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Training control and swimmers' evaluation: performance and health concerns

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The PhD street

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List of Publications

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Abstract

This thesis explored the complex dynamics of training and performance in competitive swimming, focusing on the integration of biomechanical, physiological and psychological aspects. The following evaluations were applied: anthropometric characterization, 5 x 200 m intermittent incremental protocol, isokinetic testing of shoulder and knee joints, 25 m all out sprint with and without speedometer, countermovement jump, track start (until reach the 15 m mark), front crawl 200 m maximal, 30 s tethered swimming, orthostatic test, Hooper index and sleep questionnaires, session rating of perceived exertion and hand-grip strength test. The results evidenced that: (i) the anaerobic threshold is a biophysical boundary, that can be determined in the four conventional swimming techniques and in medley; (ii) elite swimmers have higher strength levels than non-elite counterparts associated with improved stroke length and rate, and higher arm span being related to better sprint times for front crawl, butterfly and backstroke; (iii) isokinetic shoulder and knee power correlate with longer times on the starting block but not with the overall start performance; (iv) swimmers exhibit more upper limbs symmetry when evaluations mimic real practice conditions (similar angular velocity); (v) dry-land and in-water force production are directly related; (vi) training duration and countermovement jump performance are strong predictors of swimming performance, while higher body fat negatively impacts it; (vii) lower limbs contribute significantly to maintain or increase sprint swimming velocity; (viii) a mean overload of ~27% in training loads within a two-week period did not impair profile of mood state, dry-land strength and swimming performances in elite swimmers, and (ix) vagally mediated biomarkers appears to be highly sensitive and capable of predicting changes in the daily training loads imposed to swimmers. The applied evaluations and consequent results showed practical implications for the swimming training process, allowing to better objectify and control it. This thesis offers comprehensive insights into training and performance in competitive swimming, highlighting the importance of a holistic approach to monitoring training effects and interpret swimming performance.

Resumo

A presente tese procurou explorar a dinâmica complexa do treino e do rendimento na Natação Pura Desportiva, focando-se na integração de aspetos biomecânicos, fisiológicos e psicológicos. Foram realizadas as seguintes avaliações: caracterização antropométrica, protocolo intermitente incremental de 5 x 200 m, teste isocinético das articulações do ombro e do joelho, 25 m ao máximo com e sem velocímetro, salto com contramovimento, partida do bloco (até alcançar a marca dos 15 m), 200 m crol ao máximo, 30 s nado amarrado, teste ortostático, índice de Hooper e questionários de sono, avaliação da perceção subjetiva de esforço da sessão de treino e teste de força de preensão manual. Os resultados evidenciaram que: (i) o limiar anaeróbio é um limite biofísico, que pode ser determinado nas quatro técnicas convencionais de nado e em estilos; (ii) nadadores de elite têm níveis de força mais elevados do que os não elite associados a uma maior distância de ciclo e frequência gestual, estando uma maior envergadura relacionada com os melhores tempos a crol, mariposa e costas; (iii) a potência isocinética na extensão do ombro e do joelho correlaciona-se com maior permanência no bloco de partida, mas não com o desempenho geral da partida; (iv) os nadadores apresentam maior simetria nos membros superiores quando a avaliação mimetiza a condição real de prática (velocidade angular semelhante); (v) a produção de força em seco e na água relacionam-se de forma direta; (vi) a duração do treino e o desempenho no salto com contramovimento são fortes preditores de rendimento, enquanto uma maior percentagem de gordura corporal tem impacto negativo; (vii) os membros inferiores contribuem para manter ou aumentar a velocidade de sprint; (viii) uma sobrecarga média de ~27% na carga de treino num período de duas semanas não prejudicou o estado de motivação, a força em seco nem o rendimento em nadadores de elite, e (ix) biomarcadores mediados vagalmente parecem ser altamente sensíveis a alterações nas cargas de treino, sendo capazes de as prever diariamente. As avaliações apresentadas e resultados demonstraram implicações práticas para o processo de treino, permitindo uma melhor objetivação e controlo. Destaca-se a importância de uma abordagem holística para monitorizar os efeitos do treino e interpretar o rendimento em natação.

List of abbreviations and symbols

AnT	Anaerobic threshold
A.U.	Arbitrary units
BLIS	Blood lactate increase speed
BM	Body mass
CI	Confidence interval
CMJ	Countermovement jump
e.g.	As example
FINA	Fédération Internationale de Natation
GRADE	Grading of Recommendations Assessment, Development and Evaluation
[Glu ⁻]	Blood glucose concentrations
HR	Heart rate
HRV	Heart rate variability
ICC	Intraclass correlation coefficient
[La ⁻]	Blood lactate concentrations
[La ⁻] _{AnT}	Blood lactate concentrations at the anaerobic threshold
[La ⁻] _{rate}	Blood lactate concentrations increase rate
net[La ⁻]	Difference between the [La ⁻] obtained after the current step and the previous one
LnRMSSD	Logarithm of root mean square of the successive differences
PECOS	Participants, Exposition, Comparators, Outcomes and Study design
POMS	Profile of mood state
PSS	Pooled sample size
r	Person's correlation coefficient
RMSSD	Root mean square of the successive differences
RoBANS	Risk of bias for randomized and non-randomized studies
ROM	Range of motion
RPE	Rating of perceived exertion
SD	Standard deviation
SEM	Standard errors of the mean
SHAP	Shapley additive explanations
SI	Symmetry index
SL	Stroke length
SR	Stroke rate
v	Mean velocity
V _{AnT}	Velocity correspondent to the anaerobic threshold
V _{3.5}	Velocity correspondent to the 3.5 mmol·L ⁻¹ of blood lactate concentration
V ₄	Velocity correspondent to the 4 mmol·L ⁻¹ of blood lactate concentration

$v_{SL_{inf}}$	Velocity correspondent to the stroke length inflexion point
$v_{SR_{inf}}$	Velocity correspondent to the stroke rate inflexion point
$\Delta[La^-]$	Differential blood lactate concentrations between the last two steps of the incremental protocol
Δv	Differential mean velocity between the last two steps of the incremental protocol

Chapter 1

General introduction

The evaluation, control and advising of athletes training and performance potential, which is given the simplistic designation of training control, has become a fundamental aspect in the training planification of any sport (Villanueva, 1994; Mujika et al., 2018; Vilas-Boas et al., 2020). In fact, the need to control the training process as a means of increasing the quantity and quality of information available, independently of the area and scope of action is being discussed for more than 30 years (Proença, 1985; Vilas-Boas, 1989). Therefore, training control is essential for the coaches to direct the training process, assessing and evaluating the intellectual, functional and emotional modifications of the practitioner or team (Castelo, 1996; Fernandes et al., 2014; Mujika et al., 2018).

Swimming is a popular recreational and competitive sport among all generations. In a broad sense, it is one of the most widely practiced and cherished physical activities worldwide due to its effect on health and wellbeing (Maglischo, 2003; Ruiz-Navarro et al., 2023) and Portugal is no exception. In fact, competitive swimming in Portugal ranks (from 2021) as the second most popular sport among registered participants (<https://www.pordata.pt>). Among the various areas within swimming (e.g. recreational, educational, rehabilitation and competitive), the latter demands the greatest effort, discipline, persistence, self-confidence and determination (Vilas-Boas et al., 2020).

Training control has been a primordial task in competitive swimming for several years, encompassing tasks related to the evaluation of the swimming performance determinants development to assess the effectiveness of exercise and training programs (Vilas-Boas, 1989; Thompson et al., 2006; Vilas-Boas et al., 2020). In a broader way, training control consists in the art of observing, measuring and advising the swimmer to achieve greater effectiveness (Landry,

1977) and the part of the swimming preparation that tries to assess its elements and assess the swimmers true values (Teleña, 1997).

Since training control implies judgment, estimation, classification and interpretation, the measurement process is the main vehicle for obtaining information, whether in a complex or simple situation (Mathews 1980; Pyne et al., 2004). It can be divided into two inseparable activities: training loads and swimmers evolution control, based on physiological and technical variables, emphasizing that none of them has meaning without the other (Pendergast et al. 1977; Villanueva 1997; Clemente-Suárez et al., 2021). One of the primary objectives of training control specialists is to create, for each individual (regardless of age and competitive level), the means of assessing their motor skills to better understand and explore their limitations (Cazorla, 1984; Chatard et al., 1992; Mujika et al., 2018).

The importance of training control in swimming emerges from two main problematics. Firstly, the competitive swimming characteristics (individual, cyclical, continuous and closed sport) and the fact that is practiced in an environment that is averse to the human condition. These constraints imply that reaching the elite level normally requires an involvement and dedication from a very early age (Platonov & Fessenko, 1994; Maglisho, 2003). Secondly, competitive swimming depends on a multiplicity of biomechanical, physiological, psychological, genetic and contextual factors that interact both directly and indirectly in performance (see Figure 1).

On the other hand, the evolution of the training process depends on the increase in volume, intensity and frequency of training (Olbrecht, 2000; Smith, 2003). However, incredible training volumes were reported long ago (Costill, 1985), and more recently (Clemente-Suárez et al., 2017; Nugent et al., 2017), with a total of 600 training sessions in a year (365 days) and about 4000 km swum (Platonov & Fessenko, 1994). This understanding, together with the fact that elite performance in competitive swimming has reached a level so high of physical

demand (close to swimmers genetic ceiling; Turner et al., 2021) made the diagnosis and evaluation of swimmers training fundamental to their training process (Fernandes et al., 2011; Mujika et al., 2018). Therefore, the only possible solution to this problem seems to be the increase of training efficiency, being urgently required concrete and objective mechanisms that reflect the state of swimmers' preparation to optimise the available resources to maximise the final result.

