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Swimming evaluation and training control: contributions of biomechanical analysis and multidimensional determinants of front crawl performance

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List of abbreviations and symbols

ANOVA	Analysis of variance
AVI	Audio Video Interleave
B	Unstandardised regression coefficient
bpm	Beats per minute
C	Energy cost
Cd	Drag coefficient
CEFADE	Ethics Committee of the Faculty of Sport, University of Porto
CI	Confidence interval
cm	centimetre
CMJ	Countermovement jump
CO_2	Carbon dioxide
CP	Phosphocreatine
dv	Intra-cyclic variation of the horizontal velocity of the centre of mass
$\dot{E}tot$	Total energy expenditure
EMG	Electromyography
F	F statistic; Female
Fp	Propulsive force
g	Gravitational acceleration
h	Hour; jump height in the countermovement jump equation
HR	Heart rate
IdC	Index of Coordination
kg	Kilogram
L	Litre
LABIOMEP	Porto Biomechanics Laboratory
$[La^-]$	Blood lactate
m	Metre
M	Male
ma	Added water mass
min	Minute

mL	Millilitre
$mmol \cdot L^{-1}$	Millimoles per litre
O_2	Oxygen
p	p-value
R^2	Coefficient of determination
s	seconds
S	Body surface area
SD	Standard deviation
SEE	Standard error of the estimate
SF	Stroke frequency
SI	Stroke index
SL	Stroke length
SPSS	Statistical Package for the Social Sciences
t	Flight time
TTG	Total time gap
v	Mean swimming velocity
vlimbs	limb velocity
$\dot{V}O_2$	Oxygen uptake
VO_2peak	Peak oxygen uptake
x_i	Individual value
z_i	Standardised z-score
β	Standardised regression coefficient
ηp	Propelling efficiency
ηp^2	Partial eta squared
ρ	Spearman's rank correlation coefficient
μ	Sample mean

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Abstract

Swimming performance is determined by the interaction of biomechanical, mechanical, physiological and training-related factors, making evaluation and training control essential for evidence-based coaching. This dissertation aimed to contribute to swimming evaluation and training control by examining the usefulness and limitations of different assessment tools in competitive front crawl swimmers. Two experimental studies and one complementary appendix were conducted. The first study compared the kinematic organisation of maximal front crawl between full-tethered swimming and free-swimming in 28 competitive swimmers. Swimmers performed a 30 s maximal full-tethered test and a 25 m maximal free-swimming trial, while cycle duration, index of coordination, index of synchronization, upper-limb phase distribution and lower-limb action timing were analysed. Full-tethered swimming showed longer cycle duration, a less negative index of coordination and marked changes in upper-limb phase distribution, indicating that this condition does not fully reproduce the kinematic structure of maximal free-swimming. The complementary appendix analysed the relationship between force-related variables obtained during tethered swimming and free-swimming velocity, showing that tethered swimming may provide useful information about aquatic force production, although its interpretation should consider sex and task-specific constraints. The second study examined how applied field-based tests, training-related variables and physiological responses were associated with 400 m front crawl performance in 28 young competitive swimmers using a sex-specific approach. Male swimmers were faster in the 400 m test and presented higher handgrip strength, muscular resistance index, jump height and VO_2peak than females. In males, performance time was associated with body mass index, training practice and left handgrip strength. The regression model explained 73.1% of performance variance, with training practice remaining the only significant independent predictor. In females, performance time was associated with age, dry-land training volume, bilateral handgrip strength, muscular resistance index, jump height and blood lactate concentration. The regression model explained 87.0% of variance, but no individual variable remained significant after adjustment. Overall, the findings of this dissertation indicate that swimming evaluation should be multidimensional, sex-specific and context-sensitive. Full-tethered swimming can be useful for monitoring force production, but should not be interpreted as a direct technical equivalent of free-swimming. Field-based assessments and 400 m testing provide relevant information about swimmer status, but their interpretation should integrate training history, neuromuscular capacity, physiological response and task-specific constraints to support more individualised training control.

Resumo

O desempenho em natação resulta da interação entre fatores biomecânicos, mecânicos, fisiológicos e relacionados com o processo de treino, tornando a avaliação e o controlo do treino fundamentais para uma intervenção mais objetiva e individualizada. Esta dissertação teve como objetivo contribuir para a avaliação e o controlo do treino em natação, analisando a utilidade e as limitações de diferentes instrumentos de avaliação em nadadores federados na técnica de crol. Foram realizados dois estudos experimentais e um apêndice complementar. O primeiro estudo comparou a organização cinemática do crol máximo entre o nado amarrado e o nado livre em 28 nadadores. Os nadadores realizaram um teste máximo de 30 s em nado amarrado e um sprint máximo de 25 m em nado livre, tendo sido analisados a duração do ciclo, o índice de coordenação, o índice de sincronização, a distribuição temporal das fases dos membros superiores e o timing das ações dos membros inferiores. O nado amarrado apresentou maior duração do ciclo, um índice de coordenação menos negativo e alterações marcadas na distribuição das fases dos membros superiores, indicando que esta condição não reproduz totalmente a estrutura cinemática do nado livre máximo. O apêndice complementar analisou a relação entre variáveis de força obtidas no nado amarrado e a velocidade em nado livre, mostrando que o nado amarrado pode fornecer informação útil sobre a produção de força em meio aquático, embora a sua interpretação deva considerar o sexo e as restrições específicas da tarefa. O segundo estudo analisou de que forma testes de terreno, variáveis de treino e respostas fisiológicas se associavam ao desempenho nos 400 m crol em 28 jovens nadadores, através de uma abordagem específica por sexo. Os nadadores masculinos foram mais rápidos nos 400 m e apresentaram valores superiores de força de preensão manual, índice de resistência muscular, altura do salto e VO_2 máximo. Nos rapazes, o tempo nos 400 m associou-se ao índice de massa corporal, aos anos de prática e à força de preensão manual esquerda. O modelo explicou 73,1% da variância, sendo os anos de prática o único preditor independente significativo. Nas raparigas, o tempo nos 400 m associou-se à idade, ao volume de treino em seco, à força de preensão manual bilateral, ao índice de resistência muscular, à altura do salto e ao lactato sanguíneo. O modelo explicou 87,0% da variância, mas nenhuma variável individual se manteve significativa após ajustamento. No geral, os resultados indicam que a avaliação em natação deve ser multidimensional, específica por sexo e sensível ao contexto. O nado amarrado pode ser útil para monitorizar a força, mas não deve ser interpretado como equivalente técnico direto do nado livre. As avaliações de terreno e o teste de 400 m devem, por isso, ser interpretados em conjunto para apoiar um controlo do treino mais individualizado.

Chapter 1 General introduction

Evaluation and training control have become increasingly recognised and valued within sport. In competitive swimming, performance depends on the interaction between physical conditioning and technical proficiency. Therefore, training prescription should be supported by physiological and biomechanical indicators that allow coaches to structure training zones and individualise training programmes more effectively (Fernandes et al., 2024). In this context, longitudinal monitoring of swimming performance should integrate not only final race time, but also energetic and biomechanical variables, since these dimensions may change throughout the competitive season and contribute differently according to the swimmer's competitive level (Costa et al., 2012). This is particularly relevant in young swimmers, where regular monitoring across the training process can help describe changes in energetic, technical, and anthropometric profiles and support a more comprehensive interpretation of performance development (Zacca et al., 2020).

The primary objective of the assessment is to evaluate the swimmer's condition based on the performance determinants (Dick, 1989; Bourdon et al., 2017; Issurin, 2010; Morais et al., 2021), including anthropometric characteristics, physiological capacities and technical skills. These assessments should be conducted in a straightforward, objective and precise manner to ensure validity and reliability (Petrigna et al., 2022). Regarding the assessment, the evidence points to integrating training evaluations, such as periodisation and load management, with data collection at strategic moments to first establish a starting point, then verify adaptations and guide training adjustments (Zacca et al., 2020). Subsequently, the effects of each training phase should be quantified to support decisions whenever there are relevant changes in objectives or when logistical conditions permit (Borresen & Lambert, 2009; Buchheit, 2014; Bourdon et al., 2017).

Competitive swimming is a discipline with very specific characteristics, being individual, cyclic and closed in nature, with sequential upper- and lower-limb actions contributing to continuous propulsion (Fernandes & Vilas-Boas, 2006) and is practised in an environment that imposes substantial constraints on human locomotion. Therefore, reaching the highest level requires great dedication and sacrifice from a very early age (Platonov & Fessenko, 1994; Maglischo, 2003). It is also a mixed sport in which the swimmer's performance depends on both biomechanical and bioenergetic factors, indicating a biophysical dependence of performance (Di Prampero et al., 1974; Ribeiro et al., 2017).

Recent evidence using explainable artificial intelligence models indicates that swimming performance can be interpreted through the combined contribution of demographic, training, anthropometric and biomechanical variables (Carvalho et al., 2024). These performance-related factors are also influenced by broader determinants of sport expertise, including genetic, psychological, sociocultural and contextual influences (Baker & Horton, 2004). This framework is represented in the Portuguese long-term swimmer development model presented by Marinho et al. (2020), as shown in Figure 1.

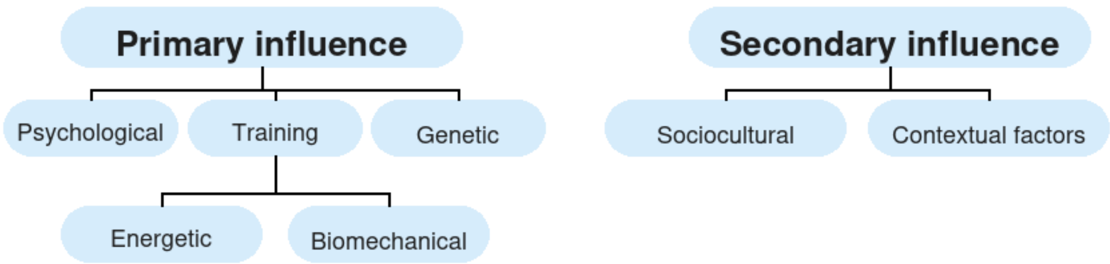

Figure 1. Model of interaction between primary and secondary influences in swimmer development (adapted from Baker & Horton, 2004; Marinho et al., 2020).

