Power and heart rate were continuously recorded during the tests. For analysis of expired gases, the subjects breathed through a two-way mouthpiece (Hans Rudolph 2700, Kansas City, MO) connected to a low-resistance, low-dead space mixing chamber (∼2 L). Expired gas fractions were analyzed with O_2 and CO_2 analyzers (D-Fend Datex, Helsinki, Finland and S3A/I Ametek, Pittsburgh, PA, respectively). During the time of analysis, expired gases were collected in a Tissot spirometer. More details are provided in the **Supplementary Material**.

Incremental Exercise Up to Exhaustion

This test was conducted to obtain maximal oxidative capacities of the athletes as well as to characterize the evolution of parameters with the increase of exercise intensity. The incremental test started at 200 W, and the increment between two successive steps was 50 W. Each step consisted of 3 min rowing and 0.4–0.5 min of rest to complete a blood sample at the earlobe (*vide infra*). The stroke rate was free. The procedure was performed up to exhaustion. During the test, the expired gases were sampled during the last 30 s of each step, analyzed for gas fractions of O_2 and CO_2 using gas analyzers (see *Devices*), and collected using the Tissot spirometer (Messonnier et al., 1997). The measurement obtained were used for the calculation of oxygen uptake ($\dot{V}O_2$, in L·min^{-1}), CO_2 production ($\dot{V}CO_2$, in L·min^{-1}), and respiratory exchange ratio (RER = $\dot{V}CO_2/\dot{V}O_2$). More details about gas analysis, calculations, and criterions used for $\dot{V}O_{2\,max}$ achievement are provided in the **Supplementary Material**. At the end of each step, the blood lactate concentration was analyzed (lactate analyzer 2300 STAT Plus™, YSI, Ohio, USA) from a 20 µl capillary whole blood sample from the hyperemic earlobe, as previously described (Geyssant et al., 1985). The values of mechanical and cardioventilatory parameters obtained at 2 and 4 mmol·L^{-1} of lactate concentration were extrapolated from the lactate vs. *ad hoc* parameter relationships using a polynomic fitting.

Performance Test

The rowers performed a simulated 2,000 m distance as fast as possible on the rowing ergometer. This test was included in the selection process of athletes for the French national team. The time required to cover the distance and the associated speed were used as performance criteria.

Calculation

The distance ran through each step of the incremental test was calculated as follows:

$$D(m) = \frac{step\ time\ (s)}{pace\ (s \cdot m^{-1})} \quad (1)$$

where, the pace is derived from the power according to the following formula (provided by the manufacturer):

$$Pace\ (s{\cdot}m^{-1}) = \sqrt[3]{\frac{2.8}{Power(W)}} \quad (2)$$

The mean speed for each step was then computed from distance and exercise time. The energy cost of rowing for each step was calculated from $\dot{V}_{O2}$(ml·min^{-1}), blood lactate accumulation between two successive measurements ($\Delta[La^-]_b$, mmol·L^{-1}), body mass (kg), and mean step speed (m·min^{-1}). To take into account the growing contribution of the non-oxidative glycolytic pathway in the energy supply with increasing exercise intensity, a metabolic equivalent of lactate of 3.3 mlO$_2$·kg^{-1}·mmol·L^{-1} of $\Delta[La^-]_b{}^{-1}$ was used (Margaria et al., 1963). Therefore, ECR can be assessed as follows:

$$ECR\ (mlO_2{\cdot}m^{-1}) = \frac{\dot{V}O_2 + \left(\frac{d[La-]_b}{dt} \times 3.3 \times body\ mass\right)}{mean\ step\ speed} \quad (3)$$

The oxidation rates of fat and carbohydrates (CHO) (g·min^{-1}) were indirectly estimated from $\dot{V}_{O2}$ (L·min^{-1}) and $\dot{V}_{CO2}$ (L·min^{-1}) according to the equation proposed by Péronnet and Massicotte (1991). The oxidation of protein was considered negligible. The conversion from g to kcal was made according to energetic equivalents for fat and CHO (Jeukendrup and Wallis, 2005). The detailed equations are provided below:

$$Fat\ oxidation\ (kcal/min) = (\dot{V}O_2 \times 1.695 - \dot{V}CO_2 \times 1.701) \times 9.75 \quad (4)$$

$$CHO\ oxidation\ (kcal/min) = (\dot{V}CO_2 \times 4.585 - \dot{V}O_2 \times 3.226) \times 4.07 \quad (5)$$

$$Fat\ oxidation\ (\%) = \frac{Fat\ oxidation}{Fat\ oxidation + CHO\ oxidation} \quad (6)$$

Data Analysis

Data are presented as mean with SD. Normality was graphically tested using the quantile-quantile plot method (Aldor-Noiman et al., 2013). The normality of the residual distribution was tested for each model. Correlation coefficients were obtained using the Pearson method (Good, 2009). The evolution of ECR data with increasing speed was analyzed using a linear mixed effect (LME) model with the "Speed" factor as the fixed effect and the "Subject" factor as the random effect. The *post-hoc* multiple comparisons were corrected using the false discovery rate method (Benjamini, 2010). All data were analyzed using RStudio software (RStudio Team, 2021), and the LME was fitted using the R package *nmle* (Pinheiro et al., 2014).

RESULTS

Demographic, anthropometric, and physiological characteristics of the rowers along with their performance data are reported in **Table 1**. The extrapolated values of $\dot{V}O_2$ and power output at 4 mmol·L^{-1} of $[La^-]_b$ ($\dot{V}O_{2BLC4}$ and $\dot{W}_{BLC4}$, respectively; **Table 1**) corresponded to 95% ± 4% and 89% ± 8% of their corresponding maximal counterparts ($\dot{V}O_{2max}$and $\dot{W}_{VO2max}$, respectively; **Table 1**).

The mean values of ECR (mlO$_2$·kg^{-1}·m^{-1}) for each step of the incremental test are displayed in **Figure 1**. Individual ECR kinetics are provided in **Supplementary Figure 1**. An increase in rowing speed had a significant impact on ECR (LME: speed effect: $p < 0.001$). ECR significantly and linearly increased with the speed until 5.23 ± 0.02 m·s^{-1} (**Figure 1**). From this point, the steepness of the speed vs. ECR relationship decreased drastically, delineating a pseudo-plateau (**Figure 1**). The maximal value of ECR reached during the maximal incremental test on the rowing ergometer was 0.21 ± 0.01 mlO$_2$·kg^{-1}·m^{-1}.

TABLE 1 | Demographic, anthropometric, physiological, and performance characteristics of the rowers (n = 21).

Demography/Anthropometry	
Age (years)	25.3 (3.7)
Height (m)	1.91 (0.05)
Weight (kg)	88.3 (5.9)
Maximal incremental test	
$[La^-]_{b,max}$ (mmol·L^{-1})	8.62 (3.19)
ECR$_{max}$ (mLO$_2$·kg^{-1}·m^{-1})	0.21 (0.01)
$\dot{V}O_{2max}$ (L·min^{-1})	5.67 (0.36)
$\dot{V}O_{2max}$ (mL·min^{-1}·kg^{-1})	64.6 (3.3)
$\dot{V}O_{2\ BLC2}$ (L·min^{-1})	4.80 (0.43)
$\dot{V}O_{2\ BLC4}$ (L·min^{-1})	5.37 (0.36)
$\dot{W}_{\dot{V}O2max}$(W)	437 (43)
$\dot{W}$BLC2(W)	328 (32)
$\dot{W}$BLC4(W)	389 (32)
$\dot{W}_{max}$ (W)	455 (35)
HR$_{max}$ (bpm)	189 (8)
2,000 m performance rowing ergometer test	
Time over 2,000 m (min)	6.00 (0.13)
Speed over 2,000 m (m·s^{-1})	5.56 (0.12)

ECR, energy cost of rowing; $\dot{V}O_2$, oxygen uptake; $[La^-]_b$, blood lactate concentration; $\dot{W}$, power; HR, heart rate. Data are presented as mean (SD).

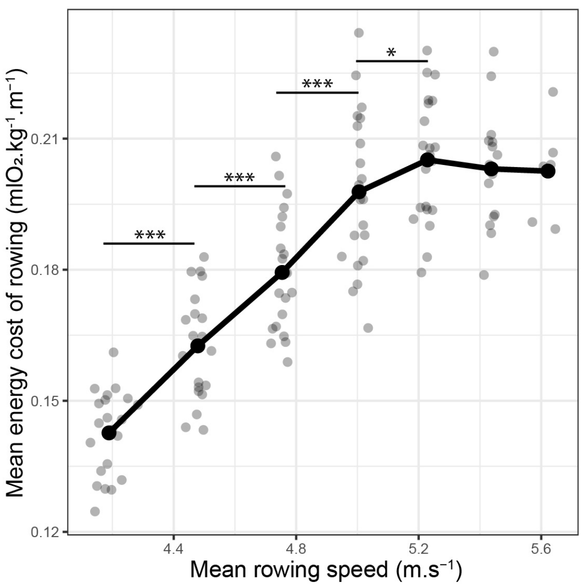

FIGURE 1 | Evolution of the energy cost of rowing (ECR) with rowing speed. Both ECR and speed were recorded for each step of a maximal incremental test on a rowing ergometer. Linear mixed-effect model: speed effect: $p < 0.001$. *Post-hoc*: $^{*}p < 0.05$; $^{***}p < 0.001$.

TABLE 2 | Correlation coefficients and probabilities between ECR (calculated at the different steps of the incremental exercise, $mlO_2 \cdot kg^{-1} \cdot m^{-1}$), and performance over a 2,000 m rowing ergometer trial (assessed by mean speed, $m \cdot s^{-1}$).

Intensity (W)	*R*	*P*-value
200	−0.47	0.03
250	−0.60	<0.001
300	−0.66	<0.001
350	−0.65	<0.001
400	−0.65	<0.001
450	−0.36	0.15
500	−0.06	0.91

Significant correlations between anthropometric parameters (body mass and height) and speed over the 2,000 m were observed ($r = 0.76$; $p < 0.001$ and $r = 0.56$; $p = 0.01$, respectively). As expected, a significant predictive value of performance for the $\dot{V}O_{2max}$ ($r = 0.64$; $p < 0.001$) and $\dot{W}_{VO2max}$ ($r = 0.60$; $p < 0.001$) was also found.

Table 2 reports correlations between ECR measured at the different steps and performance. Interestingly, ECR values obtained below the 400 W step, corresponding to 5.23 ± 0.02 $m \cdot s^{-1}$ of speed, were negatively and significantly correlated to performance. On the contrary, ECR during the plateau phase (above 5.23 ± 0.02 $m \cdot s^{-1}$) no longer correlated with performance.

The proportion of energy provided by fat oxidation was negatively correlated with ECR for exercise intensity of 300 W (mainly below $\dot{W}_{BLC2}$), 350 W (mainly between $\dot{W}_{BLC2}$ and $\dot{W}_{BLC4}$), and 400 W (mainly above $\dot{W}_{BLC4}$) (**Figure 2**). Fat oxidation at steps corresponding to 300, 350, and 400 W was also negatively correlated with the time necessary to perform 2,000 m distance (**Figure 2**). At the same steps, the RER was positively correlated with the time necessary to perform 2,000 m distance (**Supplementary Figure 2**). $[La^-]_b$ at 300, 350, and 400 W was positively correlated with ECR (**Figure 2**) and negatively correlated with fat oxidation (**Supplementary Figure 3**).

DISCUSSION

This study is the first describing (i) the metabolic ECR as a function of speed during ergometer rowing in elite oarsmen, (ii) the relationship between ECR and ergometer rowing performance, and (iii) the contribution of fat oxidation and lactate accumulation in ECR. The main findings are as follows: (i) ECR increased with rowing speed until reaching a plateau (at 5.23 ± 0.02 $m \cdot s^{-1}$ in this study), (ii) ECR at each rowing intensity/velocity before the plateau was strongly correlated with rowing performance (2,000 m time trial), and (iii) ECR during this submaximal phase is negatively and positively related to fat oxidation and blood lactate accumulation, respectively.

To our knowledge, the energy cost of rowing has been described only once. This description has been made on-water (di Prampero et al., 1971). Due to this real-life experimental design, oxygen uptake was not measured, and the energy cost of rowing was calculated from the estimated mechanical power at a given speed. A few decades ago, the rowing ergometer emerged as a major tool for on-land training. At present, it constitutes the foremost instrument to evaluate the physical ability and performance of oarsmen and oarswomen. The calculator of the ergometers displays a lot of interesting information such as the stroke rate, the power output, and the (artificial) speed. The stationary nature of the ergometer also allows a myriad of possible physiological measures including oxygen uptake and blood lactate concentration. In the aggregate, these factors make it possible to calculate ECR on the rowing ergometer. Although different by nature, it is nevertheless interesting to point out similarities between the on-water ECR (di Prampero et al., 1971) and the present on-land ECR. For intensities below 5.2 $m \cdot s^{-1}$, the energy cost of rowing described in this study was of the same magnitude order and followed the same increase in function of speed as the one predicted by the equation of di Prampero et al. (1971) (**Figure 1**). The absence of data equal or superior to 5.2 $m \cdot s^{-1}$ during the on-water study (di Prampero et al., 1971) did not allow us to conclude whether the plateau of ECR reached in our study (**Figure 1**) is specific to ergometer rowing or can be also found in on-water rowing.

In this study, we intended to consider the non-oxidative glycolytic contribution for ECR calculation because (i) part of the lactate produced during exercise is reused as a substrate mainly by oxidation (Brooks and Gaesser, 1980; Miller et al., 2002; Emhoff et al., 2013) and (ii) lactate oxidation is taken into account by the $\dot{V}O_2$, a lactate O_2 equivalent (Margaria et al., 1963) was applied to the net lactate accumulation ($\Delta[La^-]_b{}^{-1}$), which therefore constitutes only a fraction of the total lactate produced (Maciejewski et al., 2013). Despite the fact that this non-oxidative glycolytic contribution for ECR calculation was

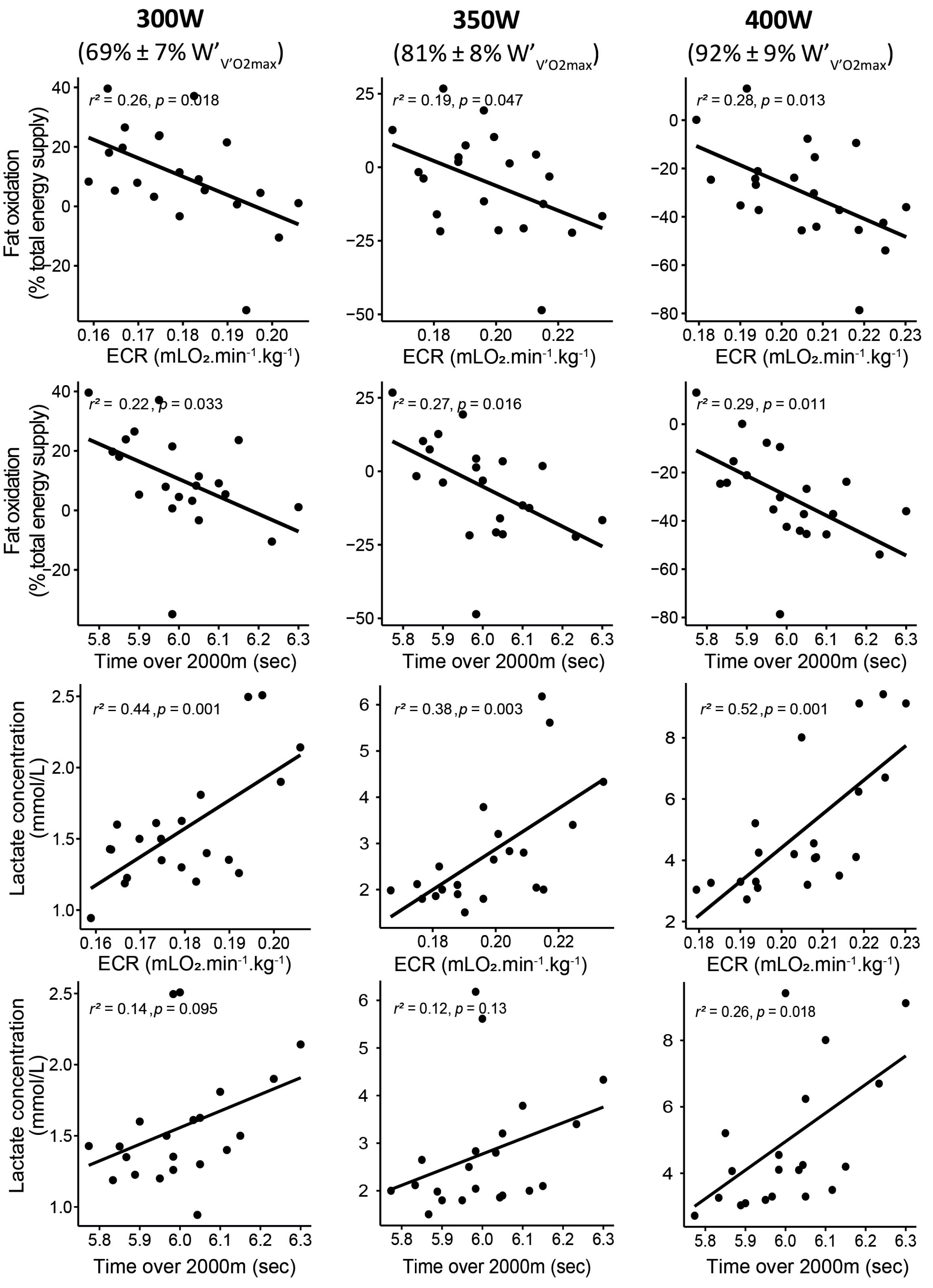

FIGURE 2 | Correlations between fat oxidation, lactate accumulation, the ECR, and performance over 2,000 m rowing. For each parameter, the correlations were displayed for an intensity corresponding to 300 W (left panel), 350 W (middle panel), and 400 W (right panel). $\dot{W}$, power; $\dot{V}O_2$, oxygen uptake.