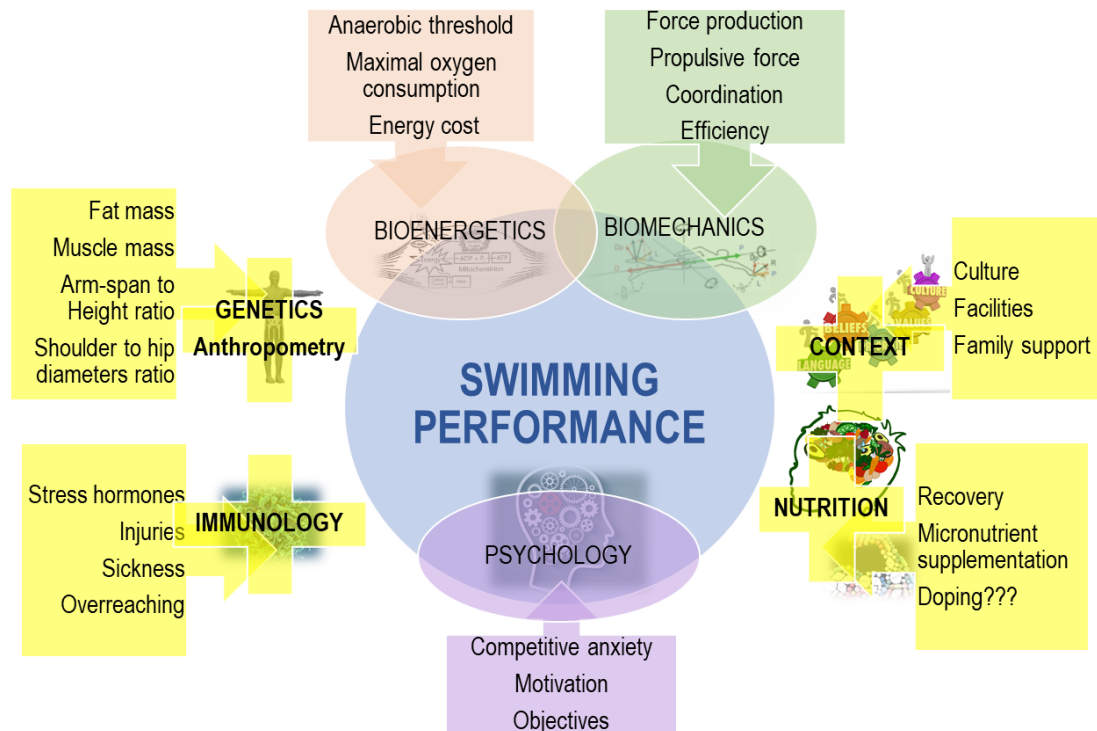


Figure 1. Synthesis diagram of the determinants of swimming performance (adapted from Fernandes & Vilas-Boas, 2006; Barbosa et al., 2006 and Figueiredo, Pendergast et al., 2013).

The critical factors related to swimming performance (considered as the time spent to cover a given distance), is one of the most attractive topics in swimming science. The moment when technical, conditioning, motivational, stress and tactics factors come together to produce a single outcome is the actual competition (Smith et al., 2002; Mujika et al., 2018), with video analysis or timing being common evaluation methods. However, it seems that these may not be sufficient to discriminate the impact of the performance determinants and to understand their strengths and weaknesses (Smith et al., 2002). Therefore, it is necessary, through various tools with clear evidence of the relationships between bioenergetic and biomechanical profiles and performance in competitive

swimming, to assess and monitor all aspects of the training process to optimize the available resources and enhance the final result (Barbosa et al., 2009; Vilas-Boas, 1993; Vilas-Boas et al., 2020).

The most appropriate way to respond to this problem seems to be the rational construction and implementation of training evaluation and advising programs for swimmers into the annual planning, to follow the swimmer's journey throughout their career. In the specialized literature, some descriptions and results of specific integrated testing and assessment systems for swimmers are available, such as: (i) protocols to find and track young talents for swimming (Cazorla, 1993; Fernandes & Vilas-Boas, 1999; Rama & Alves, 2007), (ii) programmed evaluation of young swimmers to create databases for longitudinal studies and to understand the evolution of the variables related to the performance in these swimmers throughout the training process (Navarro, 1995; Rama & Alves, 2007) and (iii) a set of tests to assess the developmental behaviour of the competitive swimming performance determinants (Wilke & Madsen, 1990; Pyne et al., 2000).

To make the programs viable to the training process it is important to understand and follow the concerns related to swimming performance in the everyday swimmers' context. The Faculty of Sports of University of Porto and Porto Biomechanics Laboratory (LABIOMEUP-UP) in collaboration with the Portuguese Swimming Federation (FPN) developed an integrated evaluation protocols and training control, combining the areas of biomechanics, physiology, anthropometry, immunology, nutrition, physiotherapy and psychology. These protocols have the general objective of multidisciplinary supporting swimmers and technicians regarding the control and evaluation of the training and competition processes in a long-term strategy (young swimmers in path to elite level), as well as in the short- and medium-term support of elite swimmers involved in the Olympic Games preparation (see Figure 2).

In this doctoral thesis, we will focus on the evaluation and training control of high-level swimmers, since its importance in the training process is undeniable and has been reported for several decades (Mathews, 1980; Castelo et al., 1996; Mujika et al., 2018), particularly in competitive swimming (e.g. Costill, 1985; Wilke and Madsen, 1990; Pyne et al., 2001; Fernandes et al., 2013). To minimize errors that could compromise swimmers' progress to the highest level of performance and to improve the effectiveness of the training process, we aim to demonstrate the use of swimmers evaluation and training control in enhancing and objectifying swimming performance, as well as its integration into daily routines addressing performance and health concerns.

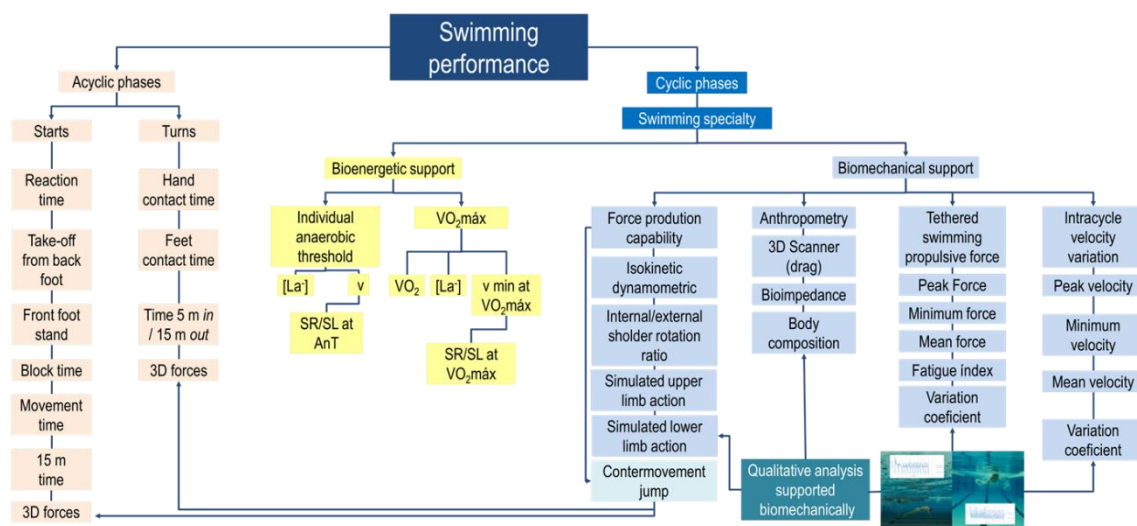


Figure 2. Evaluation tests (biomechanical, physiological and anthropometrical related fields) performed by the Olympic and pre-Olympic Portuguese swimming team.

The current thesis comprises 12 chapters, with the **Chapter 1** serving as the General Introduction where it is provided context for the training process in competitive swimming and emphasized the importance and inclusion of training evaluation and control. Additionally, it is presented and described all the chapters of this dissertation, particularly **Chapters 2** through **7** where it is featured the systematic review with meta-analysis and five experimental studies. In **Chapter 8**, the General Discussion compare the results obtained in our experimental studies with relevant literature and in **Chapters 9, 10 and 11** are contained the main conclusions of this dissertation, suggestions for future research and the respective bibliographic references. Also included in this work are the

Appendices I, II, III, IV and V, which present supplementary experimental studies that complement our primary research.

Focusing on **Chapter 2**, a systematic review with meta-analysis regarding swimmers anthropometry is presented, with the aims of evaluate the published evidence and investigate the relationship between anthropometrics and swimming performance in different competitive levels, ages, sex and specialty. Although physiological and biomechanical variables have been shown to have the greatest potential to assist swimmers in improving sports performance (Figueiredo, Pendergast, et al., 2013; Zacca et al., 2019), genetics and anthropometry appear to have a substantial influence on the overall swimming performance (Anderson et al., 2008; Fernandes & Vilas-Boas, 2006; Issurin, 2017).