Each primary influence contributes directly to swimming performance and can be represented within a model describing the determinants of competitive swimming performance (Figure 2). This is a detailed and thorough model that focuses on energetic, kinematic, motor control, kinetic, physical condition, and strength factors (Barbosa et al., 2013). These models are particularly relevant because they show that the same performance outcome may result from different combinations of physiological, biomechanical and physical characteristics. Another relevant aspect of deterministic models is that they should be sensitive to age and be adjusted to swimmers' developmental stages (Santos & Costa, 2024).

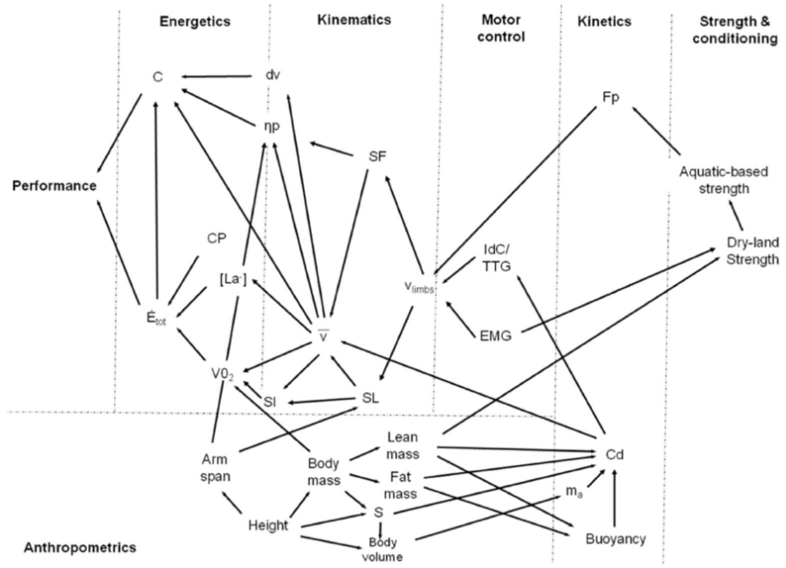

Figure 2. Deterministic model proposed for competitive swimming (Barbosa et al., 2013). Energy cost (C), energy expenditure (Ėtot), phosphocreatine (CP), blood lactate ([La-]), oxygen uptake (VO2), propelling efficiency (ηp), stroke index (SI), intra-cyclic variation of the horizontal velocity of the centre of mass (dv), stroke frequency (SF), stroke length (SL), mean swimming velocity (v), limb's velocity (vlimbs), index of coordination (IdC), total time gap (TTG), electromyography (EMG), body surface areas (S), added water mass (ma), propulsive force (Fp), drag coefficient (Cd)

Technical analysis constitutes a pillar of assessment and control of training in swimming, as it evaluates the mechanical component of performance, which influences energy production and the energy cost of movement, where it is possible to interpret adaptations that are not observed in physiological data or in the time achieved (Barbosa et al., 2010). In races and sets performed at high intensities, technique tends to vary its kinematic and coordinative patterns to adjust to the intensity and the onset of fatigue (Seifert et al., 2004; de Jesus et al., 2016). Therefore, monitoring these changes should be integrated into strategic planning to detect any relevant mechanical faults that affect performance (de Jesus et al., 2016). In terms of application, a standardised collection protocol (e.g. underwater or surface videos, marking criteria and number of cycles) is recommended to ensure intra-subject and between-moment comparability (Marinho et al., 2022; Fernandes et al., 2023).

To assess swimming technique in the water environment, a series of standardised tests have been developed to quantify how kinematics and coordination change with speed and/or fatigue. A classic procedure involves repetitions of representative race paces, filmed to identify the phases of the cycle and calculate coordination metrics, such as the Index of Coordination (IdC) (Chollet et al., 2000; Silva et al., 2022), which are sensitive to changes in propulsive continuity with intensity. Protocols with multiple intensities (e.g. 100 m at various intensities) also support the assessment of technical variables and inter-limb coordination, highlighting the expected technical adjustments as the swimmer approaches race pace (de Jesus et al., 2016).

Despite the increasing use of technical assessment in competitive swimming, an important applied problem remains. Fully tethered swimming is widely used for mechanical assessment, force profiling, and strength-oriented training control, since it allows quantification of swimmers' in-water force production under controlled conditions (Amaro et al., 2017; Morouço et al., 2011). However, its ecological validity for representing front crawl kinematics during maximal free swimming is not fully established, as tethered and free-swimming conditions may differ in swimming mechanics, coordination and propulsive organisation (Domínguez-Castells & Arellano, 2012; Samson et al., 2019). This uncertainty limits the interpretability of tethered-derived metrics when coaches attempt to transfer them directly to race-relevant sprint mechanics.

In addition to biomechanical assessment, field-based monitoring of physical and physiological characteristics is also relevant for understanding swimming performance, particularly in young swimmers. Coaches frequently collect simple measures such as anthropometric measurements, body composition, muscular endurance, and lower-limb power, as well as more complex measures such as oxygen uptake and blood lactate. The first variables are easy to obtain, require limited equipment, and can provide useful information about the swimmer's physical status and training adaptations, whilst the latter require more expensive equipment but offer highly relevant data on the swimmer's performance. However, their interpretation is often isolated, even though young swimmers' performance is multifactorial and depends on interactions among the factors discussed above (Morais et al., 2021; Price et al., 2024). Therefore, integrated monitoring approaches are needed to understand how these practical indicators relate to specific swimming events and to support more personalised training decisions (Zacca et al., 2020; Carvalho et al., 2024).

This issue is particularly relevant in the 400 m front crawl, which is a middle-distance event requiring the interaction of aerobic capacity, anaerobic contribution, pacing ability, technical efficiency and neuromuscular function (Laffite et al., 2004; Kalva-Filho et al., 2015; Ferreira et al., 2021). Unlike sprint events, where maximal power and force production may have a more direct influence, 400 m performance depends on the swimmer's ability to sustain high velocity while managing fatigue and maintaining efficient stroke mechanics (Laffite et al., 2004; Ferreira et al., 2021). Physiological responses such as oxygen uptake, heart rate and blood lactate concentration can provide information about the energetic demands of the event, whereas dry-land strength, power and muscular endurance tests may help characterise the swimmer's physical profile (Kalva-Filho et al., 2015; Price et al., 2024). Training-related variables, such as accumulated training practice and weekly training volume, may also influence performance by reflecting long-term exposure to technical, physiological and conditioning stimuli (Zacca et al., 2020; Carvalho et al., 2024).

Furthermore, the interpretation of these variables should consider sex-specific profiles, since swimming performance in young swimmers is influenced by anthropometric, biomechanical, energetic, neuromuscular and physical characteristics (Morais et al., 2021; Price et al., 2024). Male and female swimmers may differ in anthropometric characteristics, body composition, strength, power and physiological responses, which may influence the variables most strongly associated with performance (Geladas et al., 2005; Price et al., 2024). In young swimmers, these differences may be further affected by growth, biological maturation and training background, as longitudinal studies have shown changes in anthropometric, physiological and biomechanical parameters during development (Lätt et al., 2009a, 2009b; Zacca et al., 2020). Consequently, analysing male and female swimmers separately may provide a more accurate understanding of the determinants of 400 m front crawl performance and avoid conclusions based only on general group trends. This approach may help coaches identify which field-based indicators are more informative for each subgroup and how they can be used to support training control (Zacca et al., 2020; Carvalho et al., 2024).

Therefore, two applied problems guide this dissertation: (i) although fully tethered swimming is frequently used to assess in-water force production, it remains unclear whether the kinematic and coordinative characteristics observed in this condition are equivalent to those observed during maximal free swimming; (ii) although coaches often use simple field-based tests and training indicators to monitor swimmers, there is still a need to understand how these measures relate to 400 m front crawl performance, particularly when sex-specific profiles are considered. Addressing these problems may contribute to a more integrated interpretation of biomechanical, physiological and field-based assessment data in competitive swimming.

Consequently, this dissertation has two main objectives: (i) to clarify the kinematic equivalence between fully tethered and free sprint front crawl swimming; and (ii) to determine whether simple field-based measures, physiological responses and swimmers' characteristics can provide actionable information about 400 m front crawl performance and swimmer status. In addition, a complementary appendix explores the association between tethered-force variables and free-swimming velocity, providing further insight into the practical interpretation of tethered-derived mechanical outputs.

This dissertation is organised into two experimental studies and one complementary appendix. The first focuses on biomechanics through technical analyses of front crawl swimming, comparing tethered swimming and maximal free swimming (Chapter 2). The second study examines the relationship between anthropometric, training-related, neuromuscular and physiological variables and performance in the 400 m front crawl, with a sex-specific approach (Chapter 3). A general discussion integrates the findings of both studies and the complementary appendix with the existing literature (Chapter 4). The dissertation will also present the overall conclusions and recommendations for future research (Chapter 5). A list of bibliographical references will be displayed (Chapter 6) and the appendix (Chapter 7) will be provided.