taken into account, ECR plateaued at high exercise intensity. A likely hypothesis for the onset of the plateau could be an underestimation of the non-oxidative glycolytic contribution at this intensity. In fact, the inertia of lactate transport from the active skeletal muscles to the blood, which can take several minutes (Freund and Zouloumian, 1981), results in an underestimation of blood lactate accumulation and consequently of ECR. To keep the linearity of the rowing speed vs. ECR relationship, a $[La^-]_b$ of 12.2 ± 5.7 mmol·L^{-1} instead of 7.9 ± 3.0 mmol·L^{-1} should be reached at 5.4 m·s^{-1}. While these values are realistic, further studies would be necessary to test this hypothesis. At present, the underlying mechanism explaining the appearance of this ECR plateau remains unclear.

The athletes involved in this study were part of the elite French rowing team. The performances obtained over 2,000 m (**Table 1**) were close to the best performance described in the literature (Boegman et al., 2020). As expected, $\dot{V}O_{2max}$ or $\dot{W}_{VO2max}$ were strong determinants of performance (Cosgrove et al., 1999; Ingham et al., 2002). The strong correlation found between performance and body mass drove us to express the cost of rowing as a function of body mass.

In this context, this study is the first to report that the energy cost of rowing (mlO$_2$·kg^{-1}·m^{-1}) was strongly correlated with rowing performance over 2,000 m (**Table 2**). This original result echoes the previous report of Cosgrove et al. (1999), showing a negative and significant correlation between the $\dot{V}O_2$ at 4 m·s^{-1} and the rowing performance over 2,000 m in club rowers. The energy cost of rowing is mainly determined by the speed and the associated metabolic demand and also by (i) the contribution of the different metabolic pathways and (ii) both metabolic and mechanical efficiencies (Anton-Kuchly et al., 1984; Coyle et al., 1992; Rosenbaum et al., 2003). The latter two indicate that muscle characteristics (e.g., fiber type distribution, surface, and enzyme activities) and technical skills may play important roles in the ECR. During an incremental rowing test, the stroke rate progressively increases. The effect of this stroke rate on efficiency has previously been investigated (Hofmijster et al., 2009; Lindenthaler et al., 2018). The increase of stroke rate theoretically raises the metabolic rate needed to move the mass of the rower during the recovery phase (Lindenthaler et al., 2018). Surprisingly, while this should lead to a decrease in gross efficiency, previous studies reported an increase in efficiency when the work rate and, concomitantly, the stroke rate increase (Lindenthaler et al., 2018). This means that the slope of the increase in ECR observed in this study as a function of work rate should have been even steeper if rowing efficiency had not increased concomitantly.

Interestingly, we observed that the contribution of fat oxidation to energy supply for moderate-intensity exercises (i.e., 300 W, mainly below $\dot{W}_{BLC2}$) correlated with ECR (**Figure 2**). This correlation suggests that the rowers who had the lower ECR were also those who drove a larger part of the energy supply from fat oxidation. This negative relationship between ECR and fat oxidation is somewhat surprising since the number of ATP produced/oxygen consumption ratio is lower for fat than for carbohydrates. Previous reports showed that specific blockade of type I fibers during exercise increases $\dot{V}O_2$ for a given exercise intensity and thus the energy cost of the task (Krustrup et al., 2008). Therefore, this fiber type-specific efficiency can be a clue in the understanding of our results. Since a greater fat oxidation rate occurs in slow-twitch fibers (Lowry et al., 1978), the higher fat oxidation observed for the rowers who displayed the lower ECR may reflect higher recruitment and/or proportion of slow-twitch fibers in those rowers. However, this last point remains speculative, and its further confirmation is essential.

Surprisingly, similar correlations between ECR and fat oxidation have been observed for high exercise intensities, typically between $\dot{W}_{BLC2}$ and $\dot{W}_{BLC4}$ and above $\dot{W}_{BLC4}$ (**Figure 2**). These correlations where fat oxidation is virtually absent (RER > 1.00) seem aberrant at first sight and require us to interpret them with caution. However, the present results are reminiscent of a previous study, showing that the decrease in RER in the severe-intensity domain (i.e., above $\dot{W}_{BLC4}$; Beneke et al., 2003), induced by endurance training, was correlated with the concomitant increase in β-HAD activity, an enzyme involved in fat oxidation (Messonnier et al., 2005b). One possible explanation for these correlations in the severe-intensity domain is to consider the heterogeneity of the active skeletal muscles. In that context and considering that RER is the integration of O_2 consumption and CO_2 production of each muscle fiber involved in the exercise, a mean RER > 1.00 may not mean that all muscle fibers display a CO_2 production superior to O_2 consumption. Thus, for an RER of 1.00, some very oxidative fibers may work at RER < 1.00, while more glycolytic fibers may exercise at RER > 1.00. Thus, we can put forward the hypothesis that the difference between two RER > 1.00, e.g., 1.05 vs. 1.15 can be the result of a greater extent of fiber displaying individual RER < 1.00 in the first case, meaning that some fibers may still utilize fat. Type I fiber is the fiber type most likely to maintain an RER < 1.00 during high-intensity exercise, due to their ability of fat oxidation (high β-HAD activity in this fiber type) (Nicol and Johnston, 1981). Consistent with this hypothesis, previous studies have shown that the high energy cost of a task has been related to early-type II fiber recruitment (Krustrup et al., 2008). Completion of 2,000 m in ergometer rowing takes approximately 6 min and is performed close to $\dot{W}_{VO2max}$. It has been shown that improvement in time to exhaustion at $\dot{W}_{VO2max}$ (lasting 5–8 min) was linked to improvement in β-HAD activity and decreased RER (Messonnier et al., 2005b). These latest results would support the correlation between performance over 2,000 m and both RER and fat oxidation found in this study.

However, considering the correlations between fat oxidation and ECR or performance as a direct (cause-effect) relationship while fat oxidation is minimal or absent (**Figure 2** and **Supplementary Figure 2**) is highly questionable. In that context, the correlations we observed between lactate concentrations and fat oxidation (**Supplementary Figure 3**) and ECR (**Figure 2**) allow for other interpretations. Lactate accumulation can directly inhibit fat oxidation (San-Millán and Brooks, 2018) *via* at least two mechanisms. Lactate accumulation (1) inhibits lipolysis (Boyd et al., 1974; Liu et al., 2009) and (2) induces the formation of malonyl-CoA, which inhibits the carnitine-palmitoyltransferase-1 (CPT1) and consequently the entry of free fatty acids into the mitochondria (McGarry et al., 1977). From this point of view, the apparent role of improved fat oxidation and decreased blood lactate accumulation on ECR and rowing performance may reflect the better mitochondrial function of the best rowers (San-Millán and Brooks, 2018). This latter interpretation is also in accordance with the previously evoked higher recruitment and/or proportion of slow-twitch fibers in best rowers since these fibers are known to use fat and lactate as energy substrates. As a whole, this latter interpretation would indicate that ECR is related to the metabolic flexibility of the rowers (San-Millán and Brooks, 2018). Thus, one possible interpretation of our results could be that the better the rowers' metabolic flexibility, the lower their ECR and the higher their performance. However, this statement must be taken with caution given the correlational nature of this study.

The present results may also have important implications for the training of high-level rowers. Our results suggest that the improvement of fat oxidation may be a training goal. In that sense, the role of exercise training at moderate intensity (below $\dot{W}_{BLC2}$), known to enhance fat oxidation abilities (Schrauwen et al., 2002), is essential. This type of training may contribute to improving rowing performance.

Finally, the question of the transferability of these results to on-water 2,000 m races is of interest. The reliability of the rowing ergometer in the simulation of on-water physiological and mechanical demands has been demonstrated earlier (Hagerman, 1984; Lamb, 1989; Vogler et al., 2010). While the ECR has never been formally assessed by the on-water incremental test, the changes of ECR as a function of speed match the one predicted for on-water rowing by di Prampero et al. (1971), which supports the transferability of our results. However, the complex nature of on-water rowing, in particular, the technical and environmental determinants makes it essential to carry out additional studies to ensure this transferability.

Limitations

The main limitation of this study is the nature of the task used to determine the ECR. In fact, the energy cost of the task on the rowing ergometer is ruled by less determinants (technical skills, environmental constraints, etc.) than on-water rowing, which can explain lower ECR value (Vogler et al., 2010). This limitation should be addressed in the future with ECR determination for on-water rowing, using a wearable gas analyzer device for instance. The complex nature of on-water rowing (e.g., weather) can also lead to a reduced performance gap between the lightweight and heavyweight rowers than observed on the rowing ergometer. However, focusing here on a homogenous group of heavyweight rowers and expressing ECR as a function of body mass attenuates this limit. The similarities pointed out above between ECR described for on-water rowing and the one described in this study imply that the results provided in this study could be reproducible during on-water experiments.

CONCLUSION

This study is the first to describe the ECR, taking into account both oxidative and glycolytic non-oxidative contribution, during ergometer rowing. ECR followed a linear increase as a function of speed until reaching a plateau. The ECR in intensities below the plateau was found to be a determinant of ergometer rowing performance over 2,000 m in elite oarsmen. This study also provides new insights into the possible contribution of fat oxidation and delayed lactate accumulation to rowing performance.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Comité d'Éthique de la Recherche - Université Savoie Mont Blanc (CER – USMB). The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

LB was involved in hypothesis formulation, critical analysis of the data, and wrote the manuscript. MB, BC, EC, and ED were involved in study design, data collection, and analysis. LM was involved in study design and supervision, data collection, supervision of hypothesis formulation, and data analysis. All authors did a critical reading of the manuscript.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fphys.2022.827932/full#supplementary-material

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Dose of Bicarbonate to Maintain Plasma pH During Maximal Ergometer Rowing and Consequence for Plasma Volume

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Rowing performance may be enhanced by attenuated metabolic acidosis following bicarbonate (BIC) supplementation. This study evaluated the dose of BIC needed to eliminate the decrease in plasma pH during maximal ergometer rowing and assessed the consequence for change in plasma volume. Six oarsmen performed "2,000-m" maximal ergometer rowing trials with BIC (1 M; 100–325 ml) and control (CON; the same volume of isotonic saline). During CON, pH decreased from 7.42 ± 0.01 to 7.17 ± 0.04 (mean and SD; $p < 0.05$), while during BIC, pH was maintained until the sixth minute where it dropped to 7.32 ± 0.08 and was thus higher than during CON ($p < 0.05$). The buffering effect of BIC on metabolic acidosis was dose dependent and 300–325 mmol required to maintain plasma pH. Compared to CON, BIC increased plasma sodium by 4 mmol/L, bicarbonate was maintained, and lactate increased to 25 ± 7 vs. 18 ± 3 mmol/L ($p < 0.05$). Plasma volume was estimated to decrease by 24 ± 4% in CON, while with BIC the estimate was by only 7 ± 6% ($p < 0.05$) and yet BIC had no significant effect on performance [median 6 min 27 s (range 6 min 09 s to 6 min 57 s) vs. 6 min 33 s (6 min 14 s to 6 min 55 s)]. Bicarbonate administration attenuates acidosis during maximal rowing in a dose-dependent manner and the reduction in plasma volume is attenuated with little consequence for performance.

Keywords: plasma volume, bicarbonate supplementation, rowing, hypoxaemia, desaturation, acidosis, bohr effect

INTRODUCTION

Bicarbonate supplementation is considered an ergogenic agent through enhanced blood buffer capacity whereby fatigue may be attenuated. Although data are inconsistent (Christensen et al., 2014; Krustrup et al., 2015) probably related to different study protocols (Maughan et al., 2018), it seems that bicarbonate administration is associated with enhanced exercise capacity (Nielsen et al., 2002a). Thus, based on a meta-analysis of moderate to high quality, it is concluded that sodium bicarbonate supplementation enhances aerobic power, anaerobic capacity, and thus performance in endurance events lasting ~45 s to 8 min, muscle endurance, 2,000-m ergometer rowing performance, and high-intensity intermittent running (Grgic et al., 2021).

The enhanced blood buffer capacity following administration of sodium bicarbonate supports arterial O_2 saturation (SaO_2) by a Bohr effect on the oxygen-haemoglobin dissociation curve (Nielsen et al., 2002b) and could explain the increase in performance. However, neither pulmonary O_2 uptake

TABLE 1 | Bicarbonate dose and availability of blood samples.

Subject	Saline Trial	Bicarbonate Dose (ml)			Bicarbonate Dose Used in Tables
1	–	100*	270*	300*	
2	*	200*	300		200
3	*	200	325*		325
4	*	240*			240
5	*	300*			300
6	*	325*			325
7	*	100*			100

*blood sample available.

nor muscle oxygenation is affected by expanded blood buffer capacity (Nielsen et al., 2002a). The increase in blood bicarbonate expands the ability to absorb excess intramuscular hydrogen ions whereby lactate transport to blood is facilitated to serve the brain and attenuate central fatigue and thereby enhance performance (van Hall et al., 2009; Volianitis et al., 2011; Siebenmann et al., 2021). An often overlooked effect of sodium bicarbonate is that blood sodium increases. Normally exercise is associated with drop in plasma volume and that is likely attenuated by sodium bicarbonate.

The present report evaluated data from pilot studies carried out to establish the dose of bicarbonate that is required to maintain pH and SaO_2 during maximal ergometer rowing (Nielsen et al., 2002b). As the pilot studies used different doses of bicarbonate, we evaluated whether bicarbonate influences pH in a dose-response manner. The volume administered in control and intervention settings was similar which allowed for evaluation of whether the hypertonic sodium bicarbonate solution influences an estimate of changes in plasma volume.

MATERIALS AND METHODS

Seven competitive oarsmen (age 22 ± 2 yrs, height 182 ± 3 cm, weight 78 ± 2 kg; mean with SD) participated in the study after informed consent as approved by the Ethics Committee of Copenhagen (KF 01-280/98; Nielsen et al., 2002a). On the first trial day, the rowers were asked to report their personal record for "2,000-m" ergometer rowing [median 6 min 33 s (range 6 min 03 s to 7 min 02 s)]. No subject had any disease or injury in the 3 weeks prior the trials and was not taking any medication. The subjects were fasting on the day of the experiments which took place in the morning.

