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Influence of rowing cadence on the gross efficiency of professional traditional rowers

Supplementary Information

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Introduction

Rowing is a cyclical strength and endurance sport (Akça, 2014; Gee et al., 2012; Lu, Jones, Yom, Ishida, & White, 2023), encompassing two modalities that vary according to the biomechanical model employed to propel the boat through the water: mobile-bench rowing and fixed-bench rowing (Izquierdo-Gabarren, de Txabarri Expósito, de Villarreal, & Izquierdo, 2010; Penichet-Tomás, Pueo, & Jiménez-Olmedo, 2019). Mobile-bench rowing, the Olympic modality, involves a sliding seat (Penichet-Tomás et al., 2019), allowing rowers to primarily generate the propulsion of the boat through leg power and with additional contributions from the trunk and arms (González-Aramendi, 2014). By contrast, fixed-bench rowing, also referred to as *traditional rowing* (Izquierdo-Gabarren et al., 2010), uses a fixed seat, requiring greater involvement of the trunk and arms for the propulsion of the boat (Baudouin & Hawkins, 2002; Mejuto et al., 2012). Moreover, concerning the rowing track, while Olympic rowing competitions take place on calm waters such as lakes or rivers, traditional rowing was created for competition at sea (González-Aramendi, 2014; Urdampilleta & León-Guereño, 2012). Additionally, while in Olympic rowing athletes need to complete a 2000-m distance, in traditional rowing a 5556-m distant must be completed in the shortest possible time by a crew of 13 rowers and a cox (González-Aramendi, 2014; Lorenzo Buceta et al., 2014; Urdampilleta & León-Guereño, 2012). Despite these main differences, all rowing modalities are based on a cyclical movement, and in order to achieve the best stroke efficiency and performance, the arms, trunk, and legs need to work in a synchronized way (Steinacker, Kirsten, Winkert, Washington, & Treff, 2020).

Gross efficiency (GE), defined as the mechanical power produced divided by the metabolic power generated (MacDougall, Falconer, & MacIntosh, 2022), is emerging as important predictor of endurance performance (Cerda-Kohler et al., 2022; Coyle, 1995, 1999; Joyner & Coyle, 2008; van der Zwaard, Brocherie, & Jaspers, 2021). In previous studies, GE has been proposed as one of three fundamental elements, alongside maximum oxygen consumption ($\dot{V}O_2$ max) and lactate threshold, in a model explaining performance in endurance sports, despite receiving less attention than these more traditionally documented and studied indicators (Coyle, 1995). Moreover, in the context of elite levels where groups are highly homogeneous, certain studies have indicated that GE could constitute a differentiating factor between athletes when $\dot{V}O_2$ max and lactate threshold are similar (Joyner & Coyle, 2008). It is for this reason that, in the domain of endurance sports characterized by cyclic work requiring complex coordination and a highly developed physical capacity (such as rowing), GE enhancement is especially advocated as a potential performance predictor (Coyle, 1999). Additionally, while GE may depend on several factors, previous evidence has suggested that modifying cadence may be one of the key factors leading to improved GE (Kamba, Naito, Ozaki, Machida, & Katamoto, 2022). In the context of cycling, it has been shown that working at lower cadences may be a contributing factor to enhanced athlete performance, since it has been shown to result in greater GE (Graham, Zoeller, Jacobs, & Whitehurst, 2018). Similar results are found for handcycling (Kraaijenbrink, Vegter, Hensen, Wagner, & van der Woude, 2017), which are consistent with a recent study performed

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in paddle surfing (Castañeda-Babarro, Santos-Concejero, Viribay, Gutiérrez-Santamaría, & Mielgo-Ayuso, 2020), indicating that lower cadences result in higher GE. Nevertheless, there is considerable debate as to whether lower cadences are indeed the most efficient. In fact, in elite cyclists, it has been suggested that higher cadences (80–100 rpm) could lead to better GE than lower ones (60 rpm; Lucía et al., 2004). Similar results were found by Whitty et al. (Whitty, Murphy, Coutts, & Watsford, 2016), who also observed improved GE in cyclists training at higher cadences compared to those training at lower cadences. In line with the above, previous studies have shown that the cadences freely chosen by athletes tend to be higher with respect to those that are more energy efficient (Hansen & Smith, 2009; Lucía, Hoyos, & Chicharro, 2001; Vercruyssen & Brisswalter, 2010); and interestingly, the freely chosen cadence, despite being higher, showed better performance values compared to the low cadence imposed by the researchers (Kristoffersen, Gundersen, Leirdal, & Iversen, 2014).