In fact, since 1970s, it was reported that the swimmers body shape and functions were closely related, being decisive in achieving a high level of performance (Hebbelink et al., 1975; Clarys & Jiskoot, 1975). Also, since anthropometric and somatic are accepted to be more genetically determined and less trainable than most physiological attributes, they play a key role in identifying talented/gifted athletes early (Issurin, 2017; Alves et al., 2022). The analysis of the whole spectre of swimmers' development and their performance changes related to the anthropometry, allows to understand if the predisposition for swimming is more genetic related or training influenced (Sammoud et al., 2023; Pan et al., 2023). Therefore, by clarifying the relationship between anthropometrics and swimming performance and the effects of age, sex, competitive level and specialty, it is possible to provide researchers and coaches with useful guidance in swimming talent identification and trainability.

Complementarily, among the various determinants influencing swimming performance, physiological variables have been extensively studied using established testing methods where researchers have recurrently attempted to characterize different efforts (Peyrebrune et al., 2014; Pyne et al. 2001; Toubekis

& Tokmakidis, 2013; Vilas-Boas et al., 2014). It is widely acknowledged that the aerobic energy system plays a crucial role in most competitive swimming events (Capelli et al. 1998; Olbrecht, 2011; Rodríguez & Mader, 2010; Troup, 1984), being one of the most practical approaches the assessment of the anaerobic threshold (AnT; Fernandes et al., 2010; Mader et al., 1978; Wasserman et al., 1973). This physiological indicator enables the identification of the point beyond which an increase in swimming speed results in the disruption of the body's internal balance, as aerobic metabolism alone cannot meet the energy demands (Faude et al., 2009; Fernandes et al., 2011; Zacca et al., 2019). However, given that available studies on AnT have predominantly focused on the front crawl technique (de Jesus et al., 2015; Fernandes et al., 2010; Pyne et al., 2001; Thanopoulos, 2010), swimmers specializing in other conventional swim techniques find their training tailored to the specifics of front crawl.

Therefore, **Chapter 3** presents a study with a substantial number of elite swimmers, aiming to characterize the AnT in the four conventional swim techniques, i.e., butterfly, backstroke, breaststroke and front crawl. The relevance of this study also comes from the fact that defining the AnT using biomechanical variables makes it more accessible for clubs with limited economic and human resources (Figueiredo, Morais, et al., 2013). In fact, the general biomechanical variables, like stroke rate and length, can be obtained using a stopwatch, simplifying the incremental protocols implementation in the training process (Fernandes et al., 2010; Zacca et al., 2020). To this end, given that swimming technique reflects changes in energy patterns (Toussaint & Hollander, 1994; Toubekis et al., 2011; Figueiredo et al., 2016), we hypothesized that the AnT also represents the intensity at which we observe a point of inflection in stroke rate and a deflection in stroke length in the four conventional swimming techniques, as proposed before (Keskinen & Komi, 1993).

In **Appendix I**, as a complement to **Chapter 3**, a study is presented where the incremental protocol and the determination of AnT were performed in medley, since the aerobic capacity is also frequently developed using training sets that

combine the four conventional swimming techniques. Along with the AnT, the maximal oxygen uptake ($\dot{V}O_2\text{max}$) and the minimum velocity required to elicit this intensity ($v\dot{V}O_2\text{max}$; Fernandes et al., 2008; Pelayo et al., 2007; Ribeiro et al., 2017) stand out as paramount in assessing swimmers aerobic potential. $\dot{V}O_2\text{max}$ is widely presumed to be the gold standard for maximal aerobic power, an exercise intensity related to one of the primary areas of interest in swimming performance diagnostics and training prescription (Fernandes et al., 2008; Millet et al., 2023; Zacca et al., 2016). Therefore, in **Appendix II** it is presented a combination of the AnT and $\dot{V}O_2\text{max}$ analysis in medley sets, since reference values for this type of efforts are still not well described in the literature.

As displayed in Figure 1, typically there exists a consensus that the physiological and biomechanical factors are most determinant and most examined (Vilas-Boas, 2010) in enhancing performance and achieving a high level in competitive swimming (Barbosa et al., 2010; Figueiredo, Pendergast, et al., 2013; Zamparo et al., 2020). Biomechanical evaluation has a particular fundamental role to enhance swimmers performance and prevent injuries imposed by systematic cyclic movements (Batalha et al., 2013; Figueiredo et al., 2016). Increments in swimmers muscular strength in dry-land condition should translate into an increased ability to generate swimming propulsive force, with the technical aspects of upper and lower limbs mechanics largely determining the degree of transfer into faster performances (Hawley et al., 1992; Garrido et al., 2012, Ruiz-Navarro et al., 2022). However, the use of different methodologies for strength assessment and their inherent limitations makes the data difficult to interpret (Kwok et al., 2021).

Muscle strength and power should be closely monitored since they are important motor qualities that influence both swimming propulsion (Hawley et al., 1992; Batalha et al., 2015) and performance (Gola et al., 2014). As it remains uncertain how the competitive level of a swimmer influences the relationships between strength and power with sprint swimming performance (Amaro et al., 2019; Tan et al., 2021), in **Chapter 4** it is presented a study where linear associations

between each of the four conventional swimming techniques sprint performances and upper and lower limbs strength were examined. This information will assist swimming related researchers and coaches to understand if the relationships can be sustained regardless of the competitive level that is analysed or only sufficient to distinguish swimmers between their levels.

The repetition of the same movements thousand times per training unit, a characteristic of competitive swimming training (typically twice per day) can lead to the development of overload injuries (Becker, 2011; Hill et al., 2015; Serra et al., 2017). Therefore, in **Appendix III** it is presented an experimental study that involved isokinetic evaluation of elite swimmers with the objective of characterizing symmetry in movements associated with their training process (extension of the shoulder and knee) and defining the strength ratio between shoulder rotators (one of the most characteristic swimmers injuries; Van Dorssen et al., 2015). It aims to highlight the usefulness of the information obtained for the swimmer's training process by detecting potential muscle imbalances and a higher predisposition to injuries during a competitive season (Batalha et al., 2015).

The relevance of this study is rooted in the challenge of finding isokinetic strength profiles and is related to one of the most characteristic injuries in swimming (Rupp et al., 1995; Hill et al., 2015). It was hypothesized that elite swimmers exhibit muscular symmetry and shoulder rotator ratios exceeding normative values for the general population (Ivey et al., 1985; Ellenbecker & Davies, 2000; Ellenbecker & Roetert, 2003; Batalha et al., 2013). In addition, as start time in competitive swimming might represent up to ~26% of the total race time (depending on the event; Cossor & Mason, 2001; Vantorre et al., 2010) and is fundamental for the outcome, a complementary aim was to determine if isokinetic power produced during shoulder and knee extensions is directly related with swimming track start performance.

For hydrodynamic and inertial reasons, it is expected that swimming technique should be as symmetrical as possible, e.g. the contralateral movements performed by the upper and lower limbs follow the same motor path and the force and resultant power applied by each body side are similar. Regardless isokinetic evaluations usefulness for health-related purposes, the **Chapter 5** aimed to add a new dimension to isokinetic assessments in competitive swimming by seeking to identify the relationship between symmetry in force production in and out of the water. Since swimmers spend most of their training time in an aquatic environment, a distinct pattern in force production between the two settings could result from the specialization of their training. For this purpose, isokinetic assessments and tethered swimming evaluations (both previously demonstrated as capable of identifying force asymmetries; Secchi et al., 2011; Toubekis et al., 2010), were employed. It was hypothesized that the force values and symmetry indices obtained in both conditions would be similar and exhibit a strong direct relationship.

Swimming techniques that show greater intracycle velocity variations (Vilas-Boas et al., 2011) also exhibit larger intracycle variations in force production (Morouço et al., 2011) and are associated with higher energy expenditure (Fernandes et al., 2014). In **Appendix IV**, as a complementary study to **Chapter 5** topic regarding use of tethered swimming, it was examined the relationship between energy cost and propulsive force in the front crawl technique. Metabolic conditioning and propulsive force development are fundamental to achieve higher swimming performances (Figueiredo et al., 2011; Figueiredo, Pendergast, et al., 2013; Morouço et al., 2011), justifying its systematic evaluation. Given that previous research has evidenced direct relationships between propulsive force (determined using tethered swimming) and swimming performance (Yeater et al., 1981; Morouço et al., 2011), this study may add another dimension to the data obtained from tethered swimming. We aimed to assess the energy cost and propulsive force variables during front crawl maximal efforts, confirming their eventual direct relationship.

With the significant advancements in data acquisition in recent years, a considerable challenge arises in transforming the vast amount of collected data into useful information. This issue is also pertinent to the information derived from training and control processes. Therefore, new and, when possible, automatic devices and procedures are needed that can accomplish the transformation from data in practical information to be used in the everyday training process. Given the multifactorial nature of swimming performance, and the fact that a predicting model should be as practical as possible (Silva et al., 2007), the input data selection should be derived from the literature (biomechanical, physiological, psychological, genetical and contextual; Barbosa et al, 2010), and integrate data easy to collect and apply in the training context (Post et al. 2022). Artificial neural networks do not force the variables into a linear or nonlinear relationship, with the benefit of reducing the possible misinterpreting on how that variable interacts with the outcome (Hevey, 2018). On this basis, neural networks are an attractive alternative to statistical methods computing quantitative measurements of confidence and correlation (Pearl, 2001; Lundberg et al., 2020).