Rowing was performed on an ergometer (model C; Concept II, Morrisville, VT). First, the subjects rowed for 12 min at work rates increasing from 150 to 250 W in steps of 50 W every third minute (warm-up; Nielsen et al., 2002b). Then they rowed for 5 min at an individually determined pace including several strokes at maximal intensity. After 5 min of recovery, a 2,000-m all-out time trial simulated an on-water competition. The study aimed to identify the dose of bicarbonate that would abolish acidosis during maximal rowing. Thus, the subjects received doses of sodium bicarbonate (1 M) ranging from 100—325 ml (**Table 1**) separated by at least 7 days. In the control setting isotonic saline, in similar volume to that provided in the bicarbonate trials, was administered. Sodium bicarbonate comes as 1 mmol/ml; a dose of, e.g., 300 mmol is therefore interchangeable to administration of 300 ml.

A catheter (1.0 mm, 20 gauge) was placed in radial artery of the non-dominant arm and allowed for blood sampling during rowing. Infusion of sodium bicarbonate or saline was administered through a central catheter (1.7 mm, 16 gauge) inserted in an upper arm vein. The intended dose of sodium bicarbonate or saline to be infused was in 60-ml syringes emptied at a constant rate (app. 50–60 ml/min) according to the expected race time as reported by the rower.

Arterial blood samples were obtained anaerobically in heparinized syringes (4042E, SIMS, Radiometer, Copenhagen, Denmark) at rest, during the maximal row, and in the recovery. Samples were turned and kept on ice until analysed for blood-gas variables, haemoglobin (Hgb), haematocrit (Hct), glucose, sodium, calcium, potassium, glucose, and lactate by a ABL 615 apparatus (Radiometer) with co-oximetry for determination of haemoblobin O_2 saturation (SaO_2). Paired blood sample data were available for six rowers as in one subject (#1) blood sampling failed during the control trial (**Table 1**). Only data obtained from trials with a maximal dose of bicarbonate used for each individual went into analysis of the data as presented in **Tables 2**, **3**. Several doses of bicarbonate were used which allowed for construction of dose-response-like plot visualising the effect of bicarbonate on pH during ergometer rowing (**Figure 1**).

Changes in plasma volume were estimated by modified Strauss formula (Strauss et al., 1951) as also reported by Fudim and Miller (2018) in which values for Hgb and Hct variables are incorporated. Thus, changes in plasma volume was taken as {l00 X [(Hgb B/Hgb D) X (1-Hct D)/(l- Hct B)]−100}, where B is before rowing and D during rowing.

Data are presented as mean and standard deviation (SD). For the evaluation of data in **Table 2** and **3** one-way analysis of variance (ANOVA) was applied across the measure points for each parameter to be evaluated in each type of intervention. If significant interactions were found, a two-way *t*-test for paired data was used to locate differences. Evaluation of performance and plasma volume was by *t*-test only and a p–value < 0.05 was considered statistically significant.

RESULTS

The time for rowing was similar in trials with sodium bicarbonate and infusion of saline [median 6 min 27 s (range 6 min 09 s to 6 min 57 s) vs. 6 min 33 s (6 min 14 s to 6 min 55 s), respectively; $p > 0.05$] as four rowers improved their race time while two subjects (dose only 100 and 240 ml bicarbonate) demonstrated slower race time by 1 and 3 s. The perceived exertion (Borg scale) was similar in the two trials [median of 19 (range 16–19) vs. 19 (17–19), respectively; $p > 0.05$].

TABLE 2 | Blood variables during and after maximal ergometer rowing with infusion of isotonic saline.

	Rowing			Recovery		
	Rest	2 (min)	4 (min)	6 (min)	2 (min)	4 (min)
pH	7.42 ± 0.01	7.34 ± 0.01*	7.24 ± 0.02*	7.17 ± 0.04*	7.10 ± 0.04*	7.10 ± 0.03*
PaO_2(kPa)	13.51 ± 1.54	11.04 ± 0.45*	10.81 ± 0.41*	10.38 ± 0.67*	15.97 ± 0.62*	16.79 ± 0.18*
SaO_2 (%)	97.2 ± 0.5	95.0 ± 0.5*	95.0 ± 0.9*	90.2 ± 0.9*	95.3 ± 0.6*	95.7 ± 0.4*
$PaCO_2$(kPa)	5.21 ± 0.42	4.61 ± 0.22	4.41 ± 0.31*	4.42 ± 0.18*	3.74 ± 0.45*	3.50 ± 0.47*
Hct (%)	43.6 ± 1.6	47.2 ± 1.6*	47.1 ± 2.9*	49.9 ± 1.7*	46.3 ± 2.5*	45.3 ± 3.4
Hgb (mM)	8.6 ± 0.4	9.6 ± 0.3*	9.7 ± 0.6*	10.1 ± 0.4*	9.4 ± 0.5	9.2 ± 0.7
K^+ (mM)	3.7 ± 0.1	5.8 ± 0.4*	5.7 ± 0.6*	6.4 ± 0.6*	3.5 ± 0.2	3.0 ± 0.2*
Ca^+ (mM)	1.18 ± 0.05	1.24 ± 0.03	1.27 ± 0.03	1.36 ± 0.03*	1.28 ± 0.07*	1.25 ± 0.09
Na^+ (mM)	139.8 ± 1.6	145.2 ± 1.3*	147.0 ± 1.5*	147.8 ± 1.5*	144.3 ± 1.4*	143.0 ± 1.5*
HCO_3(mM)	25.2 ± 1.4	18.0 ± 0.6*	13.9 ± 0.6*	11.2 ± 0.8*	8.4 ± 1.2*	7.9 ± 1.5*
Lactate (mM)	0.9 ± 0.4	8.5 ± 1.4*	13.6 ± 2.1*	18.3 ± 3.2*	17.3 ± 1.9*	16.5 ± 2.0*
Glucose (mM)	5.97 ± 0.9	5.60 ± 0.8	5.35 ± 0.5	5.90 ± 0.5	9.35 ± 1.0*	9.05 ± 1.3*

*Values are arterial O_2 pressure (PaO_2), CO_2 pressure ($PaCO_2$), haemoglobin O_2 saturation (SaO_2), calcium (Ca+), haemoglobin (Hgb), haemotocrit (Hct), bicarbonate (HCO_3^-), bicarbonate (HCO_3^-), potassium (K^+), and sodium (Na^+) prior rowing (Rest) and in response to a 2,000-m ergometer maximal row with samples obtained after 2, 4, and 6 min as well as two and 4 mins into the recovery (n = 6). * different from rest, $p < 0.05$.*

TABLE 3 | Blood variables during and after maximal ergometer rowing with infusion of bicarbonate.

	Rowing			Recovery		
	Rest	2 (min)	4 (min)	6 (min)	2 (min)	4 (min)
pH	7.42 ± 0.01	7.39 ± 0.05†	7.36 ± 0.06†	7.32 ± 0.08*†	7.26 ± 0.09*†	7.24 ± 0.10*†
PaO_2(kPa)	13.2 ± 1.4	11.4 ± 1.1	10.3 ± 0.6*	9.9 ± 0.7*	16.5 ± 1.0*	16.4 ± 1.0*
SaO_2 (%)	96.7 ± 0.7	95.9 ± 0.7*	94.2 ± 0.1*†	93.2 ± 1.4*†	96.9 ± 0.9†	96.7 ± 1.1
$PaCO_2$(kPa)	5.12 ± 0.64	4.95 ± 0.44	5.08 ± 0.37	5.25 ± 0.56†	4.17 ± 0.42	4.13 ± 0.58†
Hct (%)	43.7 ± 2.3	45.6 ± 3.3*	45.5 ± 2.5	45.4 ± 2.3†	43.2 ± 2.3	42.7 ± 2.3
Hgb (mM)	8.8 ± 0.5	9.22 ± 0.7*	9.18 ± 0.5	9.22 ± 0.5*†	8.5 ± 0.6	8.4 ± 0.6
K^+ (mM)	3.7 ± 0.6	5.8 ± 0.6*	6.0 ± 0.4*	6.5 ± 0.8*	3.5 ± 0.4	2.9 ± 0.3*
Ca^+ (mM)	1.18 ± 0.04	1.13 ± 0.03†	1.11 ± 0.05†	1.11 ± 0.07†	1.06 ± 0.04*†	1.06 ± 0.06*†
Na^+ (mM)	140.5 ± 1.4	147.5 ± 1.9*†	149.7 ± 2.0*†	152.2 ± 2.9*†	148.0 ± 2.2*†	147.0 ± 2.7*†
HCO_3^-(mM)	24.5 ± 2.7	22.5 ± 3.9†	21.6 ± 4.2†	20.4 ± 4.8*†	14.2 ± 4.0*†	13.3 ± 3.9*†
Lactate (mM)	0.8 ± 0.2	11.2 ± 2.0*†	17.2 ± 6.3*	24.7 ± 6.7*†	23.5 ± 6.8*	22.8 ± 7.0*
Glucose (mM)	5.22 ± 0.5	5.28 ± 0.6	5.40 ± 0.4	5.83 ± 0.5	8.72 ± 1.1*	8.70 ± 1.1*

*Values are arterial O_2 pressure (PaO_2), CO_2 pressure ($PaCO_2$), haemoglobin O_2 saturation (SaO_2), calcium (Ca^+), haemoglobin (Hgb), haemotocrit (Hct), bicarbonate (HCO_3^-), potassium (K+), and sodium (Na+) prior rowing (Rest) and in response to a 2,000-m ergometer maximal row with samples after 2, 4, and 6 min as well as two and 4 mins into the recovery (n = 6). * different from rest, † different from respective parameter in same column and rowing as in first part of **Table 2**; $p < 0.05$.*

Lactate, pH, and Bicarbonate

During control maximal rowing, arterial lactate increased to the last minute of exercise (**Table 2**) with higher values with bicarbonate (**Table 3**). The level of lactate remained high in the recovery and for the sodium bicarbonate trial, lactate tended to remain higher than in response to saline ($p = 0.052$ and $p = 0.061$). Thus, blood lactate increased more (by 6.6 ± 4.1 mM) in the sodium bicarbonate compared with the control trial. The maximal lactate level was 30.8 mM.

Blood bicarbonate was markedly reduced during maximal rowing with saline to a minimum of 10.2 mM and it was further reduced in the recovery (**Table 2**). With the infusion of sodium bicarbonate (**Table 3**), blood bicarbonate remained stable until the sixth min of exercise. Both during rowing and in the recovery, blood bicarbonate remained higher than in the control trial.

In response to rowing with saline, pH decreased to reach the lowest level in the sixth minute (minimum pH 7.13) and it was further reduced in the recovery (minimum pH 7.06, **Table 2**). With infusion of sodium bicarbonate, pH remained almost stable until the sixth minute and remained higher than in the control trial in the recovery (**Table 3**). Infusion of bicarbonate abolished the rowing-induced acidosis in a dose-dependent manner (**Figure 1**). Thus to limit the rowing-induced reduction in pH, the effective dose of bicarbonate was 300–325 mM.

Blood-Gas Variables

In the control trial PaO_2 decreased during maximal exercise (lowest value 9.82 kPa) and also SaO_2 decreased to reach a minimum of 88.7% in the last minute but was re-established in the recovery (**Table 2**) and sodium bicarbonate trial improved SaO_2. The saline trial reduced $PaCO_2$ while rowing with sodium bicarbonate did not affcet $PaCO_2$ and it remained higher than in the control trial. The Hct and Hgb increased in response to maximal rowing but with bicarbonate these variables were lower than in the control trial.

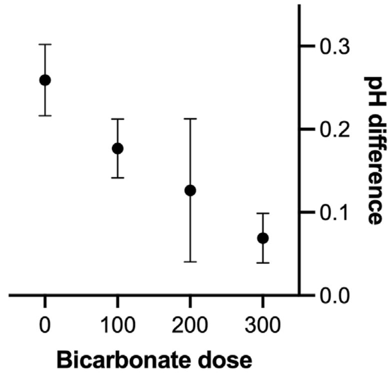

FIGURE 1 | pH effect of different doses of bicarbonate administered intravenosly during maximal ergometer rowing in seven oarsmen. *X*-axis is the dose group of bicarbonate used (100: use of 100 mmol in two subjects, 200 use of 200–240 mmol in four subjects and 300 administration of 300–340 mmol in four subjects) while "0" represent the control saline trial in six subjects. *Y*-axis is the difference between the pH at rest in samples obtained in the sixth minute of rowing. It is a limitation not all subjects received same amount of bicarbonate.

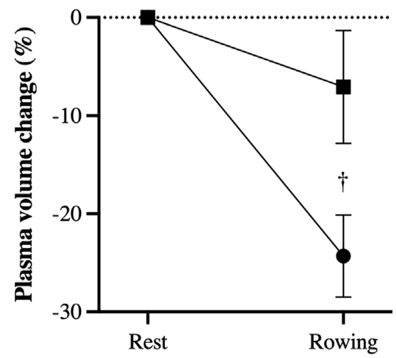

FIGURE 2 | Estimated rowing induced decrease in plasma volume (%) in trials with administration of bicarbonate (square) compared to control (circle). †, difference between rowing with bicarbonate and control; $p < 0.05$.

Plasma glucose was unchanged during rowing but increased in recovery without an effect of bicarbonate supplementation (**Tables 2**). Also potassium increased during rowing with no significant effect of sodium bicarbonate, while modest hypokalimea manifested in the recovery. During rowing with saline plasma calcium increased, while during rowing with bicarbonate it remained close to the resting level and below that observed during control exercise. Following rowing with bicarbonate, modest reduction in Ca^{++} was noted. In response to maximal rowing plasma sodium increased in both trials but to a larger extent in the trial with bicarbonate administration (by ≈ 4 mmol/L).

During rowing with saline the estimated plasma volume was reduced by 24 ± 4%, while with bicarbonate administration that reduction was by only 7 ± 6% ($p < 0.05$).

DISCUSSION

This study addresses two important issues 1) the effect of bicarbonate on acidosis and associated blood buffering capacity and 2) potential influence of bicarbonate on plasma volume. The data were collected retrospectively from a study that was conducted in a prospective manner. Here the effect of administration of bicarbonate i.v. (rather than orally as in most studies) is addressed.

The influence of maximal ergometer rowing on blood buffer capacity is pronounced (Nielsen et al., 1999). Evaluation of the dose-response effect of bicarbonate on pH reveals that about 300 mmol is required to eliminate acidosis during rowing, while administration of 100 mmol produces only a marginal effect. Thus, with production of lactate lowering blood pH towards, e.g., 7.1, administration of limited volume of sodium bicarbonate pH becomes only partially reversed. Importantly, intracellular pH is also affected by administration of bicarbonate (Nielsen et al., 2002b) and in perspective these observations provide an albeit indirect estimate of the anaerobic contribution to the work performed (Volianitis et al., 2020). With regards to the ergogenic effect of bicarbonate administration it is acknowledged that the intervention depends on the extend of acidosis provoked during the rowing trial (i.e., if the deviation from resting pH is marginal, enhancement of the blood buffering capacity will have minimal ergogenic effect). An important limitation is that it requires the subjects to be equally motivated in all trials as here supported by rate of perceived exertion of about 19. As indicated the data were obtained to evaluate the dose of bicarbonate needed to eliminate the decrease in pH associated with maximal rowing. The dose-response curve represented by **Figure 1** was constructed only with a minimal number of observations needed to conduct the main study. The ideal dose-response curve would include data from a set-up where all subjects received different doses at separate occasions but such endeavour should be undertaken in future studies. Yet, the current data provide for a perspective on anaerobic metabolism during maximal exercise.

The other important observation relates to plasma volume changes during rowing. Exercise induces a rapid fluid-shift with a drop in plasma volume during even short-term maximal exercise (Kaltreider and Mieneely, 1940; Sullivan et al., 1993). Haemoconcentration is important for maintained arterial oxygen content and may compensate for (Schierbauer et al., 2021) or likely limit an increase in cardiac output (González-Alonso et al., 2006). By use of indirect measures to estimate changes in plasma volume, administration of sodium bicarbonate was associated with attenuated decrease in plasma volume. Likely, an increase in plasma sodium counteracts transport of fluid from the intravascular compartment. Therefore, studies evaluating the effect of sodium bicarbonate on performance should account also for plasma volume changes. Such consideration may be of relevance especially for prolonged exercise and exercise in the heat.