Chapter 2

Full-tethered swimming as a technical assessment tool: a kinematic comparison with free-swimming in adolescent front crawl swimmers

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Abstract

Background: Technical assessment in front crawl requires objective and repeatable indicators to support training prescription and monitoring. Full-tethered swimming has been proposed as an alternative approach for controlling effort and quantifying in-water force production, but its ability to reproduce the kinematic organization of maximal free-swimming, particularly in front crawl, remains unclear. Methods: Twenty-eight competitive swimmers aged 14-18 years performed, in random order and using the front crawl technique, a 30 s full-tethered maximal test and a 25 m free-swimming sprint with in-water starts. Video recordings obtained from above- and underwater cameras were used to determine cycle duration, index of coordination, the relative duration of the upper-limbs cycle phases and the within-cycle timing of three lower-limbs actions. Results: Compared with free-swimming, full-tethered front crawl showed a longer cycle duration (Δ = 0.120 s, 95% CI 0.076-0.163, p = 0.001) and a more positive index of coordination (Δ = 7.306, 95% CI 5.487-9.126, p = 0.001). Significant experimental condition effects were observed for all upper-limbs phases (p < 0.001), indicating substantial temporal reorganization of the front crawl cycle. Significant experimental condition vs upper-limbs side interactions were found for downsweep, upsweep and recovery phases (all $p \leq 0.029$). Conclusions: Maximal full-tethered swimming does not fully reproduce the kinematic pattern of unimpeded front crawl sprint in adolescent swimmers. Although data obtained when full-tethered swimming may provide useful information for biomechanical assessment, it should be interpreted with caution when extrapolating to free-swimming coordination patterns, particularly in front crawl.

Keywords: front crawl; tethered swimming; kinematics; technical assessment

Introduction

Front crawl performance depends on the interaction between propulsion, coordination and hydrodynamic efficiency, with swimming velocity being regulated by the balance between propulsive and resistive forces throughout the cycle (Toussaint and Truijens, 2005; Takagi et al., 2023). In sprint swimming, even small changes in upper- and lower-limbs phases organization, interlimb coordination and the effective application of force to the water may meaningfully influence swimming speed. For this reason, kinematic analysis remains a central component of technical assessment and training control in competitive swimmers. Previous work has shown that swimming coordination is sensitive to changes in speed and that the temporal organization of the upper-limbs cycle provides useful information on how swimmers adapt their motor pattern under different constraints (Seifert et al., 2004; Silva et al., 2019). More broadly, technical and biomechanical factors are known to play a major role in swimming performance development, particularly in age-group swimmers (Morais et al., 2021). From an applied perspective, this makes the accurate characterization of front crawl technique especially relevant when the aim is to monitor progression and support individualized technical intervention, since technical organization is closely linked to the biomechanical determinants of performance (Toussaint and Truijens, 2005).

Full-tethered swimming has often been used as an alternative approach for assessment and training because it removes forward displacement while allowing the direct quantification of mechanical variables in the aquatic environment. Its practical appeal lies in the possibility of controlling effort, reducing between-trial variability and providing immediate feedback to swimmers and coaches (Morouço et al., 2011; Amaro et al., 2017). In addition, fully tethered tests have shown good reliability and have been widely used to characterize force-time outputs in swimming research and applied settings (Keating et al., 2025). However, the absence of displacement also changes the balance of forces acting on the swimmer and may alter the relative flow of water around the body. As a result, the kinematic organization observed during tethered swimming may differ from that of free-swimming, particularly in variables related to cycle timing, upper-limbs coordination and the temporal structure of the propulsive phases (Domínguez-Castells et al., 2013; Samson et al., 2019). Recent evidence has further shown that tethered and free-swimming differ not only in the magnitude of propulsive output, but also in its distribution within the cycle and in the symmetry of limb contribution, reinforcing the view that tethering modifies the mechanical context of the task (Russo et al., 2026). Since front crawl coordination is known to adapt to changes in speed and task constraints, any testing condition that substantially modifies the mechanical context may also alter the swimmer's preferred coordinative solution (Schnitzler et al., 2021; Silva et al., 2019).

Although previous studies support the usefulness of full-tethered swimming for the assessment of short-distance performance and specific force production (Morouço et al., 2011; Amaro et al., 2017), evidence regarding its kinematic comparability with maximal free-swimming remains limited. This issue is especially relevant in competitive swimmers in development, in whom technical monitoring is a key component of performance development and bilateral organization may still be evolving (Lätt et al., 2009; Silva et al., 2019). Moreover, the lack of forward motion in full-tethered conditions has been recognized as a limitation to the direct ecological transfer of the measured outputs to free-swimming performance (Keating et al., 2025). Therefore, the aim of the current study was to compare the kinematics of maximal front crawl between full-tethered swimming and maximal free-swimming in good level adolescent swimmers. It was hypothesized that full-tethered swimming would induce meaningful changes in cycle organization, upper-limb coordination and phase distribution relative to free-swimming, limiting its ecological validity as a direct technical proxy for sprint front crawl.

Methods

Twenty-eight competitive swimmers participated in this study (14 females and 14 males: 16.2±2.0 vs 16.5±1.6 years, 162.5±4.2 vs 176.0±5.6 cm, 54.4±5.9 vs 65.3±5.7 kg and 464±83 and 456±80 Aquatic points, respectively). All swimmers were engaged in regular structured training and competitive participation. Competitive level was characterized using each swimmer's best 400 m freestyle performance, expressed as World Aquatics points in a 25 m pool. Anthropometric characteristics were obtained before the in-water testing session. All participants, and guardians in the case of minors, provided written informed consent after receiving a full explanation of the study procedures. The study was conducted in accordance with the Declaration of Helsinki and approved by the local ethics committee (process number CEFADE 24 2020). Given the age range and competitive background of the sample, the inclusion of adolescent swimmers was considered appropriate because technical, biomechanical and energetic factors are known to play a major role in performance development during these stages of progression (Lätt et al., 2009; Morais et al., 2021).

A cross-sectional within-subject design was used to compare two experimental conditions: full-tethered swimming and free-swimming at maximal front crawl speed. The assessments were distributed across three data-collection sessions. In each session, participants first completed the dry-land characterization procedures followed by the in-water protocol. After a low- to moderate-intensity warm-up based on their usual routine, swimmers were randomly assigned to begin at one of two stations corresponding to the experimental conditions. Each swimmer completed one maximal trial in each condition with, at least, 30 min of recovery between trials. A within-subject comparison was considered appropriate because swimming coordination and temporal organization are highly sensitive to task constraints and swimming speed, making it important to compare conditions within the same swimmer rather than across groups (Seifert et al., 2004; Schnitzler et al., 2021). This design is also consistent with recent comparisons between tethered and free-swimming that sought to isolate condition-specific changes in technical organization and propulsive behavior (Russo et al., 2026).

Dry-land assessment was performed to characterize body dimensions and body composition (with a bioimpedance scale). The in-water protocol took place in a 25 m indoor pool with a depth of 1.90 m. In the full-tethered condition, swimmers performed a 30 s maximal front crawl test using the Swim-Spektro system (Figure 1) while attached by a belt positioned around the pelvis. The test started from a horizontal in-water position beneath the 5 m flags and swimmers were instructed to swim at maximal effort until the end signal. The use of a 30 s full-tethered front crawl test is also consistent with recent evidence supporting the reliability of force-related outputs obtained from short-duration tethered protocols in highly trained swimmers (Couvertier et al., 2026). In the free-swimming condition, swimmers completed a maximal 25 m front crawl sprint starting in-water. Both conditions were recorded simultaneously by two GoPro Hero 6 cameras operating at 120 Hz, one above water and one underwater, positioned in the sagittal plane (Fernandes et al., 2024). The recorded videos were transferred to a computer, converted to AVI format and cropped to the sections of interest for subsequent kinematic analysis.

For each condition, one complete upper-limb cycle was identified for each upper-limb (right and left) and was divided into five conventional phases: entry, downsweep, insweep, upsweep and recovery, following phase-based approaches commonly used in front crawl coordination analysis (Seifert et al., 2004; Fernandes et al., 2024). To standardize the comparison between conditions and between upper-limbs, the duration of each phase was expressed as a percentage of the corresponding cycle. Interlimb coordination was quantified through the index of coordination, calculated from the temporal relation between the propulsive phases of the right and left upper-limbs and through the index of synchronization (coordination shift between cycles). This analytical approach is consistent with previous work showing that front crawl phases distribution and coordination indices provide sensitive descriptors of how swimmers reorganize their movement pattern under different speed and task constraints (Mezêncio et al., 2020; Silva et al., 2019). In addition, recent evidence comparing tethered and free-swimming has highlighted that differences between conditions may emerge at specific moments within the front crawl cycle, particularly in the early propulsive phases (Russo et al., 2026), which supports the relevance of phase-based temporal analysis in the current design.

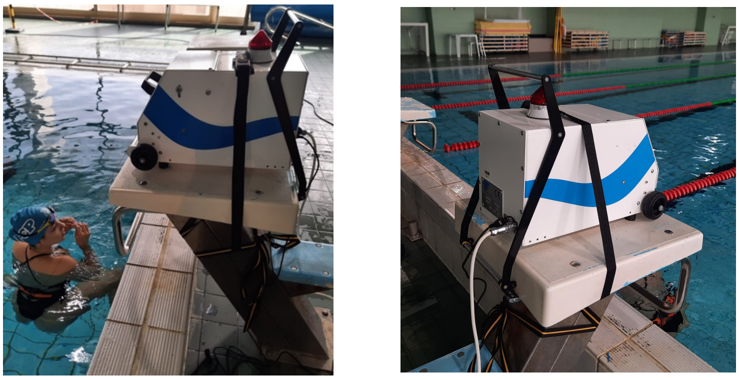

Figure 1. Swim-Spektro apparatus used for full-tethered front crawl assessment in the current study.

Descriptive statistics are presented as mean and standard deviation. Repeated-measures ANOVA was used to compare cycle duration, indices of coordination and synchronization and the timing of the lower limbs action between full-tethered and free-swimming conditions, with sex included as a between-subjects factor. The relative duration of cycle phases was analyzed using a repeated-measures ANOVA with experimental condition and upper-limb action side as within-subject factors and sex as a between-subjects factor. F values, p values and partial eta-squared are reported. Statistical significance was set at $p < 0.05$. The use of repeated-measures models was considered appropriate because all experimental conditions were tested within the same participants and the main interest was to determine whether the temporal organization of the front crawl cycle differed according to condition and between upper-limbs.