In the context of rowing, the physiological, anthropometric, and biomechanical factors that influence performance have been well documented (Castañeda-Babarro et al., 2024; Larrinaga Garcia, León Guereño, Coca Nuñez, & Arbillaga Etxarri, 2023; León Guereño, Urdampilleta, Zourdos, & Mielgo-Ayuso, 2018). These factors are useful not only in optimizing performance, but also in selecting talented individuals. However, there is limited literature concerning rowing and the effect of cadence on GE. While one study of mobile-bench rowing found no difference in GE between cadences (Hofmijster, Van Soest, & De Koning, 2009), others suggested that higher stroke rates may lead to a greater power output and boat speed (Duchene et al., 2024; Holt, Aughey, Ball, Hopkins, & Siegel, 2020), resulting in a faster race time (Dimakopoulou, Zacharogiannis, Chairopoulou, Kaloupsis, & Platanou, 2018) in this rowing modality. It is important to note that these performance improvements do not necessarily reflect changes in GE but instead arise from a complex interplay between power production, technique, and race-pace optimization. In contrast to these performance-oriented findings, comparative research examining physiological responses between dynamic and static ergometer rowing found that dynamic rowing yielded higher stroke rates but lower GE, while static rowing resulted in lower stroke rates and higher GE (Benson, Abendroth, King, & Swensen, 2011; Rossi, Piponnier, Vincent, Samozino, & Messonnier, 2015). Therefore, the impact of varying cadences on the GE of endurance athletes, particularly elite traditional rowers, remains unclear. Notably, few studies have investigated the most efficient cadence in elite-level traditional rowing, where athletes must perform in a highly coordinated and synchronized manner to maximize race speed.

Considering the biomechanical distinctions that differentiate Olympic rowing or mobile-bench rowing from traditional rowing with fixed seats, as well as the differing competitive exigencies (including distance, duration, and environmental conditions), and the exclusively group nature of traditional rowing—in contrast to the presence of individual events in Olympic rowing—there is a recognized potential for further study of the efficiency of elite traditional rowers at different cadences. The aim of this study was to investigate the influence of three different cadences (20, 25, and 30 strokes per minute) on the GE of traditional elite rowers. In addition, we explored the impact of these cadences on different gas exchange-related physiological parameters (whole-body oxygen consumption [$\dot{V}O_2$] and carbon dioxide production [$\dot{V}CO_2$], energy expenditure [EE], respiratory exchange ratio [RER], and substrate oxidation rates) and whether these results vary depending on the position rowers hold in the boat (bow and/or stern position vs. central position), as it has been shown that position in the boat can be an important factor influencing performance responses due to potential anthropometric differences (Castañeda-Babarro et al., 2024).

Materials and methods

Participants

The participants of the present cross-sectional study were elite male rowers, with a mean age of 29 ± 7 years and a mean body mass index of 23.7 ± 1.5 kg/m^2. In brief, male rowers who competed in the first division of the traditional rowing league (ACT) in Spain were included if they had no recent history of injury, were not undergoing pharmacological treatment, and were not following a specific nutritional regimen. Twenty *trainera* rowers with an average rowing experience of 12 ± 6 years and who were engaged in the same training regimen for 2–3 h/day throughout the week volunteered for the study. Prior to participation, the rower were provided with written and oral information about the research and were required to sign an informed consent document in order to accede to the study. This research was approved by the Ethics Committee of the University of Deusto (ETK-13/18-19) in accordance with the requirements of the Declaration of Helsinki. Of note, the present study used data from a larger trial—extended information about the trial can be found elsewhere (Viribay, Alcantara, López, Mielgo-Ayuso, & Castañeda-Babarro, 2024).

Procedure

The participants completed diverse physical tests during two different sessions with an interval of 1 week between assessments, to ensure that they had fully recovered (Viribay et al., 2024). At the time of data collection, the rowers were in the pre-competitive phase of the season.

On the first testing day, height (SECA 220, Hamburg, Germany) and body mass (Inbody 770, Cerritos, CA, USA) were measured and subsequently used to calculate the body mass index (BMI). Arm span was measured by a certified anthropometrist according to the International Society for the Advancement of Kinanthropometry protocol (ISAK, 2016). An incremental ergometer test was then employed to determine peak oxygen consumption ($\dot{V}O_2$ peak)

and peak power output (PPO)—see next section for details on the procedures. These data were used to determine the intensity at which the participants would perform the submaximal step test on the next testing day.

On the second testing day, the submaximal step test was conducted to determine the GE of the rowers at different cadences (20, 25, and 30 strokes per minute). To reduce potential discrepancies in performance resulting from fluctuations in the time of day of testing, all assessments were conducted at the same time each day. Additionally, participants were instructed to refrain from engaging in any strenuous exercise for a period of 24–48 h prior to testing.

Both the $\dot{V}O_2$ peak and PPO test and the submaximal step test were carried out using a Concept 2 Model C rowing ergometer (Concept 2 Inc., Morrisville, VT, USA). Of note, the seat position was fixed according to the preferences of the rowers in order to adequately simulate the traditional rowing movement (Lucía, Hoyos, Pérez, Santalla, & Chicharro, 2002), and a drag factor of 160 was employed (Koppo, Bouckaert, & Jones, 2002; Sanchis-Moysi et al., 2010). During these tests, the gas exchange was continuously measured using a K5 system (Cosmed, Rome, Italy), as described in the next section. Prior to each test, the metabolic system flow and gas analyzers were calibrated according to the manufacturer's recommendations.