Blood variables evaluate the influence of rowing on blood oxygenation. As reported by Nielsen et al. (2002a), maximal ergometer rowing is associated with significant hypoxaemia as also observed for running (Rowell et al., 1964; Dempsey et al., 1984; Dempsey and Wagner, 1999). The O_2 dissociation curve is right shifted by a decrease in pH and even a modest drop in PaO_2 becomes of consequence for SaO_2 that may reach 85–87% when large muscle mass is engaged (Rasmussen et al., 1991) including ergometer rowing (Hanel et al., 1994). Thus, when exercise-indued hypoxaemia is reversed by breathing an O_2 enriched atmosphere, exercise capacity increases (Nielsen et al., 1998; Nielsen et al., 1999). This study evaluated the amount of bicarbonate needed to maintain SaO_2 despite the drop in PaO_2 during maximal ergometer rowing.

Interpretation of data is limited by the small number of subjects included of potential consequence for statistical significance for difference in performance and, unfortunately, blood sampling failed for one subject. Thus, an increase in performance would not be expected for those subject who received smallest dose of bicarbonate. Also, plasma volume change was based on indirect measures. The use of Hgb and Hct to estimate changes in plasma volume was proposed by Strauss et al. (1951) and Dill and Costill (1974) found the approach feasible for estimation of changes during exercise. Yet, Fudim and Miller (2018) report that in heart failure patients plasma volume calculated by formulae using Hgb/Hct correlate only moderately to a direct evaluation. Furthermore, it is likely that use of isotonic saline in the control setting has supported plasma volume. Yet, a strength of the study is that subjects acted as their own control.

We conclude that the effect of bicarbonate on arterial pH and thus oxygen saturation is dose-dependent and that a potential effect of bicarbonate on performance should take into account the effect on plasma sodium and attenuated reduction in plasma volume during maximal exercise.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Ethical committee of Cogenhagen. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

HN, SV, NS contributed to execution of study, data collection and construction of manuscript.

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High Energetic Demand of Elite Rowing – Implications for Training and Nutrition

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Purpose: Elite rowers have large body dimensions, a high metabolic capacity, and they realize high training loads. These factors suggest a high total energy requirement (TER), due to high exercise energy expenditure (EEE) and additional energetic needs. We aimed to study EEE and intensity related substrate utilization (SU) of elite rowers during rowing (EEE_{ROW}) and other ($EEE_{NON\text{-}ROW}$) training.

Methods: We obtained indirect calorimetry data during incremental (N = 174) and ramp test (N = 42) ergometer rowing in 14 elite open-class male rowers (body mass 91.8 kg, 95% CI [87.7, 95.9]). Then we calculated EEE_{ROW} and SU within a three-intensity-zone model. To estimate $EEE_{NON\text{-}ROW}$, appropriate estimates of metabolic equivalents of task were applied. Based on these data, EEE, SU, and TER were approximated for prototypical high-volume, high-intensity, and tapering training weeks. Data are arithmetic mean and 95% confidence interval (95% CI).

Results: EEE_{ROW} for zone 1 to 3 ranged from 15.6 kcal·min^{-1}, 95% CI [14.8, 16.3] to 49.8 kcal·min^{-1}, 95% CI [48.1, 51.6], with carbohydrate utilization contributing from 46.4%, 95% CI [42.0, 50.8] to 100.0%, 95% CI [100.0, 100.0]. During a high-volume, a high-intensity, or a taper week, TER was estimated to 6,775 kcal·day^{-1}, 95% CI [6,651, 6,898], 5,772 kcal·day^{-1}, 95% CI [5,644, 5,900], or 4,626 kcal·day^{-1}, 95% CI [4,481, 4,771], respectively.

Conclusion: EEE in elite open-class male rowers is remarkably high already during zone 1 training and carbohydrates are dominantly utilized, indicating relatively high metabolic stress even during low intensity rowing training. In high-volume training weeks, TER is presumably at the upper end of the sustainable total energy expenditure. Periodized nutrition seems warranted for rowers to avoid low energy availability, which might negatively impact performance, training, and health.

Keywords: elite sport, indirect calorimetry, exercise energy expenditure, rowers, nutrition

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Abbreviations: EEE, Exercise energy expenditure; EEE_{ROW}, Exercise energy expenditure during rowing; $EEE_{NON\text{-}ROW}$, Exercise energy expenditure during training other than rowing; EA_{REC}, Recommended energy availability; MET, Metabolic equivalent of task; TEE, Total energy expenditure; TER, Total energy requirement.

INTRODUCTION

Elite open-class male rowers are characterized by large body dimensions of about 193 cm standing height and 94 kg body mass (Kerr et al., 2007). They also have a high aerobic capacity or maximum oxygen consumptions ($\dot{V}O_2$max) of up to 6.9 L·min^{-1} (Nielsen and Christensen, 2020), as a consequence of their high blood volume and muscle mass (Treff et al., 2014), high percentages of oxidative muscle fibers (Roth et al., 1993; Maciejewski et al., 2020), and high cardiac output (Volianitis et al., 2020). This unique combination of high aerobic and endurance capacity and overall muscular strength allows elite rowers to generate approximately 892 W peak power per rowing stroke (Lawton et al., 2013). Mechanical power output averages at approximately 590 W during a rowing race (Steinacker, 1993) in which the athletes cover the 2,000-m distance in about 5.5–6.5 min. Such performance necessitates a considerable anaerobic contribution of 12–33% (Roth et al., 1983; Pripstein et al., 1999) and the ability to tolerate extreme metabolic acidosis with a pH as low as 6.74 (Nielsen, 1999). This energy demand stresses the metabolic pathways extremely and consequently Olympic rowing has been deemed the ultimate challenge to the human body (Volianitis and Secher, 2009).

To maximize performance and to prepare for racing, rowers train 15–30 h per week. Rowing clearly dominates their training routine, but unspecific endurance training, resistance training, and stretching complement the program (Fiskerstrand and Seiler, 2004; Tran et al., 2015). Training intensity distribution, commonly accessed by a three-zone model, has been reported to follow a pyramidal distribution, with ~ 85% low intensity training, ~ 12% threshold training, and ~ 3% spent at high intensities (Plews et al., 2014; Treff et al., 2017). It is worth mentioning that training intensity distributions differ considerably among international rowing programs (Treff et al., 2021b) and shifts towards a polarized distribution during certain phases of the competition period have been reported (Treff et al., 2017).

Due to the volume and complexity of a rower's training, dedicated planning and monitoring of the total training load is warranted. This necessitates an integrated approach of external and internal training load (Bourdon et al., 2017). While the external training load (e.g., training distance or duration) is generally well assessable (Treff et al., 2017), the quantification of internal load is far more challenging. Tools like the recovery stress questionnaire (Kellmann et al., 2001), measures of the autonomous nervous system (Plews et al., 2014), or biomedical markers (Hecksteden et al., 2016; Bizjak et al., 2021) that have been proposed to mirror acute or midterm stress, are frequently applied. While all these markers are surrogates for the organism's response to repeated exercise, they fail to quantify the energetic load of training, which is on the cellular level the major stimulus connecting nutrient intake and training adaption (Hawley et al., 2018).

The energetic load of training is reflected by the energy expenditure. Messonnier and colleagues (Messonnier et al., 2005a) aimed to assess the training load in international open-class and lightweight rowers based on questionnaires. They reported a mean habitual weekly energy expenditure of 5,388 ± 159 kcal·day^{-1}. Others reported a nutrient intake of 7,000 kcal·day^{-1} in elite open-class male rowers during high-volume training (Boegman and Dziedzic, 2016).

To assess the total energy requirement (TER) of a rower precisely, non-exercise and exercise energy expenditure (EEE) need to be considered. EEE in elite open-class male rowers is presumably high, because of the large body dimensions, the high training volume, the involvement of approximately 70% active muscle mass during rowing (Steinacker, 1993), and the low mechanical efficiency of rowing of about 16–24% (Di Prampero et al., 1971). Taken altogether this suggests a very high EEE already at moderate training intensities, which represent the major part of the TER in elite rowers (Messonnier et al., 2005a). The non-exercise energy expenditure is more complex and thus difficult to predict. On the one hand, a high resting metabolic rate of 2,675 kcal·day^{-1} has already been reported in open-class male rowers (Carlsohn et al., 2011), but this high energy demand is contrasted by a sedentary behavior outside of the daily training routine (i.e., off-training) (Sperlich et al., 2017). On the other hand, a more recent study reported 2.2 h·week^{-1}of moderate to vigorous off-activities above 60% of maximal heart rate (Treff et al., 2021a), which in turn already in itself corresponds to a rather active lifestyle.

In the light of the high EEE and possibly high TER, an energetic limitation of rowing training volume seems possible (Mader and Hollmann, 1977) and sufficient energy intake becomes a potential issue when training volume is high. Thus, more adequate data on EEE and TER in elite open-class male rowers are needed to adjust energy supply and expenditure, because otherwise risk of inadequate dietary energy intake is apparent (Braakhuis et al., 2013).

We therefore aimed to quantify EEE and substrate utilization of rowing training in elite open-class male rowers during laboratory-based ergometer testing, and aimed to approximate the accumulated TER for prototypical periodized training. To the best of our knowledge, this is the first study in elite open-class male rowers dedicated to this aim.

MATERIALS AND METHODS

Overview

We retrospectively analyzed data from 174 incremental step and 42 incremental ramp tests conducted repeatedly in 14 elite open-class male rowers. All tests were part of the German Rowing federation's testing routines between 2013 and 2020. Step tests were used to determine lactate thresholds, mechanical power output, heart rate (HR), oxygen uptake ($\dot{V}O_2$), carbon dioxide production ($\dot{V}CO_2$), and respiratory exchange ratio (RER) at each stage, while ramp tests were used to measure $\dot{V}O_2$max. Based on LTs and $\dot{V}O_2$max, the intensity continuum was divided into three zones adapting previous recommendations (Seiler, 2010; Manunzio et al., 2016).

EEE during ergometer rowing (EEE$_{ROW}$) was accessed *via* indirect calorimetry, which also allowed for an estimation of the substrate utilization at a given workload. The percentage and absolute increase in carbohydrate metabolism, with a concomitant decrease in fatty acid utilization above moderate intensities (Brooks and Trimmer, 1996), is reflected by an increase in RER. Accordingly, RER allows for a specification of substrate utilization, thereby providing a further measure of (relative) exercise intensity in addition to percentage of $\dot{V}O_2$max, ventilatory, or lactate "threshold".

For a given EEE, a corresponding amount of stored energy in the form of body fat and glycogen is required. We approximated the glycogen depletion associated with a given EEE_{ROW} based on body composition data and empirical data of liver and muscle glycogen, and blood glucose.

EEE for typical non-rowing sessions ($EEE_{NON\text{-}ROW}$) was calculated based on metabolic equivalents of task (MET) corrected for resting metabolic rate of the appropriate sports mode (e.g., indoor cycling). Using EEE_{ROW} and $EEE_{NON\text{-}ROW}$, we approximated daily TER for prototypical training weeks focusing either on high volume, high intensity, or on taper training.

Participants

Fourteen elite open-class male rowers (body mass 91.8 kg, 95% confidence interval (95%CI) [87.7, 95.9], fat free mass 83.5 kg, 95% CI [80.1, 86.9], $\dot{V}O_2$max 6.6 $L{\cdot}min^{-1}$, 95% CI [6.5, 6.7] or 72.0 $ml{\cdot}min^{-1}{\cdot}kg^{-1}$ [69.6, 74.5]) decorated with several medals from Olympic Games and/or World Championships participated in this study. Participants completed a varying number of tests during the observation period, depending on whether the participants continued to qualify for the national team and/or because of absences from tests for health or other reasons. All rowers were familiar with the pre-testing and testing procedures and maintained a balanced diet. They conducted no high-intensity training 48 h prior testing and the last low intensity training session ended 20 h before each test or earlier to avoid fatigue, glycogen deficiency, and hypohydration. The study was conducted according to the declaration of Helsinki and approved by the ethical board of the University of Ulm (##267/11). All participants gave written informed consent to participate in the testing and the retrospective data analyses.

Equipment

All tests were conducted on a Concept 2 rowing ergometer (indoor rower, model D, Concept 2, Morrisville, United States). As described elsewhere (Mentz et al., 2020), the ergometer was equipped with a load cell and a rotary transducer to measure force and the travel distance of the handlebar, thereby allowing to calculate mechanical power output (Institut für Forschung und Entwicklung von Sportgeräten (FES), Berlin, Germany).

An automated metabolic analyzer equipped with a dynamic micro mixing chamber (Metamax 3x, Cortex Biophysics, Leipzig, Germany) measured $\dot{V}O_2$ and $\dot{V}CO_2$. Validity has been reported as 1.98 ± 2.98% difference to the Douglas bag method (Larsson et al., 2004). Blood lactate was measured using an amperometric-enzymatical analyzer (C-Line, EKF, Barleben, Germany). Reliability expressed as coefficient of variation (CV) of the device amounts to < 1.5% (Kohler and Boutellier, 2004). Calibration and maintenance of the ergometer setup and the metabolic and lactate analyzers were performed according to the manufacturers' guidelines (EKF-diagnostic GmbH, 2013; Cortex Medical, 2015).

Procedures and Testing

Determination of Lactate Thresholds

After a 30-min standardized warm-up at 150 W, all rowers performed a submaximum incremental test on the rowing ergometer. Steps lasted 4 min and increased by 50 W. Workload ranged 200–400 W in ten rowers or 200–450 W in five rowers with exceptionally high endurance performance, respectively. Gas exchange and ventilation were measured continuously and data were averaged over the last 30 s of each stage. During a 30-s break after each stage, 20 μL of capillary blood were drawn from the hyperemic earlobe and the concentration of capillary blood lactate was analyzed. Lactate "thresholds" 1 and 2 (LT1 and LT2) were calculated according to Dickhuth and colleagues (Dickhuth et al., 1991), using a polynomic fitting of the data (Winlactat, Mesics, Münster, Germany). Data of mechanical power output, ventilation, and gas exchange were aligned to LT1 and LT2, respectively.

Measurement of Maximum Oxygen Uptake

After a 30-min standardized warm-up at 150 W on a rowing ergometer, all rowers performed an incremental ramp test on the same rowing ergometer used for the incremental step tests. Gas exchange and ventilation were measured with the same metabolic analyzer applied in the step tests. The initial target power output was 160 W and increased by 30, 35, or 40 $W{\cdot}min^{-1}$, depending on the individual rower's estimated performance level. The test was automatically terminated if a rower failed to increase mechanical power output within a 7-W range of five strokes (Treff et al., 2018). $\dot{V}O_2$max was defined as the highest 30-s moving average and considered as maximum if $\dot{V}O_2$ failed to increase with progressive work rate (leveling-off) or at least a plateau (i.e., increase in $\dot{V}O_2 < 150\ ml{\cdot}min^{-1}$) was observed (Midgley et al., 2007).

Calculations of Exercise Energy Expenditure, Glycogen Depletion, and Total Energy Requirement

Intensity-Zones

The metabolic load at LT1, 50% of LT2 ($LT2_{50\%}$) (Manunzio et al., 2016), LT2 and $\dot{V}O_2$max was applied to a three-zone model (Seiler, 2010), with zone 1 ranging from $LT2_{50\%}$ to LT1, zone 2 ranging from LT1 to LT2, and zone 3 ranging from LT2 to $\dot{V}O_2$max.

Calculation of EEE and SU for Rowing

EEE_{ROW} and substrate utilization at LT1, $LT2_{50\%}$, LT2, and $\dot{V}O_2$max were calculated using a non-protein table by Péronnet and colleagues (Péronnet and Massicotte, 1991). EEE_{ROW} was corrected by adding additional energy derived from the anaerobic energy contribution (EC_{Lac}) and subtracting the resting metabolic rate. EC_{Lac} was derived by applying a O_2-lactate equivalent according to **Equation 1**:

$$EC_{Lac}\ [kcal] = \Delta_{blood\ lactate}\left[mmol \cdot L^{-1}\right] \times 0.0033 \left[L \cdot kg^{-1} \cdot \left(mmol \cdot L^{-1}\right)^{-1}\right] \times BM[kg] \times 5.04\ \left[kcal \cdot L^{-1}\right] \quad (1)$$

Where Δ_{blood} lactate is the difference between rest and post-step or post-test blood lactate concentration, 1 mmol · L^{-1} Δ_{blood} lactate is equivalent to the energy released by the uptake of 0.0033 L of O_2 per kg body mass (BM) (Margaria et al., 1963; Di Prampero and Ferretti, 1999), and 5.04 kcal represents the caloric equivalent of 1 liter O_2. Resting metabolic rate was calculated according to Cunningham (Cunningham, 1980).