Results

Significant main effects of condition on cycle duration ($F = 31.540$, $p < 0.001$), index of coordination ($F = 65.803$, $p < 0.001$), and index of synchronization ($F = 5.825$, $p = 0.023$), indicating that full-tethered swimming showed longer cycle duration, less pronounced temporal catch-up pattern and no phase shift in the inter limb coordination between cycles. No condition vs sex interaction was found for cycle duration or index of coordination ($p > 0.05$). However, a significant experimental condition vs sex interaction was observed for index of synchronization ($F = 7.547$, $p = 0.011$), indicating that males and females exhibited distinct adaptations according to the swimming condition. Additionally, a main effect of sex was found for index of synchronization (F = 6.674, p = 0.016), suggesting that males performed phase advances during free-swimming (Table 1).

Table 1. Cycle duration, index of coordination and index of synchronization during full-tethered and free front crawl swimming, according to sex.

Variables	Full-tethered	Free-swimming	Condition	Condition vs sex	Sex
			(F, p, ηp^2)		
Cycle duration (s)	F: 1.26 ± 0.04 M: 1.18 ± 0.04	F: 1.12 ±0.02 M: 1.07 ± 0.02	31.540, <0.001, 0.548	0.558, 0.462, 0.021	3.877, 0.060, 0.130
Index of coordination (%)	F: 0.00 ± 0.01 M: -0.02 ± 0.01	F: -6.92 ± 1.28 M: -7.70 ± 1.28	65.803, <0.001, 0.717	0.177, 0.677, 0.007	0.197, 0.661, 0.008
Index of synchronization (%)	F: 0.02 ± 0.03 M: -0.00 ± 0.03	F: -0.01 ± 0.03 M: 0.4 ± 0.11	5.825, 0.023, 0.183	7.547, 0.011, 0.225	6.674, 0.016, 0.204

Marked condition effects were observed for all phases of the upper-limbs cycle (Table 2), indicating a global reorganization of the movement pattern. Entry phase occupied a substantially shorter proportion of the cycle in tethered comparing with free-swimming, contrarily to the downsweep and insweep that were relatively longer in the tethered. Upsweep was relatively shorter in tethered swimming, whereas recovery occupied a greater proportion of the cycle in this stationary condition. Overall, these results demonstrate a substantial temporal reorganization of the upper-limbs cycle between conditions. Upper-limb side effects were phase-dependent, with significant differences between limbs observed in all phases except the downsweep, where a more symmetrical pattern was identified. Notably, significant experimental condition vs upper-limb side interactions were observed in downsweep, upsweep, and recovery ($p \leq 0.032$), indicating that inter-limb differences varied according to the swimming condition (swimmers adapted phases distribution). No consistent effects involving sex were found (Table 2).

Table 2. Relative duration of the upper-limb cycle phases during front crawl full-tethered and free-swimming, according to sex.

Variables (%)	Full-tethered	Free-swimming	Experimental condition	Upper-limb side	Upper-limb side vs experimental condition	Upper-limb side vs sex
			(F, p, ηp²)			
Entry	F: 5.8 ± 0.2 M: 4.7 ± 0.2	F: 30.91 ± 1.2 M: 31.0 ± 1.2	925.87, <0.001, 0.973	4.705, 0.039, 0.153	2.482, 0.127, 0.087	0.466, 0.501, 0.018
Downsweep	F: 31.5 ± 1.0 M: 31.9 ± 1.0	F: 18.7 ±0.5 M: 19.6 ± 0.5	166.101, <0.001, 0.865	0.364, 0.551, 0.014	107.663, <0.001, 0.805	1.687, 0.205, 0.061
Insweep	F: 22.3 ± 0.6 M: 23.7 ± 0.6	F: 15.0 ± 0.6 M: 15.8 ± 0.6	146.239, <0.001, 0.849	15.706, <0.001, 0.377	3.468, 0.074, 0.118	3.441, 0.075, 0.117
Upsweep	F: 16.8 ± 0.5 M: 16.5 ± 0.5	F: 27.4 ± 0.7 M:26.7 ± 0.7	326.499, <0.001, 0.926	38.211, <0.001, 0.595	46.054, <0.001, 0.639	2.266, 0.144, 0.080
Recovery	F: 25.6 ± 0.4 M: 8.2 ± 0.9	F: 21.1 ± 0.7 M: 6.3 ± 0.6	332.738, <0.001, 0.928	46.570, <0.001, 0.642	5.146, 0.032, 0.165	4.659, 0.040, 0.152

Swimmers performed six lower-limb actions per cycle. No significant main effects of condition were observed for any lower limb action (Table 3), indicating that the temporal organization of kicking remained stable across conditions. A significant experimental condition vs sex interaction was found only for the first lower limb action (F = 4.93, p = 0.035), suggesting a sex-specific adaptation at the beginning of the cycle. No main effects of sex were detected (all p > 0.05).

Table 3. Within-cycle timing of the six lower-limb actions during front crawl full-tethered and free-swimming, according to sex.

Variables (%)	Full-tethered	Free-swimming	Experimental condition	Experimental condition vs sex	Sex
			(F, p, ηp²)		
1st lower-limb action	F: 15.3 ± 2.0 M: 15.7 ± 1.9	F: 19.4 ± 1.9 M: 11.9 ± 1.9	0.011, 0.918, 0.000	4.930, 0.035, 0.159	3.046, 0.093, 0.105
2nd lower-limb action	F: 18.9 ± 2.3 M: 17.4 ± 2.3	F: 19.7 ± 3.0 M: 15.8 ± 3.0	0.020, 0.890, 0.001	0.153, 0.699, 0.006	1.391, 0.249, 0.051
3rd lower-limb action	F: 47.6 ± 1.9 M: 47.4 ± 1.9	F: 52.9 ± 2.0 M: 45.3 ± 2.0	0.659, 0.424, 0.025	3.763, 0.063, 0.126	4.132, 0.052, 0.137
4th lower-limb action	F: 51.5 ± 2.1 M: 50.4 ± 2.1	F: 53.2 ± 2.9 M: 49.2 ± 2.9	0.008, 0.930, 0.000	0.249, 0.622, 0.010	1.312, 0.263, 0.048

5th lower-limb action	F: 81.6 ± 1.9 M: 81.0 ± 1.9	F: 86.0 ± 1.9 M: 79.2 ± 1.9	0.528, 0.474, 0.020	2.986, 0.096, 0.103	3.415, 0.076, 0.116
6th lower limb-action	F: 84.6 ± 2.1 M: 82.6 ± 2.1	F: 84.6 ± 2.9 M: 83.0 ± 2.9	0.003, 0.956, 0.000	0.004, 0.950, 0.000	0.711, 0.407, 0.027

Discussion

The aim of this study was to compare the kinematics of maximal front crawl between full-tethered swimming and free-swimming in adolescent competitive swimmers. The main finding was that full-tethered swimming did not reproduce the temporal organization of maximal free front crawl. The longer cycle duration, the less negative index of coordination and the marked redistribution of the cycle phases indicate that tethering substantially altered the coordinative structure of the movement. This interpretation is also consistent with evidence from adolescent swimmers showing that technical variables such as stroke rate and stroke length are dynamically influenced by the broader physiological and task context during high-intensity swimming, reinforcing that coordinative behavior should be interpreted as part of an integrated performance response rather than as an isolated mechanical feature (Chen et al., 2026). In practical terms, the tethered condition reduced the catch-up profile and promoted a different temporal allocation across the upper-limb cycle, particularly by shortening entry and upsweep, and prolonging downsweep, insweep and recovery. These findings agree with previous evidence showing that tethering modifies the mechanical context of swimming and affects how propulsion is organized within the cycle (Samson et al., 2019; Russo et al., 2026). This interpretation is also consistent with hydrodynamic perspectives indicating that front crawl velocity is controlled through a continuous interaction between propulsive and resistive forces, such that any experimental condition that modifies this balance is likely to affect intra-cycle organization (Takagi et al., 2023)

The significant experimental condition vs upper-limb side interactions further suggest that full-tethered swimming affected the bilateral structure of the front crawl technique, reinforcing that its technical outputs should not be interpreted as direct equivalents of free-swimming coordination. Regarding inter-cycle organization, index of synchronization values close to zero indicate no phase shift between cycles, whereas negative and positive values reflect phase delay and phase advance (respectively). In the current study, tethered swimming was associated with values closer to zero, while males showed a phase advance during free swimming, suggesting condition-specific stabilization strategies. By contrast, lower-limb action timing remained comparatively stable across conditions, indicating that the main effects of tethering were expressed in the upper-limb coordinative pattern. Therefore, although full-tethered swimming remains useful for controlled biomechanical assessment, particularly given the good reliability reported for short-duration front crawl tethered tests, its ecological validity as a direct technical proxy for sprint front crawl appears limited (Amaro et al., 2017; Keating et al., 2025; Couvertier et al., 2026).

This study has some limitations that should be acknowledged. First, the sample included adolescent swimmers of good competitive level, which may limit generalization to elite adult populations. Second, the analysis was based on a single maximal trial per condition, which may not fully capture within-swimmer variability. Third, the comparison involved a 30 s full-tethered test and a maximal 25 m free-swimming sprint, meaning that the external constraints were not identical between conditions.

Full-tethered swimming can provide useful information for controlled biomechanical assessment, particularly for monitoring technical changes within the same testing setup over time. However, coaches and swimmers should avoid assuming that the temporal organization observed under tethered conditions directly reflects the coordinative pattern used during maximal free front crawl. Whenever possible, tethered assessment should be interpreted alongside free-swimming observation.

Conclusions

Full-tethered swimming altered cycle duration, index of coordination, index of synchronization and upper-limb phase distribution in comparison with maximal free front crawl in adolescent swimmers. These findings indicate that full-tethered swimming does not fully reproduce the kinematic structure of free sprint swimming. Although it remains a useful assessment tool in controlled conditions, its technical outcomes should be interpreted with caution when extrapolating to free-swimming performance. The authors would like to thank all swimmers, coaches and collaborators for their commitment, cooperation and valuable contribution to the completion of this study.