$\dot{V}O_2$ peak and PPO assessments

An incremental test was performed, using the aforementioned rowing ergometer, to assess $\dot{V}O_2$ peak and PPO. Prior to commencing the test, rowers completed a 5-min warm-up at an intensity between 5 and 6 on the Borg scale (Borg, 1998). The maximal test was then commenced at 135 W and increased by 25 W every 1 min, at a free cadence, until volitional exhaustion. The criteria for concluding the test were two consecutive workloads with an increase of less than 1.5 mL · kg^{-1} · min^{-1}, a RER greater than 1.15, and a heart rate (beats per minute) greater than 95% of the maximum predicted for the individual's age (Mora-Rodríguez & Aguado-Jiménez, 2006). During the test, gas exchange was continuously measured using the K5 system. Using the data obtained, PPO was calculated according to the following equation (Leirdal & Ettema, 2011):

$$PPO\,(W) = total\ completed\ intensity\,(W) + \frac{second\ at\ final\ speed}{60\ s} * 25W$$

Gross efficiency assessment

A step test was performed, using the previously mentioned rowing ergometer, to assess GE. Before the test, rowers were asked to warm-up on the rowing ergometer at 60% of the $\dot{V}O_2$ peak (assessed on the first testing day) for 5 min. The step test involved rowing at a consistent submaximal intensity of 70% of the PPO obtained in the $\dot{V}O_2$ peak test, with three different 8-min periods at stroke rates of 20, 25, and 30 strokes per minute, respectively, separated by a minimum of 5 min of rest intervals or until the heart rate dropped below 100 beats per minute and RER was below 1 (Castañeda-Babarro et al., 2020; Viribay, Alcantara, López, Mielgo-Ayuso, & Castañeda-Babarro, 2025). This intensity was selected in order to emulate the cadence typically employed during competitive events. The 8-min period length was chosen as recommended in previous literature (Santalla, Naranjo, & Terrados, 2009). To avoid an order effect, the three cadences (20, 25, and 30 strokes per minute) were performed in a random and counterbalanced sequence. The equation used to calculate the GE based on the obtained data was the one proposed by Garby and Astrup (1987). This equation has been extensively adopted in the field of physiology and applied in recent elite traditional rowing studies (Viribay et al., 2025; Voet, Lamberts, Viribay, de Koning, & van Erp, 2024):

$$GE\,(\%) = \frac{PPO\,(W)}{\frac{\dot{V}O_2}{60} * (4940 * RER + 16040)} * 100$$

Abstract

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Influence of rowing cadence on the gross efficiency of professional traditional rowers

Abstract

Gross efficiency (GE) is emerging as important predictor of endurance performance, and previous evidence suggests that modifying cadence may be a key factor in improving it. However, research in the field of elite fixed-bench rowing, also known as traditional rowing, is limited and unclear. The aim of this study was to investigate the influence of different cadences on the GE of traditional elite rowers. In total, 20 elite rowers participated in 2 days of testing. On the first visit, an incremental rowing test was performed to determine the maximal oxygen consumption ($\dot{V}O_2$ peak) and peak power output (PPO). On the second visit, a submaximal rowing step test was completed comprising three 8-min periods at 20, 25, and 30 strokes per minute, respectively, performed in a random sequence and separated by 10-min rest intervals. Repeated measures analysis of variance showed no mean differences on GE values across cadences ($P = 0.526$). However, a considerable inter-individual difference in the response of the GE across cadences was observed. Linear regression analysis showed a negative relationship ($\beta = -0.15$, $R^2 = 0.21$, $P = 0.04$) between the coefficient of variance (CV, %) for GE across cadences and the rowers' experience in rowing (years). These results indicate that traditional elite rowers, especially those with less experience, may not respond uniformly to different work cadences. This underlines the relevance of individualizing the training and work cadences of traditional elite rowers, particularly for less experienced rowers. The evidence currently available is insufficient to determine the impact of cadence on the GE of elite traditional rowers.

Keywords

Stroke rate · Performance · *Traineras* rowing · Elite athletes · Physiological responses · Energy cost

Gas exchange data management

Throughout the duration of the incremental and the step tests, the K5 system was used to continuously collect gas exchange data, and was configured to operate in the breath-by-breath mode. Gas exchange data were downloaded at the maximum frequency (i.e., one data point per breath). For the incremental test, mean $\dot{V}O_2$ and $\dot{V}CO_2$ values were averaged for the period meeting the previously defined criteria. For the step test, $\dot{V}O_2$ and $\dot{V}CO_2$ values were averaged dividing each 8-min step into 30-s intervals. Using these data from both tests, GE (Garby & Astrup, 1987), EE (de V Weir, 1949), RER ($\dot{V}CO_2$-to-$\dot{V}O_2$ ratio), fat oxidation (FATOx), and carbohydrate oxidation (CHOOx; Jeukendrup & Wallis, 2005) were subsequently estimated using their respective equations.

