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Intracycle velocity variations and their relationship with on-water rowing performance

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Supervisor: Ricardo J. Fernandes, PhD

Co-supervisor: Beatriz Gomes, PhD

Maria Joana dos Santos Leão

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Abstract

Rowing performance is influenced by the ability to maintain boat velocity efficiently, minimizing intracycle velocity variation (IVV) that lead to energy losses. Even if this variable has emerged as a relevant biomechanical metric, its role during real rowing competitive conditions remains underexplored. This dissertation investigated IVV and its associations with key biomechanical variables, and the differences between sexes and boat disciplines and sizes. Data were collected during 2000 m rowing competitions, where boat position and velocity were recorded using a 15 Hz GPS and triaxial accelerometer at 100 Hz, ontaining race time, mean velocity and cycle rate. From these primary variables, additional metrics were derived (distance per cycle, IVV, CVV and technical index. In single scullers, men showed higher mean, maximum and minimum velocities, distance per cycle, coefficient of velocity variation (CVV) and technical index compared with women. Associations were observed between mean velocity and IVV, CVV and cycle rate ($r = 0.68$, 0.74 and 0.65) in men, while in women mean velocity was mainly related with technical index ($r = 0.87$). Distance per cycle was associated with technical index in both sexes ($r = 0.76$ and 0.66). Despite these differences, male and female scullers adopted similar pacing strategies and CVV remained constant throughout the 2000 m event, suggesting it may not be affected by fatigue. In team boats, sculling showed higher average velocity and lower IVV than sweep boats, possibly due to symmetrical propulsion. Long boats reached higher velocities, technical index and distance per cycle, due to the combined propulsive force of multiple rowers and hydrodynamic advantages. Large associations were found between maximum and minimum velocity ($r = 0.79$) and cycle rate with distance per cycle ($r = –0.50$) in long boats, and between average velocity with minimum velocity ($r = 0.76$), technical index ($r = 0.84$) and distance per cycle ($r = 0.64$) in short boats. The findings of these studies offer valuable insights that can support coaching practices and contribute to the optimization of rowing performance in the future. In particular, the data provided new information on how IVV associates to commonly used biomechanical variables in rowing.

Resumo

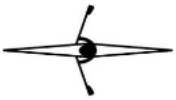
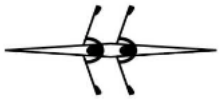
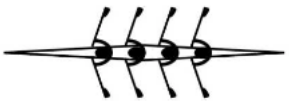
O desempenho no remo é influenciado pela capacidade de manter a velocidade do barco de forma eficiente, minimizando as variações intraciclicas da velocidade (IVV) que conduzem a perdas de energia. Embora esta variável tenha emergido como uma métrica biomecânica relevante, o seu papel em condições reais de competição de remo permanece pouco explorado. Esta dissertação investigou o IVV e as suas associações com variáveis biomecânicas-chave, bem como as diferenças entre sexos, disciplinas e tamanhos de embarcações. Os dados foram recolhidos durante competições de 2000 m, onde a posição e a velocidade do barco foram registadas com um GPS de 15 Hz e um acelerómetro triaxial a 100 Hz, obtendo o tempo de prova, a velocidade média e a taxa de ciclo. A partir destas variáveis primárias, derivaram-se métricas adicionais (distância por ciclo, IVV, CVV e índice técnico). Nos barcos de um só remo, os homens apresentaram valores superiores de velocidade média, máxima e mínima, distância por ciclo, coeficiente de variação da velocidade (CVV) e índice técnico, em comparação com as mulheres. Observaram-se associações entre a velocidade média e o IVV, o CVV e a taxa de ciclo (r = 0,68; 0,74; 0,65) nos homens, enquanto nas mulheres a velocidade média se relacionou sobretudo com o índice técnico (r = 0,87). A distância por ciclo associou-se ao índice técnico em ambos os sexos (r = 0,76 e 0,66). Apesar destas diferenças, remadores e remadoras adotaram estratégias de ritmo semelhantes, e o CVV manteve-se constante ao longo dos 2000 m, sugerindo que poderá não ser afetado pela fadiga. Nos barcos de equipa, os de sculling) apresentaram maior velocidade média e menor IVV do que os de sweeping, possivelmente devido à propulsão simétrica. Os barcos longos atingiram velocidades mais elevadas, maior índice técnico e distância por ciclo, em virtude da força propulsiva combinada de vários remadores e das vantagens hidrodinâmicas. Foram observadas fortes associações entre a velocidade máxima e mínima (r = 0,79) e entre a taxa de ciclo e a distância por ciclo (r = –0,50) nos barcos longos, bem como entre a velocidade média e a velocidade mínima (r = 0,76), o índice técnico (r = 0,84) e a distância por ciclo (r = 0,64) nos barcos curtos. Os resultados destes estudos oferecem informações valiosas que

podem apoiar as práticas de treino e contribuir para a otimização do desempenho no remo no futuro. Em particular, os dados fornecem novas evidências sobre a forma como o IVV se relaciona com variáveis biomecânicas habitualmente utilizadas no remo.

Chapter 1 General introduction

Rowing is a cyclic sport characterized by the continuous repetition of coordinated movement patterns, where both upper and lower limbs contribute to propelling the boat through the interaction between the oar blades and the water (Cardoso et al., 2021; Cardoso et al., 2025; Kleshnev, 2016). The current Olympic rowing events are conducted over a 2000 m course and are divided in sweeping and sculling disciplines, with one or two oars per rower (respectively). Boat classes are categorized based on the number of rowers and the presence of a coxswain. In sculling, the Olympic boat classes include: the single-scull (one rower), double-scull (two rowers) and quadruple-scull (four rowers). In sweep rowing, it is included the coxless pair (two rowers), coxless four (four rowers) and the coxed eight (eight rowers and the cox). Table 1 presents the boat classes typology currently included in the Olympic Games.

Table 1. Current Olympic rowing events.

Boat class	Abbreviation	Image	Discipline
Single-scull	1x		Sculling
Double-scull	2x		Sculling
Quadruple-scull	4x		Sculling
Pair	2-		Sculling
Four	4-		Sculling
Coxed eight	8+		Sculling

As displayed in Figure 1, on-water rowing performance is multifactorial and primarily driven by the interactions of bioenergetics, biomechanics, psychology and boat mechanics related variables (Ingham et al., 2002; Mäestu et al., 2005; Soper & Hume, 2004b). As the enhancement of rowing performance can no longer be obtained only by the increasing of training volume, systematic training control and evaluation are currently fundamental tools to increase the efficiency of the training process and competition (Legge, Draper, et al., 2024; Olbrecht, 2000; Wilmore et al., 2008). Given the recognized importance of the biomechanical factors on overall rowing performance, they should also be the focus of attention of training control and evaluation in cyclic sports in general (Fernandes et al., 2013).

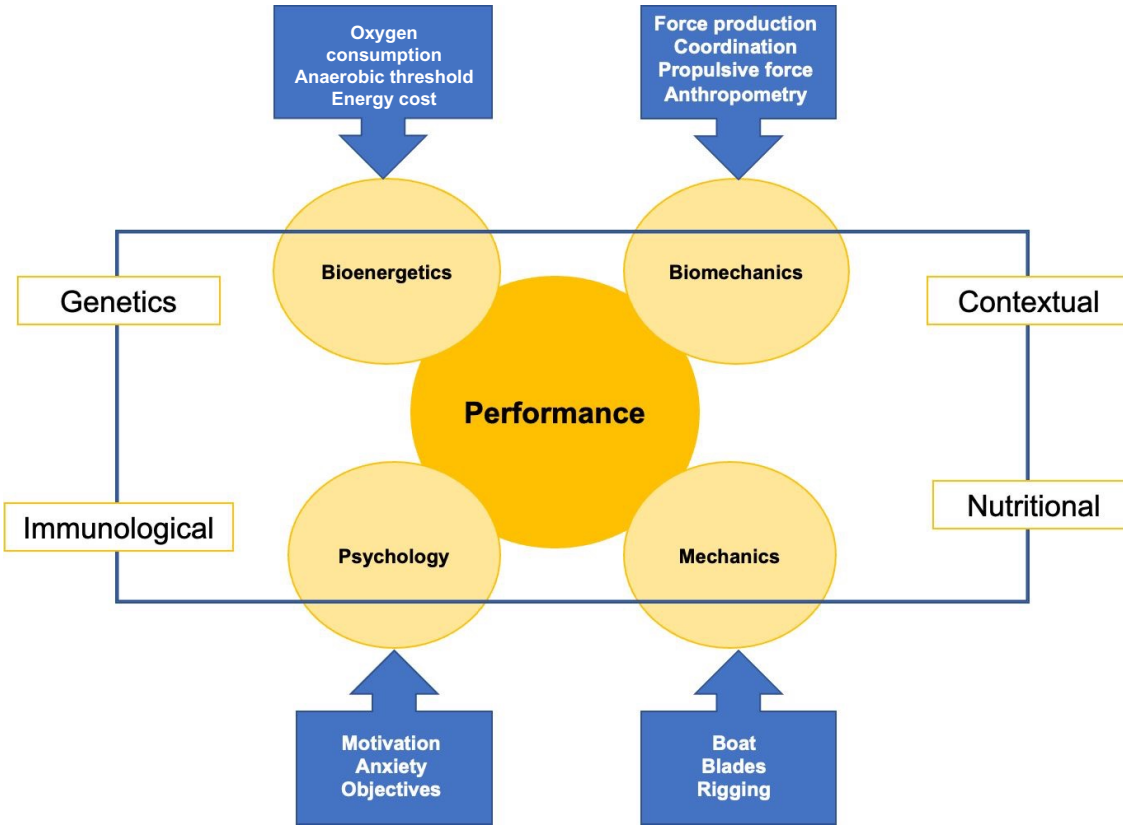


Figure 1. Deterministic model of rowing performance.

From a biomechanical perspective, rowing performance can be improved by either increasing propulsion or decreasing the resistance acting on the boat (Barrett & Manning, 2004; Legge, Slattery, et al., 2024) By improving the movement technical efficiency, rowers can maximize propulsion per cycle (while minimizing unnecessary energy loss), thereby improving overall performance (Holt et al., 2020; Legge et al., 2024; Warmenhoven, Cobley, Draper, & Smith, 2018). Higher intracycle velocity variations (IVV) are associated with higher energy losses and their minimization is generally considered beneficial for enhancing rowing efficiency, because they require repeated acceleration of the system, increasing hydrodynamic drag and mechanical energy expenditure**.** This will contribute to higher average boat velocity and improved performance (Legge, Draper, et al., 2024).

Despite the relevance of IVV, this variable remains insufficiently studied in rowing competitive contexts, particularly regarding its association to other biomechanical metrics and its eventual differences per sex (Hill & Fahrig, 2009). The main aim of this research is to investigate the influence of IVV in Olympic rowing and its association with key biomechanical variables in a competitive context. We hypothesized that IVV would be strongly associated with velocity and cycle rate in both male and female rowers, with potentially distinct relationships between sexes. We also hypothesized that IVV would significantly differ between rowing disciplines and boat sizes, with large and sculling boats showing lower IVV and more efficient biomechanical patterns compared to small and sweep boats. By studying different boat configurations, we aim to understand how IVV patterns vary according to rowing discipline and boat size and how these variations impact performance.

This dissertation starts with the current general introduction and has two experimental studies. The first study focuses on single-scull rowing, assessing IVV in male and female rowers using GPS devices, during a 2000 m race, and analysing its relationship with commonly used biomechanical variables. The second study examines team boats, evaluating IVV across Olympic sweep and

sculling classes during official 2000 m events and exploring its association with relevant biomechanical variables analysed in the first study. These studies are expected to elucidate differences in IVV patterns between sexes and boat disciplines and sizes, and to identify the key biomechanical determinants most strongly associated with movement efficiency. The dissertation ends with the presentation of the main conclusions, followed by recommendations for future research and a comprehensive list of bibliographic references.

Chapter 2

Intracycle velocity variation during a single-sculling 2000 m rowing competition

Joana Leão [1,2], Ricardo Cardoso [1,2], J. A. Abraldes [3], Susana Soares [1,2], Beatriz B. Gomes [4] and Ricardo J. Fernandes

[1]Centre of Research, Education, Innovation and Intervention in Sport, Faculty of Sport, University of Porto,
4200-450 Porto, Portugal; susana@fade.up.pt (S.S.); ricfer@fade.up.pt (R.J.F.)