We calculated EEE_{ROW} and corresponding substrate utilization for typical steady-state sessions within the three intensity zones for different durations.

Calculation of $EEE_{NON\text{-}ROW}$

We calculated $EEE_{NON\text{-}ROW}$ for steady-state exercise at a given intensity and duration using estimated METs that were corrected for resting metabolic rate according to **Equation 2** (Ainsworth et al., 2011):

$$EEE_{NON-ROW}\left[kcal \cdot min^{-1}\right] = (MET - 1) \times RMR\left[kcal \cdot min^{-1}\right] \quad (2)$$

where MET values were taken from the Compendium of Physical Activities (Ainsworth et al., 2011) for cycling (compendium codes 1,050/1,040), strength training (2,050), calisthenics (2,030), stretching (2,101), and soccer (15,610). Again, resting metabolic rate (RMR) was calculated according to Cunningham (Cunningham, 1980).

Calculation of Glycogen Depletion

Glycogen depletion was calculated as a function of glycogen consumption (g·min^{-1}) and duration of rowing training (minutes), for a given intensity zone based on the sum of carbohydrates from blood glucose, liver, and active skeletal muscle glycogen stores. Blood glucose mass was calculated based on plasma volume according to **Equation 3**:

$$Blood\ glucose\ [g] = \left(0.07\ \left[L \cdot kg^{-1}\right] \times LBM\ [kg] + 0.06[L]\right) \times 1\ \left[g \cdot L^{-1}\right] \quad (3)$$

with the first term representing the plasma volume estimated from lean body mass (LBM) (data provided from Treff et al., 2014) and the second term (1 g·L^{-1}). which is the upper limit of the normal glucose concentration in the blood plasma in the fasting state. LBM was determined *via* bioimpedance measurements (InBody 720, BioSpace, Seoul, Korea). Liver glycogen energy was calculated based on **Equation 4**:

$$Liver_{Energy}\ [kcal] = (BM\ [kg] \times 0.025) \times 195\ \left[kcal \cdot kg^{-1}\right] or\ 365\ \left[kcal \cdot kg^{-1}\right] \quad (4)$$

with 0.025 corresponding to the proportion of liver *vs*. body mass (BM) (Valentin, 2002), assuming 2.3 kg, 95% [2.2; 2.4] liver mass and 195 kcal·kg^{-1} or 365 kcal·kg^{-1} representing the lower and upper end of liver glycogen density (Rapoport, 2010). For muscle glycogen, we determined an active skeletal muscle mass (SMM_{Active}) of 33.7 kg, 95% [32.2, 35.2] *via* bioimpedance measurements and we assumed 70% active muscle mass in rowing (Steinacker, 1993). The lower and upper muscle glycogen content was further calculated according to **Equation 5**:

$$Muscle_{Glycogen}\ [g] = (SMM_{Active}[kg] \times 0.2) \times 0.18\ \left[g \cdot mmol^{-1}\right] \times 500\ \left[mmol \cdot kg^{-1}\right] or\ 700\ \left[mmol \cdot kg^{-1}\right] \quad (5)$$

were 0.2 is the transformation factor from wet to dry weight (dw), 0.18 g·$mmol^{-1}$ is the molecular weight of glucose, 500 mmol · kg^{-1} or 700 mmol · kg^{-1} are the assumed lower and upper limits of glycogen density per kg dw (Hearris et al., 2018).

To convert mass (g) of carbohydrates into energy (kcal), or vice versa, we applied the caloric equivalent of 4.1 kcal·g^{-1}.

Calculation of Recommended Energy Availability and Total Energy Need

To account for the additional energy requirements of activities outside of EEE_{ROW} and $EEE_{NON\text{-}ROW}$, we calculated the TER as the sum of EEE and the recommended energy availability (EA_{REC}). The latter describes the amount of energy that is available for all other physical functions after subtracting the EEE from total energy expenditure (TEE) (Loucks, 2013) and was calculated according to **Equation 6** (Areta et al., 2020):

$$EA_{REC}\left[kcal \cdot d^{-1}\right] = 40\ \left[kcal \cdot kg^{-1} \cdot day^{-1}\right] \times FFM\ [kg] \quad (6)$$

where FFM depicts the fat free mass that was determined *via* bio impedance measurements. Based on these calculations, we approximated accumulated daily TER according to **Equation 7**:

$$TER\ \left[kcal \cdot d^{-1}\right] = AEE_{ROW}\ \left[kcal \cdot d^{-1}\right] + AEE_{NON-ROW}\ \left[kcal \cdot d^{-1}\right] + EA_{REC}\ \left[kcal \cdot d^{-1}\right] \quad (7)$$

Prototypical Training Sessions and Weeks

As a blueprint for typical training weeks we used original training plans of elite German rowers and calculated TER according to the previous equations. We selected exemplary high volume, high intensity, and tapering weeks. Training volume of these weeks amounted to 1,605, 1,055, and 555 min·$week^{-1}$, respectively. Percentage of training spent in Zone 1–Zone 2–Zone 3 was 97.5%-2.5%-0.0% in the high-volume, 92.8%-0.0%-7.2% in the high-intensity, and 97.8%-0.0%-2.2% in the tapering week, respectively. Additional information is given in **Table 1**.

Statistical Analysis

To account for dependency of repeated step test (4–20 tests per rower) and ramp test (1-4 test per rower) measurements, unweighted individual mean values were calculated (**Supplementary Table S1**), with homogeneous individual standard deviations indicating no dependency of measurement variation on individual test repetitions. Consequently, individual mean values were further used to calculate robust descriptive data by the arithmetic mean with 95% CI. Descriptive data were calculated using SPSS (IBM

TABLE 1 | Training indices for exemplary high volume, high intensity, and tapering rowing training weeks.

		Mo.	Tu.	We.	Th.	Fr.	Sa.	Su.	Sum
High volume	Sessions (N) (rowing/other)	4 (2/2)	2 (1/1)	3 (2/1)	4 (2/2)	2 (1/1)	3 (2/1)	3 (2/1)	23 (13/10)
	Duration (min) (rowing/other)	295 (190/105)	160 (100/60)	230 (170/60)	305 (200/105)	170 (90/80)	220 (160/60)	225 (180/45)	1,605 (1,090/515)
	TID (%) rowing (Z1/Z2/Z3)	(100/0/0)	(100/0/0)	(100/0/0)	(100/0/0)	(70/30/0)	(100/0/0)	(100/0/0)	(97.5/2.5/0)
High intensity	Sessions (N) (rowing/other)	3 (2/1)	3 (2/1)	2 (1/1)	3 (2/1)	2 (1/1)	3 (2/1)	2 (1/1)	18 (11/7)
	Duration (min) (rowing/other)	190 (160/30)	170 (125/45)	140 (80/60)	170 (125/45)	140 (80/60)	170 (125/45)	75 (45/30)	1,055 (740/315)
	TID (%) rowing (Z1/Z2/Z3)	(95/0/5)	(93.2/0/6.8)	(90/0/10)	(93.2/0/6.8)	(93/0/7)	(93.9/0/6.1)	(85/0/15)	(92.8/0/7.2)
Tapering	Sessions (N) (rowing/other)	3 (2/1)	free	2 (2/0)	2 (1/1)	2 (2/0)	2 (1/1)	1 (1/0)	12 (9/3)
	Duration (min) (rowing/other)	135 (105/30)	free	90 (90/0)	90 (60/30)	105 (105/0)	90 (60/30)	45 (45/0)	555 (465/90)
	TID (%) rowing (Z1/Z2/Z3)	(97.4/0/2.6)	free	(100/0/0)	(95/0/5)	(97.7/0/2.3)	(100/0/0)	(95/0/5)	(97.8/0/2.2)

TABLE 2 | Mechanical, cardiorespiratory, metabolic demand and perceived rate of exhaustion [mean (95% CI)] for rowing at individual lactate thresholds and maximum oxygen consumption.

Variable	LT1	LT2	$\dot{V}O_2$max
Power (W)	274 [264, 284]	360 [348, 373]	520 [499, 540]
$\dot{V}O_2$ (L·min^{-1})	4.4 [4.2, 4.7]	5.5 [5.3, 5.7]	6.6 [6.5, 6.7]
%$\dot{V}O_2$max (%)	67.6 [64.2, 70.9]	83.6 [81.3, 85.8]	100.0 [100.0, 100.0]
RER ( )	0.90 [0.89, 0.91]	0.96 [0.96, 0.97]	1.07 [1.05, 1.09]
EEE (kcal·min^{-1})	21.3 [20.2, 22.4]	29.0 [28.0, 30.0]	48.3 [46.7, 49.9]
HR (min^{-1})	144 [140, 148]	168 [165, 171]	192 [187, 197]
Lac (mmol·L^{-1})	0.9 [0.8, 1.0]	2.4 [2.3, 2.5]	12.1 [11.4, 12.9]
RPE (a.u.)	3.0 [2.7, 3.3]	5.0 [5.0, 6.0]	—

Notes: Lactate threshold 1&2 (LT1&2) based on Dickhuth and colleagues (Dickhuth et al., 1991) based on incremental test. Maximum oxygen consumption data ($\dot{V}O_2$max) is based on ramp tests. $\dot{V}O_2$, oxygen consumption data; RER, respiratory exchange ratio; EEE, exercise energy expenditure; HR, heart rate; Lac, blood lactate concentration; RPE, rate of perceived exertion.

Corp. Released 2017. IBM SPSS Statistics for Windows, Version 25.0. Armonk, NY: IBM Corp.).

RESULTS

Table 2 includes mechanical power output, cardiorespiratory, metabolic, and RPE data aligned to LT1, LT2, and $\dot{V}O_2$max.

Table 3 includes mechanical power output, cardiorespiratory, and metabolic data with corresponding EEE_{ROW} and SU for a three-zone model based on LT1, LT2, and $\dot{V}O_2$max. EEE_{ROW} ranged from 15.6 kcal·min^{-1}, 95% CI [14.8, 16.3] to 49.8 kcal·min^{-1}, 95% CI [48.1, 51.6] and carbohydrate utilization ranged from 46.4%, 95% CI [42.0, 50.8] to 100%, 95% CI [100.0, 100.0], respectively.

Figure 1 shows the accumulated daily mean EEE, separated for EEE_{ROW} in zones 1-3 and $EEE_{NON\text{-}ROW}$ for each of the prototypical training weeks. Descriptive training data for these weeks are shown in **Table 1**. The estimated mean weekly EEE_{ROW} during a high volume, high intensity, or tapering week amounted to 2,899 kcal·day^{-1}, 95% CI [2,749, 3,049], 2,110 kcal·day^{-1}, 95% CI [1,970, 2,251], or 1,257 kcal·day^{-1}, 95% CI [1,157, 1,356]. $EEE_{NON\text{-}ROW}$ was 533 kcal·day^{-1}, 95% CI [455, 612], 319 kcal·day^{-1}, 95% CI [268, 371], or 27 kcal·day^{-1}, 95% CI [27, 27], respectively. Summarized with an estimated EA_{REC} of 3,343 kcal·day^{-1}, 95% CI [3,211, 3,474], mean weekly TER amounted to 6,775 kcal·day^{-1}, 95% CI [6,651, 6,898], 5,772 kcal·day^{-1}, 95% CI [5,644, 5,900] or 4,626 kcal·day^{-1}, 95% CI [4,481, 4,771] for these prototypical weeks.

Figure 2 illustrates the accumulated EEE_{ROW} as a function of rowing training duration for each intensity zone.

Figure 3 illustrates the muscle glycogen depletion as a function of the intensity zones, utilization rate of carbohydrates, and duration of rowing training. Approximated blood glucose, liver, and muscle glycogen stores amounted to 6 g, 95% CI [5, 6], 109 g, 95% CI (104, 114) to 201 g, 95% CI (193, 210), and 607 g, 95% CI [580, 634] to 850 g, 95% CI [812, 888], respectively. In total, this corresponded to 2,959 kcal, 95% CI [2,828, 3,091] to 4,333 kcal, 95% CI [4,141, 4,526].

DISCUSSION

We studied EEE and substrate utilization of ergometer rowing in elite male open-class rowers. Indirect calorimetry data were obtained during repeated incremental step and ramp testing to calculate EEE_{ROW} and substrate utilization in three intensity zones. Further, we approximated daily TER as the sum of EEE_{ROW}, $EEE_{NON\text{-}ROW}$, and EA_{REC} for prototypical high volume, high intensity, and tapering training weeks.

The main results are a high EEE_{ROW} in elite open-class male rowers ranging 15.6 kcal·min^{-1}, 95% CI [14.8, 16.3] to 48.8 kcal·min^{-1}, 95% CI [48.1, 51.6] from zone 1 to 3. The energetic contribution of fat metabolism was never higher

TABLE 3 | Mechanical, cardiorespiratory and metabolic demand of rowing corresponding to a three-zone model.

Variable	Zone 1		Zone 2		Zone 3	
	LL	UL	LL	UL	LL	UL
Power (W)	180 [174, 186]	274 [264, 284]	275 [265, 285]	360 [348, 373]	361 [349, 374]	520 [499, 540]
HR (min^{-1})	122 [117, 128]	144 [140, 148]	145 [141, 149]	168 [165, 171]	169 [166, 172]	192 [187, 197]
$\%HR_{max}$ (%)	63.7 [61.6, 65.7]	74.8 [73.4, 76.1]	75.3 [74.0, 76.7]	87.5 [86.1, 89.0]	88.1 [86.6, 89.5]	100.0 [100.0, 100.0]
$\dot{V}O_2$ ($L \cdot min^{-1}$)	3.4 [3.3, 3.6]	4.4 [4.2, 4.7]	4.4 [4.2, 4.7]	5.5 [5.3, 5.7]	5.5 [5.3, 5.7]	6.6 [6.5, 6.7]
$\%\dot{V}O_2max$ (%)	52.2 [49.8, 54.6]	67.6 [64.2, 70.9]	67.6 [64.3, 70.9]	83.6 [81.3, 85.8]	83.6 [81.4, 85.8]	100.0 [100.0, 100.0]
RER ( )	0.83 [0.82, 0.85]	0.9 [0.89, 0.91]	0.91 [0.90, 0.92]	0.96 [0.95, 0.97]	0.97 [0.96, 0.98]	1.07 [1.05, 1.09]
Lac ($mmol \cdot L^{-1}$)	0.7 [0.6, 0.7]	0.9 [0.8, 1.0]	1.0 [0.9, 1.1]	2.4 [2.3, 2.5]	2.5 [2.4, 2.6]	12.1 [11.4, 12.9]
EEE ($kcal \cdot min^{-1}$)	15.6 [14.8, 16.3]	21.3 [20.2, 22.5]	21.4 [20.2, 22.6]	29.2 [28.2, 30.2]	29.4 [28.4, 30.4]	49.8 [48.1, 51.6]
CHO (%)	46.4 [42.0, 50.8]	67.6 [64.4, 70.8]	67.6 [64.4, 70.8]	88.1 [85.7, 90.5]	88.4 [86.2, 90.6]	100.0 [100.0, 100.0]
LIP (%)	53.6 [49.2, 58.0]	32.4 [29.2, 35.6]	32.4 [29.2, 35.6]	11.9 [9.5, 14.3]	11.6 [9.4, 13.8]	0.0 [0.0, 0.0]
CHO ($g \cdot min^{-1}$)	1.8 [1.6, 2.0]	3.5 [3.2, 3.8]	3.6 [3.2, 3.9]	6.3 [6.0, 6.7]	6.4 [6.1, 6.7]	12.2 [11.7, 12.6]
LIP ($g \cdot min^{-1}$)	0.9 [0.8, 1.0]	0.7 [0.7, 0.8]	0.7 [0.7, 0.8]	0.3 [0.3, 0.4]	0.3 [0.3, 0.4]	0.0 [0.0, 0.0]

Notes: Data are arithmetic means and [95% confidence interval] within a three-zone model with lower limits (LL) and upper limits (UL) based on zone 1 $LT2_{50\%}$–LT1, Zone 2 LT1–LT2, Zone 3 LT2 - maximum oxygen consumption ($\dot{V}O_2max$). Calculation of exercise energy expenditure (EEE) and substrate utilization in carbohydrates (CHO) and lipids (LIP) based on a non-protein table (Péronnet and Massicotte, 1991) and corrected for resting metabolic rate (Cunningham, 1980) and anaerobic energy contribution (Di Prampero and Ferretti, 1999). HR, heart rate; $\dot{V}O_2$, oxygen consumption; RER, respiratory exchange ratio; Lac, blood lactate concentration.

than 53.6 ± 7.6%. Furthermore, we calculated a high TER ranging 4,626 $kcal \cdot day^{-1}$, 95% CI [4,481, 4,771] to 6,775 $kcal \cdot day^{-1}$, 95% CI [6,651, 6,898] during prototypical training weeks. This indicates that isocaloric energy intake may become challenging during high volume training weeks and points to a metabolic limitation of reasonable rowing training volume.