Statistical analysis

Results are presented as mean and standard deviation (SD). For every rower, the GE coefficient of variation among cadences (CV, expressed as a percentage) was calculated as (standard deviation/mean) × 100. To determine differences in descriptive outcomes between groups (i.e., rowers located at the bow and stern vs. those located in the central positions of the boat), we used the unpaired Student's *t* test. To study differences in the GE values across the three different cadences (i.e., 20, 25, and 30 strokes per minute), we used one-way repeated measures analysis of variance (ANOVA), with Bonferroni post hoc comparisons. We then conducted the same one-way ANOVA analyses separately for rowers located at the bow and stern and for those located in the central positions of the boat, respectively. In addition, to further explore these potential differences between groups and cadences, we used analysis of covariance (ANCOVA), adjusting for rowing position. The same ANCOVA analysis was used to test whether the best GE value (i.e., the highest efficiency value obtained among periods) was different between rowing position groups. We conducted ANCOVA analyses, adjusting for rowing position, to examine the delta (i.e., changes) values between periods for all gas exchange outcomes retrieved from the test. To this end, we computed the deltas as the highest cadence (e.g., cadence 3) minus the lowest cadence (e.g., cadence 1) values. Complementarily, a mixed-design ANOVA (mixed ANOVA) was conducted to examine the interaction effect between rowing position (between-subjects factor) and stroke rate (within-subjects factor) on GE. Of note, the same ANCOVA analyses were conducted for all gas exchange outcomes (i.e., GE, $\dot{V}O_2$, $\dot{V}CO_2$, RER, EE, CHOOX and FATOX, and their respective deltas). Finally, as an exploratory analysis, we conducted a simple linear regression analysis to investigate whether the CV for GE across cadences might be related to rowing experience, hypothesizing that greater variability (i.e., higher CV values) would be associated with less experience in rowing, considering that technical mastery may be reflected not only in mean performance values but also in the consistency of physiological responses. In this context, examining the relationship between years of experience and the CV of GE allows us to explore whether accumulated experience is associated with more stable energy conversion patterns across cadences, without implying causality.

All analyses were conducted using the Statistical Package for Social Sciences (SPSS; v.22.0 IBM SPSS Statistics, IBM Corp., Chicago, IL, USA). All figures were created using GraphPad Prism software (v.10, San Diego, CA, USA). The significance level was set at $P < 0.05$.

Results

Participants' characteristics, GE, and CV for GE outcomes are presented in **Table 1**. Results from the unpaired Student's *t* test showed significant body weight differences ($P = 0.027$), i.e., rowers who were located in the central positions of the boat were heavier than those located at the bow and stern of the boat (**Table 1**). No differences between groups were observed for the outcomes presented in **Table 1** or for the $\dot{V}O_2$, $\dot{V}CO_2$, RER, EE, FATOx, and CHOOx across rowing cadences presented in **Table 2**.

Figure 1 shows individual GE values across rowing cadences. One-way repeated measures ANOVA showed no mean differences on GE values across cadences ($P = 0.526$). Complementary mixed ANOVA confirmed these findings, showing no significant interaction between rowing position and cadence ($P = 0.485$), nor a main effect of rowing position ($P = 0.726$). These results were similar after conducting one-way repeated measures ANOVA separately for each rowing position (P values ≥ 0.274). After adjusting for rowing position, ANCOVA results confirmed the previously mentioned results and showed no between-group differences regardless of the cadence (all P values ≥ 0.589). ANCOVA was used to test whether the best GE value was different between rowing-position groups, and no differences were observed ($P = 0.953$).

After adjusting for rowing position, ANCOVA results showed no between-groups delta differences in GE, $\dot{V}O_2$, $\dot{V}CO_2$, and EE (**Table 3**), although differences for the RER (delta RER cadence 1 vs. 2; $P = 0.049$; **Table 3**), for the FATOx (delta FATOx cadence 1 vs. 2, and cadence 2 vs. 3; P values 0.034 and 0.044, respectively; **Table 3**), and for the CHOOx (delta CHOOx cadence 1 vs. 2; $P = 0.045$; **Table 3**) were identified.

Finally, a negative relationship was observed between the CV for GE across cadences and the rowers' experience in rowing (**Fig. 2**). To verify that this relationship was not dependent on a single influential observation, sensitivity analysis was performed by excluding the participant with the most extreme years of experience. The relationship remained significant ($R^2 = 0.22$; $P = 0.04$), confirming the robustness of the association.

Discussion

The aim of this study was to evaluate the influence of three rowing cadences (20, 25, and 30 strokes per minute) on the GE of traditional elite rowers. The findings revealed no significant differences in GE across cadences, regardless the position of the rowers in the boat, indicating that

Table 1 Descriptive characteristics of rowers.

	All (*N* = 20)			Position 1 (*N* = 12)			Position 2 (*N* = 8)		
	Mean ± SD	Min	Max	Mean ± SD	Min	Max	Mean ± SD	Min	Max
Age (years)	29 ± 7	19	48	27 ± 7	19	42	33 ± 7	26	48
Rowing experience (years)	12 ± 6	2	23	11 ± 6	2	21	14 ± 5	9	23
Body mass (kg)	78.2 ± 7.8	66	93	75.1 ± 7.6	66	93	82.8 ± 5.7	72	89
Height (cm)	181.6 ± 6.2	170	192	179.7 ± 6.3	170	192	184.5 ± 5.3	177	191
BMI (kg/m^2)	23.7 ± 1.5	21	27	23.2 ± 1.3	21	26	24.3 ± 1.6	22	27
Arm span (cm)	183.4 ± 6	172	198	182 ± 6	172	188	186 ± 6	179	198
$\dot{V}O_2$ peak (mL/kg/min)	63.3 ± 6.7	47.8	72.9	65 ± 7.1	47.8	72.9	60.8 ± 5.5	53.6	70.2
Peak power output (W)	348 ± 27.5	310	385	352 ± 28.7	310	385	344 ± 26.5	310	385
Power output during GE trial (W)	194 ± 12	171	216	190 ± 13	171	216	199 ± 10	185	216
Gross efficiency at 20 strokes per minute (%)	15.8 ± 1.4	13	19	15.7 ± 1.3	13	18	15.9 ± 1.6	14	19
Gross efficiency at 25 strokes per minute (%)	15.9 ± 1.5	13	19	15.8 ± 1.6	13	18	16.2 ± 1.4	15	19
Gross efficiency at 30 strokes per minute (%)	15.7 ± 1.6	13	19	15.7 ± 1.6	13	18	15.8 ± 1.7	14	19
CV for gross efficiency (%)	3.3 ± 1.9	0.7	6.5	3.8 ± 2	1.2	6.5	2.6 ± 1.4	0.7	4.9