In **Chapter 6** it is presented a study that, using a three hidden layers deep artificial neural network model with Shapley additive explanations values, aiming to assess the prediction capability and relationships strength of age, training background and duration, anthropometrics, countermovement jump and general biomechanical (stroke rate and length) related variables on swimming performance. It was hypothesized that, when artificial neural network models are employed (by not forcing linear or nonlinear relationships), simple and training specific evaluations should be capable of explaining variations in competitive swimming performance.

Complementarily, swimming is a demanding form of locomotion that requires coordination of the upper and lower limbs to efficiently propel the body in a highly resistant environment (Seifert et al., 2014; Guignard et al., 2019). When analysing the swimming technique an old question remains unanswered: the lower limbs propulsion contribution in front crawl swimming (Ribeiro et al., 2015; Bartolomeu

et al., 2018). The accepted literature values of 10-15% (Andersen & Sanders, 2018;ourgoulis et al., 2014; Deschodt et al., 1999) contrasts with other emerged findings, indicating that swimmers can attain roughly 57-86% of the velocity achieved during full-body swimming when relying solely on the lower limbs (Bucher, 1975; Bartolomeu et al., 2018). Therefore, these controversial results put in question the believe that swimming propulsion is almost entirely due to upper limbs and trunk motion (Toussaint & Beek, 1992), at least over short duration and very high intensity bouts. In **Appendix V**, an exploratory work conducted on high level swimmers is presented, using wavelet transforms on velocity vs. time curve to separate and analyse the energy of the frequencies assigned to upper and lower limbs actions to the total energy of the transformed velocity signal.

Regardless the importance of cross-sectional studies and their ability to compare various population groups (e.g. cohort groups) and different variables at a single point in time, the insights gained in a long-term perspective are narrow if only a single data point is available (Costa et al., 2012; Lee et al., 2017). Longitudinal data significantly contribute to assisting coaches in establishing practical goals and designing training protocols during intervals between competitions or seasons (Costa et al., 2010; Mujika et al., 2018; Pyne et al., 2004; Zacca et al., 2019). Moreover, the daily effects of training on elite swimmers physiological and psychological traits remain underexplored, as do reference values for biomarkers and their response to varying types of training combinations (Lee et al., 2017; Pedlar et al., 2019). Consequently, **Chapter 7** presents a study that aimed to evaluate the autonomic nervous system, sleep quality, motivation and swimming and strength performance patterns/behaviours during three consecutives seven-day cycles of training with different intensity and volume dynamics. We hypothesize that the autonomic nervous system response to the training loads may be capable to reproduce the external load and may explain modifications in swimming and strength performances.

Chapter 2

Exploring the evolution of swimmers' anthropometrics and its impact on performance: a systematic review with meta-analysis

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Abstract

Background: Swimmers' specialization according to his anthropometric profile has been and continue to be one of the most pressing problems in the training process once has implications in the specific training methods adopted, in the choice of the main swimming technique and distance to go.

Aim: To synthesize the evidence on the relationships between anthropometrics and swimming performance in different swimming techniques, distances, sex and competitive levels.

Methods: A systematic search was conducted across several electronic databases including PubMed, Scopus and Web of Science (core collection), as well as the Proceedings Books of the Biomechanics and Medicine in Swimming Symposia, with no filters applied. Using different keywords and Boolean operators for the search, all articles indexed up to July 2023 were considered for inclusion. In addition, the PECOS criteria were applied: (i) participants: competitive (minimum Tier 2) healthy swimmers of any age or sex, excluding disabled and injured; (ii) exposition: regular swimming training excluding other swimming disciplines (e.g., artistic swimming, open water) or swimming with additional apparatus (e.g., fins, paddles); (iii) comparators: not mandatory; (iv) outcomes: relationships (e.g., correlation, association) between anthropometric characterization (e.g., height, somatotype, skinfolds) and swimming performance (e.g., FINA, or World Aquatics points, speed, race times); and (v) study design: without limitations. Certainty of evidence was assessed with the GRADE approach. An inverse variance random effects model meta-analysis and moderator analysis were performed using R software (version 4.2.1).

Results: The certainty of the evidence was found to be low for arms span in female swimmers and for height and lean mass in male swimmers, and very low for arms span in male swimmers all for distances up to 100 m. The studies included mainly Tier 3 competitive level swimmers and it were assessed 138 different anthropometrical variables but only height, arm span, body fat mass and body lean mass allowed to perform meta-analyses. The body height (Fisher's $Z = -0.612$, 95% CI -0.817 to -0.408 , $p = 0.000$), arm span Fisher's ($Z = -0.666$,

95% CI -0.957 to 0.-375, $p = 0.000$) and body lean mass (Fisher's $Z = -0.712$, 95% CI -0.916 to -0.508, $p = 0.000$) showed large effect sizes, where higher height, arm span and body lean mass favour better performances (lower times) in front crawl distances up to 100m for male swimmers. However, body lean body mass tests for the magnitude of the impact of heterogeneity were identified as significant ($p < 0.000$) and high ($I^2 = 77.2\%$). The moderator analysis showed that Tier level and year of articles publication did not significantly explain the correlation of height, either as isolated or combined factors in the model ($p > 0.208$).

Conclusion: It was only possible to identify positive effects of anthropometric traits in front crawl swimming in distances up to 100m for swimmers corresponding to Tiers 2 and 3. Does not exist sufficient information yet to describe how anthropometry can affect de swimming performance in Tiers 4 and 5.

Registration: The original protocol was registered (<https://osf.io/eayzi>) at the Open Science Framework.

Keywords: anthropometry, competitive swimming, performance

Introduction

The ideal athletes' body size and shape adapted to the specificities of any sport has been a topic of great interest through the years (Norton & Olds, 2001; Rejman et al., 2018). Some physical characteristics can provide an edge in one sport or another, allowing to define competitive levels (Carvalho et al., 2023; Morais et al., 2013) and even playing positions (Kawama et al., 2022; Vega et al., 2020). Highlighting the variations in body dimensions and proportions specific to different sports or events has consistently held great significance from both theoretical and practical standpoints.

However, it is crucial to remain concerned of the dynamic nature of sports, where the rules, techniques, equipment technologies and facilities are subject to continuous evolution (Foster et al., 2012; Mujika et al., 2018). The role and contribution of various biological features associated with sports performance is therefore relative and transient (Issurin, 2017). Early on, studies on anthropometrics primarily adopted a descriptive approach, focusing on detailing rather than analyzing the data (Ackland, 1999; Carter, 1970; Hebbelinck et al., 1975; Helmuth, 1980). More recently, there is growing interest in understanding how anthropometric traits relate to (or even predict) performance and even including in predicting models (T. M. Barbosa et al., 2019; Dopsaj et al., 2020; Lätt et al., 2010).

Swimming is a very popular sport around the world performed with the aim of covering any given distance as fast as possible. Given its characteristics (individual, cyclical, continuous and closed) and being practiced in an aquatic environment adverse to the human condition, swimmers are involved in training at very young ages and start competing before 10 years old (Kojima et al., 2012; Silva et al., 2012). Swimming performance depends on a multiple influence of biomechanical, physiological, psychological, genetic and contextual factors that interact both directly and indirectly (T. M. Barbosa et al., 2019). Although among them physiological and biomechanical variables have been shown to have the

greatest potential to assist swimmers in improving sports performance (Barbosa et al., 2010; Carvalho et al., 2020; Figueiredo, Pendergast, et al., 2013), genetics and anthropometry appear to have a substantial influence on the overall swimming performance.

In fact, in competitive swimming, the shape and dimensions of the swimmers' body and upper limbs influence the propulsive capacity and the intensity of the hydrodynamic drag force to which the swimmer is subjected to a given swimming speed. Moreover, anthropometric factors have an important role in detection and selection of talent in swimming (Ackland, 1999; T. M. Barbosa et al., 2019). For example, in children / young age swimmers, the found predispositions for swimming at an initial stage of selection are low body mass with superior body height, wide hands and long feet, as well as narrow ankles and wrists (Morais, Marques, et al., 2014). However, it is worth noting that anthropometrics is more genetically controlled compared with physical fitness attributes (Issurin, 2017), and the most reliable prognostic traits in swimming include the skeletal dimensions (Morais et al., 2013). Therefore, talent development and follow-up depend on genetics and environmental conditions, as well as its interactions (Barbosa et al., 2010; Figueiredo, Pendergast, et al., 2013).

Since 1970s, it was reported that the swimmers body shape and functions were closely related to each other, being decisive in achieving a high level of performance (Hebbelinck et al., 1975). Swimmers' specialization according to his anthropometric profile has been and continue to be one of the most pressing problems in the training process once has implications in the specific training methods adopted, in the choice of the main swimming technique and distance to go (Dopsaj et al., 2020; Hebbelinck et al., 1975; Sammoud et al., 2018b). Swimmers with tall stature and long limbs have better potential to become elite swimmers across all distances, especially in short distance swimming, because they have better mechanical advantage in the development of propulsive force, while swimmers with shorter and more robust have higher potential to became elite breaststrokes or long-distance swimmers (Ackland, 1999; Sammoud et al.,

2018a; Sekulić et al., 2007). In addition, swimmers with higher skinfolds (more subcutaneous fat) are prone to high-level long-distance open-water events (Shaw & Mujika, 2018).