Chapter 3

Applied testing and performance monitoring in young competitive swimmers: sex-specific determinants of 400 m front crawl performance

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Abstract

Performance monitoring in competitive swimming requires practical, ecologically valid and interpretable assessment approaches that can be integrated into regular training environments. This study examined whether a multidimensional battery combining training history, anthropometric characteristics, dry-land neuromuscular assessments and physiological responses could help explain 400 m front crawl performance in young competitive swimmers. Twenty-eight swimmers, comprising 14 males and 14 females, completed anthropometric and body-composition assessments, handgrip strength testing, countermovement jump assessment and a muscular resistance index derived from 60 s sit-up, push-up and squat tests. Swimmers also performed a maximal 400 m front crawl test in a 25 m pool, during which performance time, peak oxygen uptake, peak heart rate and peak blood lactate concentration were determined. Associations with performance were analysed separately by sex, followed by exploratory sex-specific regression models including variables significantly associated with 400 m time. Male swimmers were faster and presented higher handgrip strength, muscular resistance, jump height and peak oxygen uptake than female swimmers. In males, performance was associated with body mass index, training practice and left handgrip strength, with training practice remaining the only independent predictor and explaining 73.1% of performance variance. In females, performance was associated with age, dry-land training volume, bilateral handgrip strength, muscular resistance, jump height and blood lactate concentration, with the exploratory model explaining 87.0% of variance but without any single independent predictor after adjustment. These findings suggest that 400 m front crawl performance in young swimmers should be interpreted through sex-specific and multidimensional monitoring frameworks rather than isolated indicators, supporting the use of feasible applied testing strategies to inform coaching practice.

Keywords

Swimming; 400 m front crawl; performance monitoring; applied testing; youth swimmers; neuromuscular assessment; training history; physiological responses

Introduction

The 400 m front crawl is a central event in competitive swimming, requiring swimmers to sustain high velocities for approximately four to six minutes while preserving technical effectiveness under progressive fatigue. Performance over this distance depends on the interaction between aerobic metabolism and a meaningful anaerobic contribution, particularly during the start, turning phases and final section of the race (Toussaint & Hollander, 1994; Gastin, 2001; Kalva-Filho et al., 2015). This interaction influences the ability to maintain metabolic power output while controlling the mechanical and energetic cost of swimming, which is recognised as a key determinant of the power–speed relationship in this sport (Zamparo et al., 2020). Accordingly, performance in the 400 m front crawl cannot be fully explained by a single physiological, morphological or neuromuscular variable, particularly in young swimmers whose training history, maturation and technical development may progress at different rates.

Although laboratory-based assessments provide high experimental control and methodological precision, their integration into daily training contexts is often limited by cost, logistical complexity and potential interference with training organisation. For this reason, field-based and applied testing approaches have gained relevance in swimming, especially when they provide useful information with limited disruption to regular training routines (Sousa et al., 2014; Stellingwerff, 2025). Training volume, accumulated practice and dry-land training exposure are commonly available indicators that may help contextualise acute performance responses and long-term development (Myer et al., 2013; Feijen et al., 2020). However, training load and training history do not translate uniformly into performance improvement, reinforcing the need for multidimensional monitoring frameworks that integrate training exposure, recovery, physical capacity and sport-specific performance (Bourdon et al., 2017; Nugent et al., 2017).

Anthropometric and body-composition characteristics are also relevant to swimming performance because of their potential influence on buoyancy, propulsion and hydrodynamic resistance. Recent evidence indicates that body-composition variables may be associated with active drag under controlled swimming conditions, supporting the inclusion of morphological indicators in performance assessment models (Narita et al., 2025). Nevertheless, these variables should not be interpreted in isolation, since their functional relevance depends on the swimmer's technical ability, event distance, training background and developmental stage. In youth swimming, this point is particularly important because growth-related changes may affect body dimensions, strength, aerobic responses and race performance simultaneously.

Dry-land neuromuscular tests are widely used by coaches and sport scientists because they are practical, repeatable and easily incorporated into monitoring routines. Handgrip strength has been proposed as a general indicator of upper-limb strength and has shown associations with swimming performance, although these relationships may vary according to sex, age group, swimming stroke and race distance (Garrido et al., 2012; Price et al., 2024). Similarly, countermovement jump performance may provide information about lower-limb power, with potential relevance for starts and turns, particularly in short-course swimming (Potdevin et al., 2011). Muscular endurance tests may also be informative because the 400 m event requires the repeated production of propulsive actions under increasing fatigue, making local muscular resistance a potentially relevant component of a broader applied testing battery.

Physiological responses obtained during or after maximal swimming tests can complement training and dry-land indicators. Peak oxygen uptake, heart rate and blood lactate concentration provide information about the cardiorespiratory and metabolic demands of the effort, although their interpretation must consider the methodological constraints of swimming assessment (Sousa et al., 2014). In the 400 m front crawl, blood lactate concentration and other markers of anaerobic contribution have been related to performance, while oxygen uptake responses may reflect the ability to sustain high-intensity work over the full race distance (Kalva-Filho et al., 2015; Laffite et al., 2004). However, the extent to which these variables improve the interpretation of performance when combined with practical dry-land tests and training indicators remains insufficiently clarified in young competitive swimmers.

The practical problem addressed in this study is therefore not simply to identify isolated determinants of 400 m front crawl performance, but to examine whether a feasible multidimensional assessment approach can provide interpretable information for applied performance monitoring. This perspective is especially relevant for young swimmers, in whom coaches must integrate training history, physical development, strength-related variables and physiological responses when making decisions about training prescription and performance evaluation. Moreover, sex-specific interpretation may be required because male and female swimmers can differ in anthropometric, neuromuscular and physiological profiles during adolescence and early competitive development.

The main aim of this study was to examine the relationships between 400 m front crawl performance and anthropometric, training-related, neuromuscular and physiological variables in young competitive swimmers using an applied multidimensional testing approach. Specifically, this study sought to compare male and female swimmers in 400 m performance, physiological responses and dry-land assessment outcomes, analyse sex-specific associations between the assessed variables and performance time and explore whether variables significantly associated with performance could explain performance variance through sex-stratified regression models. It was hypothesised that faster 400 m performance would be associated with greater training experience, higher neuromuscular capacity and stronger physiological responses to maximal effort. It was further expected that the relevant performance-related variables would differ between sexes, supporting the need for sex-specific interpretation within applied performance monitoring.

Methods

Twenty-eight competitive swimmers, comprising 14 males and 14 females, participated in this study. All swimmers were involved in structured competitive swimming and trained regularly. The general characteristics of the sample are presented in Table 1. Competitive level was determined from each swimmer's personal best time in the 400 m freestyle, converted into World Aquatics points for a 25 m pool. Participants were informed about the study aims and procedures before data collection, and written informed consent was obtained from all participants or, in the case of minors, from their legal guardians. The study was conducted in accordance with the Declaration of Helsinki and approved by the local ethics committee (process number CEFADE 24 2020).

Table 1. Swimmers' main physical, training and performance characteristics.

Variables	Male	Female
Age (years)	16 (2)	15 (2)
Height (cm)	176.0 ± 5.5	162.5 ± 4.4*
Body mass (kg)	65.3 ± 5.9	54.4 ± 6.1*
Body mass index ($kg{\cdot}m^{-2}$)	21.1 ± 1.4	20.6 ± 1.9
Dry-land training ($h{\cdot}week^{-1}$)	5 (2)	3 (3)
Training volume ($km{\cdot}week^{-1}$)	30 (14.8)	29 (5.1)
Training practice (years)	7.3 ± 2.8	8.2 ± 3.2
World Aquatics points	419 (101)	456 (143)

This study used a cross-sectional experimental design based on a multidimensional assessment battery combining anthropometric, training-related, neuromuscular and physiological variables. Each swimmer completed one testing session comprising two sequential components. First, dry-land assessments were conducted at LABIOMEP and included anthropometry, body composition, handgrip strength, countermovement jump and muscular resistance testing. Second, swimmers performed a maximal 400 m front crawl test in a 25 m swimming pool, during which performance time and post-exercise physiological responses were recorded. This design was selected to reflect an applied monitoring approach that could be adapted to regular training environments while preserving sufficient methodological standardisation.

Body mass and body composition were assessed using bioelectrical impedance analysis (InBody 230, Seoul, Republic of Korea). Height was measured with a wall-mounted stadiometer while swimmers stood barefoot in an upright position. Body mass index was calculated from body mass and height. Training-related information included weekly swimming volume, weekly dry-land training volume and accumulated training practice, expressed as years of structured swimming training. These variables were included because training history and training exposure provide relevant contextual information for interpreting performance and physical testing outcomes in young swimmers (Myer et al., 2013; Feijen et al., 2020; Bourdon et al., 2017; Nugent et al., 2017).

Handgrip strength was assessed using a digital dynamometer (Takei TKK 5401, Tokyo, Japan). Swimmers performed three maximal trials with each hand while standing with the tested upper limb extended, positioned along the body and slightly abducted. The best attempt for each hand was retained for analysis. Countermovement jump performance was assessed using a force platform (Bertec, Columbus, OH, USA). Swimmers performed three trials with hands placed on the hips and a self-selected countermovement depth, without pausing at the lowest position. The best jump was retained, and jump height was calculated from flight time using the equation $h = (g \cdot t^2)/8$, where g corresponds to gravitational acceleration ($9.81\ m \cdot s^{-2}$) and t corresponds to flight time.