Results are presented as mean ± standard deviation (*SD*), minimum (*Min*) and maximum (*Max*) values. Position 1 represents rowers located at the bow and stern, while position 2 represents those located in the central positions of the boat. *CV* represents the coefficient of variation (expressed as percentage) across the three different cadences. *$\dot{V}O_2$ peak* represents the maximum oxygen uptake of the incremental test. The power output during the gross efficiency (*GE*) trial corresponded to the submaximal workload set at 70% of the peak power output (*PPO*) achieved during the incremental $\dot{V}O_2$ peak test

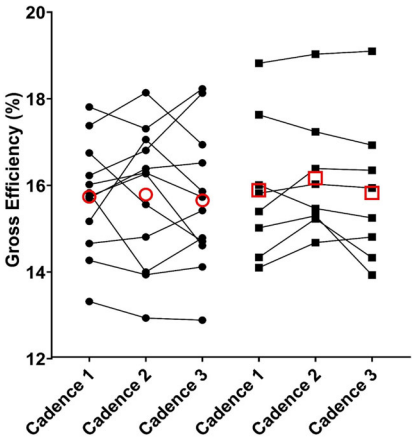

Fig. 1 ▲ Gross efficiency values across the three different cadences (20, 25, and 30 strokes per minute). Data are presented as individual values (closed circles and squares) and as mean values (open red circles and squares). Circles represent rowers located at the bow and stern. Squares represent rowers located in the central positions of the boat. Cadences 1, 2, and 3 were 20, 25, and 30 strokes per minute, respectively

within this range of stroke rates, no single cadence was more efficient for the group as a whole. However, there was notable inter-individual variability in GE responses to cadence.

Our finding is consistent with previous scientific evidence in the field of cycling, which has indicated that establishing an optimal cadence is challenging due to the significant inter-individual differences observed (MacDougall et al., 2022; Mater, Clos, & Lepers, 2021). Furthermore, it is well established that the influence of cadence on GE may differ depending on the individual's skeletal muscle fiber type composition, which is a highly heterogeneous physiological characteristic among athletes (MacDougall et al., 2022). The categorization of cadences as "high" or "low" may be arbitrary if it falls within the range of cadences freely chosen by the athletes. This is because some researchers use absolute cadences, while others use cadences relative to athletes' preferred stroke rates, a discrepancy that may influence conclusions regarding the impact of different cadences on GE (Mater et al., 2021).

In our present study, we observed no effect of the cadences under investigation on GE and, furthermore, this finding was consistent when the analysis was conducted on the basis of position in the boat. The findings related to the rowing position within the boat should be interpreted cautiously. Although anthropometric characteristics are likely a primary factor influencing crew distribution and boat settings in fixed-bench rowing, rowing position is not determined exclusively by these variables. In applied settings, coaches may also assign positions according to technical, biomechanical, or tactical considerations aimed at optimizing crew balance and overall boat performance. Therefore, the present analyses should be interpreted descriptively rather than as evidence of an independent effect of rowing position on physiological or performance-related outcomes. Nevertheless, these observations may still provide practically relevant information for coaches and practitioners working in traditional rowing contexts. This result is in line with those previously reported in studies of Olympic rowing modality, in which there was no difference in GE between cadences (Hofmijster et al., 2009). Similarly, previous research on other endurance sports such as cycling or running has also suggested that altering cadence does not necessarily affect GE (Hafer, Brown, deMille, Hillstrom, & Garber, 2015; Mora-Rodríguez & Aguado-Jiménez, 2006), highlighting the need to consider other factors to optimize performance (Moore, 2016). In the context of cycling, a recent study has demonstrated that an increase in pedal force, but not cadence, can result in a positive change in GE (Kamba et al., 2022). Specifically, they observed that GE increased linearly with increasing pedal force at a fixed cadence; however, GE remained unaltered at different cadences when pedal force remained constant (Kamba et al., 2022). These findings align with those of previous studies, which observed that increasing pedal

Table 2 Rower gas exchange data across cadences.