[2]Porto Biomechanics Laboratory, Faculty of Sport, University of Porto, 4200-450 Porto, Portugal

[3]Research Group Movement Sciences and Sport (MS&SPORT), Department of Physical Activity and Sport, Faculty of Sport Sciences, University of Murcia, Spain; abraldes@um.es

[4]CIPER, Faculty of Sport Sciences and Physical Education (FCDEFUC), University of Coimbra,
3040-248 Coimbra, Portugal; beatrizgomes@fcdef.uc.pt

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Abstract

Rowing is a cyclic sport that consists of repetitive biomechanical actions, with performance being influenced by the balance between propulsive and resistive forces. The current study aimed to assess the relationships between intracycle velocity variation (IVV) and key biomechanical and performance variables in male and female single scullers. Twenty-three experienced rowers (10 females) completed a 2000 m rowing competition, during which boat position and velocity were measured using a 15 Hz GPS, while cycle rate was derived from the integrated triaxial accelerometer sampling at 100 Hz. From these data, it was possible to calculate distance per cycle, IVV, the coefficient of velocity variation (CVV) and technical index values. Males presented higher mean, maximum and minimum velocity, distance per cycle, CVV and technical index values than females (15.40 ± 0.81 vs. 13.36 ± 0.88 km/h, d = 0.84; 21.39 ± 1.68 vs. 18.77 ± 1.52 km/h, d = 1.61; 11.15 ± 1.81 vs. 9.03 ± 0.85 km/h, d = 1.45; 7.68 ± 0.32 vs. 6.89 ± 0.97 m, d = 0.69; 14.13 ± 2.02 vs. 11.64 ± 1.93%, d = 2.06; and 34.25 ± 4.82 vs. 26.30 ± 4.23 (m^2/(s·cycle)), d = 4.56, respectively). An association between mean velocity and intracycle IVV, CVV and cycle rate (r = 0.68, 0.74 *and* 0.65, respectively) was observed in males but not in female single scullers (which may be attributed to anthropometric specificities). In female single scullers, mean velocity was related with distance per cycle while was associated with technical index in both males and females (r = 0.76 and 0.66, respectively). Despite these differences, male and female single scullers adopted similar pacing strategies and CVV remained constant throughout the 2000 m race (indicating that this variable might not be affected by fatigue). Differences were also observed in the velocity–time profile, with men reaching peak velocity first and having a faster propulsive phase. Data provided new information on how IVV and CVV relate to commonly used biomechanical variables in rowing. Future studies should include other boat classes and other performance variables such as the power output and arc length.

Keywords: rowing; biomechanics; intracycle velocity variation

Introduction

Rowing is a cyclic and symmetrical sport characterized by repetitive movement cycles involving coordinated movements of both the upper and lower limbs, with the oars functioning as levers that transmit force to the water and generate propulsion to accelerate the boat (Cardoso et al., 2025; Warmenhoven, Cobley, Draper, & Smith, 2018; Warmenhoven, Smith, et al., 2018). Each rowing cycle can be divided into two distinct phases: the propulsive phase, which starts when the blade enters the water (catch) and ends when it exits (finish) and the recovery phase, which spans from blade exit to its next water entry, during which no propulsion is produced and the rower repositions the body for the subsequent cycle (Warmenhoven, Cobley, Draper, & Smith, 2018). The only external propulsive force applied to the system is produced through blade–water interaction during the propulsive phase, while hydrodynamic drag (comprising both viscous and wave resistance) acts continuously throughout the rowing cycle (Baudouin & Hawkins, 2002; Cardoso, Fonseca, et al., 2022; Smith & Hopkins, 2012).

Effective propulsion results from the ability to maximize force application during the drive while minimizing resistive losses during recovery, making rowing efficiency highly dependent on the optimization of cycle mechanics and temporal coordination. Consequently, rowing performance is multifactorial, influenced by the rower's physiological profile (e.g., aerobic and anaerobic capacities and muscular strength), anthropometric characteristics (e.g., limb length and body mass) and biomechanical execution (e.g., cycle length, force curve profile, timing and blade trajectory) (Ingham et al., 2002; Mäestu et al., 2005; Soper & Hume, 2004a). These interrelated components underscore the importance of an integrated approach to training and technique development in competitive rowing.

Advances in biomechanical instrumentation have improved the accessibility, reliability and validity of data collection, enabling precise on-water technical assessments (Holt et al., 2020; Legge, Draper, et al., 2024). High-frequency sensors and GPS-integrated systems allow real-time analysis of kinematics,

kinetics and boat dynamics, providing coaches and researchers data that allows performance enhancement (Holt et al., 2020; Smith & Hopkins, 2012). These tools have enabled a more detailed examination of the rowing cycle, including velocity variations within each cycle. In this context, there has been growing interest in transferring biomechanical performance indicators from other cyclic sports to rowing, particularly those developed and validated in swimming and canoeing.

The quantitative analysis of technique in cyclic sports (such as swimming and canoeing) has gained increasing interest, leading to a deeper understanding of velocity behaviour during competition and training (Michael et al., 2009; Sperlich & Baker, 2002; Vaquero-Cristóbal et al., 2013). The concept of the technical index, originally introduced in swimming, is defined as the product of swimming velocity and distance per cycle. A swimmer with a high technical index covers more distance per cycle at higher velocity, suggesting better propulsion. This index offers a biomechanical indicator of global technical proficiency that is applicable across cyclic sports where movement efficiency is critical to performance (Costill et al., 1985; Holt et al., 2020; Sánchez & Arellano, 2002). In addition, research on intracycle velocity variation (IVV) in swimming has demonstrated an evident association between IVV and velocity, indicating that lower values of this variable corresponds to greater technical proficiency (Fernandes et al., 2023; Figueiredo et al., 2012).

IVV is associated with the interaction between the cycle propulsive and recovery phases and its minimization is generally regarded as beneficial for enhancing efficiency, ultimately contributing to higher average boat velocity and improved race performance (Legge, Draper, et al., 2024). In addition, IVV in rowing has been related to cycle rate, since its increase often resulting in elevated inertial forces and greater accelerations of both the rowers body mass and the boat, thereby influencing the magnitude of velocity fluctuations throughout the rowing cycle (Hill & Fahrig, 2009). A deeper understanding of the interactions among these variables provides valuable insights into performance and energy efficiency

in rowing, but research on this topic remains limited, since most studies have not been conducted in real competitive environments or over race distances typical of elite performance. Furthermore, research on the relationships between IVV and other biomechanical variables critical to rowing performance, particularly over a 2000 m race, remains limited. The aim of the current study was to assess the IVV of single scullers during a 2000 m competition and examine its relationships with other relevant biomechanical variables. We hypothesized that IVV would be strongly associated with velocity and cycle rate in both male and female rowers, with potentially distinct relationships between sexes.

Materials and Methods

Twenty-three rowers (10 females), all with significant experience in national and international regattas and regular training volumes of 10–20 h per week, volunteered to participate in this study. Twenty-three races were recorded during three national regattas held at a high-performance rowing venue. Boat position, velocity and acceleration were obtained using a 15 Hz GPS unit with 12 channel receivers and a tri-axial accelerometer sampling at 100 Hz (GPSPORT, Canberra, Australia) both integrated within the same device mounted on the boat bow deck (Fernandes et al., 2021; Hill & Fahrig, 2009; Holt et al., 2020). Environmental conditions at the start and finish of each trial were recorded using a weather station (NK 5400, Kestrel, Boothwyn, PA, USA) positioned at water level and measured at the finish line. All participants provided informed consent prior to commencement of this study and signed an informed consent in accordance with the local research ethics committee and the Declaration of Helsinki.

Data were downloaded into a computer and analysed using a validated custom-made MATLAB (version 2023a; Mathworks Inc., Natick, MA, USA) algorithm (Fernandes et al., 2021). The race time (mean duration), mean velocity (ratio of distance to completion time) and cycle rate (mean number of cycles per min) were obtained from the collected data. From these primary variables, additional metrics were derived: distance per cycle (ratio of average velocity to the

corresponding cycle rate), IVV (difference between maximum and minimum velocity within each cycle), coefficient of velocity variation (CVV; ratio of standard-deviation (SD) to mean velocity) and technical index (product of distance per cycle and velocity) (Costill et al., 1985). The mean velocity–time profile was then calculated as the average of all complete cycles (including both propulsion and recovery phases) of each race.

All variables were calculated as mean and SD values for the complete race and per 100 m splits. Data normality and homogeneity were assessed using the Kolmogorov–Smirnov and Levene tests. All statistical procedures were performed using SPSS 27 (Chicago, IL, USA) and a 5% significance level was set. An independent sample t-test was conducted to identify sex-related differences with Cohen's d effect sizes categorized as trivial (<0.2), small (0.2–0.6), moderate (0.6–1.2), large (1.2–2.0) and very large (>2.0) (Hopkins et al., 2009). Pearson correlation coefficients were used to evaluate linear relations between variables and interpreted as large (0.5–1.0), medium (0.3–0.5) and small (0.1–0.3). A repeated-measures ANOVA with Bonferroni post hoc tests was used to compare distance per cycle, velocity, IVV and cycle rate across all 100 m splits for each sex. To compare the mean velocity profile between male and female rowers, Statistical Parametric Mapping (SPM) with independent two-sample t-test was conducted in MATLAB using SPm1d toolbox (Morais et al., 2022), with all statistical analyses being conducted in SPSS 27 (Chicago, IL, USA).

Results

During the 2000 m competition, male rowers demonstrated higher mean, maximum and minimum velocity, distance per cycle, technical index and CVV values as presented in Table 1. The Pearson correlation coefficients for each variable, for both male and female rowers, are displayed in Table 2. A large association was observed between the mean, maximum, minimum velocity, cycle rate and IVV for male rowers. In addition, maximum velocity showed a large corelation with both CVV and IVV, the latter being largely related with cycle rate

in male rowers. For female single scullers, mean velocity was largely related with maximum and minimum velocity and distance per cycle. For both groups, cycle rate exhibited an inverse relation with distance per cycle and technical index.

Table 1. Mean ± SD of the selected biomechanical variables during the single sculling 2000 m competition.

Variables	Males	Females	*p*	Effect Size (Cohen's d)
Mean velocity (km/h)	15.40 ± 0.81	13.36 ± 0.88	<0.001	0.84
Maximum velocity (km/h)	21.39 ± 1.68	18.77 ± 1.52	<0.001	1.61
Minimum velocity (km/h)	11.15 ± 1.81	9.03 ± 0.85	0.002	1.45
Cycle rate (cycles.min^{-1})	33.65 ± 1.63	32.40 ± 4.09	0.343	0.30
Distance per cycle (m/cycle)	7.68 ± 0.32	6.89 ± 0.97	0.015	0.69
IVV (km/h)	5.78 ± 1.05	5.50 ± 1.11	0.521	1.08
CVV (%)	14.13 ± 2.02	11.64 ± 1.93	0.010	2.06
Technical Index (m^2/(s·cycle))	34.25 ± 4.82	26.30 ± 4.23	<0.001	4.56

Data on mean velocity, cycle rate, distance per cycle and CVV values, regarding the 100 m split segments of the race are displayed in Figure 1. Mean velocity values presented a slight decrease over the course of the competition, as differences were present between the 1st and the 10th and 20th splits for both groups. Both sexes presented stable values of CVV across splits, with males presenting higher values than females. The distance per cycle values were constant for female but not for male rowers, with differences being found between the 1st and the following 17 splits. The cycle rate values also presented changes over the competition in both groups with differences being found between 1st and the 10th and 20th splits. The rowing cycle velocity–time and the T-test profile are presented in Figure 2 (upper and lower panel, respectively). Male rowers presented higher velocity than females, particularly during the first half of the cycle (~0–60%), in addition higher SD in the final phase of the cycle (from ~80–100%) was also observed.

Table 2. Pearson linear correlation coefficients for each variable for male (M) and female (F) single-scullers.

Variables	Mean Velocity	Maximum Velocity	Minimum Velocity	Cycle Rate	Distance Per Cycle	Intracycle Velocity Variation (IVV)	Coefficient of Velocity Variation (CVV)
	M/F	M/F	M/F	M/F	M/F	M/F	M/F
Mean velocity	-						
Maximum velocity	0.59 */0.55 *						
Minimum velocity	0.64 */0.74 *	–0.03/0.66 *					
Cycle rate	0.65 */0.37	0.28/0.21	0.49/0.20				
Distance per cycle	0.40/0.42	0.4/0.024	0.17/0.21	–0.41/–0.56 *			
Intracycle velocity variation (IVV)	0.68 */0.17	0.61 */0.72 *	0.27/0.28	0.63 */0.09	0.13/–0.01		
Coefficient of velocity variation (CVV)	0.74 */0.34	0.70 */0.32	0.40/–0.11	0.68 */0.19	0.15/–0.11	0.59 */0.77 *	
Technical index	0.35/0.87 *	0.62 */0.58 *	0.03/0.76 *	–0.22/–0.11	0.76 */0.66 *	0.09/0.19	0.09/–0.18

* $p \leq 0.05$.