Usually, swimmers' characterization is performed by contrasting with non-swimmers' groups (Marek et al., 2015; Rejman et al., 2018) or only with a specific group of swimmers (Dopsaj et al., 2020). It is important to understand which variables can be explored and manipulated with/by swimming training and which are genetically dependent. For example, in early ages the anthropometric advantage is related with the early maturational development (Baxter-Jones et al., 1995; Lätt et al., 2009b; Silva et al., 2012). However, in adult swimmers, anthropometric variables (e.g., height, weight, body mass index) did not discriminate between performance levels (Dopsaj et al., 2020; Lätt et al., 2010). Therefore, it is still not clear what anthropometrics discriminates between elite and non-elite swimmers and if they can be achieved by practicing swimming.

The analysis of the whole specter of swimmers' development and their performance changes related to the anthropometry (exists a compelling evidence that anthropometric and somatic characteristics play a key role in the early identification of talented/gifted swimmers), allows to understand if the predisposition for swimming is more genetically determined or training influenced, since somatic characteristics are less trainable than most physical fitness attributes (Issurin, 2017). In addition, it may help to understand why so many good young swimmers with national and international records do not reach Olympic standards and feels force to drop out from the modality (Issurin, 2017). Therefore, longitudinal approaches have been increasing and gaining more relevance in scientific research (Ferreira et al., 2021; Morais et al., 2015; Zacca, Azevedo, Ramos, et al., 2020).

The aims of this systematic review were to evaluate the published evidence and investigate the relationship between anthropometrics and swimming performance in different swimming techniques, distances, sex, and competitive level. In

addition, we detail of the pattern of change(s) in swimmer anthropometric characteristics since inception. Clarifying the relationship between anthropometrics and swimming performance and the effects of age, sex, competitive level, and stroke specialty, can provide coaches with useful guidance in swimming talent identification and trainability.

Methods

The systematic review protocol was designed according to PRISMA 2020 (Page et al., 2021) and the Cochrane Handbook 2nd edition (Cumpston et al., 2022).

Eligibility criteria

Original research articles (if published in peer-reviewed journals) and meeting works specifically from the Proceedings Book of the Biomechanics and Medicine in Swimming¹ were eligible for inclusion with no restrictions on language or publication date. Letters, editorials, commentaries, and reviews were excluded. The research questions were defined by the Participants, Exposition, Comparators, Outcomes and Study design (PECOS) as follows: (i) participants: competitive (minimum Tier 2 of the Participant Classification Framework²) (McKay et al., 2021) healthy swimmers of any age or sex, excluding disabled and injured; (ii) exposition: regular swimming training excluding other swimming disciplines (e.g., artistic swimming, open water) or swimming with additional apparatus (e.g., fins, paddles); (iii) comparators: not mandatory; (iv) outcomes: relationships (e.g., correlation, association) between anthropometric characterization (e.g., height, somatotype, skinfolds) and swimming performance

¹ The International Symposia for Biomechanics and Medicine in Swimming have been held every four years since 1970 and are considered the most prestigious international aquatic-oriented scientific congresses. These meetings have provided the swimming science community with some of the most outstanding contributions books and collections (Available at <https://www.iat.uni-leipzig.de/datenbanken/iks/bms/> accessed on x 2023), as sought and valuable as some of the available studies published in high-impact, peer reviewed journals. All submissions go through a peer review process, leading to a collection of peer-reviewed scientific papers, serving as a valuable resource for all who are interested in keeping up to date with aquatic research. Relevant pioneering works were published in the 13 editions of the Symposium, adding relevant information to the current review.

² Tier 2: Trained/Developmental; Tier 3: Highly Trained/National Level (Provincial/State or Academy Programs); Tier 4: Elite/International Level; Tier 5: World Class.

(e.g., FINA or World Aquatics points, speed, race times); and (v) study design: without limitations.

Information sources

Searches were conducted on July 11, 2023, in PubMed, Scopus and Web of Science (core collection), as well as in the Proceedings Books of the Biomechanics and Medicine in Swimming Symposia, with no filters applied. After automated searches, the reference lists of the included studies were screened. The prospective snowball citation tracking of the included studies was performed using the databases mentioned after full text analysis, to retrieve potentially relevant studies that had not emerged in the initial search. Two external experts with Ph.D. degrees in sports sciences and published research on biomechanics and physiology was consulted to provide further suggestions for potentially relevant studies. Search strategy will not be provided, to avoid biasing the experts' search. After the final list of studies completed, all the databases were again consulted to retrieve errata, corrigenda/corrections, or retractions of the included studies, as some may have been found to be fraudulent or retracted. Pre-published protocols or open-access trial registrations of the included studies was retrieved to complement the analyses (e.g., risk of selective reporting).

Strategy search

Boolean operators AND/OR were used and the full search strategy for each database is available in the Supplementary Material (Table S1). The general search strategy used free text terms: swim* [in title or abstract] AND (Perform* OR test* OR velocity* OR speed* OR Distance* OR "FINA point*" OR "World Aquatic" OR time OR Bout*) [in title or abstract] AND (Anthropometr* OR somat* OR "body composition" OR Bioimpedance OR morpholo* OR skinfold* OR "skin fold*") [in title or abstract].

Selection process

DDC and MA independently screened all database records and performed manual searches, as well as snowballing citation tracking, with disagreements

resolved by MJC and RJF. Automated removal of duplicates was performed using EndNote 20.6 (Clarivate™ Analytics, Philadelphia, PA, USA), but further manual duplicate removal was required.

Data collection process and data items

DDC and MA completed initial data extraction independently and no automation tools was used. JA and RRC later reviewed the entire process and consensus had to be achieved. The data required for meta-analysis was fulfilled by DDC and MA and then reviewed by JA and MJC. RRC provided a final verification of the quality of data inserted into the table. The data items included the author, year, country, sample size, anthropometric traits (e.g., height, weight, skinfolds, somatotype), swimming performance (e.g., velocity, time, scoring points), swimming specialty (e.g., distance and/or swimming technique), competitive level (tiers 2 to 5), additional data (e.g., age, sex, health, training status, other participant characteristics). Information on competing interests and funding were also collected.

Data management

The articles that did not provide information on relationships / correlations / associations between anthropometric and swimming performance were excluded without reaching the authors. This was determined to reduce publication year bias and possible unavailability of authors of older publications as anthropometric related studies are reported from the 1970s or earlier. Anthropometric and performance variables (mean $\pm$ SD) were recorded and, if the study presented 95% confidence intervals (CIs) or standard errors of the mean (SEM), means and standard deviations were derived from the 95% CI or SEM using Cochrane's RevMan Calculator for Microsoft Excel (Drahotka & Beller, 2020). When articles had different formats but reported individual values, means $\pm$ SD were calculated by DDC and RRC. When articles present relationships in without separating different performance levels, the lower performance level was assumed. In cases where articles contained multiple evaluation moments and their corresponding relationships, only the first moment was collected. Finally, for papers in which

data was presented in graphs, values were extracted independently by two authors (DDC and JA) using the WebPlotDigitizer software v4.6 (Ankit Rohatgi, California, USA; available at <https://automeris.io/WebPlotDigitizer>) with all values rounded to two decimal places (Rohatgi, 2022).

Study risk of bias

This assessment was performed applying Cochrane's risk of bias for randomized and non-randomized studies (RoBANS) instrument to six domains (Kim et al., 2013): (i) selection of participants (e.g., inadequate participant); (ii) confounding variables (e.g., inadequate confirmation and consideration of variables); (iii) measurement of exposure (e.g., insufficient information described); (iv) blinding of the outcome assessments (e.g., prior knowledge of interventions); (v) incomplete outcome data (e.g., restricted available information, missing participants); and (vi) selective outcome reporting (e.g., unregistered protocol, reporting of results deriving from analyses not reported in the methods). DDC and MA independently assessed RoBANS for all studies. Two assessment types were presented: one per outcome domain (e.g., anthropometrics, performance) and one per study (worst case scenario, i.e., based on the worst per outcome assessment).

Effect measures

For the main outcomes, means and standard deviations were presented (or median and interquartile range when appropriate). Correlation values between main outcomes (e.g., anthropometrics; swimming performance tests) were presented alongside their confidence intervals.

Synthesis methods

A minimum of three studies that provided data (e.g., correlation) for the same outcome were considered for meta-analyses (García-Hermoso et al., 2019), to avoid small sample sizes (Abt et al., 2020), thus, to minimize chances of reduced confidence in the body of evidence (Guyatt et al., 2011). The main meta-analysis was based on correlation coefficients (r) as a well-known effect size estimate.

Correlational data was used to compute the effect size (and its variance) for each study. Correlations computations were carried out using Fisher's Z-transformed values. Correlation coefficients were entered along with the corresponding sample size or related data (i.e., standard error; variance; Fisher's Z; t value; p-value), and the software (Comprehensive Meta-Analysis program, version 2; Biostat, Englewood, NJ, USA) was set to produce pooled r with 95% CI using random effects models. The inverse variance random effects model (DerSimonian and Laird) for meta-analyses was used because it allocates a proportionate weight to trials based on the size of their individual standard errors (Deeks et al., 2019) to better account for inaccuracy in the estimation of between-study variance (Hardy & Thompson, 1996) and enables analysis while accounting for heterogeneity across studies (Kontopantelis et al., 2013). The pooled effect size for r was classified as small (≤ 0.1), moderate (0.1–0.29), or large (≥ 0.30) (Cohen, 1988). The impact of study heterogeneity was assessed using the I² statistic, with values of < 25%, 25–75%, and > 75% considered to represent low, moderate, and high levels of heterogeneity, respectively (Higgins & Thompson, 2002). Meta-analyses were conducted exclusively with studies that reported correlations for males and females separately, to avoid the high risk of bias and misinterpretation that could arise from combining data from both sexes. This caution is necessary since males are typically faster than female swimmers in the pool events and differ in terms of height, body mass, lean and fat mass (Knechtle et al., 2020), as evidenced by the consistently faster times in male categories in world record data (<https://www.swimrankings.net>). Moderator analyses are planned for potential sources of heterogeneity (Knechtle et al., 2020; Neiva et al., 2011; Partridge, 2011; Pelayo et al., 1996; Seifert et al., 2010; Sonia & Nigam, 2010), including age, competitive level, swimming specialty, rule changes (e.g., prohibition of "super suits"). Computation of meta-regression is planned with at least 10 studies per covariate (Sterne et al., 2011).