Metabolic Demand of Ergometer Rowing

The metabolic demand within ergometer rowing is already high at LT1 and LT2. The mechanical power output at these "thresholds" (**Table 2**) corresponds well with previous data published for elite male open-class rowers (Tran et al., 2015). However, for the first time, we report $\dot{V}O_2$- and RER-data aligned to these points as well as to $\dot{V}O_2max$. While the high metabolic demand at $\dot{V}O_2max$ is apparently related to the remarkably high absolute aerobic capacity of elite male open-class rowers, sub-maximum $\dot{V}O_2$ data at LT1 and LT2 are far more interesting. Here, the metabolic demand is considerably higher than corresponding results for e.g., cyclists, ranging 3.6–4.3 $L \cdot min^{-1}$ (Garvican et al., 2013). This is attributable to the relatively large body dimensions of rowers, especially their high body and muscle mass. Nevertheless, also a particularly of ergometer rowing — or more exactly its measurement — contributes to this phenomenon: During the drive phase, when the rower pushes off from the foot stretcher with his legs and moves backwards on his sliding seat, the rower exerts force on the handle or oar and this force is measured. Afterwards, the rower has to bring himself back to the starting position, which also requires force and energy. This additional mechanical power output—amounting to roughly 38 W (Mentz et al., 2021)—is not measured by common ergometers. Consequently, the actual mechanical power output is underestimated and the metabolic load of ergometer rowing *vs.* cycling at a given (displayed power output is considerably higher (Turner and Rice, 2021). Thus, the mechanical efficiency is significantly lower in ergometer rowing *vs.* cycling (Lindenthaler et al., 2018). Nevertheless, it is worth mentioning that ergometer rowing has been reported to induce similar metabolic stress as on-water rowing (Vogler et al., 2010). Another factor that contributes to the high $\dot{V}O_2$ data at LT1, LT2, and $\dot{V}O_2max$ during rowing is the high amount of muscle mass recruited and the high venous return due to the sitting position of the rower (Volianitis and Secher, 2009), thereby resulting in a relatively high EEE at any given mechanical power output.

Metabolic Demand of Ergometer Rowing at Low, Moderate, and High Intensities

The $\dot{V}O_2max$ percentages derived from the lactate thresholds in our study fit well to previous categorizations (Seiler, 2010), underlining the validity of our data that allowed us to estimate the metabolic demand within each zone of the three-zone model (**Table 2**). EEE_{ROW} in all intensity zones was apparently high, ranging from 15.6 $kcal \cdot min^{-1}$, 95% [14.8.16.3] to 49.8 $kcal \cdot min^{-1}$, 95% [48.1, 51.6], equaling to an 10- to 31-fold increase in RMR, respectively. It seems worth to highlight that a "basic" endurance training in an elite open-class male rower at the upper range of zone 1 around LT1 already necessitates a $\dot{V}O_2$ of 4.4 $L \cdot min^{-1}$ something that is simply not possible for e.g., an elite distance runner with a $\dot{V}O_2max$ of 4.2 $L \cdot min^{-1}$ (Jones et al., 2021). This illustrates the energetic differences between these elite athletes of different endurance sports disciplines.

However, aside from EEE, substrate utilization is of particular importance to rate the metabolic stress of exercise. While we estimate lipid stores in this sample of elite open-class male rowers as high as ~ 77,000 kcal (9.3 $kcal \cdot g^{-1}$ x 8,300 g body fat mass), maximum energy stores from glycogen and blood glucose are limited to 2,959 kcal, 95% CI [2,828, 3,091] to 4,333 kcal, 95% CI [4,141, 4,526] with almost perfectly filled glycogen stores. Since glycogen stores largely depend on the loading status and assuming that no more than 90% depletion of the initial muscle glycogen store

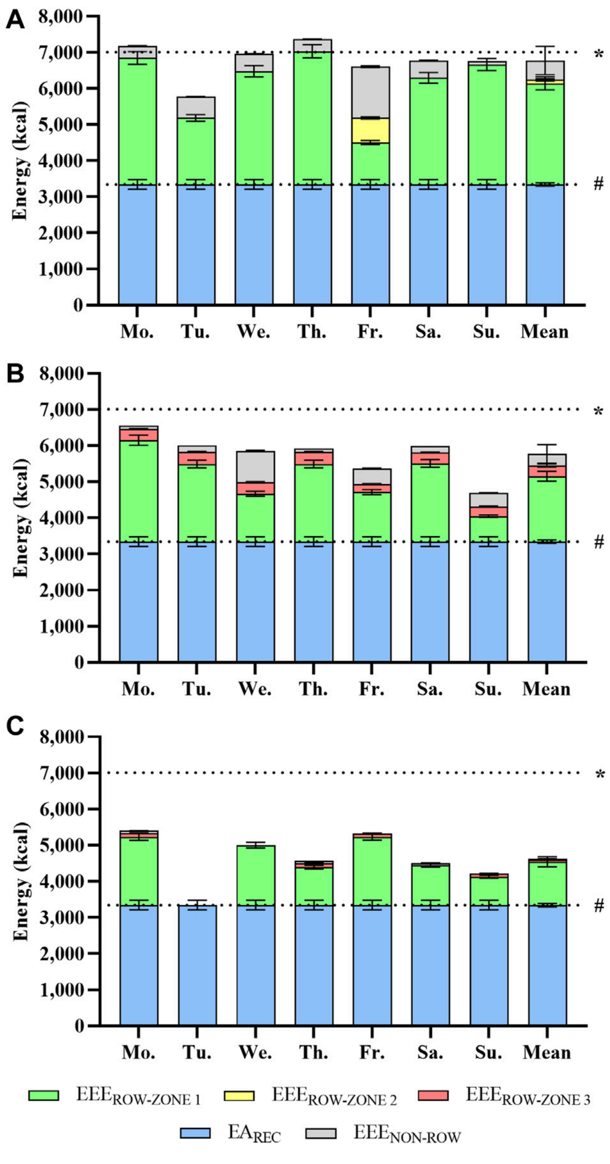

FIGURE 1 | Total energy requirement by exercise energy expenditure and recommended energy availability (EA_{REC}) for an exemplary high volume **(A)**, high intensity **(B)**, and tapering rowing training week **(C)** (mean [95% confidence interval]). Calculation of exercise energy expenditure for rowing (EEE_{ROW}) training based on a non-protein table (Péronnet and Massicotte, 1991) and corrected for resting metabolic rate (RMR) and anaerobic energy contribution (Di Prampero and Ferretti, 1999). EEE for other training ($EEE_{NON-ROW}$) is approximated using corrected MET data (Kozey et al., 2010). EA_{REC} (dashed line #) is given as 40 kcal·kg^{-1} fat free mass·day^{-1} (Koehler et al., 2016). A total energy expenditure of three times the RMR (7,011 kcal·day^{-1}, dashed line *) was assumed to reflect the upper limit of the manageable total energy expenditure (Thurber et al., 2019).

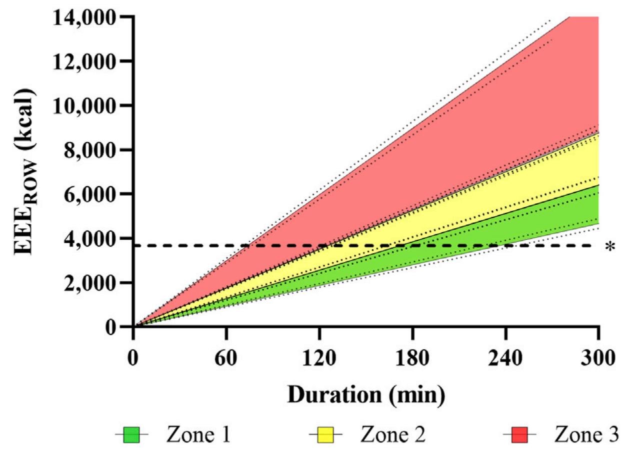

FIGURE 2 | Illustration of estimated, accumulated exercise energy expenditure over time during rowing (EEE_{ROW}) for a three-zone model, based on indirect calorimetry data obtained in incremental step testing. The Figure visualizes accumulated EEE for each training zone over time, assuming a linear progression with 95% confidence intervals. R^2 ranged 0.968–0.988. Dashed line represents EEE of 3,668 kcal·day^{-1}, 95% CI [3,580, 3,756], which is assumably the maximum refuelable EEE.

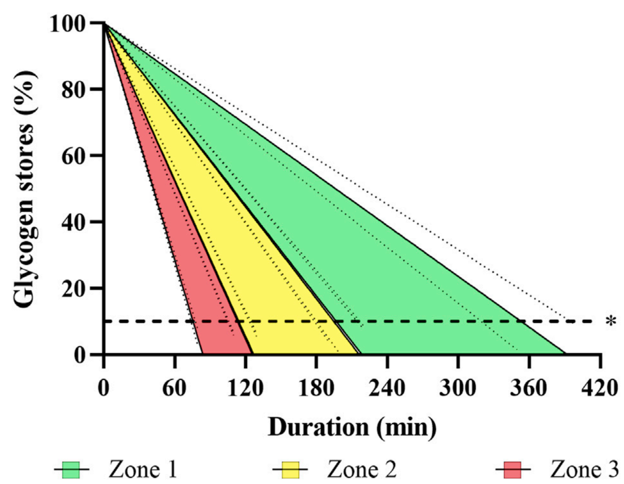

FIGURE 3 | Illustration of estimated glycogen depletion over time during rowing for a three-zone model, based on indirect calorimetry data obtained in incremental step testing. The Figure visualizes depletion of individually estimated glycogen stores (including blood, liver, and muscle; see text for details) over time, assuming a linear progression with 95% confidence intervals. R^2 ranges 0.781–0.985. *Dashed line represents the 90% maximum depletion threshold of glycogen stores (Burke et al., 2017).

are tolerable (Burke et al., 2017), the lower value seems to reflect a more realistic scenario.

Our data indicate that energy during ergometer rowing training is mainly derived from carbohydrates, because even during a zone 1 training, about 47–68% of the energy originates from carbohydrates equaling 1.8 g·min^{-1}, 95% CI [1.6, 2.0] to 3.5 g·min^{-1}, 95% CI [3.2, 3.8]. Leaving aside other factors of fatigue or refueling, available energy stores from glycogen and blood glucose in this sample of elite rowers will theoretically allow for about 5.7 h, 95% CI [5.1, 6.3] to 3.1 h, 95% CI [2.8, 3.4] training in zone 1. In zone 2 and 3 theoretical maximum duration will be reduced by 47–74% (3.1 h, 95% CI [2.8, 3.4] to

1.8 h, 95% CI [1.6, 1.9]) and 70–86% (1.8 h, 95% CI [1.6, 1.9] to 1.0 [0.8, 1.0]), respectively. Again, due to other factors of fatigue and the unlikelihood of perfectly filled glycogen stores, the lower values are more realistic for common training scenarios.

Especially long-distance runners and cyclists try to maximize the fat oxidation rate through very low training intensities (Jeukendrup and Achten, 2001). Due to the high utilization of CHO observed in our rowers, such a "FatMax" training is apparently unlikely to be realized even during low zone 1 rowing. In line with this notion, Dandanell and colleagues (Dandanell et al., 2018) reported FatMax at 46% of $\dot{V}O_2max$ in highly trained cross-country skiers. That is about 6% lower than the bottom of zone 1 training in our study (**Table 3**). While beyond the scope of this study, it seems worth to evaluate if such low intensities are warranted to prepare for high-intensity rowing races lasting not more than 7 min (Messonnier et al., 2005b).

Metabolic Demand of Rowing Training Sessions

Based on the metabolic demand at each intensity zone, we calculated the EEE_{ROW} and substrate utilization for prototypical rowing training sessions and weeks, assuming that the metabolic demand of ergometer rowing generally reflects on water rowing (Vogler et al., 2010). Due to the high metabolic demand, a long basic endurance session lasting 100 min constantly rowed in zone 1 will result in an EEE_{ROW} ranging from 1,556 kcal, 95% CI [1,479, 1,670] to 2,133 kcal, 95% CI [2,019, 2,300]. Notably, such rowing sessions — at least in German rowing — are usually not performed at intensities considerably lower than LT1, because this would not allow to row the boat with the targeted propulsion and speed, corresponding to 72–80% of a boat's world best time (Schwarzrock et al., 2017). Hence, the upper limit of the range is more likely to reflect the EEE_{ROW} of a realistic, 100-min basic endurance rowing session.

During such a 100-min zone 1 rowing session, the carbohydrate stores (muscle and liver glycogen as well as blood glucose) of the rowers will deplete with a degradation rate of 2.2 $g{\cdot}min^{-1}$, 95% CI [2.0, 2.4] to 3.9 $g{\cdot}min^{-1}$, 95% CI [3.6, 4.2], when accounting for EEE and RMR. This corresponds to a reduction to 75%, 95% CI [72, 77] to 54%, 95% CI [50, 59] of initial values (**Figure 3**)—with the latter being more realistic, as discussed before. Similar results were reported by Stepto and colleagues (Stepto et al., 2001) for aerobic interval training in competitive cyclists with muscle glycogen depletion ranging from 36 to 64%. Hence, not only the muscular impact of long rowing endurance sessions is demanding - they also include the risk of glycogen depletion. Consequently, sufficient carbohydrate ingestion during such exercises seems crucial to maintain glucose availability and pace. Importantly, in case of insufficient refueling, low pre-exercise muscle glycogen concentrations will not only result in reduced high-intensity performance (Maughan and Poole, 1981), but might also compromise immune function and training readiness (Stellingwerff et al., 2011).

Metabolic Demand During Prototypical Training Weeks

Elite rowers regularly perform 2-4 sessions a day and they usually train for at least 6 days a week (Tran et al., 2015). To estimate the TER, we added the accumulated EEE of EEE_{ROW} and $EEE_{NON\text{-}ROW}$ to the resting metabolic rate and EA_{REC}. As shown in **Figure 1** this leads to an energy demand that increases from tapering week, to high-intensity week, and finally peaks in the high-volume week with 6,778 $kcal{\cdot}day^{-1}$, 95% CI [6,651, 6,905]. If we assume that zone 1 training is in fact performed at the upper end of its intensity range, TER for the high-volume week would be even higher, and amount to 7,231 $kcal{\cdot}days^{-1}$, 95% CI [7,082, 7,380]. This is three times the resting metabolic rate of 2,337 $kcal{\cdot}day^{-1}$, 95% CI [2,262, 2,411].