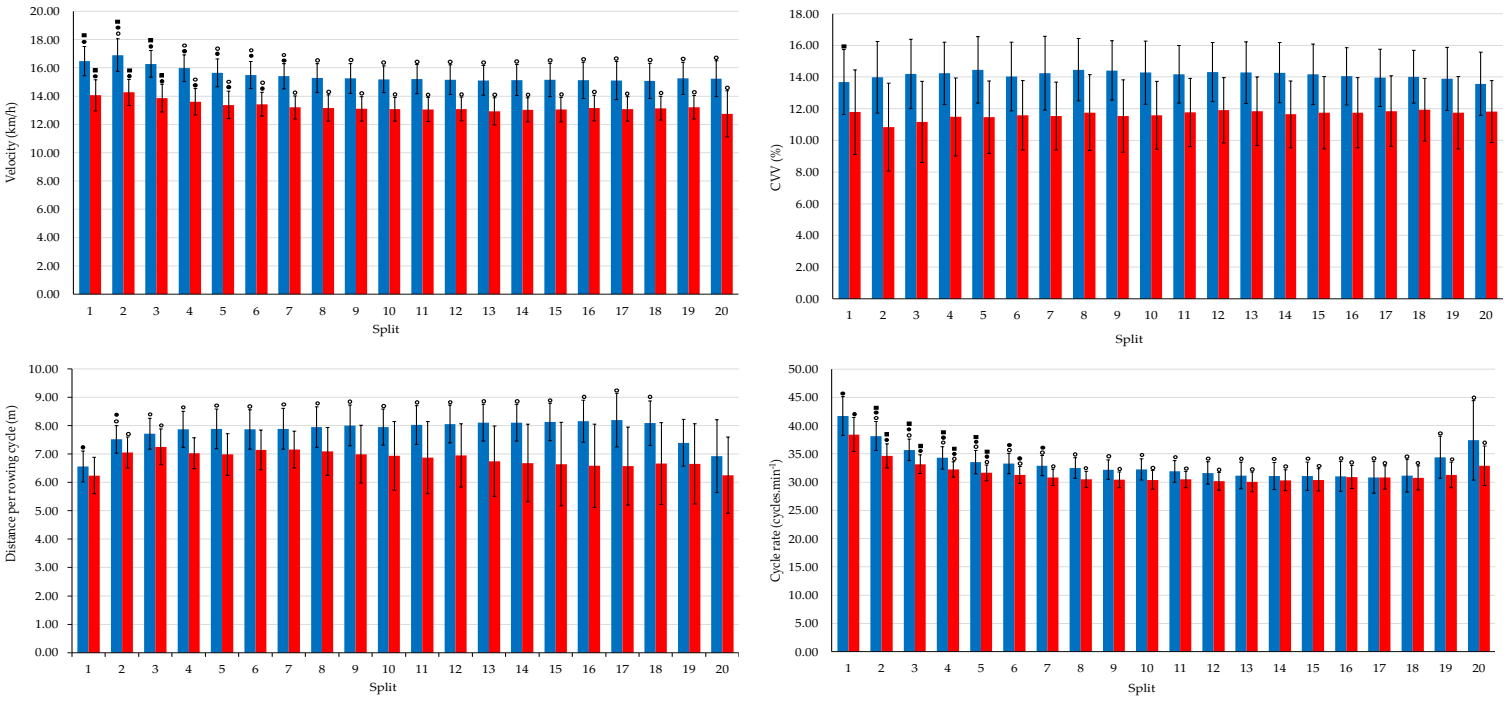


Figure 1. Mean ± SD values of velocity and CVV (upper left and right panels), as well as distance per cycle and cycle rate (lower left and right panels) for the different segments of the competition for male and female single-scullers (blue and red, respectively), O, ● and ■ corresponds to differences between the indicated split and the 1st, the 10th and the 20th splits (respectively) ($p < 0.05$).

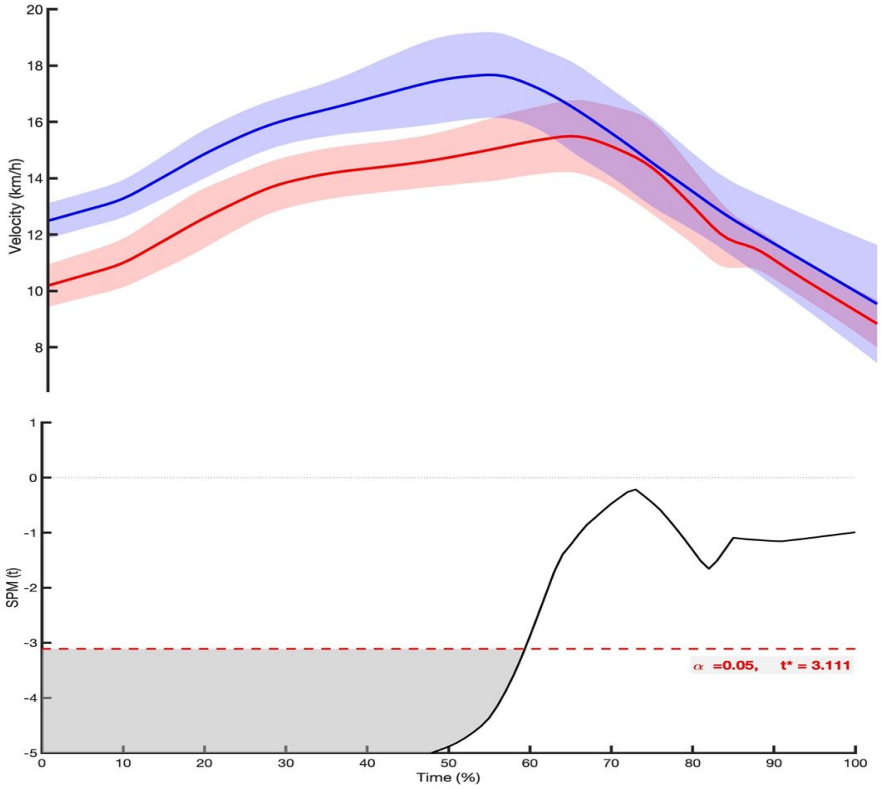


Figure 2. Mean ± SD of the mean velocity–time profile per rowing cycle of male and female single-scullers (upper panel, blue and red lines, respectively) and the independent SPM curve with the limits of significance (red dashed lines) displaying the differences between male and female rowers (lower panel) * $p \leq 0.05$.

Discussion

Analysing the velocity profile of a rower provides valuable insights and can highlight distinct technical strategies to optimize performance (Legge, Draper, et al., 2024; Warmenhoven, Harrison, et al., 2018). In rowing, increased water resistance is associated with higher IVV values, whereas maintaining a more constant velocity may enhance efficiency (Holt et al., 2020). In the current study, differences in mean and maximum velocities were observed between male and female single scullers likely reflecting the former greater force production capacity

(McGregor et al., 2008; Podstawski et al., 2022). Previous research indicates that male rowers tend to apply greater force over a shorter period, leading to higher peak velocity followed by a greater decline, whereas female rowers distribute their force more evenly, resulting in smaller velocity variations and a longer propulsive phase (Kleshnev, 2010; McGregor et al., 2008; Smith & Spinks, 1995; Warmenhoven, Harrison, et al., 2018). Moreover, male single scullers demonstrated a higher technical index, indicating that more distance is covered per cycle at a higher velocity. This reflects a more efficient application of force, which is particularly important for maintaining performance throughout a 2000 m race (Costill et al., 1985; Figueiredo et al., 2012; Kleshnev, 1998; Sánchez & Arellano, 2002).

Our data supported the initial hypothesis that IVV would have a large relation with mean velocity and cycle rate, even if this association was only observed on male rowers. As previously reported, male rowers typically generate higher absolute power outputs and greater peak forces, resulting in higher mean velocity but also greater variations in velocity during each cycle, possibly explaining the large relation between IVV and mean velocity for men but not for women (Attenborough et al., 2012; Warmenhoven, Cobley, Draper, Harrison, et al., 2018). In addition, male rowers typically have higher body mass, which could lead to different momentum and inertia effects, amplifying the relation between IVV and cycle rate (Ng et al., 2013; Seifert et al., 2017).

We also observed that cycle rate had a large and a direct relation with mean velocity for men and no association for women, with previous studies indicating that male rowers rely more on a higher cycle rate to generate velocity likely due to their ability to sustain higher power output over repeated cycles (Warden et al., 2002). These findings are similar to those reported in canoeing, revealing that cycle rate has a greater impact on male performance compared to women (McDonnell et al., 2013; Sperlich & Baker, 2002). This suggests that some technical metrics traditionally used in rowing may not have uniform effects across sexes, potentially affecting efficiency differently in female rowers. In fact, previous

research has already pointed out the necessity of adapting the cycle rate according to the power output, aiming to preserve technical efficiency and benefit overall performance (Bompa, 1980; Holt et al., 2020; Kleshnev, 1998; Smith & Spinks, 1995).

Regarding the different race segments, the observed biomechanical variables presented distinctive behaviours. In the first two splits of the competition, males covered less distance per cycle compared to the remaining of the race, while women presented constant values throughout the race. Recent studies highlighted sex-based differences in pacing and effort distribution during 2000 m rowing races, with males generally exhibiting higher velocity and cycle rate in beginning of the race, while females tend to adopt more even pacing strategies (Garland, 2005; Podstawski et al., 2022). However, in our data, both male and female single scullers displayed similar velocity profiles across race segments, suggesting comparable pacing strategies despite other sex-based biomechanical differences.

Studies in canoeing have observed consistent distance per cycle values during a 200 m maximal effort, whereas in rowing previous research indicates that the 2000 m distance and lower cycle rates may influence how athletes manage their technique (Holt et al., 2020; Kleshnev, 2010; Vaquero-Cristóbal et al., 2013). Cycle rate was higher at the beginning of the race, followed by a period of stabilization in both groups, with this early increase being also verified among rowers in previous studies (since a higher cycle rate is typically used to accelerate the boat and achieve greater velocity (Garland, 2005)). The constant CVV values through the race for both groups might indicate that this variable was not affected by the changes on other biomechanical variables, neither by the presence of fatigue.

The observed mean cycle velocity–time profile suggests a similar curve for both male and female rowers, indicating comparable approaches to velocity regulation throughout the cycle. The beginning of the curve represents the instant when the boat starts to experience positive acceleration, immediately after the water entry

and concludes with the subsequent cycle when the boat resumes accelerating. Male rowers exhibited higher velocities than their female counterparts throughout the rowing cycle, particularly during the first half of the cycle (~0–60%), representing mainly the cycle propulsive phase. The location of the peak velocity indicates the time taken to reach its maximum value with male single scullers reaching peak velocity in less time, likely due to their greater power output compared to females (as noted on previous studies (Cardoso et al., 2024; Kleshnev, 1998).

No differences were observed between groups during the final phase of the velocity–time profile, corresponding to the recovery phase and the entry of the blades into the water. However, male rowers presented higher SD, possibly due to the higher mass moving towards the catch phase. Also, there might be small differences in how each male rower controls this mass, particularly during the deceleration and repositioning of the body. These subtle variations in technical execution (such as differences in the timing of trunk and arm movement during recovery) can result in more fluctuation in velocity, particularly at higher cycle rates (Kleshnev, 2010; Soper & Hume, 2004b). Even if the current study presents original data and relevant outcomes, it presents some limitations. The inclusion of data on other biomechanical variables (such as rowing arc length and power) could provide a more comprehensive understanding of rowing mechanics and performance differences between genders. We acknowledge that the absence of direct anthropometric data (e.g., body mass, height, or limb length) in our study represents a limitation, as these factors are known to influence dynamics and overall mechanical efficiency.

Conclusions

The current study provides new information on how IVV relates to commonly used biomechanical variables in rowing. Male rowers exhibited greater CVV due to their ability to generate higher peak forces in a short duration effort, while female rowers demonstrate a more even force distribution leading to steadier velocity through the rowing cycle. CVV remained stable across all race segments despite

variations in other biomechanical variables, indicating that it may not be affected by fatigue. The mean cycle velocity–time profile was similar in both groups, with male rowers showing higher velocity through the propulsive phase of the cycle (also reaching peak velocity earlier) compared to females. These findings suggest that coaches should consider adjusting training strategies to adopt a more efficient race strategy**.** Since studies on IVV and CVV during competition are scarce, the current study provides a starting point for future research that should include other boat classes in a competitive setting, using specialized boat instrumentation to measure other rowing-specific variables like force and arc length.

Chapter 3

Effects of boat class and size on intracycle velocity variation in 2000 m rowing

Authors: Joana Leão [1,2]*, Ricardo Cardoso [1,2], Beatriz Gomes [3] and Ricardo J. Fernandes [1,2]

[1] Centre of Research, Education, Innovation and Intervention in Sport, Faculty of Sport, University of Porto, Porto, Portugal.

[2] Porto Biomechanics Laboratory, Faculty of Sport, University of Porto, 4200-450 Porto, Portugal

[3] CIPER (Interdisciplinary Centre for the Study of Human Performance), Faculty of Sport Sciences and Physical Education (FCDEFUC), University of Coimbra, Portugal.

Keywords: Intracycle velocity variation; Rowing; Biomechanics

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Abstract

Rowing performance depends on boat velocity and technical efficiency, which vary across boat classes. This study quantified intracycle velocity variation (IVV) in olympic rowing boats during 2000 m competitions and examined its relationship with biomechanical variables. A total of 49 races were recorded during three national regattas, involving 206 experienced rowers (72 females). Boats were classified by discipline (sweep vs. sculling) and length (short vs. long). Boat velocity and position were recorded using GPS (15 Hz) and accelerometery (100 Hz). Sculling boats demonstrated higher average velocity and lower IVV than sweep boats ($p \leq 0.05$), possibly due to reduced lateral asymmetries. Long boats reached higher maximum, average and minimum velocities ($p \leq 0.05$), as well as greater technical index and distance per cycle, due to the combined propulsive force of multiple rowers and hydrodynamic advantages of longer hulls. Correlation of IVV analysis identified large associations ($r \geq 0.5$): in long boats, maximum and minimum velocity ($r = 0.79$) and cycle rate with distance per cycle ($r = –0.50$); in short boats, average velocity with minimum velocity ($r = 0.76$), technical index ($r = 0.84$) and distance per cycle ($r = 0.64$). In conclusion, IVV is influenced by boat class and crew characteristics, representing a relevant indicator of efficiency in rowing.