Risk of reporting bias assessment

Risk of reporting bias was explored using the extended Egger's test. To adjust for risk of reporting bias, a sensitivity analysis was conducted using the trim and

fill, with LO as the default estimator for the number of missing studies. The risk of reporting bias was explored with ≥ 10 studies per outcome, with $p < 0.05$ suggesting risk of bias. However, we were cautious when interpreting these results, since the results of these tests may be explained by multiple factors not related to publication bias (Afonso et al., 2023).

Certainty assessment

Quality of studies was assessed using the Grading of Recommendations Assessment, Development, and Evaluation (GRADE). We started by assuming high quality (Cuello-Garcia et al., 2022), which could be downgraded according to four dimensions (Risk of bias, Risk of Publication bias, Inconsistency, Imprecision). Indirectness was considered low by default, due to how the eligibility criteria were defined. The criteria for the remaining dimensions are provided in Table 3. The GRADE was applied only to the principal outcomes (correlation of anthropometry and swimming performance variables), and following the Cochrane's recommendations (Deeks et al., 2019), a maximum of seven main comparisons were elected to be analysed through GRADE.

Results

Study selection

Figure 1 illustrates a flow diagram of the study selection process. Initial database searches returned 12,633 records, of which 5,684 were duplicated and 6,795 were excluded based on title or abstract screening. One-hundred and fifty-four texts were analysed for eligibility, two were removed for reasons related to participants (Knechtle et al., 2010; Tuuri et al., 2002) and eighty-six related to outcomes (Abbott et al., 2023; Alptekin, 2014; Anderson et al., 2006; Avlonitou, 1994; Bar Or et al., 1974; T. M. Barbosa et al., 2019; Bejan et al., 2010; Beretic et al., 2023; Boie & Montpetit, 1987; Caspersen et al., 2010; Cochrane et al., 2015; Cordain & Kopriva, 1991; da Silva et al., 2022; Dias et al., 2012; Dunman et al., 2006; Edmond & Milton, 2023; Figueiredo et al., 2016; Fiori, Bandeira, et al., 2022; Fiori, Zacca, et al., 2022; Georgianna et al., 2004; Gilev et al., 2021;

Gomez et al., 1997; Grimston & Hay, 1986; Hellard et al., 2003; Hohmann et al., 1999; Hue et al., 2013; Kavouras & Troup, 1996; Kjendlie et al., 2004; Kuberski et al., 2022; Kunski et al., 1988; Latt et al., 2010; Lobato et al., 2023; López Téllez et al., 2002; Maszczyk et al., 2012; Matarazzo & D'Anastasio, 2022; Mezzaroba & Machado, 2014; Mitchell et al., 2018; Moness et al., 2021; J. Morais et al., 2021; Morais, Costa, et al., 2014; J. E. Morais, P. Forte, et al., 2021; Morais et al., 2022; Morais et al., 2020; Morais et al., 2013; Morais et al., 2018; Morais et al., 2017; Morais, Silva, Marinho, Marques, & Barbosa, 2016; Morais et al., 2015; Moura et al., 2014; Naemi et al., 2012; Nevill et al., 2015; Nicol et al., 2022; Oliveira et al., 2021; Oliveira et al., 2020; Pan et al., 2023; Papic et al., 2023; Pilipko & Pilipko, 2019, 2021; Pilipko & Druzhyninska, 2015; Pogodina & Aleksanyants, 2019; Politko & Sheyko, 2020; Rejman et al., 2018; Rozi et al., 2020; Ruiz-Navarro et al., 2022; Saavedra et al., 2003; Sammoud et al., 2018a, 2018b; Shephard et al., 1974; Sidney et al., 1996; Silva et al., 2019; Silva et al., 2014; Sokołowski et al., 2023; Sprague, 1976; Stefani, 2014; Taskin, 2020; Thorland et al., 1983; Toussaint, 1992; Van Tilborgh et al., 1983; Vitor Fde & Böhme, 2010; Wadrzyk et al., 2021; Wang & Kabala, 2022; Zacca, Azevedo, Chainok, et al., 2020; Zacca, Azevedo, Ramos, et al., 2020; Zamparo et al., 1996; Zera et al., 2022; Zuniga et al., 2011). All full texts of the studies were retrieved, leading to the inclusion of 66 studies in the qualitative synthesis. Ten potentially relevant studies were identified by manually searching the reference lists of the included studies and one additional study were included in the review (Manas Banerjee, 2019). Ten further studies were identified through snowballing citation tracking and two included in the synthesis (Abbes et al., 2023; Strzala et al., 2005). Forty-eight additional studies were suggested by experts, with two fulfilling all eligibility criteria and being included in the review (Carvalho et al., 2023; Espada et al., 2023). A total of 71 studies corresponding to 67 independent trials were included in all analyses.

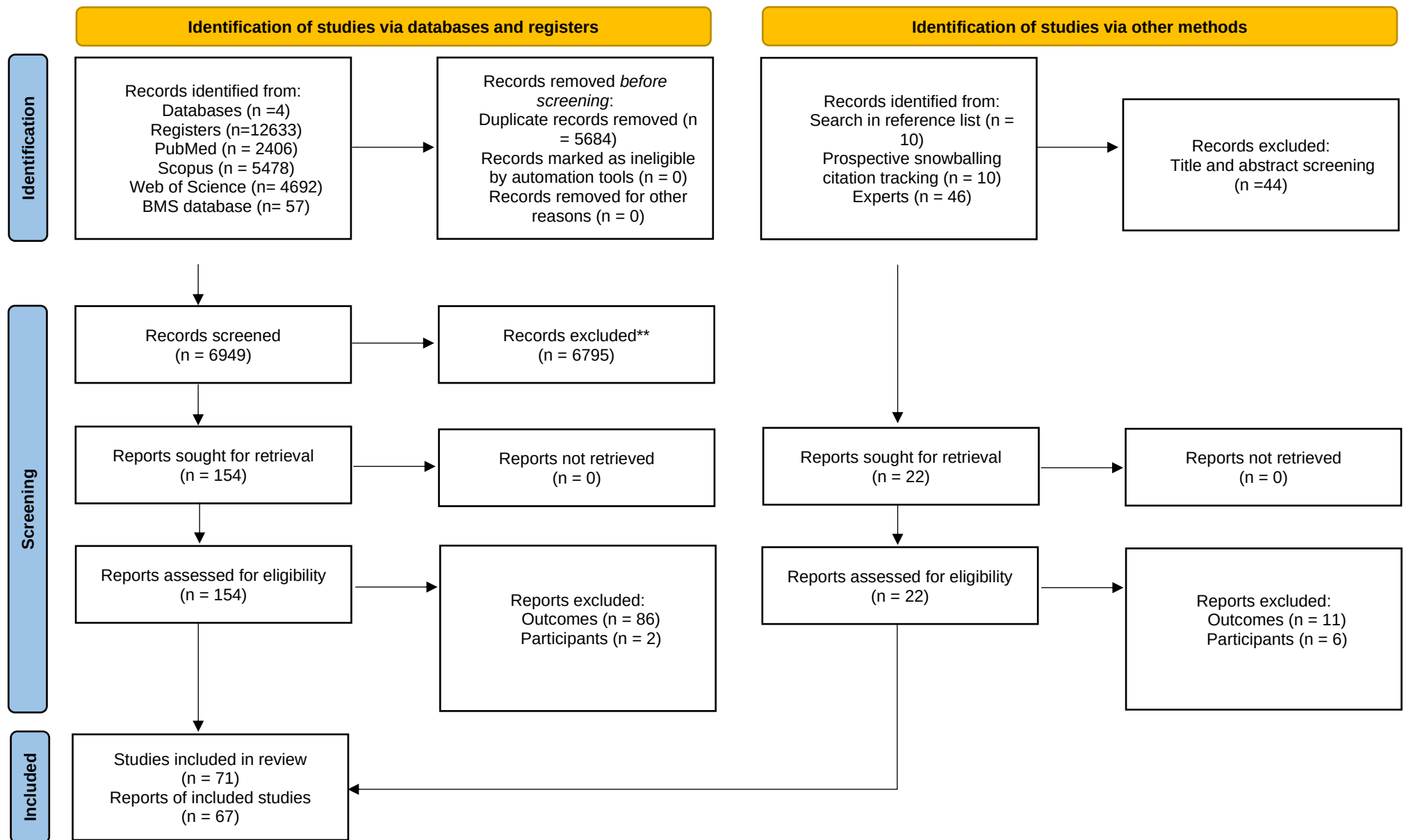


Figure 1. PRISMA 2020 flow diagram for new systematic reviews which included searches of databases, registers and other sources.