	All (*N* = 20)			Position 1 (*N* = 12)			Position 2 (*N* = 8)		
	Mean ± SD	Min	Max	Mean ± SD	Min	Max	Mean ± SD	Min	Max
$\dot{V}O_2$ at cadence 1 (mL/min)	3626 ± 328	3105	4239	3572 ± 311	3119	4135	3706 ± 357	3105	4239
$\dot{V}O_2$ at cadence 2 (mL/min)	3607 ± 341	2953	4193	3562 ± 384	2953	4193	3674 ± 274	3152	4048
$\dot{V}O_2$ at cadence 3 (mL/min)	3633 ± 379	3052	4268	3581 ± 406	3123	4268	3711 ± 346	3052	4244
$\dot{V}CO_2$ at cadence 1 (mL/min)	3202 ± 314	2796	4071	3143 ± 239	2796	3680	3292 ± 402	2860	4071
$\dot{V}CO_2$ at cadence 2 (mL/min)	3150 ± 340	2586	3862	3188 ± 336	2586	3650	3092 ± 360	2594	3862
$\dot{V}CO_2$ at cadence 3 (mL/min)	3286 ± 327	2875	4095	3255 ± 368	2954	4095	3334 ± 271	2875	3789
RER at cadence 1	0.89 ± 0.07	0.77	1.00	0.88 ± 0.07	0.77	0.95	0.89 ± 0.08	0.77	1.00
RER at cadence 2	0.87 ± 0.07	0.72	0.98	0.9 ± 0.05	0.80	0.95	0.84 ± 0.08	0.72	0.98
RER at cadence 3	0.91 ± 0.06	0.78	0.98	0.91 ± 0.06	0.81	0.98	0.9 ± 0.06	0.78	0.97
EE at cadence 1 (kcal/min)	17.8 ± 1.5	15	21	17.6 ± 1.4	16	20	18.2 ± 1.7	15	21
EE at cadence 2 (kcal/min)	17.7 ± 1.6	15	20	17.6 ± 1.8	15	20	17.9 ± 1.3	15	20
EE at cadence 3 (kcal/min)	18 ± 1.8	15	21	17.7 ± 1.9	16	21	18.3 ± 1.6	15	20
FATOx at cadence 1 (g/min)	0.7 ± 0.49	0.00	1.6	0.71 ± 0.48	0.3	1.6	0.68 ± 0.55	0.00	1.58
FATOx at cadence 2 (g/min)	0.76 ± 0.46	0.10	1.9	0.61 ± 0.37	0.3	1.4	0.97 ± 0.53	0.10	1.89
FATOx at cadence 3 (g/min)	0.58 ± 0.41	0.13	1.6	0.54 ± 0.4	0.1	1.3	0.63 ± 0.45	0.20	1.60
CHOOx at cadence 1 (g/min)	2.74 ± 1.08	1.06	5.0	2.65 ± 0.97	1.1	3.7	2.88 ± 1.29	1.08	5.00
CHOOx at cadence 2 (g/min)	2.58 ± 1.05	0.31	4.6	2.87 ± 0.79	1.8	4.0	2.14 ± 1.27	0.31	4.61
CHOOx at cadence 3 (g/min)	3.08 ± 0.87	1.29	4.6	3.1 ± 0.88	1.8	4.6	3.04 ± 0.9	1.29	4.37

Results are presented as mean ± standard deviation (***SD***), minimum (***Min***) and maximum (***Max***) values. Position 1 represents rowers located at the bow and stern, while position 2 represents those located in the central positions of the boat. Cadences 1, 2, and 3 were 20, 25, and 30 strokes per minute, respectively
$\dot{V}O_2$ volume of oxygen consumption, $\dot{V}CO_2$ volume of carbon dioxide production, ***RER*** respiratory exchange ratio; ***EE*** energy expenditure, ***FATOx*** fat oxidation rate, ***CHOOx*** carbohydrate oxidation rate

force at a fixed cadence resulted in a gradual improvement in GE during incremental cycling tests (Zameziati, Mornieux, Rouffet, & Belli, 2006). It is important to note that the current study is focused on individual sports, and that the available evidence on rowing primarily encompasses Olympic rowing, which also comprises individual boats (e.g., single scull). Regarding this issue, research in the field of Olympic rowing has revealed that the factors influencing performance vary between competitors in individual and pair categories (Holt et al., 2020). This suggests that the conclusions drawn from such studies based on individual modalities may not be directly applicable to exclusively team sports such as traditional rowing, a sport in which the crew, as a whole, must work in a synchronized manner (Izquierdo-Gabarren et al., 2010). Therefore, it may be particularly relevant to ascertain the cadence that enables the crew, as a whole, to be more efficient and optimize their performance. The homogenization of individual GE and its alignment with the cadence that, in turn, enables the optimal performance of the crew could be crucial for traditional rowing.

Concerning other gas exchange-derived parameters, the $\dot{V}O_2$ peak and PPO values observed in the present study appear consistent with those previously reported in highly trained traditional rowers. In particular, Penichet et al. (2023) described $\dot{V}O_2$ peak values of $62.1 \pm 4.7\,mL \cdot kg^{-1} \cdot min^{-1}$ in male traditional rowers, supporting the high aerobic demands associated with this modality. Although fixed bench rowing differs biomechanically from traditional mobile-bench rowing, particularly due to the reduced dynamic contribution of the lower limbs, the PPO values obtained in the present study suggest a physiologically coherent relationship between aerobic capacity and mechanical power output. Nevertheless, the specific biomechanics of fixed-bench rowing, characterized by substantial trunk stabilization and force transmission demands, may still contribute to differences in GE compared with mobile-bench rowing modalities (González-Aramendi, 2014; Agius et al., 2023). Therefore, the present findings should be interpreted within the context of the unique biomechanical characteristics of traditional rowing. Additionally, a lower RER was observed in the lowest cadence compared to the middle cadence (20 vs. 25 strokes per minute). This finding is consistent with the results of other studies, which have also reported that the most efficient cadence was the lowest (Castañeda-Babarro et al., 2020). This finding can be attributed to the predominant use of fat as an energy substrate in cadence 1 (20 strokes per minute) compared to cadence 2 (25 strokes per minute), which suggests that lower cadences could be the most efficient in traditional rowing (González-Aramendi, 2014; Urdampilleta & León-Guereño, 2012). Although this pattern aligns with previous reports, RER alone cannot be interpreted as an indicator of greater efficiency, as it may reflect differences in substrate use, ventilatory behavior, or individual metabolic characteristics. On the other hand, we observed a negative relationship between the CV of GE across cadences and the rowers' experience in rowing. This vari-