Keywords: Intracycle velocity variation; Rowing ; Biomechanics

Introduction

Rowing is a cyclic sport in which boat velocity is the primary external indicator of performance (Cardoso et al., 2025; Holt et al., 2020; Warmenhoven, Smith, et al., 2018). Olympic rowing events are held over a 2000 m course and are divided into two disciplines: sculling (with two oars per rower) and sweep (with one oar per rower). In sculling the olympic classes comprise the single scull (one rower), double scull (two rowers) and quadruple scull (four rowers). In sweep rowing, the coxless pair (two rowers), coxless four (four rowers) and coxed eight (eight rowers plus coxswain) are included (Kleshnev, 2016; Secher, 1993). Across these different boat classes, technical efficiency plays a crucial role in determining boat velocity, with measurable differences observed depending on boat size and configuration (Cardoso, Fonseca, et al., 2022; Holt et al., 2020; Kleshnev, 1998; Nolte, 2005).

Technical efficiency can be described as the ability to transfer propulsive work to the water while minimising energy losses and resistive drag forces. Biomechanical analysis could help to enhance technical efficiency and increasing boat velocity (Barrett & Manning, 2004; Legge, Slattery, et al., 2024). However, research in rowing has been mainly made using ergometers and laboratory facilities, as on-water rowing presents substantial challenges for biomechanical data collection, due to environmental constrains (Cardoso et al., 2024; Legge, Draper, et al., 2024; Sousa et al., 2014). These challenges are further amplified in team boats, where the requirement to synchronise data across multiple rowers introduces additional technical and interpretive complexities (Kleshnev, 2016; Legge, Draper, et al., 2024; Mpimis et al., 2023). In addition, feedback-oriented biomechanical monitoring has been proposed as a practical tool to address such complexities (Smith & Loschner, 2002).

Advances in biomechanical instrumentation and the development of new technologies, such as GPS, have improved the accessibility, reliability and validity of data collection, where traditional laboratory methods are not feasible (Holt et al., 2020; Legge, Draper, et al., 2024). As a result, the quantitative

analysis of technique in cyclic sports (such as swimming, canoeing and rowing) has gained increasing interest (Michael et al., 2009; Romagnoli et al., 2025; Sperlich & Baker, 2002; Vaquero-Cristóbal et al., 2013). The concept of the technical index**,** originally introduced in swimming, is defined as the product of velocity and distance per cycle. A swimmer (or rower) with a high technical index covers more distance per cycle at higher velocity, which reflects superior propulsion (Holt et al., 2020; Sánchez & Arellano, 2002). Research on intracycle velocity variation (IVV) in swimming has demonstrated its strong association with velocity, showing that lower IVV values correspond to greater technical proficiency (Fernandes et al., 2023; Figueiredo et al., 2012).

IVV has been investigated in relation to rowing performance, with larger variations in boat velocity within a cycle being associated with decreased movement efficiency (Fernandes et al., 2023; Hill & Fahrig, 2009; Leão et al., 2025). A deeper understanding of the interaction between IVV and other biomechanical variables could provide valuable insights into technical efficiency in rowing. However, research on this topic remains limited, particularly under real competitive conditions and across different boat classes. The aim of the present study was to assess IVV and other relevant biomechanical variables in olympic boat classes during official 2000 m competitions and to examine how they differ across rowing disciplines and boat sizes. We hypothesized that IVV would significantly differ between rowing disciplines and boat sizes, with larger and sculling boats showing lower IVV and more efficient biomechanical patterns compared to smaller and sweep boats.

Materials and Methods

A total of 49 races were recorded during three national regattas held at a high-performance rowing venue, involving 206 experienced rowers (72 females) with considerable experience in national and international regattas and regular training volumes of 10–20 h per week. The sample included 12 male and tem female single-sculls, ten male and seven female double-sculls, six male and five female quadruple-sculls, six male and two female pairs, six male fours, six male

and four female eights. For analysis purposes, the pair, four and eight were grouped as sweep rowing boats, while the single-sculls, double- sculls and quadruple-sculls were grouped as sculling boats. In addition, the quadruple scull, four and eight were classified as long boats, whereas the single-sculls, the double-sculls and pairs were considered short boats.

Boat position, velocity and acceleration were obtained using a 15 Hz GPS unit with 12 channel receivers integrated with a tri-axial accelerometer sampling at 100 Hz (GPSPORT, Canberra, Australia), mounted on the bow deck of each boat (Anderson et al., 2004; Baca et al., 2010; Fernandes et al., 2021; Holt et al., 2020). Sensor placement was standardized for all measurements and devices were calibrated according to the manufacturer's instructions before data collection. Environmental conditions at the start and finish of each race, including wind velocity and direction, air temperature and relative humidity, were recorded using a portable weather station (NK 5400, Kestrel, Boothwyn, PA, USA) positioned at water level. All participants provided written informed consent in accordance with the local research ethics committee and the Declaration of Helsinki.

Data were analysed using a validated custom MATLAB algorithm (version 2023a; MathWorks Inc., Natick, MA, USA) (Fernandes et al., 2021) adapted for rowing analysis, allowing to assess maximum velocity (highest velocity registered during the race), minimum velocity (lowest velocity registered after the maximum velocity is achieved), average velocity (ratio of distance covered to the time taken), time to peak velocity (time since the beginning of the race until maximum velocity is achieved), technical index (product of distance per cycle and velocity), cycle rate (mean number of rowing cycles per minute), distance per cycle (ratio of mean velocity to the corresponding cycle rate), IVV (difference between maximum and minimum velocity in each cycle) and relative IVV (ratio between IVV and average velocity).

All variables were calculated as mean ± SD values for the complete race and per 100 m splits. Data normality and homogeneity were verified using the

Kolmogorov-Smirnov and Levene tests. All statistical procedures were performed using SPSS 27 (Chicago, IL, USA) with the significance level set at $\alpha \leq 0.05$. A two-way analysis of variance (ANOVA) was used to conducted to examine the main effects of boat type (long vs short; sweep vs sculling) and sex (male vs female), as well as the interaction effect between these factors, on the calculated variables. When significant main effects were identified, post hoc pairwise comparisons with Bonferroni adjustment were applied. For each ANOVA, effect sizes were calculated using partial eta squared (η^2) and interpreted as small ($\eta^2 = 0.01$), medium ($\eta^2 = 0.06$) or large ($\eta^2 \geq 0.14$). Pearson correlation coefficients were used to evaluate linear relations between variables and interpreted as large (0.5-1.0), medium (0.3-0.5) and small (0.1-0.3). Heatmaps of velocity, cycle rate and IVV were generated over a 2000 m distance using MATLAB. Data were averaged in 100 m segments and color-coded to enable visual comparison of performance patterns.

Results

Mean ± SD values of the selected biomechanical variables across rowing discipline (sweep vs sculling) and boat size (long vs short) for male and female crews during the 2000 m competition are presented in Table 1. Sculling boats achieved higher average velocity and lower IVV compared with sweep boats, with no differences being observed for maximum velocity, minimum velocity, technical index, cycle rate, time to peak velocity or distance per cycle. Male crews presented greater maximum, average and minimum velocities, higher technical index, longer distance per cycle and greater IVV than female crews, with no significant interaction effects between rowing discipline and sex. Long boats presented higher maximum, average and minimum velocities, technical index, distance per cycle and lower IVV compared with short boats. No significant interaction effects between boat size and sex were detected, except for cycle rate.

Heatmaps representing the distribution of velocity, cycle rate and IVV over the 2000 m race are presented in Figure1. The Pearson correlation coefficients for each variable, for both male and female rowers are displayed in Table 2. In sculling, maximum velocity showed large associations with average velocity, minimum velocity, technical index and distance per cycle. Average velocity also showed large associations with minimum velocity and distance per cycle. In sweep boats, maximum velocity presented medium association with average velocity, minimum velocity and technical index, while the relation between average and minimum velocity was medium. In long boats, maximum velocity showed large associations with minimum velocity, technical index and distance per cycle and a medium relation with average velocity. Average velocity further showed large associations with minimum velocity and distance per cycle. In short boats, maximum velocity demonstrated large associations with average velocity, cycle rate, technical index and distance per cycle, with average velocity also showing large associations with minimum velocity and distance per cycle.

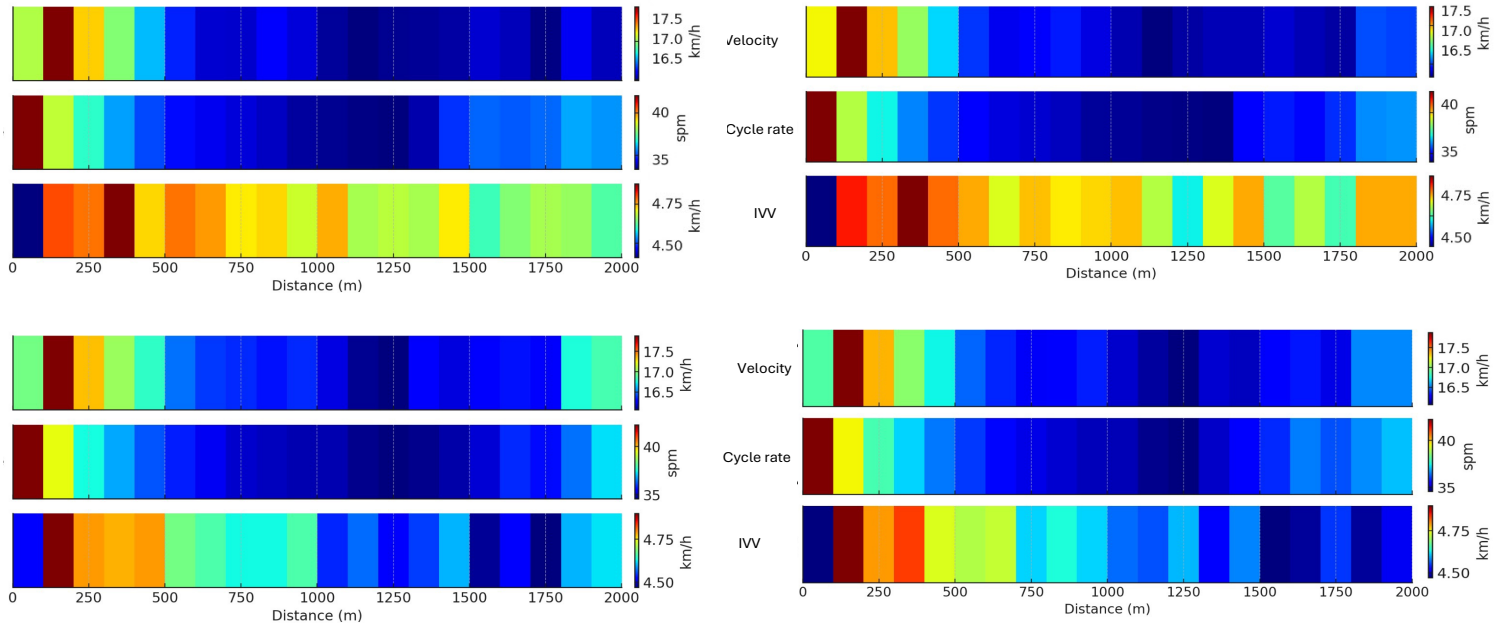


Figure 1. Distribution of velocity, cycle rate and intracycle velocity variation during a 2000 m competition for different boat classes: sculling, short, sweep and long boats (upper left, upper right, lower left and lower right panels, respectively).

Table 1. Biomechanical variables and Two-way ANOVA according to boat discipline (sweep vs sculling) and size (long vs short) during the 2000 m competition in male and female crews.

	Sweep		Sculling		Long		Short	
	Male	**Female**	**Male**	**Female**	**Male**	**Female**	**Male**	**Female**
Maximum velocity (km/h)	22.09±1.64 $^{c, \alpha}$	19.61±1.56$^{\alpha}$	22.65±1.66 $^{c, \alpha}$	18.86±2.40$^{\alpha}$	22.89±1.53 $^{c, \alpha}$	20.56±1.45$^{\alpha}$	21.94±1.70 $^{b, c, \alpha}$	18.85±1.66 $^{b, \alpha}$
Average velocity (km/h)	16.34±1.13 $^{c, \alpha}$	14.09±1.46$^{\alpha}$	17.13±1.49 $^{a, c, \alpha}$	15.94±0.67 $^{a, \alpha}$	17.33±1.53 $^{c, \alpha}$	15.95±3.09$^{\alpha}$	16.22±1.01 $^{b, c, \alpha}$	13.8±0.94 $^{b, \alpha}$
Minimum velocity (km/h)	12.3±1.75 $^{c, \alpha}$	10.16±1.46$^{\alpha}$	12.39±1.34 $^{c, \alpha}$	10.91±0.69$^{\alpha}$	12.85±1.05 $^{c, \alpha}$	11.2±0.64$^{\alpha}$	12.01±1.79 $^{b, c, \alpha}$	9.9±1.41 $^{b, \alpha}$
Time to peak velocity (s)	16.14±4.81$^{\alpha}$	15.08±5.36$^{\alpha}$	15.85±9.21$^{\alpha}$	13.36±7.82$^{\alpha}$	16.67±5.10$^{\alpha}$	12.93±2.92$^{\alpha}$	15.52±9.09$^{\alpha}$	14.11±8.71$^{\alpha}$
Technical index (m^2/(s·cycle))	36.68±4.05 $^{c, \alpha}$	28.77±3.99$^{\alpha}$	37.85±4.73 $^{c, \alpha}$	28.29±3.89$^{\alpha}$	39.11±4.02 $^{c, \alpha}$	30.98±2.58 $^{\alpha}$	35.39±3.84 $^{b, c, \alpha}$	27.58±4.00 $^{b, \alpha}$
Cycle rate (cycles.min^{-1})	34.86±2.18 $^{c, \beta}$	33.69±3.47$^{\alpha}$	36.85±2.97 $^{c, \beta}$	35.09±4.34$^{\alpha}$	35.85±2.33$^{\alpha}$	35.18±3.38$^{\alpha}$	35.48±3.18 $^{b, c, \alpha}$	32.95±3.08 $^{b, \alpha}$
Distance per cycle (m/cycle)	7.84±0.37 $^{c, \alpha}$	7.1±0.71$^{\alpha}$	7.70±0.61 $^{c, \alpha}$	7.21±0.48$^{\alpha}$	7.97±0.97 $^{c, \alpha}$	7.33±0.33$^{\alpha}$	7.68±0.37 $^{b, c, \alpha}$	7.03±0.77 $^{b, \alpha}$
IVV (km/h)	5.38±0.93 $^{c, \alpha}$	4.67±1.60$^{\alpha}$	4.92±0.98 $^{a, c, \alpha}$	3.83±0.82 $^{a, \alpha}$	4.87±0.88 $^{c, \alpha}$	4.95±1.62$^{\alpha}$	5.14±0.98 $^{b, c, \alpha}$	4.07±1.16 $^{b, \alpha}$
Relative IVV (%)	28.89±6.26	24.50±4.59	33.36±5.55 $^{a, c, \alpha}$	36.00±9.98	28.28±5.56	25.67±6.56	33.75±5.76 $^{b, c, \alpha}$	38.17±9.00

$^{a, b \text{ and } c}$: Differences from sweep, long and females (respectively) for a $p \leq 0.05$. Eta square: $^{\alpha}$: [0.25–0.50]; $^{\beta}$: [0.51–0.75]; #: [0.76–1].