Study characteristics

A summary of participants' characteristics, anthropometric variables and swimming performance, as well as the predictive models used in the studies included in this review, are detailed in Tables 1 and 2 (respectively). Additional information on all the correlations described in the studies, which were later utilized for conducting meta-analyses, and conflict and funding details for each study, can be found in Tables S2 and S3 (respectively), in the Supplementary Material.

Publication years and geographic locations

From the studies in this review, the first was published in 1978 and the last in 2023. The number of publications was stable until around 2009 (close to 2% each year) where it was verified a substantial increase until 2015, with ~22% of the publications in 6 years (see Figure 2). Probably the interest on how to manipulate or the degree of influence of anthropometric traits on swimming performance gained more importance after the prohibition of the so-called “super suits” that allowed more muscular swimmers (and higher strength levels) to achieve incredible performance due to the reduced drag (Foster et al., 2012; O'Connor & Vozenilek, 2011). Also, a new increase in publication was observed from 2019 and after, accounting for > 45% of the selected studies in this review regarding the anthropometric relations with performance. This outcome could be related with the period of pandemic caused by COVID-19 (Arsoniadis et al., 2022; Haddad et al., 2021; Tsalis & Mougios, 2022) due to the training that swimmers were forced to perform and the changes in manipulatable anthropometries (like body fat and lean mass).

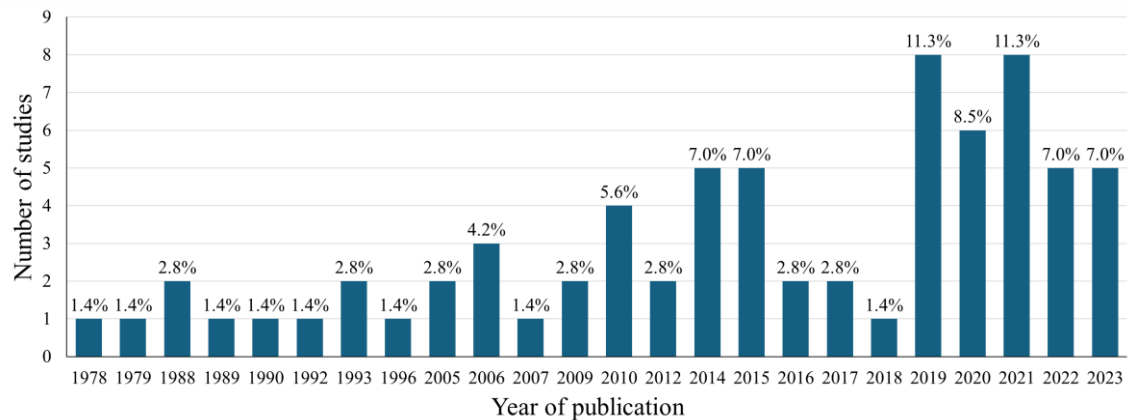


Figure 2. Distribution of number of studies published per year.

Europe emerged as the predominant continent for publications, accounting for 69% of the selected studies in this review were the remaining continents collectively contributed only 31% (see Figure 3). Within Europe, Portugal and Poland were notable contributors to the research on the relationship between anthropometry and swimming performance, with 12 and 9 studies (respectively).

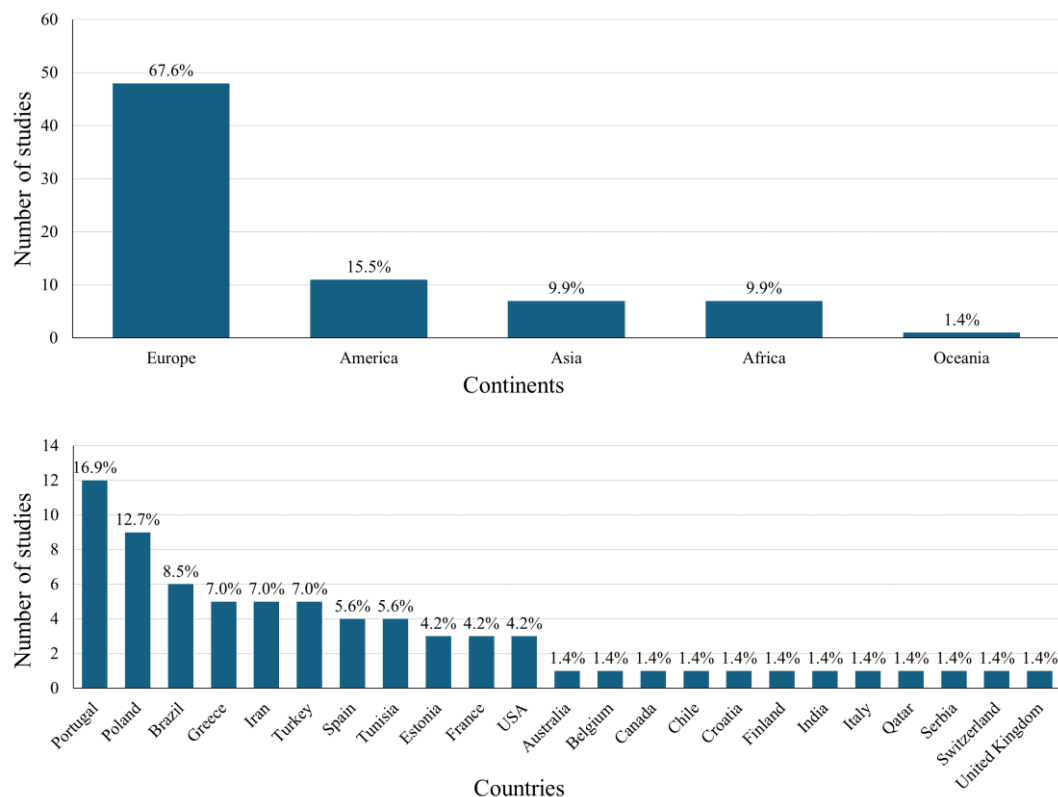


Figure 3. Distribution of number of studies published per place of publication.

Table 1. Participants and studies characteristics.

Authors (year)	Total sample - Females (%) / Males (%) G1 - n Males / n Females G2 - n Males / n Females ...	Tier Age (mean ± SD)	Test distance (intensity) Swimming techniques	Anthropometric domain Male / Female Group 1 / Group 2 / ... (mean ± SD)	Performance domain Male / Female Group 1 / Group 2 / ... Distance technique variable (unit): (mean ± SD)	Correlations (all sample or separate samples)
Abbes et al., (2023)	16 - Males (100%)	Tier 2 13.13 ± 2.06 years	200 m (maximal) front crawl	Height (cm): 164.75 ± 13.77 Body mass (kg): 60.88 ± 18.58	200 m front crawl v (m.s ⁻¹): 1.27 ± 0.14	all sample
Akşit et al., (2017)	50 - Males (50%) / Females (50%) 25 Males / 25 Females	Tier 3 Males / Females 12.4 ± 1.2/ 12.0 ± 0.9 years	200 and 400 m (maximal for a submaximal variable) front crawl	Males / Females Abdominal skinfold (mm): 15.6 ± 6.3 / 12.6 ± 4.0 Thigh skinfold (mm): 16.5 ± 5.7 / 16.8 ± 4.8 Calf skinfold (mm): 13.1 ± 4.2 / 14.6 ± 3.7 Sum of 9 skinfolds: 105.3 ± 34.3 / 97.1 ± 26.7 Sitting Height (cm): 77.5 ± 5.6 / 77.9 ± 5.0 Arm Span (cm): 159.5 ± 15.2 / 156.1 ± 9.3 Arm length (cm): 69.8 ± 11.6 / 69.6 ± 4 Forearm length (cm): 23.6 ± 6.5 / 21.1 ± 2.4 Thigh length (cm): 47.0 ± 3.6 / 46.9 ± 3.0 Leg length (cm): 36.0 ± 2.8 / 35.2 ± 2.7 Lower limb length (cm): 90.6 ± 6.5 / 89.5 ± 5.0 Foot length (cm): 24.4 ± 1.9 / 23.3 ± 1.2 Biacromial diameter (cm): 28.8 ± 2.8 / 28.4 ± 1.8 Transverse chest breadth (cm): 24.4 ± 2.8 / 22.8 ± 1.8 Bideloid breadth (cm): 37.7 ± 4.0 / 35.8 ± 2.3 Bitrochanteric breadth (cm): 26.7 ± 2.6 / 26.1 ± 2.6 Biepicondylar humerus breadth (cm): 6.6 ± 0.5 / 5.9 ± 0.3 Styloid breadth (cm): 5.2 ± 0.3 / 5.0 ± 0.3 Hand width (cm): 7.7 ± 0.7 / 7.2 ± 0.4 Biepicondylar femur breadth (cm): 9.5 ± 0.5 / 8.4 ± 0.5 Foot width (cm): 9.1 ± 0.8 / 8.0 ± 0.7 Shoulder width (cm): 98.0 ± 10.4 / 91.9 ± 6.5 Thoracic breadth (cm): 79.3 ± 9.4 / 77.6 ± 7.7 Relaxed arm circumference (cm): 24.5 ± 3.1 / 22.8 ± 2.7 Arm flexed circumference (cm): 26.8 ± 3.6 / 24.3 ± 2.6 Forearm circumference (cm): 22.8 ± 2.2 / 20.8 ± 1.6 Wrist circumference (cm): 15.0 ± 1.1 / 13.9 ± 0.7 Hip circumference (cm): 82.3 ± 7.3 / 79.8 ± 7.5 Thigh circumference (cm): 47.5 ± 5.2 / 45.3 ± 5.1 Calf circumference (cm): 32.2 ± 3.3 / 30.1 ± 2.8 Ankle circumference (cm): 21.0 ± 1.9 / 19.8 ± 1.5 Endomorphy: 3.8 ± 1.2 / 3.2 ± 1.0 Mesomorphy: 5.0 ± 0.9 / 3.7 ± 1.2 Ectomorphy: 2.5 ± 1.1 / 3.6 ± 1.4	Males / Females 200 m front crawl time (s): 158.3 ± 20.1 / 173.4 ± 19.6 400 m front crawl time (s): 333.4 ± 44.8 / 365.4 ± 44.5 Critical velocity (m.s ⁻¹): 1.16 ± 0.15 / 1.05 ± 0.13	separate sexes
Araújo et al., (1979)	16 - Males (69%) / Females (31%) 11 Males / 5 Females	Tier 3 Males / Females 15.4 ± 0.4 / 15.2 ± 0.6 years	12.5 m (maximal) front Crawl	Males / Females Height (m): 1.74 ± 0.09 / 1.59 ± 0.04 Body mass (kg): 63.15 ± 2.19 / 53.08 ± 4.43 Endomorphy: 2.48 ± 0.23 / 3.45 ± 0.54 Mesomorphy: 4.09 ± 0.17 / 3.83 ± 0.17 Ectomorphy: 3.45 ± 0.20 / 2.46 ± 0.16	Males / Females 12.5 m front crawl time (s): 7.53 ± 0.11 / 8.10 ± 0.18	separate sexes