Table 3 Differences in gross efficiency and gas exchange-related values expressed as deltas across cadences.

	All ($N = 20$)			Position 1 ($N = 12$)			Position 2 ($N = 8$)		
	Mean ± SD	Min	Max	Mean ± SD	Min	Max	Mean ± SD	Min	Max
Delta gross efficiency cadence 1 vs. 3 (%)	−0.1 ± 0.9	−2.0	1.9	−0.1 ± 1.1	−2.0	1.9	−0.1 ± 0.7	−1.1	0.9
Delta gross efficiency cadence 1 vs. 2 (%)	0.1 ± 0.8	−1.8	1.9	0.1 ± 1	−1.8	1.9	0.3 ± 0.6	−0.5	1.0
Delta gross efficiency cadence 2 vs. 3 (%)	−0.2 ± 0.8	−1.7	1.3	−0.1 ± 1	−1.7	1.3	−0.3 ± 0.5	−1.4	0.1
Delta VO_2 cadence 1 vs. 3 (mL/min)	7 ± 193	−425	416	8 ± 218	−425	416	5 ± 162	−211	297
Delta VO_2 cadence 1 vs. 2 (mL/min)	−19 ± 157	−309	374	−10 ± 186	−309	374	−32 ± 110	−191	69
Delta VO_2 cadence 2 vs. 3 (mL/min)	26 ± 169	−239	425	18 ± 195	−239	425	37 ± 133	−100	267
Delta VCO_2 cadence 1 vs. 3 (mL/min)	84 ± 292	−406	675	112 ± 328	−406	675	42 ± 241	−282	368
Delta VCO_2 cadence 1 vs. 2 (mL/min)	−53 ± 324	−509.0	651.0	46 ± 317	−509.0	651.0	−200 ± 292	−476.0	275.0
Delta VCO_2 cadence 2 vs. 3 (mL/min)	137 ± 261	−301.0	585.0	67 ± 277	−301.0	447.0	241 ± 206	−73.0	585.0
Delta RER cadence 1 vs. 3	0.02 ± 0.05	−0.09	0.11	0.03 ± 0.05	−0.09	0.11	0.01 ± 0.04	−0.03	0.08
Delta RER cadence 1 vs. 2	−0.01 ± 0.07	−0.12	0.09	0.01 ± 0.06	−0.07	0.09	−0.05 ± 0.07	−0.12	0.06
Delta RER cadence 2 vs. 3	0.03 ± 0.05	−0.06	0.12	0.01 ± 0.05	−0.06	0.10	0.06 ± 0.05	−0.01	0.12
Delta EE cadence 1 vs. 3 (kcal/min)	0.1 ± 1	−1.9	2.4	0.2 ± 1.2	−1.9	2.40	0.1 ± 0.9	−1.1	1.4
Delta EE cadence 1 vs. 2 (kcal/min)	−0.1 ± 0.9	−1.8	2.2	0 ± 1.1	−1.8	2.20	−0.3 ± 0.6	−1.2	0.6
Delta EE cadence 2 vs. 3 (kcal/min)	0.3 ± 0.9	−1.3	2.2	0.1 ± 1	−1.3	2.20	0.4 ± 0.7	−0.2	1.7
Delta FATOx cadence 1 vs. 3 (g/min)	−0.12 ± 0.29	−0.64	0.52	−0.17 ± 0.32	−0.64	0.52	−0.05 ± 0.24	−0.48	0.20
Delta FATOx cadence 1 vs. 2 (g/min)	0.06 ± 0.4	−0.47	0.75	−0.09 ± 0.3	−0.47	0.34	0.29 ± 0.44	−0.35	0.75
Delta FATOx cadence 2 vs. 3 (g/min)	−0.18 ± 0.29	−0.72	0.37	−0.07 ± 0.24	−0.52	0.37	−0.34 ± 0.31	−0.72	0.10
Delta CHOOx cadence 1 vs. 3 (g/min)	0.33 ± 0.81	−1.39	1.79	0.45 ± 0.91	−1.39	1.79	0.16 ± 0.67	−0.69	1.32
Delta CHOOx cadence 1 vs. 2 (g/min)	−0.17 ± 1.08	−1.80	1.63	0.22 ± 0.89	−1.23	1.63	−0.75 ± 1.12	−1.80	0.95
Delta CHOOx cadence 2 vs. 3 (g/min)	0.5 ± 0.79	−0.99	1.72	0.23 ± 0.71	−0.99	1.48	0.91 ± 0.75	−0.25	1.72