Table 2. Associations between biomechanical variables in sweep and sculling boat disciplines during a 2000 m competition.

Variables	Maximum velocity (km/h)		Average velocity (km/h)		Minimum velocity (km/h)		Time to peak velocity (s)		Technical index ($m^2/(s \cdot cycle)$)		Cycle rate ($cycles.min^{-1}$)		Distance per cycle (m/cycle)		IVV (km/h)		Relative IVV (%)	
	Sweep/ Long	Sculling / Short	Sweep/ Long	Sculling/ Short	Sweep/ Long	Sculling/ Short	Sweep/ Long	Sculling/ Short	Sweep/ Long	Sculling/ Short	Sweep/ Long	Sculling/ Short	Sweep/ Long	Sculling/ Short	Sweep/ Long	Sculling/ Short	Sweep/ Long	Sculling/ Short
Maximum velocity (km/h)	-	-	0.49*/0.37	0.79*/0.79*	0.66*/0.79*	0.58*/0.48	0.14/0.19	0.13/0.12	0.69*/0.65*	0.80*/0.77*	0.59*/0.49*	0.33*/0.37*	0.32/0.15	0.55*/0.65*	0.36/0.42*	0.22/0.29*	0.18/0.21	0.16//-0.04
Average velocity (km/h)					0.37/0.47*	0.84*/0.76*	0.02/0.05	0.19/0.20	0.47*/0.38*	0.86*/0.90*	0.21/0.12	0.42*/0.54*	0.24/0.16	0.68*/0.55*	0.33/0.37	0.11/0.13	0.21/-0.165	0.57/-0.34*
Minimum velocity (km/h)							0.00/0.00	0.17/0.16	0.58*/0.76	0.71*/0.61	0.21/0.38	0.42*/0.44*	0.24/0.39	0.55*/0.46*	0.33/0.31	0.03/0.02	-0.21/0.03	0.27/-0.33*
Time to peak velocity (s)									0.27/0.20	0.13/0.15	-0.18/-0.13	0.14/0.12	0.37/0.34	0.09/0.11	-0.32/-0.23	-0.02/-0.04	-0.04/-0.32	-0.04/-0.13
Technical index ($m^2/(s \cdot cycle)$)											0.03/-0.10	0.14/0.16	0.72*/0.66*	0.84*/0.75*	0.07/0.19	0.11/0.17	-0.18/-0.03	0.03/-0.257
Cycle rate ($cycles.min^{-1}$)													0.09/-0.50*	-0.27/-0.20	0.26/0.01	-0.10/0.00	0.25/-0.08	-0.12/-0.19
Distance per cycle (m/cycle)															-0.04/0.16	0.08/0.09	0.24/0.06	0.05/-0.17
IVV (km/h)																	0.88*/0.86*	0.926*/0.87*

* Significant correlation for $p < 0.05$

Discussion and implication

The current results highlight the relevance of boat discipline and size for characterizing biomechanical variables and performance outcomes during competitive rowing. Data revealed that sculling boats demonstrated higher average velocity and lower IVV compared to sweep boats. In rowing, increased water resistance is associated with higher IVV values, whereas maintaining a more constant velocity may enhance efficiency (Fernandes et al., 2023; Holt et al., 2020). This suggests that sculling promotes a more stable propulsion, which can be possibly attributed to the symmetrical contribution of two oars per rower and reduced lateral asymmetries (Hill & Fahrig, 2009; Kleshnev, 2010; Nolte, 2005). Relative IVV reflects the extent to which fluctuations in velocity influence average velocity. Lower relative IVV was observed in sculling boats, which possibly means they are achieving that velocity with less wasted energy compared do sweep boats (Holt et al., 2020; Vaquero-Cristóbal et al., 2013) .

When comparing boat disciplines across sexes, male crews exhibited higher values across maximum, average and minimum velocities, technical index, distance per cycle and IVV. These differences might be explained by sex disparities in muscle strength, power output, aerobic capacity and anthropometric characteristics (Cardoso et al., 2021; Kleshnev, 2010; Warmenhoven, Cobley, Draper, Harrison, et al., 2018). Despite these differences, no significant interaction effects were found between boat discipline and sex. This suggests that while absolute performance differs, the differences observed between sculling and sweep rowing are consistent across sexes.

Data revealed that long boats reached higher maximum, average and minimum velocities, which could be mainly attributed to the greater number of rowers contributing to propulsion. Long boats demonstrated higher technical index, cycle rate, distance per cycle and lower IVV, due to both biomechanical and hydrodynamic advantages. Longer hulls might allow a more efficient transfer of mechanical power into boat propulsion, reducing wave drag and minimizing IVV and relative IVV (Baudouin & Hawkins, 2002; Boucher et al., 2018; Cardoso,

Fonseca, et al., 2022; Day et al., 2011). The combined effect of increased propulsive force from multiple rowers and the stabilizing influence of a longer hull enables sustaining higher velocity throughout the race (Kleshnev, 2010).

When comparing male and female crews across different boat sizes, differences were observed in all variables except for cycle rate. Female crews might compensate for lower absolute power by increasing cycle rate. However, this approach may not be the most efficient, since previous research has emphasized the importance of adjusting cycle rate according to power output to maintain technical efficiency and optimize overall performance. (Bompa, 1980; Cardoso et al., 2024; Holt et al., 2020; Smith & Spinks, 1995) In addition, no significant interaction effects were found between boat size and sex, indicating that the advantages of long boats apply similarly to both male and female crews. This suggests that while absolute power and strength differ between sexes, the biomechanical and hydrodynamic benefits of longer hulls benefit all crews equally.

The analysis of the 100 m race segments throughout the competition revealed that biomechanical variables behaved differently over the 2000 m. It was observed that sculling and long boats maintained higher average velocity and more stable IVV, compared do sweep and short boats, respectively. Velocity showed an initial increment followed by a progressive decline across all boat classes, with sculling and long boats maintaining higher values compared to sweep and short boats (respectively). Sweep oars have a larger surface area since each rower uses only one oar. As a result, the bigger blade generates greater impulse, which over the course of a race, may compromise the ability to maintain a steady boat velocity (Caplan & Gardner, 2007). Cycle rate decreased over the race in all conditions, possibly due to fatigue accumulation (Ettema et al., 2022; McDonnell et al., 2013). IVV maintained more stable values for long boats throughout the distance, possibly due the stabilizing effect of longer hulls (Boucher et al., 2018; Fernandes et al., 2023; Hill & Fahrig, 2009; Leão et al., 2025).

Data evidenced that some large associations were specific to each rowing discipline. In sculling, large associations were observed between maximum velocity, average velocity and distance per cycle, as well as between average velocity and technical index and distance per cycle. These associations may be explained by the symmetrical use of two oars in sculling, which ensures balanced force application and minimizes lateral asymmetries. This symmetry produces a more uniform propulsion pattern, contributing to steadier boat velocity and supporting the observed relationships with the technical index and distance per cycle (Kleshnev, 1998; Kleshnev, 2010). However, some large associations, such as those between maximum velocity and minimum velocity, technical index and IVV, as well as between minimum velocity, technical index and distance per cycle, were present in both disciplines. This reflects that some biomechanical relationships are fundamental to rowing performance and independent of boat discipline (Cardoso, Rios, et al., 2022; Smith & Loschner, 2002).

Long boats presented large relation between maximum velocity and minimum velocity and a large inverse relation between cycle rate and distance per cycle. This relation may be explained by the greater inertia and hydrodynamic drag resulting from the larger hull and the higher number of rowers, which together increase the overall mass and resistance of long boats (Kleshnev, 2010; Soper & Hume, 2004b). In short boats average velocity had a large association to minimum velocity, technical index and distance per cycle. The lower number of rowers, may explain why average velocity had a large association with technical index, since even small differences in power application or disparities in cycle coordination between rowers are more rapidly reflected in velocity (Cardoso et al., 2025; Cuijpers et al., 2015). Moreover, in short boats, longer cycles related largely with average velocity likely due to the lighter hull and reduced hydrodynamic drag, enabling each cycle to generate immediate acceleration and sustain velocity (Cuijpers et al., 2015; Kleshnev, 2016).

From a practical perspective, these findings suggest that monitoring IVV can provide coaches with a sensitive indicator of technical efficiency during

competition. Therefore, coaches may use IVV analysis to identify technical inefficiencies, adjust crew composition and optimize cycle rate accordingly. Integrating IVV monitoring with other biomechanical variables may support individualized feedback and contribute to more effective training interventions across olympic boat classes. However, a limitation of the present study is the absence of data from the women's four, a boat class not represented in the regattas analysed. This gap restricts the generalization of the findings to all olympic categories and should be addressed in future research. In addition, future studies could integrate power output measurements to better understand the relationship between IVV, technical efficiency and performance, ultimately contributing to the development of normative values for each crew and boat class.

Conclusions

This study demonstrated that boat discipline and size substantially influence biomechanical variables and performance outcomes during competitive rowing. Sculling and long boats were associated with higher velocities, technical efficiency and lower IVV compared with sweep and short boats. Male crews achieved superior absolute values across most variables, although no significant interaction effects with boat discipline or size were observed, indicating that the biomechanical and hydrodynamic benefits of sculling and long boats apply consistently across sexes. These findings reinforce the importance of considering both boat characteristics and crew composition when analysing rowing performance.

Chapter 4 General discussion

Rowing performance is determined by multiple factors, including technical execution and energy efficiency (Kleshnev, 1998; Warmenhoven, Cobley, Draper, & Smith, 2018; Cardoso et al., 2023). Recent technological advances have made biomechanical evaluation in rowing increasingly feasible and highly relevant for improving performance (Holt et al., 2020; Romagnoli et al., 2025). Traditionally, the assessment of rowing technique was limited to visual observation and laboratory-based testing (Sousa et al., 2014), which restricted the accuracy and applicability of feedback in real training and competition settings. With the development of portable sensors such as GPS systems and accelerometers, as seen on Figure 1, it is now possible to collect precise biomechanical data directly on the water, providing coaches and rowers with objective insights into performance (Fernandes et al., 2013; Holt et al., 2020; Legge, Slattery, et al., 2024; McGregor, 2003).



Figure 1. A waterproof container with the GPS and triaxial accelerometer device was fixed on the rowing bow deck to record boat position, velocity, and cycle rate.

These advances have enabled access to biomechanical variables that were previously difficult to quantify, such as IVV, which reflects fluctuations in boat velocity within each cycle. IVV is particularly relevant because it integrates information about how efficiently rowers balance the recovery and propulsive phases of the rowing cycle (Leão et al., 2025; Hill & Fahrig, 2009; Kleshnev, 2010). Higher IVV values are often associated with greater energy losses due to increased water resistance, whereas lower IVV values indicate smoother propulsion and improved efficiency. As a result, monitoring IVV alongside traditional variables like boat velocity, cycle rate and distance per cycle allows for a more comprehensive evaluation of rowing performance, supporting targeted technical adjustments and more effective training interventions (Kleshnev, 1999; Legge, Draper, et al., 2024).

In our first study, described on **Chapter 2**, we examined single scullers to investigate sex-based differences in biomechanical variables and velocity profiles during 2000 m competitions. Results showed that males achieved higher mean and maximum velocities than female rowers, which can be explained by their greater muscle strength, power output and body mass. This was reflected in a higher technical index, suggesting that men covered more distance per cycle at higher speeds. However, these advantages were accompanied by higher IVV and CVV compared to women, as it was also observed on **Chapter 3**.