While these TER values are very high, results from other sports underline their plausibility. Aside from extreme values of 9,869 ± 4,129 or 11,246 ± 1,083 $kcal{\cdot}day^{-1}$ reported during ultra-endurance competitions (Heydenreich et al., 2017; Geesmann et al., 2014), high caloric needs were also reported for elite male cross-country skiers. Sjödin and colleagues (Sjödin et al., 1994), for example, determined TEE *via* double labelled water during a 6-days training camp with an average training volume of 212 $min{\cdot}day^{-1}$ to be as high as 7,213 ± 1,003 $kcal{\cdot}day^{-1}$, notably with a slightly negative energy balance of -0.6%. These data fit well to TER estimated in our elite open-class male rowers. The "manageable" TEE during daily training conditions by resupplied energy through nutrition can be assumed to be three times the RMR (Thurber et al., 2019), amounting to 7,011 $kcal{\cdot}day^{-1}$, 95% CI [6,787, 7,234] in our elite open-class rowers (**Figure 1**). Assuming an EA_{REC} of 3,343 $kcal{\cdot}day^{-1}$, 95% CI [3,207, 3,479], about 3,668 $kcal{\cdot}day^{-1}$, 95% CI [3,580, 3,756] will remain for EEE (**Figure 2**). Hence, it becomes apparent that high-volume training of 1,605 $min{\cdot}week^{-1}$ in elite open-class male rowers is at the upper end of what is energetically possible or–more precisely–sustainable. Moreover, insufficient dietary energy intake with suppressed energy availability can disrupt different aspects of homeostasis in humans, a topic which is discussed as *relative energy deficiency in sport* (RED-S) (Mountjoy et al., 2018) and the *female athlete triad* (De Souza et al., 2014; De Souza et al., 2019a; De Souza et al., 2019b), both providing theoretical frameworks for physiological dysregulations and adverse effects on training capacity, performance, and health.

Considering the high EEE_{ROW} and the suspected need to exercise with relatively high intensities in order to provide an effective stimulus for improvements of already highly trained athletes (Treff et al., 2021a), it becomes clear that the capacity of elite athletes to complete high training volume is relatively lower than in untrained persons. The untrained can exercise with a lower absolute intensity, therefore need less energy and yet profit more from low metabolic demands. This dilemma highlights the limiting role of a high TEE in elite sports.

Practically, it is worth to consider that the differences in TER calculated for the three exemplary training weeks require an adjustment of energy intake. The latter is known as *periodized nutrition* (Jeukendrup, 2017). To account for fluctuations in training load, periodized nutrition necessitates at least an approximated TER. Thereby, estimates of an adequate reduction in energy intake from a high intensity to a tapering week can prevent unwarranted body mass gain. Vice versa, periodized nutrition based on valid data can help to prevent energy deficiency or RED-S (Mountjoy et al., 2018).

Our data also indicate that availability and recovery of glycogen stores may be a key factor for successful rowing training. With a mean rate of muscle glycogen synthesis ranging 5–6 $mmol \cdot kg^{-1} \cdot h^{-1}$ of wet muscle mass, normalization of muscle glycogen levels after extreme depletion will require 20–24 h (Coyle, 1991). Consequently, the calculated depletion to 75–54% of initial glycogen and blood glucose energy stores after 100 min zone 1 rowing training is unlikely to be sufficiently restored between daily training sessions. Especially during high volume training camps with repeated sessions on consecutive days (**Table 3**), athletes may not be able to fully restore muscle glycogen. Hence, glycogen concentration in active muscle will fall progressively over the day or a period of days. This may accidentally lead to a situation where glycogen stores are low in the second or third daily training session, where the achievable metabolic rate and exercise capacity are limited, because fat and protein metabolism are augmented. This is — in the end—an extended catabolic situation.

Practical Implications

Due to the dominant contribution of carbohydrates during basic endurance training, their availability through restoration of glycogen stores and immediate provision is warranted during low-intensity rowing training lasting longer than 60 min. Of note, and in contrast to e.g., cyclists or triathletes (Sareban et al., 2016), such procedures seem to be not very common in the rowing culture, at least according to our own observations. Daily recommendation for the macronutrients range from 6–12 g $carbohydrates \cdot kg^{-1}$ body $mass \cdot day^{-1}$, 1.5–1.7 g $protein \cdot kg^{-1}$ body $mass \cdot day^{-1}$, and 0.8–2.0 g $fat \cdot kg^{-1}$ body $mass \cdot day^{-1}$ (Stellingwerf et al., 2011). If athletes fail repeatedly to consume the recommended amounts of dietary carbohydrates (Baranauskas et al., 2015), the EEE of rowing may become a limiting factor. We recommend to consider this when planning training and nutrition for rowers. Otherwise, EEE and TER might surpass the maximum energy intake leading to potentially adverse effects for both health and performance.

Limitations

As the intensity zones were calculated based on lactate "thresholds," we want to underline that we do not uncritically use the threshold term, and that we are aware of the undeniable changes associated with its conceptual basis (Poole et al., 2021). However, LT1 and LT2 still provide useful key measures for exercise description and definition of intensity zones.

We approximated EEE_{ROW} based on repeated ergometer tests, $EEE_{NON\text{-}ROW}$ *via* corrected METs and we calculated EA_{REC}. Due to the assumptions underlying such calculations, uncertainties are inherent. However, the repeated measurements in elite athletes during highly standardized laboratory conditions provide a previously unseen data quality. The transfer of ergometer rowing to on-water rowing may also be deemed a limitation, however Vogler and colleagues (Vogler et al., 2010) reported strong correlations between ergometer *vs.* on-water based incremental tests (blood lactate concentration r = 0.84, $\dot{V}O_2$ r = 0.91) and trivial to small differences of metabolic variables (blood lactate concentration −4.4% to 23.1%, $\dot{V}O_2$ −1.1% to −1.2%). Nevertheless, further individual validation seems warranted.

Notably, we simplified our calculations, assuming continuous, even paced steady-state training sessions with constant EEE and substrate utilization, neglecting that real-life training sessions are often characterized by changing pace, cardiovascular drift, and slow component kinetics in $\dot{V}O_2$ for intensities above LT1, surely causing fluctuations in EEE and substrate utilization. Finally, it was shown that the percentage of training spent below zone 1 may be as high as 30% of the total training time (Treff et al., 2021a), thereby suggesting another real-life scenario we did not account for. Though including the lactate equivalent, we did not precisely account for the oxidation of lactate, which spares glucose and glycogen during intense exercise (Miller et al., 2002) and we did not include the impact of lactate as a gluconeogenic precursor, as we are not aware of any data for sufficiently precise quantification that may be applied for our context.

Although our projections of EEE, TER, and substrate utilization during different training scenarios were made on the basis of highly unique data set of laboratory data designed to closely monitor real-life scenarios in elite athletes and include well-established literature references, external validation is warranted. The current gold standard for quantifying TEE that can be implemented in free-living individuals with minimal subject burden is the doubly labelled water method (Ainslie et al., 2003). In contrast, techniques to measure substrate utilization and specifically glycogen depletion are to this date highly invasive and require repeated collection of muscle biopsies (Hearris et al., 2018) and highly specialized imaging equipment and training (van Zijl et al., 2007). Future studies in elite rowers should aim to include these measures to confirm our predictions.

CONCLUSION

Due to their large body dimensions and high metabolic capacity with high $\dot{V}O_{2max}$, the outstanding metabolic demand of rowing, and high training loads, the energy expenditure of elite open-class male rowers is extraordinarily high. At least in high volume weeks a metabolic limitation is likely, as the energy need is at the upper range of the maximum daily nutrient intake.

Importantly, the percentage of carbohydrates oxidized during slow long-distance rowing training is always dominant and rowing training mainly utilizing fat metabolism seems unrealistic. A single training session is suspected to cause a relevant glycogen depletion. Therefore, we recommend the consumption of carbohydrates during long rowing session and a systematic refilling between daily sessions. These notions should also be considered when planning training volume at a given intensity and the timing of individual sessions, because otherwise hypocaloric conditions and adverse effects are likely.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Ethical board Ulm University. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

KW collecte data, performed the calculations, statistical analysis and wrote the first draft of the manuscript. JS contributed to manuscript revision. KK contributed to the calculations, manuscript revision. GT performed the conception and design of the study, collected data, and revised the manuscript.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fphys.2022.829757/full#supplementary-material

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Can the 20 and 60 s All-Out Test Predict the 2000 m Indoor Rowing Performance in Athletes?

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Purpose: The purpose of this study was to look for a new, simple, and fast method of assessing and monitoring indoor race performance and to assess the relationship between 20 s, 60 s, and 2000 m indoor rowing performances of youth rowers to evaluate their anaerobic profile.

Methods: For three consecutive days, 17 young able-bodied male rowers (15.8 ± 2.0 years), performed three tests (20 s, 60 s, and 2000 m) on a rowing ergometer. Mean power (W_{20}, W_{60}, and W_{2000}) and 2000 m time (t_{2000}) were considered for the analysis. In addition, 14 athletes (15–18 years) performed a 20 s, 60 s, and 2000 m tests and used this as a control group. To define the anaerobic profile of the athletes, W_{20} and W_{60} were normalized as percentages of W_{2000}. Associations between variables were determined by means of the Pearson correlation coefficient (*r*).

Results: Mean power decreased with increasing test duration (W_{20} = 525.1 ± 113.7 W; W_{60} = 476.1 ± 91.0 W; $W_{2000=}$312.9 ± 56.0 W) and negative correlations emerged between t_{2000} (418.5 ± 23.1 s) and W_{20} ($r = -0.952$, $p < 0.0001$) and W_{60} ($r = -0.930$, $p < 0.0001$).

Conclusion: These findings indicate that W_{20} and W_{60} are significant predictors of 2000 m rowing ergometer performances. Furthermore, normalized W_{20} and W_{60} can be used to evaluate athletes and as a reference for planning anaerobic training sessions, on a rowing ergometer.

Keywords: indoor rowing, youth rowers, anaerobic profile, all-out test, rowing race performance

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INTRODUCTION

The sport of rowing, classically practiced on flat water, is a highly regulated sport in which athletes aim to cover the specified race distance as fast as possible, with the standard race distance being 2000 m in a straight-line distance as specified in the World Rowing Rule Book (FISA, 2020, http://worldrowing.com). In general, rowing performance, both on-water and indoor, depends on anthropometric (Podstawski et al., 2014), physiological (Secher, 1993; Ingham et al., 2003; Riechman et al., 2002; Bourdin et al., 2017), and psychological (Kellmann and Gunther, 2000;

Shields et al., 2018) characteristics of the athletes, technical aspects (Den Hartigh et al., 2017), tactical strategies (Garland, 2005; Akça, 2014; Cerasola et al., 2018), and environmental conditions. Despite anthropometric and aerobic capacity being considered relevant for rowing performances (Ingham et al., 2003; Cosgrove et al., 1999; Smith and Hopkins, 2012), the anaerobic metabolism is crucial to allow athletes to accomplish fast starts and final spurts, which could vary in terms of duration ranging from 20 to 60 s in relation to the race strategy (Garland, 2005; Maestu et al., 2006; Cataldo et al., 2015; Martin and Tomescu, 2017). In fact, recent evidence shows that power output, and not just aerobic capacity, could be an important predictor of race outcomes (Izquierdo-Gabarren et al., 2010; Lawton et al., 2011; Cataldo et al., 2015; Bourdin et al., 2017; Martin and Tomescu, 2017; Cerasola et al., 2020).

In agreement with the reported contribution of the aerobic and anaerobic metabolisms to rowing races (Secher, 1993), the training plan of successful rowers normally encompasses 65–70% aerobic exercises and 30–35% anaerobic ones (Maestu et al., 2006). To evaluate athletes and monitor their training plan, coaches routinely assess the boat speed with specific devices such as Global Position System (GPS). Also closely monitored is the performance of athletes on the rowing ergometer, typically through the rowing ergometer speed (measured with an integrated computer) or other parameters which can be accurately reported as a function of time or distance rowed. In fact, from all the possible parameters, most coaches prefer to consider "speed" as the most crucial parameter because specific training sessions are planned in considering different percentages of race speed (Jensen, 1994). Furthermore, coaches often make use of standardized indoor rowing tests to monitor the effects of their training plans.

Measuring changes in performance is important not only for monitoring the progress of rowers during training, but also to further develop the knowledge of the sport through research assessing the effect of training and other interventions. For example, there seems to be a consensus amongst the researchers and practitioners in the field that anaerobic tests for measuring mean and peak power outputs on a rowing ergometer show a high positive correlation with respect to "all-out" 2000 m indoor rowing performance in elite athletes (Riechman et al., 2002; Cataldo et al., 2015; Bourdin et al., 2017). In contrast, the assessment of anaerobic power in youth athletes is still somewhat controversial (Mikulic, 2008; Mikulic et al., 2009; Cataldo et al., 2015; Maciejewski et al., 2016) probably due to large variability in body dimension and in technical proficiency of this population (Mikulic, 2008; Maciejewski et al., 2016). At this crucial age, in a number of countries, coaches, and sports associations are encouraged to design their training schedule on Balyi's "Long Term Athletic Development" (LTAD) model which suggests that the athletic potential of youngsters should be carefully aligned with their biological growth. The model suggests that there should be a focus to optimize performance "longitudinally" and recognize the importance of very particular and specific developmental "windows of opportunity" time periods. (Ford et al., 2011). At the same time, youth athletic success is considered relevant for talent detection, selection, and development (Capranica and Millard-Stafford, 2011). In rowing, youth competitions are organized at local, regional, national, continental, and world levels, and are also included in the Youth Olympic Games.

Experts agree that, given the specific needs of this special population, the training and competitions which are standard for senior and elite athletes may need to be adapted. To meet the characteristics of youth athletes and to facilitate the development of their technical and tactical skills, youth competitions could, ideally, encompass also 1,000 m and 1,500 m distances (Maciejewski et al., 2016). In particular, the literature highlighted that in rowing races effort regulation depends on the performance level, with marked end-spurts occurring more often at sub-elite levels (Brown et al., 2010). In considering the developmental phase of youth rowers, several authors considered relevant the evaluation of the anaerobic capability of youth athletes (Mikulic, 2008; Mikulic et al., 2009; Mikulic and Markovic 2011; Cataldo et al., 2015; Maciejewski et al., 2016; Cerasola et al., 2020).

The aim of this study was to look for a new method, simple and fast, of assessing and monitoring indoor race performance and to investigate the relationship between the fixed-time 20 s and 60 s all-out tests and the fixed-distance 2000 m indoor rowing performance in youth athletes. In particular, this work will test the hypothesis that mean power performance during 20 s and 60 s all-out tests could predict the 2000 m performance of youth rowers.

METHODS

Participants

The institutional review board of the University of Palermo approved the within-subjects experimental design, which included 17 male youth (age: 15.8 ± 2.0 years; height 176.1 ± 7.8 cm; body mass: 70.9 ± 10.0 kg) rowers affiliated to the Italian Rowing Federation and finalists in the Italian Men's Junior Rowing Championship (15–18 years). Furthermore, an independent sample of 14 youth rowers (15–18 years) was considered to cross-validate the findings of the experimental sample. After a detailed explanation of the nature and purpose of the study, written informed consent to participation was obtained from the athletes and their parents before the commencement of the study. Athletes had at least three 3) years of previous rowing training consisting of 18–20 h week^{-1} according to the recommendations of the Italian Rowing Federation FIC. In addition, 13 older male high-level athletes (21.1 ± 0.8 years) performed similar 20 s, 60 s, and 2000 m tests, the results of which were used to preliminarily assess whether the tests can be applied to athletes of a different age group.

Experimental Design

During the pre-competitive period of the 2019–2020 season, the experimental period included three sessions, with a "rest day" in-between, during which the participants were required to perform a 20 s, a 60 s, and 2000 m all-out tests, respectively. Participants were habituated to these tests, routinely administrated during the

TABLE 1 | Correlation between 2000 m rowing ergometer performance time (t_{2000}) and anaerobic characteristics of the 17 participants.

	t_{2000} vs. absolute mean power		t_{2000} vs. relative mean power	
	W_{20} (W)	W_{60} (W)	W_{20} (W kg^{-1})	W_{60} (W kg^{-1})
R	−0.920	−0.914	−0.746	−0.615
R2	−0.847	0.836	0.836	0.372
P	< 0.0001	< 0.0001	0.0006	0.0008

season by their coach. Prior to the test session, body mass and stature were measured by means of a stadiometer and an electronic scale (SECA, Germany). This was followed by a 15-min standard warm-up eliciting ~140 beats·min^{-1}. Throughout the test, the rowers received verbal encouragement from their coach to perform their best.

The tests were performed on a Concept2 rowing ergometer (mod. D, Concept2, Morrisville, United States, fitted with a PM5 monitor) with a 120-drag factor. The apparatus provided information, amongst other things, on the mean power for the 20 s, 60 s, and 2000 m events, W_{20}, W_{60}, and W_{2000}, measured in watts (W), where 1 W = 1 J s^{-1} and the 2000 m performance time (t_{2000}, s). Absolute W_{20} and W_{60} values were normalized relative to body weight. Finally, the mean speed (V_{2000}, m·s^{-1}) of the 2000 m performance was also calculated. The same sequence was used in the counter-test group.