Muscular resistance was assessed using three 60 s maximal repetition tests: sit-ups, push-ups and squats. At least three minutes of rest were provided between tests. Standardised execution criteria were used for all exercises. During sit-ups, swimmers performed the movement in a supine position with the feet stabilised by a colleague and the hands touching the knees at each valid repetition. During push-ups, the elbows were required to flex to approximately 90°. During squats, the angle between the thigh and lower leg was required to reach approximately 90°. The highest number of valid repetitions in each test was recorded. To allow comparability across tests, each repetition score was standardised using z-scores according to the following equation $z = (x - \text{mean}) / \text{standard deviation}$, where x represents the individual repetition count for a given test. The muscular resistance index was then calculated as the mean of the three z-scores obtained from the sit-up, push-up and squat tests. This index was used as the primary indicator of dry-land muscular endurance in subsequent analyses.

Following dry-land testing, swimmers moved to the pool and completed a low-to-moderate intensity warm-up according to their usual routine. Subsequently, each swimmer performed a maximal 400 m front crawl test with an in-water start in a 25 m pool with 1.80 m depth. Performance time was recorded as the main outcome variable. Pulmonary oxygen uptake was measured breath-by-breath immediately after completion of the 400 m test during a five-minute recovery period using a portable gas analyser system (Cosmed K5, Rome, Italy). The gas analyser and turbine volume transducer were calibrated before each testing session using gases of known concentration, comprising 16% O_2 and 5% CO_2, and a 3 L syringe.

Oxygen uptake data were inspected to exclude occasional errant breaths, and only values within ±3 standard deviations were retained. Peak oxygen uptake was estimated by backward extrapolation to zero recovery time using linear regression applied to the first 20 s of recovery, following previously described procedures for post-swim oxygen uptake assessment (Sousa et al., 2014; Monteiro et al., 2020). Heart rate was continuously recorded at baseline and after test completion using a chest strap (Polar H10, Polar Electro Oy, Kempele, Finland), which transmitted data to the portable gas analyser unit. Blood lactate concentration was obtained from fingertip capillary blood samples collected at rest, immediately after the test and at one, three, five and/or seven minutes post-exercise until the maximal value was identified. Samples were analysed using a portable lactate analyser (Lactate Pro2, Arkay, Inc., Kyoto, Japan).

Statistical analyses were performed using IBM SPSS Statistics, version 30 (IBM Corp., Armonk, NY, USA), with statistical significance set at $p < 0.05$. Data distribution was assessed using the Shapiro–Wilk test. Normally distributed variables were presented as mean ± standard deviation and compared between sexes using independent-samples t-tests. Non-normally distributed variables were presented as median and interquartile range and compared between sexes using the Mann–Whitney U test. According to the Shapiro–Wilk test, height, training practice, body mass index, fat mass, body mass, lean mass, handgrip strength, jump height, muscular resistance index and 400 m performance time showed normal distribution in both sexes. Age, weekly training volume and dry-land training volume showed non-normal distribution and were analysed using non-parametric procedures. Bivariate associations between candidate variables and 400 m performance time were examined separately by sex using Spearman's rank correlation coefficient. Exploratory sex-stratified multiple linear regression analyses were then performed using the variables significantly associated with 400 m performance in the bivariate analysis. Given the small sex-specific sample size, regression models were interpreted as exploratory explanatory models rather than definitive predictive models.

Results

Table 2 presents swimmers' 400 m performance, physiological responses and dry-land assessment outcomes according to sex. Significant sex-related differences were observed for most neuromuscular and performance variables. Male swimmers were faster in the 400 m front crawl test than female swimmers (293.09 ± 18.15 s vs 320.73 ± 16.05 s, $p < 0.001$). Males also presented higher right and left handgrip strength ($p < 0.001$), higher muscular resistance index ($p = 0.002$), higher jump height ($p < 0.001$) and higher peak oxygen uptake ($p = 0.038$). In contrast, no significant sex-related differences were observed for peak blood lactate concentration or peak heart rate.

Table 2. Swimmers' performance, physiological responses to the 400 m maximal test and dry-land physical assessment outcomes

Variables	**Male**	**Female**	***p***
Right handgrip strength (kg)	37.03 ± 6.71	25.71 ± 4.02	< 0.001
Left handgrip strength (kg)	36.56 ± 6.11	25.08 ± 3.31	< 0.001
Muscle resistance index	0.47 ± 0.93	-0.47 ± 0.48	0.002
Jump height (cm)	33.5 ± 3.7	22.6 ± 3.6	< 0.001
400 m performance (s)	293.09 ± 18.15	320.73 ± 16.05	< 0.001
Peak oxygen uptake (mL·kg^{-1}·min^{-1})	48.9 ± 9.9	40.9 ± 9.5	0.038
Blood lactate concentrations (mmol·L^{-1})	11.2 ± 3.2	9.4 ± 3.0	0.120
Peak heart rate (bpm)	184 ± 7	183 ± 8	0.709

Table 3 presents Spearman correlation coefficients between 400 m performance time and the assessed variables, separately for males and females. In male swimmers, 400 m performance time was negatively correlated with body mass index, training practice and left handgrip strength. No significant associations were observed between performance time and the remaining anthropometric, training-related, neuromuscular or physiological variables in males. In female swimmers, significant negative correlations were found between 400 m performance time and age, dry-land training volume, right and left handgrip strength, muscular resistance index, jump height and blood lactate concentration. Weekly swimming volume showed a near-significant negative association with performance time. These results indicate that faster female swimmers tended to be older, stronger, more powerful, more resistant in dry-land muscular endurance testing and able to attain higher peak blood lactate concentrations after the maximal 400 m test.

Table 3. Spearman correlation coefficients between 400 m performance time and the assessed variables.

Variables	Male		Female	
	ρ	*p*	ρ	*p*
Age (years)	-0.492	0.074	-0.764	0.001
Height (cm)	-0.007	0.982	-0.292	0.311
Body mass (kg)	-0.493	0.073	-0.349	0.221
Body mass index ($kg{\cdot}m^{-2}$)	-0.591	0.026	-0.099	0.737
Fat mass (%)	-0.332	0.246	-0.011	0.970
Lean mass (%)	0.121	0.680	-0.026	0.929
Dry-land training ($h{\cdot}week^{-1}$)	0.012	0.967	-0.545	0.044
Training volume ($km{\cdot}week^{-1}$)	0.052	0.859	-0.519	0.057
Training practice (years)	-0.817	< 0.001	-0.408	0.148
Right handgrip strength (kg)	-0.389	0.169	-0.882	< 0.001
Left handgrip strength (kg)	-0.538	0.047	-0.697	0.006
Muscle resistance index	-0.508	0.064	-0.724	0.003
Jump height (cm)	-0.099	0.736	-0.604	0.022
Peak oxygen uptake ($mL{\cdot}kg^{-1}{\cdot}min^{-1}$)	-0.279	0.334	-0.292	0.311
Peak heart rate (bpm)	-0.036	0.939	-0.257	0.623
Blood lactate concentrations ($mmol{\cdot}L^{-1}$)	-0.447	0.109	-0.711	0.004

Sex-specific multiple linear regression analyses were performed using variables that were significantly associated with 400 m performance in the bivariate analysis. In male swimmers, the regression model including body mass index, left handgrip strength and training practice was statistically significant ($F(3,10) = 9.08$, $p = 0.003$), explaining 73.1% of the variance in 400 m performance time ($R^2 = 0.731$; adjusted $R^2 = 0.651$; standard error of the estimate = 10.73 s). Within this model, training practice was the only significant independent predictor of 400 m performance time ($B = -5.05\ s{\cdot}year^{-1}$; $\beta = -0.790$; $p = 0.007$), indicating that greater accumulated training experience was independently associated with shorter 400 m times.

In female swimmers, the regression model including age, dry-land training volume, right and left handgrip strength, muscular resistance index, jump height and blood lactate concentration was also statistically significant ($F(7,6) = 5.75$, $p = 0.024$), explaining 87.0% of the variance in 400 m performance time ($R^2 = 0.870$; adjusted $R^2 = 0.719$; standard error of the estimate = 8.51 s). However, no individual variable remained statistically significant after adjustment. Right handgrip strength showed the strongest standardised association with performance time ($\beta = -0.820$; $p = 0.081$), although this effect did not reach statistical significance. Given the number of predictors relative to the sample size, this model should be interpreted cautiously as an exploratory description of a multidimensional performance profile rather than as a definitive predictive model.

Discussion

This study examined the relationships between 400 m front crawl performance and a set of anthropometric, training-related, neuromuscular and physiological variables in young competitive swimmers using a multidimensional applied testing approach. The main findings showed clear sex-specific profiles. Male swimmers were faster and presented higher handgrip strength, muscular resistance index, jump height and peak oxygen uptake than female swimmers. In males, 400 m performance was associated with body mass index, training practice and left handgrip strength, with training practice remaining the only significant independent predictor in the exploratory regression model. In females, performance was associated with age, dry-land training volume, bilateral handgrip strength, muscular resistance index, jump height and blood lactate concentration, although no single variable remained significant after multivariable adjustment.

The initial hypotheses were therefore partially confirmed. Better 400 m performance was associated with training experience, neuromuscular capacity and physiological response, but the relevant variables differed between sexes and only training practice remained an independent predictor in males. These findings are consistent with the multifactorial nature of swimming performance, in which anthropometric, neuromuscular, energetic and biomechanical factors interact to determine race outcomes (Zamparo et al., 2020; Price et al., 2024). From an applied monitoring perspective, the present results reinforce that 400 m performance in young swimmers should not be interpreted through isolated test results. Instead, it should be considered within an integrated framework combining training history, dry-land physical capacities and physiological responses to maximal swimming effort.

In male swimmers, training practice emerged as the main independent explanatory variable. This finding suggests that accumulated exposure to structured swimming training may underpin adaptations relevant to middle-distance performance, including technical efficiency, pacing ability, tolerance to fatigue and the capacity to sustain a high swimming velocity over the full 400 m distance. Previous evidence indicates that young swimmers' performance development depends not only on isolated physical capacities, but also on interactions between training exposure, energetics, technique and growth-related changes (Price et al., 2024; Zacca et al., 2016). The observed association between training practice and performance is therefore plausible, particularly in a sample of developing swimmers in whom accumulated sport-specific experience may reflect both biological development and long-term technical consolidation.