Considering boat size, long boats **(Chapter 3)** reached higher maximum, average and minimum velocities, as well as greater technical index, distance per cycle and IVV, due to the combined effects of increased propulsive force from multiple rowers and the hydrodynamic stability of longer hulls (Pulman, 2004; Yusof et al., 2022). In addition, when comparing boat disciplines, sculling boats demonstrated higher average velocity and lower IVV than sweep boats, which can be attributed to the symmetrical propulsion of two oars per rower reducing lateral asymmetries and energy loss (Hill & Fahrig, 2009). These benefits were consistent across sexes, indicating that while men and women differ in several biomechanical

variables as seen in **Chapter 2**, the mechanical and hydrodynamic advantages of long and sweeping boats apply equally to both.

In **Chapter 2**, the analysis of single-scullers revealed that IVV had a large association with mean velocity and cycle rate, but only in men. Male rowers, who generally produce higher absolute power outputs and peak forces, achieved grater mean velocities but also experienced greater IVV. Their higher body mass likely contributed to momentum and inertia effects, amplifying the association between IVV and cycle rate. Furthermore, cycle rate showed a direct relationship with mean velocity for men, but not for women, suggesting that men rely more heavily on higher cycle rates to generate speed, consistent with their capacity to sustain greater power output (Cardoso et al., 2021; Ettema et al., 2022; Rios et al., 2025). In contrast, women appeared less dependent on cycle rate, reflecting a more uniform application of force. These results indicate that technical metrics such as cycle rate and IVV may not exert uniform effects across sexes, which might indicate that different crews might have different individual technical demands.

To address this concern, **Chapter 3** examined the associations between biomechanical variables across different boat disciplines and sizes. Sculling boats displayed large associations between velocity, technical index, distance per cycle and IVV, possibly reflecting the symmetrical use of both oars causing more stable propulsion and greater efficiency (Lin, 2019; Warmenhoven, Cobley, Draper, Harrison, et al., 2018). Some associations, such as those between maximum and minimum velocity, technical index and distance per cycle, were observed across disciplines, showing that certain biomechanical relationships are fundamental regardless of boat type.

Boat size further influenced these dynamics: long boats demonstrated strong associations between maximum and minimum velocity, as well as an inverse relation between cycle rate and distance per cycle, which can be explained by the greater inertia and hydrodynamic drag of larger hulls (Boucher et al., 2018;

Mattes et al., 2015). In contrast, short boats showed strong associations between average velocity, technical index and distance per cycle, reflecting their sensitivity to coordination and similarity between rowers, since lighter hulls respond more directly to variations in power application causing greater acceleration.

The evolution of velocity, IVV, cycle rate and distance per cycle, throughout the 2000 m race was analysed both in **Chapters 2** and **3**. As shown in **Chapter 2**, male rowers initially relied on higher cycle rates to accelerate the boat, covering less distance per cycle in the early phases, whereas female rowers maintained steadier pacing and more consistent values across race segments (Garland, 2005; Mentzoni & Losnegard, 2021). In **Chapter 3**, the analysis revealed that sculling (1x, 2x, 4x) and long boats (4-, 4x, 8+) sustained higher velocities and more stable IVV across the race, while sweep and short boats displayed greater fluctuations over these variables. This might be attributed to the fact that sweep blades have a larger surface area since each rower uses only one oar. As a result, the bigger blade generates greater impulse, which over the course of a race, may compromise the ability to maintain a steady boat velocity (Caplan & Gardner, 2007)

The analysis of the mean cycle velocity–time profile on **Chapter 2** suggests a similar curve for both male and female rowers, indicating comparable approaches to velocity regulation throughout the cycle. However, male scullers tended to apply greater peak forces over shorter durations, reaching maximum velocity earlier in the cycle but also experiencing a sharper decline, while female rowers distributed force more evenly throughout the cycle. This resulted in smaller velocity variations and a longer propulsive phase, aligning with the lower IVV values observed among women. Such differences reinforce that cycle rate and IVV may not have the same impact across sexes, highlighting the importance of adapting technical metrics to power output in order to optimize efficiency (Cardoso et al., 2024; Kleshnev, 1998).

The findings of the present studies expand current knowledge on how IVV relates to rowing performance in competition, however some limitations must be

acknowledged. Some boat types, such as the women's four, were not represented, restricting generalization. This limitation reflects the lower participation of women in rowing in Portugal, where this boat class is not currently included in national regattas. Furthermore, additional rowing-specific variables (e.g., force, arc length, power output) were not measured. Future research should integrate specialized instrumentation and broader boat class coverage to establish normative values of IVV and related metrics, enhancing their application in training and performance monitoring.

From a statistical perspective, the relatively small and unbalanced sample sizes across certain subgroups may have reduced statistical power and limited the detection of interaction effects. Future research should use more advanced statistical models and analysis methods to better capture the structure of the data, improve the understanding of technical efficiency, and provide deeper insights into race strategies. In addition, functional or intra-cycle analyses (e.g., SPM, FDA) would allow a more detailed characterization of how IVV and velocity evolve throughout the cycle and across the 2000 m.

Chapter 5 Conclusions

Considering the findings across the experimental studies presented in this dissertation, it is concluded the following:

I. IVV and CVV variables provide meaningful insights into the biomechanics of rowing, with differences emerging between male and female rowers.

II. Male rowers exhibited greater IVV and CVV possibly due to their ability to generate higher peak forces, while females distributed force more evenly, resulting in steadier boat velocity.

III. Cycle rate showed a strong association with mean velocity in men but not in women, reflecting sex specificity in some technical variables.

IV. These differences highlight the need for training approaches tailored to sex-specific physiological and biomechanical characteristics.

V. Sculling boats achieved higher average velocities, greater technical efficiency and lower IVV compared with sweep boats, likely due to symmetrical propulsion of two oars per rower and reduced lateral asymmetries.

VI. Long boats demonstrated superior performance metrics (maximum, average and minimum velocities, technical index and distance per cycle) and lower IVV compared with short boats, owing to hydrodynamic and biomechanical advantages such as longer hulls and the greater propulsive force from more rowers.

VII. These advantages applied consistently across sexes, as no significant interaction effects were observed between sex and boat discipline or size.

VIII. Velocity profiles across the 2000 m revealed an early increase in velocity followed by a progressive decline across all boat classes.

IX. Sculling and long boats sustained higher velocities and more stable IVV throughout the race compared with sweep and short boats.

X. Cycle rate declined across the race, reflecting fatigue, while IVV remained stable, suggesting that this variable may be less sensitive to fatigue under competition conditions.

The findings emphasize the role of IVV as an indicator of technical efficiency and its associations with commonly used biomechanical variables in rowing. This body of work underscores the importance of integrating IVV monitoring with other biomechanical variables to optimize performance.

Chapter 6 Recommendations for future research

The current dissertation has examined how IVV interfered with some of the most common biomechanical variables in rowing during 2000 m competitions, across sexes and boat classes. Based on our findings, it would be important to continue researching in this topic particularly focusing on:

I. The integration of specialized instrumentation to measure direct outputs (e.g. power, arc length and force curves) which would provide a more complete biomechanical profile.
II. Including under-represented boat classes and balance subgroup sizes.
III. Adopting advanced statistical approaches should be adopted to better capture the effects of intra-cycle nature of rowing data.
IV. Developing normative values for IVV and related metrics across sexes and boat classes will strengthen their practical application in coaching and performance monitoring.

Chapter 7 References

Attenborough, A. S., Smith, R. M., & Sinclair, P. J. (2012). Effect of gender and stroke rate on joint power characteristics of the upper extremity during simulated rowing. Journal of Sports Sciences, 30, 449 - 458.

Barrett, R. S., & Manning, J. M. (2004). Relationships between rigging set-up, anthropometry, physical capacity, rowing kinematics and rowing performance. Sports Biomechanics, 3(2), 221-235. https://doi.org/10.1080/14763140408522842

Baudouin, A., & Hawkins, D. (2002). A biomechanical review of factors affecting rowing performance [Review]. British Journal of Sports Medicine, 36(6), 396-402. https://doi.org/10.1136/bjsm.36.6.396

Boucher, J.-P., Labbé, R., Clanet, C., & Benzaquen, M. (2018). Thin or bulky: Optimal aspect ratios for ship hulls. Physical Review Fluids, 3(7), 074802. https://doi.org/10.1103/PhysRevFluids.3.074802

Caplan, N., & Gardner, T. N. (2007). Optimization of oar blade design for improved performance in rowing [Article]. Journal of Sports Sciences, 25(13), 1471-1478. https://doi.org/10.1080/02640410701203468

Cardoso, Fonseca, P., Goethel, M., Abraldes, J. A., Gomes, B. B., Vilas-Boas, J. P., & Fernandes, R. J. (2022). Effect of Randall foils on the rowing propulsive cycle. Sports Biomechanics, 1-10. https://doi.org/10.1080/14763141.2023.2298968

Cardoso, Rios, M., Carvalho, D. D., Monteiro, A. S., Soares, S., Arturo Abraldes, J., Gomes, B. B., Vilas Boas, J. P., & Fernandes, R. J. (2022). Mechanics and energetic analysis of rowing with Big blades with Randall foils. International Journal of Sports Medicine. https://doi.org/10.1055/a-1990-9787

Cardoso, R., Carvalho, D. D., Morris, K., Abraldes, J. A., & Fernandes, R. J. (2021). Anthropometry of rowing: An update. In New Studies on

Anthropometry (pp. 93-106). https://www.scopus.com/inward/record.uri?eid=2-s2.0-85110382388&partnerID=40&md5=98dd8e7400d59215587e6fa1ecf1413c

Cardoso, R., Rios, M., Cardoso, F., Bouicher, S., Abraldes, J. A., Gomes, B., Vilas-Boas, J. P., & Fernandes, R. (2025). Randall Foils Versus Big Blades: Comparative Analysis in On-Water Sprint Rowing. International Journal of Sports Physiology and Performance. https://doi.org/10.1123/ijspp.2024-0515

Cardoso, R., Rios, M., Fonseca, P., Leão, J., Cardoso, F., Abraldes, J. A., Gomes, B., Vilas-Boas, J. P., & Fernandes, R. (2024). Assessment of Angular and Straight Linear Rowing Ergometers at Different Intensities of Exercise. Sensors, 24, 5686. https://doi.org/10.3390/s24175686

Costill, D., Kovaleski, J., Porter, D., Kirwan, J., Fielding, R., & King, D. (1985). Energy Expenditure During Front Crawl Swimming: Predicting Success in Middle-Distance Events. International Journal of Sports Medicine, 6, 266-270. https://doi.org/10.1055/s-2008-1025849

Cuijpers, L. S., Zaal, F. T., & de Poel, H. J. (2015). Rowing Crew Coordination Dynamics at Increasing Stroke Rates. 10(7), e0133527. https://doi.org/10.1371/journal.pone.0133527

Day, A., Campbell, I., Clelland, D., Doctors, L. J., & Cichowicz, J. (2011). Realistic evaluation of hull performance for rowing shells, canoes, and kayaks in unsteady flow. Journal of Sports Sciences, 29(10), 1059-1069. https://doi.org/10.1080/02640414.2011.576691

Ettema, G., Haug, A., Ludvigsen, T. P., & Danielsen, J. (2022). The role of stroke rate and intensity on rowing technique. Sports biomechanics. https://doi.org/10.1080/14763141.2022.2135457

Fernandes, A., Afonso, J., Noronha, F., Mezêncio, B., Vilas-Boas, J. P., & Fernandes, R. J. (2023). Intracycle Velocity Variation in Swimming: A

Systematic Scoping Review. Bioengineering, 10(3), 308. https://www.mdpi.com/2306-5354/10/3/308

Fernandes, R., Oliveira, E., & Colaço, P. (2013). Bioenergetical assessment and training control as useful tools to improve performance in cyclic sports. Sports Medicine and Training Tools, 61-88.

Fernandes, R. A., Alacid, F., Gomes, A. B., & Gomes, B. B. (2021). Validation of a global positioning system with accelerometer for canoe/kayak sprint kinematic analysis. Sports biomechanics, 1-12. https://doi.org/10.1080/14763141.2021.2005128

Figueiredo, P., Kjendlie, P. L., Vilas-Boas, J. P., & Fernandes, R. J. (2012). Intracycle velocity variation of the body centre of mass in front crawl [Article]. International Journal of Sports Medicine, 33(4), 285-290. https://doi.org/10.1055/s-0031-1301323

Garland, S. W. (2005). An analysis of the pacing strategy adopted by elite competitors in 2000 m rowing. British Journal of Sports Medicine, 39(1), 39-42. https://doi.org/10.1136/bjsm.2003.010801

Hill, H., & Fahrig, S. D. (2009). The impact of fluctuations in boat velocity during the rowing cycle on race time. Scandinavian Journal of Medicine & Science in Sports, Aug;19(4):585-94. doi: 10.1111/j.1600-0838.2008.00819.x

Hopkins, W. G., Marshall, S. W., Batterham, A. M., & Hanin, J. (2009). Progressive Statistics for Studies in Sports Medicine and Exercise Science. Medicine & Science in Sports & Exercise, 41(1), 3-12. https://doi.org/10.1249/MSS.0b013e31818cb278

Ingham, S. A., Whyte, G. P., Jones, K., & Nevill, A. M. (2002). Determinants of 2,000 m rowing ergometer performance in elite rowers. European Journal of Applied Physiology, 88(3), 243-246. https://doi.org/10.1007/s00421-002-0699-9

Kleshnev, V. (1998). Estimation of biomechanical parameters and propulsive efficiency of rowing. Australian Institute of Sport, 1-17.

Kleshnev, V. (1999). Propulsive efficiency of rowing. Proceedings of the XVII International Symposium on Biomechanics in Sports, 224-228.