Statistical Analysis

Statistical significance was accepted with an alpha level of $p \leq 0.05$. Data are presented as "means ± SD". At first, the Kolmogorov-Smirnov and Shapiro–Wilk normality tests were used to assess the normal distribution of the experimental variables W_{20}, W_{60}, W_{2000}, t_{2000}, and V_{2000}. Pearson correlation coefficients (r) and linear regression analysis (R^2) were used to determine the association between t_{2000}, W_{60}, and W_{20} variables. According to the literature Hopkins (2000), R^2 was considered trivial, small, moderate, large, very large, nearly perfect, and perfect for values <0.01, >0.01–0.09, >0.09–0.25, >0.25–0.49, >0.49–0.81, >0.81, 1.0, respectively. Furthermore, a stepwise regression analysis was used to examine the relationship between V_{2000}, absolute W_{20}, and W_{60}. Finally, to plot the anaerobic profile of the youth rowers, absolute W_{20} and W_{60} values were expressed as percentages of W_{2000}.

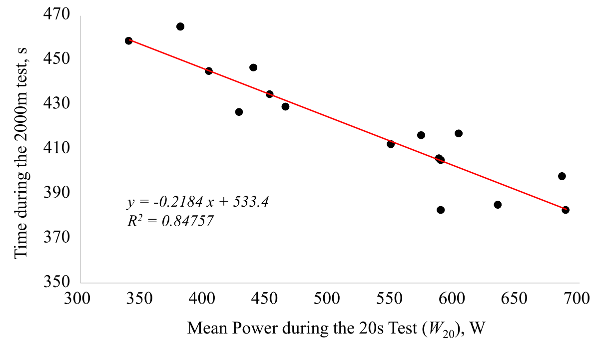

FIGURE 1 | The relationship between the 2000 m performance time (t_{2000}) and mean power (W_{20}) during the 20 s all-out test.

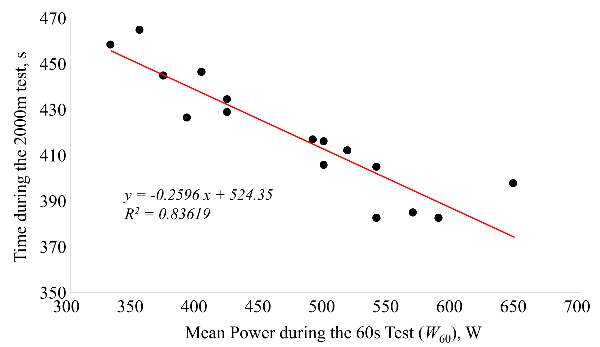

FIGURE 2 | The relationship between the 2000 m performance time (t_{2000}) and mean power (W_{60}) during the 60 s all-out test.

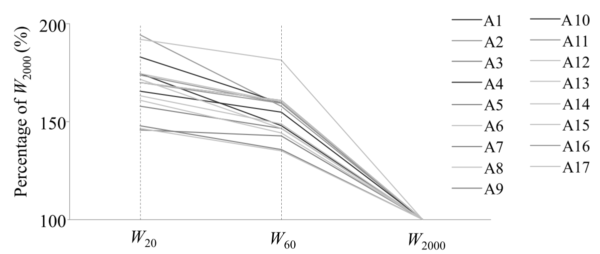

FIGURE 3 | Anaerobic power profiles of the 17 youth athletes expressed through the percentages of the mean power W_{20} and W_{60} during the 20 and 60s tests with respect to the 2000m actual performance.

RESULTS

Absolute and relative W_{20} values were 525.1 ± 113.7 W (range: 340–690 W) and 7.4 ± 0.9 W kg^{-1} (range: 6.17–8.46 W kg^{-1}), respectively; whilst absolute and relative W_{60} values of 476.1 ± 91.0 W (range: 333–649 W) and 6.7 ± 0.8 W kg^{-1} (range: 6.22–7.44 W kg^{-1}), respectively. The 2000m indoor rowing performance lasted 418.5 ± 23.1 s, with a V_{2000} of 4.8 ± 0.3 m s^{-1} and absolute W_{2000} of 312.9 ± 56.0 W. These values substantiate their good athletic level in relation to age. Anaerobic parameters always showed negative relationships ($p < 0.001$) with respect to t_{2000}, resulting in higher absolute values with respect to relative values (**Table 1**).

Figure 1 and **Figure 2** show the regression equations between t_{2000} and absolute W_{20} and W_{60} values, respectively. Significant correlations were observed between V_{2000} and W_{20} (r = 0.95; $p < 0.004$) and W_{60} (r = 0.98; $p < 0.0005$). The stepwise multiple regression identified the prediction equation V_{2000} = 2.795 - (0.0005303 *W_{20}) + (0.004680 *W_{60}), with W_{20}, and W_{60} accounting for 96.8% of the variance of V_{2000} ($p < 0.01$). The cross-validation of the prediction equation with the independent

TABLE 2 | The measured W_{20} and W_{60} values of the 13 additional older volunteers (mean age 21.1 ± 0.8) and the percentage difference between the achieved 2000m event speed and model predicted speed for a 2000m event.

W_{20} (W)	W_{60} (W)	Achieved speed in 2000 m event (ms^{-1})	Predicted speed in 2000 m event (ms^{-1})	Speed difference (%)
847.2 ± 45.9	710.6 ± 34.4	5.49 ±0.1	5.67 ± 0.1	0.97 ± 0.02

sample of youth rowers showed a high correlation between actual and predicted rowing speed (r = 0.98; p = 0.0005) and prediction limits ranging from -0.12 to 0.11 m s^{-1} (-2.74–2.78%). **Figure 3** shows the anaerobic profile of the youth rowers, with W_{20} and W_{60}, presented as percentages of W_{2000}. In particular, W_{20} showed the highest values (168.1 ± 14.1%) with respect to W_{60} (153.1 ± 11.3%). Also reported in **Table 2**, as discussed below, are the findings from preliminary tests on a cohort of older athletes.

DISCUSSION

The main findings of this study were the definition of 1) the mathematical model to predict actual 2000 m indoor rowing performance and 2) the anaerobic profile of youth rowers. Furthermore, this study substantiates the significant correlation between average power outputs of 20 and 60 s (Cataldo et al., 2015; Cerasola et al., 2020), and the time to complete 2000 m indoor rowing performance.

In the present study, t_{2000} resulted coherent with the literature of Cerasola et al. (2020); Cataldo et al. (2015); Mikulic et al. (2009). This is an important finding, especially considering the athletic level of the participants but needs to be considered in the context of the present knowledge in this field. For example, despite the well-known and relevant aerobic contribution to rowing (Cosgrove et al., 1999), estimated at ~30–35% (Secher, 1993), it is now also known that the VO_{2max} parameter presents limited predictive capability with some authors (Maestu et al., 2006) proposing anaerobic power as an overall index of 2000 m performance. As an alternative, Cerasola and co-workers have proposed that coaches should consider W_{20} and W_{60} relevant parameters for monitoring the capability of their athletes to perform high-intensity phases, which are crucial during the first part of the race for increasing the boat speed to gain advantages over the opponents and to sustain a final rush to achieve the best ranking when the boats are "tip to tip", respectively (Garland, 2005; Cerasola et al., 2018). In fact, data was collected during a 30 s modified Wingate test (Mikulic et al., 2009), a 20 s all-out rowing support mean power (Cataldo et al., 2015) and a 60 s all-out rowing support mean power (Cerasola et al., 2020) proved to be as a better predictor of the time to complete 2000 m with respect to VO_{2max}. Furthermore, Egan-Shuttler et al. (2014; 2017) show that the force is relevant to increasing the rowing performance during the 500 m time trial.

This present study adds more confidence to this claim favoring the use of such 20 and 60 s all-out power tests. In fact, by investigating 20 and 60 s all-out anaerobic performances of youth rowers, the present study confirms and implements these results and indicates that this newly developed model is safe (i.e., youth rowers were able to perform the test without any personal risk), accurate and effective (i.e., the 20 and 60 s are very simple tests, therefore all rowers can express the maximum performance) in predicting 2000 m rowing ergometer performance. This finding becomes even more relevant in view of the fact that, in general, indoor rowing performances are considered good predictors of on-water 2000 m time of elite youth rowers, with a standard error of the estimate ranging between 2.6 and 7.2% (Smith and Hopkins, 2012).

More specifically, W_{20} and W_{60} resulted in the most significant variables for predicting t_{2000}, probably due to the relevant combined contribution of the alactacid and lactacid anaerobic metabolisms, respectively (Jensen, 1994). According to Steinacker (1993), senior elite athletes compete in a typical rowing race in the single scull reach a mean power of 450–600 W during the first 10 s of the initial phase and 400–500 W during the 60 s of the final phase, respectively. In the present study, youth athletes reached similar mean power values during the 20 s (e.g., 340–690 W) and 60 s tests (e.g., 333–649 W), which substantiate their good athletic level.

Finally, with respect to the literature (Cosgrove et al., 1999; Riechman et al., 2002; Cataldo et al., 2015; Cerasola et al., 2020) the integration of W_{20} and W_{60} in the mathematical model for the prediction of 2000 m speed provides a better evaluation of performance (e.g., < 3% error) and further evidence on the relevance of testing anaerobic capacity of youth athletes.

Before concluding it is important to highlight the strengths and limitations of the present work.

The main strengths of this work are the novelty and implications of the findings which are of significant practical importance within the context of rowing federations and clubs as monitoring tests and talent identification.

To sustain the 5.5–7.0 min of rowing competitions both aerobic and anaerobic training are important components of training programs, with training stimuli differing depending on the type, length, and intensity of each session (Maestu et al., 2006). In particular, during the preparation period, the main goal of rowing training is to build up the aerobic endurance of athletes, whereas during the competition period the focus is on the development of the aerobic and anaerobic components. In general, training intensities can be defined as percentages of power at race pace, considering intensities of 110–180% to develop anaerobic capacity, 90–105% aerobic transportation, 75–85% anaerobic threshold, and 65–70% aerobic utilization (Jensen, 1994). Despite the evaluation of the aerobic capacity of rowers is well documented in the literature and commonly used to structure individualized training, information on the anaerobic capacity is much less evaluated (Izquierdo-Gabarren et al., 2010). To establish appropriate training stimuli in relation to the developmental phase and athletic level of the youth rowers, coaches are urged to routinely monitor their progress to structure sound training sessions (Capranica and Millard-Stafford, 2011). Considering that youth rowers habitually undergo a training volume of 18–20 h week^{-1} (FIC, 2020) (http://www.canottaggio.org) the evaluation of their anaerobic capacity could be effectively achieved by means of computerized rowing ergometers that provide information on time, power, speed, and stroke rate. Thus, the anaerobic power curve shown in this study could help the coaches to define different levels for anaerobic intensities, to monitor the effectiveness of their training plan, and to identify and promote talents by predicting athletic success in 2000 m competitions (Maestu et al., 2006). In considering that this study is limited to the peculiar sample of finalists in the Italian Men's Junior Rowing Championship, further studies are needed to verify whether these tests are useful for the evaluation of youth rowers of different athletic levels, ages, and sex.

Talent identification and promotion of youth athletes is a complex phenomenon, often based on the assessment of their sport-specific performance. Despite rowing also several environmental (e.g., wind, water currents, and temperature) and tactical aspects of successful performances should be considered, comparisons between the time needed to cover distances during on-water and indoor races presented limited discrepancies (Izquierdo-Gabarren et al., 2010; Vogler et al., 2010). Therefore, 2000 m time indoor trials have become an important selection tool for national rowing organizations (Smith and Hopkins, 2012), with coaches ranking athletes on the team in a controlled environment. The findings of this study not only provided valuable insights into the evaluation of the anaerobic capability of youth athletes but also a good prediction model for their 2000 m speed performances. Thus, coaches should consider the 20 and 60 s all-out tests also for talent identification and progress.

Strengths and Limitations

Like any other study, this work has its own limitations. In particular, the results for the mean power values W_{20} and W_{60} had associated with them a large standard deviation since the youth athletes reached quite a wide range of mean power values during the 20 s (340–690 W) and 60 s tests (333–649 W). This profile of data, unfortunately, is unavoidable when testing athletes of age (age 15.8 ± 2.0 years). At such age, different athletes are expected to be at different levels of their biological development with the resultant variations in somatic growth, body composition, and somatic proportions (height 176.1 ± 7.8 cm; body mass: 70.9 ± 10.0 kg) that could have a direct influence on aerobic and anaerobic sports performances (Malina et al., 2004; Beunen and Malina, 2008). It must furthermore, it should be highlighted that the effectiveness of such a method applies within the realm of this study and to the characteristic of the participants tested. Indeed, as the participants tested were young athletes, all males (age range: 15.8 ± 2.0 years old), any speculation on the possibility to apply such a method to a different gender, age and athletes level groups require further testing. In this respect, it is encouraging that preliminary tests we conducted on the second group of 13 older volunteer high-level adult athletes (male, age: 21.1 ± 0.8; height 191.2 ± 6.6 cm; body mass: 88.3 ± 4.9 kg) who underwent tests to preliminary assess the transferability of the tests to different age categories suggested that these predictive tools are still applicable. In these additional tests, we calculated the percentage difference between the achieved speed in the 2000 m event and the predicted speed computed using the 20 and 60 s all-out tests according to previous stepwise multiple regression and they found that the achieved speed measured in 2000 m all-out event, 5.49 ± 0.1 m s^{-1}, only differed by 0.97% compared to the speed estimated from the predictive tests, 5.67 ± 0.1 m s^{-1} (see **Table 2**). In view of these positive findings, we hope this work will provide an impetus to other researchers to collect additional data from different cohorts so as to further rigorously validate the reliability of the 20 and 60 s tests as a monitoring tool for the standard 2000 m event. Such further validation studies could also look into aspects such as the correlation between trials, measures of reliability coefficient, Cronbach's alpha, coefficient of variation between trials on a particular day and/or between days, etc. Given this is a newly proposed paradigm, such validation studies are important before these tests can be implemented universally worldwide as a training monitoring tool. Furthermore, the present study was focused on predicting the 'mean power', but it is well known that other parameters, such as the "peak power" (i.e., highest value observed) are also useful training monitoring tools (Egan-Shuttler et al., 2014; 2017). In fact, peak and mean are, sometimes, considered to be complementary approaches to measure rowing performance and the rowing community has not yet determined which of these might be more valuable, particularly in view of the fact athletes often take part in different types of events. It is thus essential that future studies would also look at the peak power, as well as other variables which could be predictable through the quick 20 and 60 s tests.

Nevertheless, it is envisaged that such limitations can be addressed through further studies and tests, ideally conducted by independent researchers, particularly in view of the fact that a major strength of this work is the relative simplicity to carry out the proposed 20 and 60 s tests, their role in the talent identification process and as a monitoring tool, and their ability to make accurate and fast predictions. Moreover, the proposed tests, particularly the 20 s test, are quick and easy to do, without fatiguing the athletes, or creating anxiety hence allowing more time/rigorous training to follow within the same session and, at the same time, allowing tracking of athletes. This makes them ideal for routine monitoring of athletes: a 20 s all-out row will practically go unnoticed and is hardly going to make an impact on the rest of the training session.

CONCLUSION

By not requiring expensive equipment, specific scientific expertise, and long duration, the 20- and 60-s tests could be a valuable tool to routinely assess youth athletes during training sessions. Furthermore, they could be considered a more feasible and accurate option to predict 2000 m performances with respect to the assessment VO_{2max}, which requires expensive equipment, invasive methods, and some attendant risks might be present. Therefore, the proposed mathematical model could offer coaches a simple workout to propose to athletes to predict their performance, with a frequency greater than the test of 2000 m that is not commonly used in training due to the great effort required.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the University of Palermo. Written informed consent to participate in this study was provided by the participant's legal guardian/next of kin.

AUTHOR CONTRIBUTIONS

DC, DZ, AB, and LC designed the study. DC and DZ performed the research. DC wrote the manuscript. AB, PD, NM, LC, and JG reviewed and edited the manuscript. All authors contributed to the article and approved the submitted version.

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