The association between body mass index and performance in males should be interpreted with caution. Although anthropometric and body-composition characteristics can influence swimming performance through their effects on buoyancy and hydrodynamic resistance, body mass index is a crude indicator and cannot distinguish lean mass, fat mass or body shape. Recent work has shown that body composition may relate to active drag under specific swimming conditions (Narita et al., 2025), but such relationships are likely to depend on stroke mechanics, velocity, body position and propelling efficiency. Therefore, the present association should not be interpreted as evidence that higher body mass index directly improves performance. Rather, it may reflect the combined influence of growth, muscular development and training background in this group of male swimmers.

Female swimmers showed a broader pattern of associations between performance and assessed variables. Faster 400 m times were associated with older age, greater dry-land training volume, higher bilateral handgrip strength, higher muscular resistance index, greater jump height and higher blood lactate concentration. This profile suggests that, in this group, performance may have been more strongly linked to neuromuscular development and physiological responsiveness to maximal effort than to training practice alone. The strong associations observed for handgrip strength support previous findings indicating that upper-limb strength, although non-specific, may be related to swimming performance in young swimmers (Garrido et al., 2012; Price et al., 2024). Similarly, the association with jump height is compatible with the relevance of lower-limb power for starts and turns, particularly in a 25 m pool where turning contribution is repeated throughout the 400 m test (Potdevin et al., 2011).

The relationship between blood lactate concentration and performance in females further supports the importance of anaerobic contribution in the 400 m front crawl. Although this event is predominantly aerobic, previous studies have shown that both aerobic and anaerobic parameters may relate to 400 m performance (Kalva-Filho et al., 2015; Laffite et al., 2004). Higher post-exercise blood lactate concentration in faster swimmers may reflect a greater capacity to tolerate and sustain high-intensity effort, particularly during the final phase of the race. However, blood lactate concentration should be interpreted as a response to the completed effort rather than as an isolated determinant of performance. The absence of significant associations between peak oxygen uptake and performance in both sexes also suggests that aerobic capacity alone may not explain inter-individual variability in this distance, reinforcing the need to combine physiological, neuromuscular and training-related indicators.

The exploratory regression models provide additional but cautious insight into the combined influence of the assessed variables. In males, the model explained a substantial proportion of performance variance, with training practice remaining the only independent predictor. This supports the practical relevance of considering accumulated swimming experience when interpreting performance in young male swimmers. In females, the model explained a high proportion of variance but no individual predictor remained significant after adjustment. This likely reflects the small sex-specific sample size and collinearity among strength-related variables, particularly right and left handgrip strength. Consequently, the female model should be interpreted as evidence of a multidimensional performance profile rather than as a hierarchy of independent determinants.

These findings have practical implications for applied performance monitoring in youth swimming. Coaches and sport scientists frequently use simple dry-land tests to assess strength, power and muscular endurance, but the present results indicate that their interpretation should be sex-specific and integrated with training history and physiological responses. In males, accumulated training practice may provide important contextual information when interpreting 400 m performance. In females, a broader monitoring profile including strength, power, muscular endurance and metabolic response may be more informative. This does not imply that different variables are inherently relevant only to one sex, but rather that sex-specific developmental profiles may influence which indicators are most closely associated with performance at a given stage of competitive progression.

Some limitations should be acknowledged. First, the relatively small sample size, particularly after sex stratification, limits statistical power and generalisability. Second, the cross-sectional design does not allow causal inference; therefore, the observed associations cannot determine whether the assessed variables directly influence performance or simply characterise faster swimmers. Third, biological maturation was not directly assessed, despite its recognised influence on strength, aerobic responses, body composition and swimming performance in young athletes. Recent evidence suggests that biological age and oxygen uptake kinetics may play relevant roles in force production and 400 m front crawl performance, reinforcing the importance of considering maturation in youth swimming research (Strzała et al., 2023). Finally, although field-based dry-land tests increase ecological applicability, they provide indirect information and should ideally be interpreted alongside swimming-specific technical and mechanical measures.

Future studies should include larger samples, longitudinal designs and direct maturation assessment to clarify how training history, growth, neuromuscular development and physiological responses interact over time. The inclusion of swimming-specific biomechanical variables, such as stroke rate, stroke length, intracycle velocity variation, start and turn performance and propulsion-related measures, would also improve the explanatory value of multidimensional monitoring models. Nevertheless, the present study provides an applied and feasible assessment framework that may help coaches interpret 400 m front crawl performance using variables that can be collected with limited disruption to regular training environments.

Conclusions

This study showed that 400 m front crawl performance in young competitive swimmers is associated with different multidimensional profiles in males and females. In males, performance was associated with body mass index, training practice and left handgrip strength, with accumulated training practice emerging as the only independent explanatory variable. In females, performance was associated with age, dry-land training volume, bilateral handgrip strength, muscular resistance, jump height and blood lactate concentration, although no single variable remained independently significant after adjustment.

From an applied perspective, these findings suggest that coaches and sport scientists should avoid relying on isolated indicators when monitoring 400 m front crawl performance in young swimmers. Instead, performance interpretation should integrate training history, dry-land neuromuscular assessments and physiological responses within a sex-specific framework. Such an approach may support more informed training evaluation and performance monitoring in competitive youth swimming, particularly when laboratory resources are limited and practical, repeatable testing strategies are required.

Chapter 4 General discussion

Swimming performance is determined by multiple interacting factors, including technical execution, force production, energetic contribution, anthropometric characteristics and training background (Barbosa et al., 2010; Barbosa et al., 2013; Morais et al., 2021). For this reason, evaluation and training control should go beyond the isolated analysis of performance but should integrate biomechanical, physiological and field-based indicators that help coaches understand how swimmers produce, maintain and adapt performance under different constraints. In competitive swimming, this approach is particularly relevant because small changes in coordination, propulsive capacity or fatigue tolerance may influence performance, especially in young swimmers whose technical and physical profiles are still developing (Zacca et al., 2020; Morais et al., 2021).

The relevance of an integrated interpretation in young swimmers is supported by longitudinal studies showing that 400 m front crawl performance changes across training periods are associated with both biomechanical and physiological adaptations. One study showed that performance gains during an 11-week macrocycle were related to changes in stroke length, stroke index and physiological variables (Ferreira et al., 2019). These findings support the idea that 400 m performance in young swimmers should be monitored through a multidimensional approach, combining technical, physiological and training-related indicators. This is particularly relevant because some energetic components, especially anaerobic performance, remain difficult to assess directly in young swimmers, reinforcing the need to interpret physiological markers within a broader and context-specific monitoring framework (Sampaio, 2024).

The studies included in this dissertation were designed around this central idea, to improve the interpretation of training control data by clarifying what different assessment tools can actually represent. In this context, kinematic analysis, tethered swimming force assessment, dry-land testing and a maximal 400 m front crawl test were used as complementary sources of information, with each of these tools providing a different perspective on performance. Kinematic assessment describes how the swimmer organises movement, tethered swimming characterises force production under controlled aquatic conditions, dry-land tests provide practical indicators of neuromuscular status and the 400 m integrates performance, physiological response and training background. Therefore, this dissertation emphasises that different assessment methods should be viewed as complementary tools, each contributing specific information to the interpretation of swimming performance.

In the first study, described in Chapter 2, full-tethered swimming was compared with maximal free-swimming to determine whether this commonly used assessment condition reproduces the kinematic organisation of front crawl. The results showed that full-tethered swimming altered cycle duration, index of coordination, index of synchronisation and the relative duration of the upper-limb phases. Specifically, the tethered condition induced a substantial reorganisation of the swimming cycle, demonstrating that the absence of forward displacement changes the mechanical context of the task. This finding reinforces that, although tethered swimming is useful for controlled assessment, it should not be interpreted as a direct technical equivalent of free swimming.

These results are consistent with previous evidence showing that front crawl coordination can be interpreted within a constraints-led perspective, in which movement patterns emerge from the interaction between swimmer-related, task-related and environmental constraints (Newell, 1986). In swimming, swimmer-related constraints may include anthropometric characteristics, buoyancy, strength level and technical proficiency, whereas task constraints include swimming velocity, distance and fatigue (Newell, 1986; Silva et al., 2019). Environmental and mechanical constraints, such as aquatic resistance or the specific condition in which the swimmer performs, may also influence stroke organisation (Toussaint & Truijens, 2005; Samson et al., 2019). This framework is relevant to the present dissertation because fully tethered and free-swimming conditions impose different mechanical constraints on the swimmer, which may partly explain the observed differences in phase organisation and coordination patterns (Seifert et al., 2004; Silva et al., 2022).

The findings of Chapter 2 reinforce that the interpretation of technical assessment depends on the specific task constraints imposed by the testing condition. Tethered swimming has clear practical value because it allows coaches and researchers to assess in-water force production under controlled conditions. Studies showed that a 30 s tethered swimming test in adolescent swimmers was useful for estimating short-distance freestyle performance, supporting its application as a specific force-assessment tool (Morouço et al., 2012). Nevertheless, the present findings indicate that this mechanical usefulness should not be confused with technical equivalence. Therefore, from a training-control perspective, tethered swimming may be used to monitor force-related adaptations over time, but its kinematic variables should not be directly transferred to free-swimming technique without considering the constraints of the testing condition.

The appendix presented in Chapter 7 complements this interpretation by examining the association between force variables obtained during tethered swimming and velocity during free swimming. The results showed that force-related outputs, particularly mean force, were associated with free-swimming velocity, although this relationship should be interpreted with caution when sex is considered. This suggests that tethered swimming may have practical value for characterising the swimmer's force-production profile, even if it does not reproduce free-swimming kinematics. This distinction is important because it prevents an overly simplistic interpretation of tethered swimming as either valid or invalid. Instead, the present findings indicate that tethered swimming is useful for assessing specific force production but limited as a direct proxy for free-swimming coordination.