Kleshnev, V. (2010). Boat acceleration, temporal structure of the stroke cycle, and effectiveness in rowing. Proceedings of the Institution of Mechanical Engineers Part P-Journal of Sports Engineering and Technology, 224(P1), 63-74. https://doi.org/10.1243/17543371jset40

Kleshnev, V. (2016). The Biomechanics of Rowing. Crowood Press. https://books.google.pt/books?id=wnc9jwEACAAJ

Leão, J., Cardoso, R., Abraldes, J. A., Soares, S., Gomes, B. B., & Fernandes, R. J. (2025). Intracycle Velocity Variation During a Single-Sculling 2000 m Rowing Competition. Sensors, 25(15), 4696.

Legge, N., Draper, C., Slattery, K., O'Meara, D., & Watsford, M. (2024). On-water Rowing Biomechanical Assessment: A Systematic Scoping Review. Sports Medicine - Open, 10(1), 101. https://doi.org/10.1186/s40798-024-00760-2

Legge, N., Slattery, K., O'Meara, D., McCleave, E., Young, D., Crichton, S., & Watsford, M. (2024). Physical and technical attributes associated with on-water rowing performance in junior and elite rowers. Journal of Sports Sciences, 1-11. https://doi.org/10.1080/02640414.2024.2408521

Lin, W. (2019). Biomechanical comparative analysis on the body segments velocity of Elite rowers with different stroke rate in men's lightweight pair and ITS parameters of results. Acta Medica Mediterranea, 35(1), 175-185. https://doi.org/10.19193/0393-6384_2019_1_28

Mäestu, J., Jürimäe, J., & Jürimäe, T. (2005). Monitoring of performance and training in rowing. Sports Medicine, 35(7), 597-617. https://doi.org/10.2165/00007256-200535070-00005

Mattes, K., Schaffert, N., Manzer, S., & Böhmert, W. (2015). Non-oarside-arm pull to increase the propulsion in sweep-oar rowing [Article]. International Journal of Performance Analysis in Sport, 15(3), 1124-1134. https://doi.org/10.1080/24748668.2015.11868856

McDonnell, K. L., Hume, A. P., & Nolte, V. (2013). Place time consistency and stroke rates required for success in K1 200-m sprint kayaking elite competition. International Journal of Performance Analysis in Sport, 13(1), 38-50. https://doi.org/10.1080/24748668.2013.11868630

McGregor, A. H., Patankar, Z. S., & Bull, A. M. J. (2008). Do men and women row differently? a spinal kinematic and force perspective. Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology, 222(2), 77-83. https://doi.org/10.1243/17543371JSET22

Mentzoni, F., & Losnegard, T. (2021). World and European Rowing Medallists Pace with Smaller Variation Than Their Competitors. Frontiers in Sports and Active Living, 3. https://doi.org/10.3389/fspor.2021.790198

Michael, J. S., Smith, R., & Rooney, K. B. (2009). Determinants of kayak paddling performance. Sports Biomechanics, 2009 Jun;8(2):167-79. doi: 10.1080/14763140902745019. PMID: 19705767.

Morais, J. E., Marinho, D. A., Oliveira, J. P., Sampaio, T., Lopes, T., & Barbosa, T. M. (2022). Using Statistical Parametric Mapping to Compare the Propulsion of Age-Group Swimmers in Front Crawl Acquired with the Aquanex System. Sensors, 22(21), 8549. https://www.mdpi.com/1424-8220/22/21/8549

Mpimis, T., Gikas, V., & Gourgoulis, V. (2023). A Rigorous and Integrated On-Water Monitoring System for Performance and Technique Improvement in Rowing. Sensors, 23(13), Article 6150. https://doi.org/10.3390/s23136150

Ng, L., Campbell, A., Burnett, A., & O'Sullivan, P. (2013). Gender Differences in Trunk and Pelvic Kinematics During Prolonged Ergometer Rowing in Adolescents. Journal of Applied Biomechanics, 29(2), 180-187. https://doi.org/10.1123/jab.29.2.180

Nolte, V. (2005). Rowing Faster. Human Kinetics. https://books.google.ch/books?id=-wmLeDL0MbAC

Olbrecht, J. (2000). The science of winning: planning, periodizing and optimizing swim training. Samozal. https://books.google.pt/books?id=11bttQEACAAJ

Podstawski, R., Borysławski, K., Katona, Z. B., Alföldi, Z., Boraczyński, M., Jaszczur-Nowicki, J., & Gronek, P. (2022). Sex Differences in Anthropometric and Physiological Profiles of Hungarian Rowers of Different Ages [Article]. International Journal of Environmental Research and Public Health, 19(13), Article 8115. https://doi.org/10.3390/ijerph19138115

Pulman, C. (2004). The Physics of Rowing. Gonville & Caius College, University of Cambridge

Rios, M., Cardoso, R., Monteiro, A. S., Vilas-Boas, J. P., & Fernandes, R. J. (2025). Physiological Demands Across Exercise Intensity Domains in Rowing: Implications of Weight Category and Sex Differences. Sports (Basel), 13(8). https://doi.org/10.3390/sports13080245

Romagnoli, C., Bonaiuto, V., Padua, E., & Annino, G. (2025). Editorial: Assessment and monitoring of human movement [Editorial]. Frontiers in Physiology, Volume 16 - 2025. https://doi.org/10.3389/fphys.2025.1686977

Sánchez, J. A., & Arellano, R. (2002). Stroke index values according to level, gender, swimming style and event race distance. XXth International Symposium on Biomechanics in Sports, Cáceres (Spain).

Secher, N. H. (1993). Physiological and Biomechanical Aspects of Rowing: Implications for Training [Article]. Sports Medicine: An International Journal of Applied Medicine and Science in Sport and Exercise, 15(1), 24-42. https://doi.org/10.2165/00007256-199315010-00004

Seifert, L., Lardy, J., Bourbousson, J., Adé, D., Nordez, A., Thouvarecq, R., & Saury, J. (2017). Interpersonal Coordination and Individual Organization Combined with Shared Phenomenological Experience in Rowing Performance: Two Case Studies. Frontiers in Psychology, 8. https://doi.org/10.3389/fpsyg.2017.00075

Smith, R. M., & Loschner, C. (2002). Biomechanics feedback for rowing [Article]. Journal of Sports Sciences, 20(10), 783-791. https://doi.org/10.1080/026404102320675639

Smith, R. M., & Spinks, W. L. (1995). Discriminant analysis of biomechanical differences between novice, good and elite rowers. Journal of Sports Sciences, 13(5), 377-385. https://doi.org/10.1080/02640419508732253

Smith, T. B., & Hopkins, W. G. (2012). Measures of Rowing Performance. Sports Medicine, 42(4), 343-358. https://doi.org/10.2165/11597230-000000000-00000

Soper, C., & Hume, P. A. (2004a). Rowing: Reliability of power output during Rowing changes with Ergometer type and race distance. Sports biomechanics, 3(2), 237-248. https://doi.org/10.1080/14763140408522843

Soper, C., & Hume, P. A. (2004b). Towards an ideal rowing technique for performance - The contributions from biomechanics. Sports Medicine, 34(12), 825-848. https://doi.org/10.2165/00007256-200434120-00003

Sousa, A., Ribeiro, J., Sousa, M., Vilas-Boas, J. P., & Fernandes, R. J. (2014). Influence of prior exercise on VO2 kinetics subsequent exhaustive rowing performance. PLoS ONE, 9(1), e84208. https://doi.org/10.1371/journal.pone.0084208

Sperlich, J., & Baker, J. (2002). Biomechanical Testing in Elite Canoeing. ISBS 2002, Caceres - Extremadura - Spain.

Vaquero-Cristóbal, R., Alacid, F., López-Plaza, D., Muyor, J. M., & López-Miñarro, P. A. (2013). Kinematic Variables Evolution During a 200-m Maximum Test in Young Paddlers. J Hum Kinet, 38, 15-22. https://doi.org/10.2478/hukin-2013-0041

Warden, S. J., Gutschlag, F. R., Wajswelner, H., & Crossley, K. M. (2002). Aetiology of rib stress fractures in rowers. Sports Medicine, 32(13), 819-836. https://doi.org/10.2165/00007256-200232130-00002

Warmenhoven, J., Cobley, S., Draper, C., Harrison, A., Bargary, N., & Smith, R. (2018). How gender and boat-side affect shape characteristics of force-angle profiles in single sculling: Insights from functional data analysis. Journal of Science and Medicine in Sport, 21(5), 533-537. https://doi.org/10.1016/j.jsams.2017.08.010

Warmenhoven, J., Cobley, S., Draper, C., & Smith, R. (2018). Over 50 Years of Researching Force Profiles in Rowing: What Do We Know? [Review]. Sports Medicine, 48(12), 2703-2714. https://doi.org/10.1007/s40279-018-0992-3

Warmenhoven, J., Harrison, A., Robinson, M. A., Vanrenterghem, J., Bargary, N., Smith, R., Cobley, S., Draper, C., Donnelly, C., & Pataky, T. (2018). A force profile analysis comparison between functional data analysis, statistical parametric mapping and statistical non-parametric mapping in on-water single sculling. Journal of Science and Medicine in Sport, 21(10), 1100-1105. https://doi.org/10.1016/j.jsams.2018.03.009

Warmenhoven, J., Smith, R., Draper, C., Harrison, A. J., Bargary, N., & Cobley, S. (2018). Force coordination strategies in on-water single sculling: Are asymmetries related to better rowing performance? Scandinavian Journal of Medicine and Science in Sports, 28(4), 1379-1388. https://doi.org/10.1111/sms.13031

Wilmore, J. H., Costill, D. L., & Kenney, W. L. (2008). Physiology of Sport and Exercise. Human Kinetics. https://books.google.pt/books?id=zQGKmbg18J8C

Yusof, A. M., Harun, M. N., Nasruddin, F. A., & Syahrom, A. (2022). Rowing Biomechanics, Physiology and Hydrodynamic: A Systematic Review. International Journal of Sports Medicine, 43(07), 577-585. https://doi.org/10.1055/a-1231-5268

References

Attenborough, A. S., Smith, R. M., & Sinclair, P. J. (2012). Effect of gender and stroke rate on joint power characteristics of the upper extremity during simulated rowing. *Journal of Sports Sciences*, *30*, 449 - 458.

Barrett, R. S., & Manning, J. M. (2004). Relationships between rigging set-up, anthropometry, physical capacity, rowing kinematics and rowing performance. *Sports Biomech*, *3*(2), 221-235. https://doi.org/10.1080/14763140408522842

Baudouin, A., & Hawkins, D. (2002). A biomechanical review of factors affecting rowing performance [Review]. *British Journal of Sports Medicine*, *36*(6), 396-402. https://doi.org/10.1136/bjsm.36.6.396

Boucher, J.-P., Labbé, R., Clanet, C., & Benzaquen, M. (2018). Thin or bulky: Optimal aspect ratios for ship hulls. *Physical Review Fluids*, *3*(7), 074802. https://doi.org/10.1103/PhysRevFluids.3.074802

Caplan, N., & Gardner, T. N. (2007). Optimization of oar blade design for improved performance in rowing [Article]. *Journal of Sports Sciences*, *25*(13), 1471-1478. https://doi.org/10.1080/02640410701203468

Cardoso, Fonseca, P., Goethel, M., Abraldes, J. A., Gomes, B. B., Vilas-Boas, J. P., & Fernandes, R. J. (2022). Effect of Randall foils on the rowing propulsive cycle. *Sports biomechanics*, 1-10. https://doi.org/10.1080/14763141.2023.2298968

Cardoso, Rios, M., Carvalho, D. D., Monteiro, A. S., Soares, S., Arturo Abraldes, J., Gomes, B. B., Vilas Boas, J. P., & Fernandes, R. J. (2022). Mechanics and energetic analysis of rowing with Big blades with Randall foils [Article]. *International Journal of Sports Medicine*. https://doi.org/10.1055/a-1990-9787

Cardoso, R., Carvalho, D. D., Morris, K., Abraldes, J. A., & Fernandes, R. J. (2021). Anthropometry of rowing: An update. In *New Studies on Anthropometry* (pp. 93-106). https://www.scopus.com/inward/record.uri?eid=2-s2.0-85110382388&partnerID=40&md5=98dd8e7400d59215587e6fa1ecf1413c

Cardoso, R., Rios, M., Cardoso, F., Bouicher, S., Abraldes, J. A., Gomes, B., Vilas-Boas, J. P., & Fernandes, R. (2025). Randall Foils Versus Big Blades: Comparative Analysis in On-Water Sprint Rowing. *International Journal of Sports Physiology and Performance*. https://doi.org/10.1123/ijspp.2024-0515

Cardoso, R., Rios, M., Fonseca, P., Leão, J., Cardoso, F., Abraldes, J. A., Gomes, B., Vilas-Boas, J. P., & Fernandes, R. (2024). Assessment of Angular and Straight Linear Rowing Ergometers at Different Intensities of Exercise. *Sensors*, *24*, 5686. https://doi.org/10.3390/s24175686

Costill, D., Kovaleski, J., Porter, D., Kirwan, J., Fielding, R., & King, D. (1985). Energy Expenditure During Front Crawl Swimming: Predicting Success in

Middle-Distance Events. *International Journal of Sports Medicine*, *6*, 266-270. https://doi.org/10.1055/s-2008-1025849

Cuijpers, L. S., Zaal, F. T., & de Poel, H. J. (2015). Rowing Crew Coordination Dynamics at Increasing Stroke Rates. *PLoS ONE*, *10*(7), e0133527. https://doi.org/10.1371/journal.pone.0133527

Day, A., Campbell, I., Clelland, D., Doctors, L. J., & Cichowicz, J. (2011). Realistic evaluation of hull performance for rowing shells, canoes, and kayaks in unsteady flow. *Journal of Sports Sciences*, *29*(10), 1059-1069. https://doi.org/10.1080/02640414.2011.576691

Ettema, G., Haug, A., Ludvigsen, T. P., & Danielsen, J. (2022). The role of stroke rate and intensity on rowing technique [Article]. *Sports biomechanics*. https://doi.org/10.1080/14763141.2022.2135457

Fernandes, A., Afonso, J., Noronha, F., Mezêncio, B., Vilas-Boas, J. P., & Fernandes, R. J. (2023). Intracycle Velocity Variation in Swimming: A Systematic Scoping Review. *Bioengineering*, *10*(3), 308. https://www.mdpi.com/2306-5354/10/3/308

Fernandes, R., Oliveira, E., & Colaço, P. (2013). Bioenergetical assessment and training control as useful tools to improve performance in cyclic sports. *Sports Medicine and Training Tools*, 61-88.