Results are presented as mean ± standard deviation (*SD*), minimum (*Min*) and maximum (*Max*) values. Position 1 represents rowers located at the bow and stern, while position 2 represents those located in the central positions of the boat. Cadences 1, 2, and 3 were 20, 25, and 30 strokes per minute, respectively. Deltas were calculated as the highest cadence (e.g., cadence 3) minus the lowest cadence (e.g., cadence 1) values

VO_2 volume of oxygen consumption, *VCO_2* volume of carbon dioxide production, *RER* respiratory exchange ratio, *EE* i energy expenditure, *FATOx* fat oxidation rate, *CHOOx* carbohydrate oxidation rate

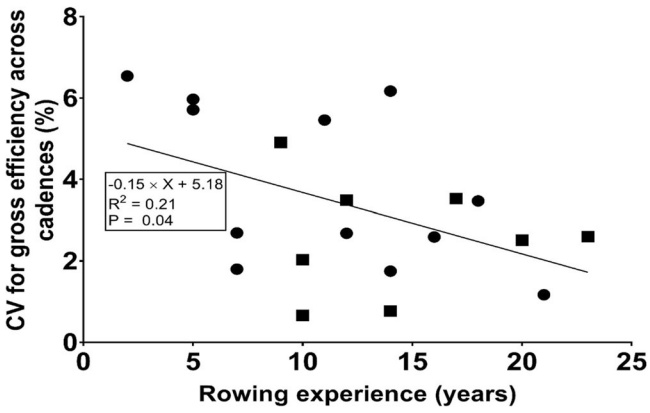

Fig. 2 ▲ Relationship between the coefficient of variation (CV, as a percentage) of gross efficiency across cadences and rowers' experience in rowing (in years). Data are presented as individual values, and as regression equation, R-squared (R^2), and *P* values from simple linear regression. Circles represent rowers located at the bow and stern. Squares represent rowers located in the central positions of the boat

ability does not necessarily reflect lower efficiency but instead suggests a less stable response to changes in cadence. This could be explained, to a greater or lesser extent, by the previously mentioned issue regarding the naturally chosen cadence and its tendency to generate a better performance (Kristoffersen et al., 2014). As indicated in a recent review, although the preferred cadence is not always the most efficient, more training experience could explain the achievement of these physiological adaptations (Mikulic & Gulin, 2024; Zameziati et al., 2006). Therefore, it reasonable to expect a greater variability in GE (expressed as higher CV values) when rowing experience is limited. Moreover, previous studies have indicated that the trainability of GE is a key determinant of endurance performance, with the potential to improve and adapt favorably with accumulated

experience over time (Coyle, 2005; Jobson, Hopker, Korff, & Passfield, 2012; Staff, Solli, Osborne, & Sandbakk, 2023).

Therefore, the inter-individual differences identified in this study underline the relevance of individualizing the training and work cadences of traditional elite rowers, particularly for those who are novice rowers. These results provide valuable information for traditional rowing coaches to adjust modulations in rowing cadence during training sessions, taking into consideration their athletes' experience. However, the current evidence is insufficient to conclusively determine the impact of cadence on the GE of elite traditional rowers. Future studies should focus on investigating the potential for standardizing the response to certain physiological demands among elite traditional rowers. Furthermore, studies incorporating detailed kinematic analyses could contribute to a better understanding of whether any differences in stroke mechanics occur across different stroke rates in traditional rowing. This may facilitate the development of efficient performance strategies that minimize physiological demands during competition.

Limitations

As limitations of the study, it is important to acknowledge that although the assessments were performed on an adapted ergometer, the results could be susceptible to alteration when conducted on open waters (outside the laboratory conditions). Furthermore, accurately simulating the demands of competition is challenging, mostly due to the inherent variability in the natural environment, as the conditions can change during the course of a race. In addition, for this study, a work rate of 70% of PPO was applied, and thus our results may not extend to higher or lower work rates. Moreover, setting absolute cadences without considering the freely chosen cadences of the participants may have constituted a limitation too. Nevertheless, our research helps expand the limited existing knowledge on traditional rowing and offers potential directions for future research into the factors that may contribute to enhanced performance, thereby providing a basis for targeted interventions. Finally, as this is a cross-sectional study, it does not allow us to establish causality.

Conclusion

The present study found no significant differences in gross efficiency (GE) across three rowing cadences (20, 25, and 30 strokes per minute) in elite traditional rowers, although notable inter-individual differences were observed. Additionally, the negative association between GE variability and rowing experience highlights the relevance of accumulated experience in achieving greater GE and consistency across cadences. These findings are particularly relevant for rowers and coaches, as they suggest that optimal cadence may differ between individuals and emphasize the need to tailor training strategies to individual physiological responses, especially for less experienced traditional rowers.

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Data availability. All data supporting the findings of this work are included in the article.

Declarations

Conflict of interest. S. Agirre-Elordui, J.M. A. Alcántara, I. López., P. León-Guereño and A. Castañeda-Babarro declare that they have no competing interests.

This study was performed in line with the principles of the Declaration of Helsinki. Approval was granted by the Ethics Committee of the University of Deusto (ref: ETK-13/18-19).

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