This interpretation agrees with previous research showing relationships between tethered force and swimming performance (Morouço et al., 2011; Morouço et al., 2014), while also aligning with more recent evidence suggesting that tethered and free-swimming differ in propulsion and cycle organisation (Samson et al., 2019; Russo et al., 2026). Therefore, the combined findings of Chapter 2 and

Appendix I reinforce that the usefulness of tethered swimming depends on the assessment objective. If the goal is to evaluate aquatic force production under standardised conditions, tethered swimming provides relevant information. However, if the goal is to analyse race-relevant technical organisation, free-swimming assessment remains necessary.

Chapter 3 extended the multidimensional approach to the 400 m front crawl, focusing on anthropometric, training-related, neuromuscular and physiological variables. The results showed that male swimmers were faster in the 400 m and presented higher handgrip strength, muscle resistance index, jump height and VO_2peak than female swimmers. These differences are consistent with the multifactorial nature of swimming performance, in which strength, power, energetic capacity, anthropometry, and technique interact to determine performance (Fernandes et al., 2005; Morais et al., 2021; Price et al., 2024). In this sense, the results reinforce that 400 m performance should not be interpreted as the outcome of a single determinant, but rather as the result of several interacting dimensions that contribute differently according to the swimmer's profile and training context (Ferreira et al., 2019).

The sex differences observed in strength, power and VO_2peak also support the need for sex-specific interpretation when monitoring young swimmers. Previous research has shown that muscle strength, muscle power, lean body mass and aerobic and anaerobic metabolism measures are relevant determinants of swimming performance in youth swimmers (Price et al., 2024). Moreover, multidimensional approaches combining training, anthropometric and physical testing variables have shown practical value for explaining swimming performance and supporting coach decision-making (Zacca et al., 2020; Carvalho et al., 2024). Therefore, the most relevant contribution of Chapter 3 was not only the identification of differences between male and female swimmers, but the observation that the variables associated with 400 m performance were not the same in both sexes.

The observed regression results further reinforce the need for cautious and sex-specific interpretation. Although the male model explained a substantial proportion of performance variance, training practice was the only variable that remained independently associated with performance. In females, the model also explained a high proportion of variance, but no individual predictor remained significant after adjustment, which may be related to the small sample size and the shared variance between neuromuscular variables. This is important because field-based tests are useful in applied contexts, but their interpretation should consider the interaction between variables rather than assuming that each test independently explains performance (Morais et al., 2021; Carvalho et al., 2024). This perspective is consistent with recent approaches suggesting that swimming performance prediction and monitoring should integrate practical tests, training variables and swimmer characteristics in a multidimensional way (Carvalho et al., 2023).

From a training-control perspective, Chapter 3 shows that simple field-based measures can provide relevant information about swimmer status, but their meaning depends on swimmers' sex, swimming event demands and the interaction between variables. In males, accumulated training practice appeared to be the most informative variable, suggesting the importance of long-term exposure to structured swimming training. In females, performance was more broadly associated with neuromuscular and physiological indicators, suggesting that strength, power, muscular resistance and metabolic response may deserve particular attention in monitoring.

Overall, the findings from the two studies and the complementary appendix suggest that swimming evaluation and training control should be based on a multidimensional and context-specific interpretation, recognising that each assessment method provides partial information about performance rather than a complete representation of the swimmer's competitive capacity. Free-swimming kinematics help characterise technical organisation under ecological conditions, whereas tethered swimming provides information about force production within a constrained task. Dry-land tests complement this analysis by offering accessible markers of neuromuscular status, while the 400 m test brings together performance, physiological response and training history. Therefore, the practical value of assessment does not depend only on collecting several variables, but on understanding what each variable means and how it should be interpreted within the training process.

From an applied perspective, the findings suggest that coaches should combine outcome measures, such as swimming time and velocity, with process measures, such as cycle organisation, force production, physiological responses and training history. This is consistent with general recommendations for training monitoring, which emphasise that assessment should support training prescription, detect adaptations and guide individualised decision-making, particularly in young swimmers, where monitoring training load in the pool and during dry-land training is considered an important component of coaching practice (Halson, 2014; Bourdon et al., 2017; Pyne, 2021). In swimming, this is particularly important because similar performance outcomes may result from different combinations of technical, mechanical and physiological characteristics (Barbosa et al., 2010). Thus, a swimmer may improve performance through better coordination, greater force production, improved pacing, enhanced aerobic/anaerobic contribution or a combination of these factors (Laffite et al., 2004; Zacca et al., 2020; Morais et al., 2021).

The present dissertation also highlights the relevance of sex-specific interpretation in swimming assessment and training control. In Chapter 3, the variables associated with 400 m front crawl performance differed between male and female swimmers, suggesting that similar performance outcomes may be supported by different anthropometric, neuromuscular, physiological and training-related profiles. Similarly, in Appendix I, the relationship between tethered force variables and free-swimming velocity was modified when sex was considered, indicating that mechanical outputs obtained under constrained conditions may not have the same meaning across male and female swimmers. This interpretation is supported by previous evidence showing that youth swimming performance is influenced by sex-related differences in anthropometric, physiological, neuromuscular and biomechanical characteristics (Morais et al., 2021; Price et al., 2024).

Continuing with the previous idea, these findings indicate that sex should not be treated solely as a descriptive variable, but as a relevant factor in the interpretation of assessment data. This is especially important in young swimmers, where growth, biological maturation, body dimensions, oxygen uptake kinetics, and force-production capacity may influence performance differently between males and females (Lätt et al., 2009; Strzała et al., 2023). Moreover, recent evidence on fully tethered and semi-tethered swimming indicates that the relationship between mechanical outputs and sprint swimming performance may differ according to sex and assessment condition, reinforcing the need for cautious interpretation of tethered-derived variables (Keating et al., 2025). Therefore, training-control decisions should avoid universal reference values and should instead consider individual and sex-specific profiles, particularly when monitoring young swimmers across training periods (Zacca et al., 2020).

Notwithstanding, the data and conclusions obtained in this dissertation have some limitations that should be acknowledged when interpreting its overall findings. First, the sample size was relatively small, particularly when analyses were stratified by sex, which may have limited statistical power and increased uncertainty in regression models. Second, the cross-sectional design does not allow causal inference, meaning that the observed associations cannot confirm whether the assessed variables directly caused improved performance. Third, biological maturation was not directly controlled, despite its potential influence on body dimensions, strength, peak oxygen uptake, force production and swimming performance.

Chapter 5 Conclusions and recommendations for future research

This dissertation reinforces that evaluation and training control in swimming should be understood as an integrated and context-specific process. Full-tethered swimming provides useful information about aquatic force production, but does not directly reproduce free-swimming kinematics. Field-based assessments and the 400 m front crawl test provide relevant information about performance status, but their interpretation depends on sex, training history, neuromuscular capacity and physiological response. Therefore, coaches should avoid relying on a single variable or test to guide training decisions. Instead, the results support a multidimensional assessment strategy in which biomechanical, mechanical, physiological and field-based indicators are combined to improve the interpretation of performance and support more individualised training control.

Future research should adopt longitudinal designs across different phases of the training season to determine whether the variables analysed in this dissertation are sensitive to training-induced adaptations. It would also be important to include maturation indicators, repeated testing moments and larger samples to allow more robust modelling. Future studies should also integrate tethered force-time data with simultaneous free-swimming kinematics and physiological responses, allowing a deeper understanding of how force production, coordination and fatigue interact during performance. Such an approach would strengthen the practical application of assessment batteries and contribute to more individualised training prescriptions.

Chapter 6 References

Chapter 1

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Chapter 2

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Associação entre o perfil de força em nado amarrado e a velocidade em nado livre em jovens nadadores

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A monitorização da força propulsiva em natação tem sido indicada como uma estratégia importante para compreender fatores associados ao desempenho desportivo, sendo o nado amarrado uma metodologia frequentemente utilizada para esse fim. Contudo, permanece pouco claro até que ponto as variáveis relacionadas com a produção de força obtidas nesse contexto se relacionam com o desempenho em nado livre. O presente estudo teve como objetivo analisar a associação entre os valores de força máxima, força média, índice de fadiga, decaimento da força e coeficiente de variação da força obtidos durante um teste de nado amarrado e a velocidade do nado livre na técnica de crol em 28 nadadores federados (14 rapazes, 14 raparigas), com idades compreendidas entre 14 e 21 anos. As relações entre variáveis foram avaliadas pelo coeficiente de correlação de *Pearson* e pela correlação parcial (controlando o efeito do sexo), sendo estabelecido um nível de significância de $p<0,05$. A força média ($179,7 \pm 43,9$ N) apresentou associação positiva significativa ($r = 0,862$; $p < 0,001$), com a velocidade do nado ($1,67 \pm 0,13$ m/s), assim como a força máxima ($327,8 \pm 80,46$ N) que apresentou correlação estatisticamente significativa ($r = 0,720$; $p < 0,001$). Adicionalmente, na variável decaimento da força ($-4,77 \pm 2,74$ N/s) observou-se uma associação negativa significativa entre a velocidade ($r = -0,667$; $p < 0,001$). Em contraste, as restantes variáveis não apresentaram associação significativa. Após controlo do sexo, a magnitude das associações diminui, mas mantém-se significativa entre a velocidade e a força média ($r = 0,682$; $p < 0,001$), a força máxima ($r = 0,400$; $p = 0,039$) e o decaimento da força ($r = -0,449$; $p = 0,019$). Deste modo, verifica-se que, nesta amostra, a velocidade de nado associa-se às variáveis que refletem a magnitude e a manutenção da força produzida no nado amarrado e que, embora o controlo do sexo tenha reduzido a magnitude das associações, estas permaneceram estatisticamente significativas para a força média, a força máxima e o decaimento da força.

Palavras-chave: Natação; Nado amarrado; Força; Nado livre; Crol