Fernandes, R. A., Alacid, F., Gomes, A. B., & Gomes, B. B. (2021). Validation of a global positioning system with accelerometer for canoe/kayak sprint kinematic analysis. *Sports biomechanics*, 1-12. https://doi.org/10.1080/14763141.2021.2005128

Figueiredo, P., Kjendlie, P. L., Vilas-Boas, J. P., & Fernandes, R. J. (2012). Intracycle velocity variation of the body centre of mass in front crawl [Article]. *International Journal of Sports Medicine*, *33*(4), 285-290. https://doi.org/10.1055/s-0031-1301323

Garland, S. W. (2005). An analysis of the pacing strategy adopted by elite competitors in 2000 m rowing. *British Journal of Sports Medicine*, *39*(1), 39-42. https://doi.org/10.1136/bjsm.2003.010801

Hill, H., & Fahrig, S. D. (2009). The impact of fluctuations in boat velocity during the rowing cycle on race time. *Scandinavian Journal of Medicine & Science in Sports*, *19*.

Hopkins, W. G., Marshall, S. W., Batterham, A. M., & Hanin, J. (2009). Progressive Statistics for Studies in Sports Medicine and Exercise Science. *Medicine & Science in Sports & Exercise*, *41*(1), 3-12. https://doi.org/10.1249/MSS.0b013e31818cb278

Ingham, S. A., Whyte, G. P., Jones, K., & Nevill, A. M. (2002). Determinants of 2,000 m rowing ergometer performance in elite rowers [Article]. *European Journal of Applied Physiology*, *88*(3), 243-246. https://doi.org/10.1007/s00421-002-0699-9

Kleshnev, V. (1998). Estimation of biomechanical parameters and propulsive efficiency of rowing. *Australian Institute of Sport*, 1-17.

Kleshnev, V. (1999). Propulsive efficiency of rowing. *Proceedings of the XVII International Symposium on Biomechanics in Sports*, 224-228.

Kleshnev, V. (2010). Boat acceleration, temporal structure of the stroke cycle, and effectiveness in rowing. *Proceedings of the Institution of Mechanical Engineers Part P-Journal of Sports Engineering and Technology*, *224*(P1), 63-74. https://doi.org/10.1243/17543371jset40

Kleshnev, V. (2016). *The Biomechanics of Rowing*. Crowood Press. https://books.google.pt/books?id=wnc9jwEACAAJ

Leão, J., Cardoso, R., Abraldes, J. A., Soares, S., Gomes, B. B., & Fernandes, R. J. (2025). Intracycle Velocity Variation During a Single-Sculling 2000 m Rowing Competition. *Sensors*, *25*(15), 4696.

Legge, N., Draper, C., Slattery, K., O'Meara, D., & Watsford, M. (2024). On-water Rowing Biomechanical Assessment: A Systematic Scoping Review. *Sports Medicine - Open*, *10*(1), 101. https://doi.org/10.1186/s40798-024-00760-2

Legge, N., Slattery, K., O'Meara, D., McCleave, E., Young, D., Crichton, S., & Watsford, M. (2024). Physical and technical attributes associated with on-water rowing performance in junior and elite rowers. *Journal of Sports Sciences*, 1-11. https://doi.org/10.1080/02640414.2024.2408521

Lin, W. (2019). Biomechanical comparative analysis on the body segments velocity of Elite rowers with different stroke rate in men's lightweight pair and ITS parameters of results [Article]. *Acta Medica Mediterranea*, *35*(1), 175-185. https://doi.org/10.19193/0393-6384_2019_1_28

Mäestu, J., Jürimäe, J., & Jürimäe, T. (2005). Monitoring of performance and training in rowing [Review]. *Sports Medicine*, *35*(7), 597-617. https://doi.org/10.2165/00007256-200535070-00005

Mattes, K., Schaffert, N., Manzer, S., & Böhmert, W. (2015). Non-oarside-arm pull to increase the propulsion in sweep-oar rowing [Article]. *International Journal of Performance Analysis in Sport*, *15*(3), 1124-1134. https://doi.org/10.1080/24748668.2015.11868856

McDonnell, K. L., Hume, A. P., & Nolte, V. (2013). Place time consistency and stroke rates required for success in K1 200-m sprint kayaking elite competition. *International Journal of Performance Analysis in Sport*, *13*(1), 38-50. https://doi.org/10.1080/24748668.2013.11868630

McGregor, A. H., Patankar, Z. S., & Bull, A. M. J. (2008). Do men and women row differently? a spinal kinematic and force perspective. *Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology*, *222*(2), 77-83. https://doi.org/10.1243/17543371JSET22

Mentzoni, F., & Losnegard, T. (2021). World and European Rowing Medallists Pace With Smaller Variation Than Their Competitors [Original Research]. *Frontiers in Sports and Active Living*, *3*. https://doi.org/10.3389/fspor.2021.790198

Michael, J. S., Smith, R., & Rooney, K. B. (2009). Determinants of kayak paddling performance. *Sports biomechanics*, *8*, 167 - 179.

Morais, J. E., Marinho, D. A., Oliveira, J. P., Sampaio, T., Lopes, T., & Barbosa, T. M. (2022). Using Statistical Parametric Mapping to Compare the Propulsion of Age-Group Swimmers in Front Crawl Acquired with the Aquanex System. *Sensors*, *22*(21), 8549. https://www.mdpi.com/1424-8220/22/21/8549

Mpimis, T., Gikas, V., & Gourgoulis, V. (2023). A Rigorous and Integrated On-Water Monitoring System for Performance and Technique Improvement in Rowing [Article]. *Sensors*, *23*(13), Article 6150. https://doi.org/10.3390/s23136150

Ng, L., Campbell, A., Burnett, A., & O'Sullivan, P. (2013). Gender Differences in Trunk and Pelvic Kinematics During Prolonged Ergometer Rowing in Adolescents. *Journal of Applied Biomechanics*, *29*(2), 180-187. https://doi.org/10.1123/jab.29.2.180

Nolte, V. (2005). *Rowing Faster*. Human Kinetics. https://books.google.ch/books?id=-wmLeDL0MbAC

Olbrecht, J. (2000). *The science of winning: planning, periodizing and optimizing swim training*. samozal. https://books.google.pt/books?id=11bttQEACAAJ

Podstawski, R., Borysławski, K., Katona, Z. B., Alföldi, Z., Boraczyński, M., Jaszczur-Nowicki, J., & Gronek, P. (2022). Sex Differences in Anthropometric and Physiological Profiles of Hungarian Rowers of Different Ages [Article]. *International Journal of Environmental Research and Public Health*, *19*(13), Article 8115. https://doi.org/10.3390/ijerph19138115

Pulman, C. (2004). The Physics of Rowing.

Rios, M., Cardoso, R., Monteiro, A. S., Vilas-Boas, J. P., & Fernandes, R. J. (2025). Physiological Demands Across Exercise Intensity Domains in Rowing: Implications of Weight Category and Sex Differences. *Sports (Basel)*, *13*(8). https://doi.org/10.3390/sports13080245

Romagnoli, C., Bonaiuto, V., Padua, E., & Annino, G. (2025). Editorial: Assessment and monitoring of human movement [Editorial]. *Frontiers in Physiology*, *Volume 16 - 2025*. https://doi.org/10.3389/fphys.2025.1686977

Sánchez, J. A., & Arellano, R. (2002). Stroke index values according to level, gender, swimming style and event race distance. XXth International Symposium on Biomechanics in Sports,, Cáceres (Spain).

Secher, N. H. (1993). Physiological and Biomechanical Aspects of Rowing: Implications for Training [Article]. *Sports Medicine: An International Journal of Applied Medicine and Science in Sport and Exercise*, *15*(1), 24-42. https://doi.org/10.2165/00007256-199315010-00004

Seifert, L., Lardy, J., Bourbousson, J., Adé, D., Nordez, A., Thouvarecq, R., & Saury, J. (2017). Interpersonal Coordination and Individual Organization

Combined with Shared Phenomenological Experience in Rowing Performance: Two Case Studies [Original Research]. *Frontiers in Psychology*, *8*. https://doi.org/10.3389/fpsyg.2017.00075

Smith, R. M., & Loschner, C. (2002). Biomechanics feedback for rowing [Article]. *Journal of Sports Sciences*, *20*(10), 783-791. https://doi.org/10.1080/026404102320675639

Smith, R. M., & Spinks, W. L. (1995). Discriminant analysis of biomechanical differences between novice, good and elite rowers. *Journal of Sports Sciences*, *13*(5), 377-385. https://doi.org/10.1080/02640419508732253

Smith, T. B., & Hopkins, W. G. (2012). Measures of Rowing Performance. *Sports Medicine*, *42*(4), 343-358. https://doi.org/10.2165/11597230-000000000-00000

Soper, C., & Hume, P. A. (2004a). Rowing: Reliability of power output during Rowing changes with Ergometer type and race distance [Article]. *Sports biomechanics*, *3*(2), 237-248. https://doi.org/10.1080/14763140408522843

Soper, C., & Hume, P. A. (2004b). Towards an ideal rowing technique for performance - The contributions from biomechanics. *Sports Medicine*, *34*(12), 825-848. https://doi.org/10.2165/00007256-200434120-00003

Sousa, A., Ribeiro, J., Sousa, M., Vilas-Boas, J. P., & Fernandes, R. J. (2014). Influence of prior exercise on VO2 kinetics subsequent exhaustive rowing performance. *PLoS ONE*, *9*(1), e84208. https://doi.org/10.1371/journal.pone.0084208

Sperlich, J., & Baker, J. (2002). Biomechanical Testing in Elite Canoeing. ISBS 2002, Caceres - Extremadura - Spain.

Vaquero-Cristóbal, R., Alacid, F., López-Plaza, D., Muyor, J. M., & López-Miñarro, P. A. (2013). Kinematic Variables Evolution During a 200-m Maximum Test in Young Paddlers. *J Hum Kinet*, *38*, 15-22. https://doi.org/10.2478/hukin-2013-0041

Warden, S. J., Gutschlag, F. R., Wajswelner, H., & Crossley, K. M. (2002). Aetiology of rib stress fractures in rowers. *Sports Med*, *32*(13), 819-836. https://doi.org/10.2165/00007256-200232130-00002

Warmenhoven, J., Cobley, S., Draper, C., Harrison, A., Bargary, N., & Smith, R. (2018). How gender and boat-side affect shape characteristics of force-angle profiles in single sculling: Insights from functional data analysis. *Journal of Science and Medicine in Sport*, *21*(5), 533-537. https://doi.org/10.1016/j.jsams.2017.08.010

Warmenhoven, J., Cobley, S., Draper, C., & Smith, R. (2018). Over 50 Years of Researching Force Profiles in Rowing: What Do We Know? [Review]. *Sports Medicine*, *48*(12), 2703-2714. https://doi.org/10.1007/s40279-018-0992-3

Warmenhoven, J., Harrison, A., Robinson, M. A., Vanrenterghem, J., Bargary, N., Smith, R., Cobley, S., Draper, C., Donnelly, C., & Pataky, T. (2018). A

force profile analysis comparison between functional data analysis, statistical parametric mapping and statistical non-parametric mapping in on-water single sculling [Review]. *Journal of Science and Medicine in Sport*, *21*(10), 1100-1105. https://doi.org/10.1016/j.jsams.2018.03.009

Warmenhoven, J., Smith, R., Draper, C., Harrison, A. J., Bargary, N., & Cobley, S. (2018). Force coordination strategies in on-water single sculling: Are asymmetries related to better rowing performance? [Article]. *Scandinavian Journal of Medicine and Science in Sports*, *28*(4), 1379-1388. https://doi.org/10.1111/sms.13031

Wilmore, J. H., Costill, D. L., & Kenney, W. L. (2008). *Physiology of Sport and Exercise*. Human Kinetics. https://books.google.pt/books?id=zQGKmbg18J8C

Yusof, A. M., Harun, M. N., Nasruddin, F. A., & Syahrom, A. (2022). Rowing Biomechanics, Physiology and Hydrodynamic: A Systematic Review. *International Journal of Sports Medicine*, *43*(07), 577-585. https://doi.org/10.1055/a-1231-5268