Table 1. (continued)

Authors (year)	Total sample - Females (%) / Males (%) G1 - n Males / n Females G2 - n Males / n Females ...	Tier Age (mean $\pm$ SD)	Test distance (intensity) Swimming techniques	Anthropometric domain Male / Female Group 1 / Group 2 / ... (mean $\pm$ SD)	Performance domain Male / Female Group 1 / Group 2 / ... Distance technique variable (unit): (mean $\pm$ SD)	Correlations (all sample or separate samples)
Banerjee, (2019)	25 - Males (100%)	Tier 3 16.5 $\pm$ 0.5 years	50 m (maximal) front crawl	Foot width (cm): 8.24 $\pm$ 0.49 Foot Length (cm): 24.3 $\pm$ 2.06 Calf circumference (cm): 25.21 $\pm$ 8.82 Thigh circumference (cm): 37.76 $\pm$ 13.43 April / August 2016 Body mass (kg): 77.0 / 77.3 Body fat (%): 8.4 / 7.1 Lean body mass (kg): 70.5 / 71.8 Body fat (kg): 6.5 / 5.5 G1 / G2 / G3	50 m front crawl time (s): 26.72 $\pm$ 0.87	separate distances
Barbosa et al., (2019)	1 - Males (100%)	Tier 5 25 years	50 m (maximal) front crawl	Height (cm): 168.5 $\pm$ 8.5 / 171.7 $\pm$ 6.1 / 168.8 $\pm$ 5.1 Body mass (kg): 52.5 $\pm$ 6.4 / 57.8 $\pm$ 6.3 / 59.1 $\pm$ 5.4 BMI (kg/m ²): 18.5 $\pm$ 2.0 / 19.6 $\pm$ 1.4 / 10.5 $\pm$ 1.3 Sum skinfolds (mm): 108.2 $\pm$ 21.0 / 97.0 $\pm$ 23.3 / 100.1 $\pm$ 23.0 Body fat (%): 29.0 $\pm$ 2.1 / 17.6 $\pm$ 2.2 / 17.5 $\pm$ 2.3	April / August 2016 50 m front crawl time (s): 21.82 / 21.96	all sample
Barzdukas et al., (1992)	101 - Females (100%) G1: 49 Females G2: 28 Females G3: 24 Females	Tier 3 G1: 168.48 $\pm$ 11.45 months G2: 184.36 $\pm$ 3.96 months G3: 196.43 $\pm$ 3.95 months	200 m (maximal) front crawl	Body Height (cm): 154.2 $\pm$ 8.7 / 157.4 $\pm$ 10.2 Hand Width (cm): 7.6 $\pm$ 0.5 / 7.4 $\pm$ 0.5 Hand Length (cm): 16.5 $\pm$ 1.1 / 16.7 $\pm$ 1.0 Arm Span (cm): 154.4 $\pm$ 9.3 / 157.2 $\pm$ 10.1 Body Mass (kg): 45.0 $\pm$ 8.8 / 47.0 $\pm$ 9.7 BMI (kg/m ²): (kg/m ²): 19.1 $\pm$ 3.1 / 18.9 $\pm$ 2.0 Body Fat (%): 18.1 $\pm$ 4.5 / 22.5 $\pm$ 3.0 All / Males / Females	G1 / G2 / G3 200 m front crawl time (s): 131 $\pm$ 0.11 / 128 $\pm$ 0.23 / 126 $\pm$ 0.26	all sample
Bielec & Jurak, (2019)	41 - Males (63%) / Females (37%) 26 Males / 15 Females	Tier 2 Males / Females 12.1 $\pm$ 0.5 / 12.2 $\pm$ 0.5 years	50 m (maximal) front crawl 200 m (maximal) medley	Males / Females Body Height (cm): 154.2 $\pm$ 8.7 / 157.4 $\pm$ 10.2 Hand Width (cm): 7.6 $\pm$ 0.5 / 7.4 $\pm$ 0.5 Hand Length (cm): 16.5 $\pm$ 1.1 / 16.7 $\pm$ 1.0 Arm Span (cm): 154.4 $\pm$ 9.3 / 157.2 $\pm$ 10.1 Body Mass (kg): 45.0 $\pm$ 8.8 / 47.0 $\pm$ 9.7 BMI (kg/m ²): (kg/m ²): 19.1 $\pm$ 3.1 / 18.9 $\pm$ 2.0 Body Fat (%): 18.1 $\pm$ 4.5 / 22.5 $\pm$ 3.0 All / Males / Females	Males / Females 50 m front crawl (FINA points): 202 $\pm$ 64.4 / 279.2 $\pm$ 58.3 200 m medley (FINA points): 211.5 $\pm$ 55.9 / 280.6 $\pm$ 46.4	separate sexes and techniques
Bond et al., (2015)	50 - Males (42%) / Females (58%) 21 Males / 29 Females	Tier 3 Males / Females 13.6 $\pm$ 1.7 / 13.4 $\pm$ 1.3 years	100 m (maximal) front crawl	Height (cm): 164 $\pm$ 1.5 / 169 $\pm$ 2.9 / 161 $\pm$ 0.9 Body mass (kg): 54.4 $\pm$ 1.4 / 58.9 $\pm$ 2.7 / 51.2 $\pm$ 1.2 Arm Length (cm): 32.2 $\pm$ 0.43 / 32.9 $\pm$ 0.47 / 31.6 $\pm$ 0.39 Forearm length (cm): 25.5 $\pm$ 0.59 / 25.3 $\pm$ 0.68 / 25.6 $\pm$ 0.61 Hand length (cm): 18.4 $\pm$ 0.19 / 18.8 $\pm$ 0.24 / 18.1 $\pm$ 0.20 thigh length (cm): 52.2 $\pm$ 0.62 / 52.9 $\pm$ 0.81 / 51.7 $\pm$ 0.70 leg length (cm): 49.2 $\pm$ 0.62 / 50.6 $\pm$ 0.86 / 47.8 $\pm$ 0.71 Foot length (cm): 24.9 $\pm$ 0.32 / 26.1 $\pm$ 0.31 / 23.8 $\pm$ 0.38 Sum of skinfolds (mm): 94.2 $\pm$ 4.8 / 84.6 $\pm$ 6.3 / 98.3 $\pm$ 5.1	All / Males / Females 100m front crawl time (s): 68.8 $\pm$ 1.0 / 68.7 $\pm$ 1.1 / 69.9 $\pm$ 0.93	all sample

Table 1. (continued)

Authors (year)	Total sample - Females (%) / Males (%) G1 - n Males / n Females G2 - n Males / n Females ...	Tier Age (mean $\pm$ SD)	Test distance (intensity) Swimming techniques	Anthropometric domain Male / Female Group 1 / Group 2 / ... (mean $\pm$ SD)	Performance domain Male / Female Group 1 / Group 2 / ... Distance technique variable (unit): (mean $\pm$ SD)	Correlations (all sample or separate samples)
Carvalho et al., (2023)	30 - Males (50%) / Females (50%) G1 Elite: 9 Males / 7 Females G2 Non-elite: 6 Males / 8 Females	Tier 3 and Tier 4 Males / Females G1: 20.7 $\pm$ 3.3 / 20.7 $\pm$ 3.3 years G2: 15.9 $\pm$ 1.7 / 15.9 $\pm$ 1.7 years	25 m (maximal) front crawl backstroke breaststroke butterfly	Males / Females Body mass (kg): G1: 76.1 $\pm$ 8.9 / 60.0 $\pm$ 4.2 G2: 68.8 $\pm$ 9.0 / 54.9 $\pm$ 7.0 Height (cm): G1: 180.4 $\pm$ 4.8 / 169.6 $\pm$ 5.3 G2: 179.5 $\pm$ 2.7 / 162.5 $\pm$ 7.3 BMI (kg/m ²): (kg.m ²): G1: 23.3 $\pm$ 2.0 / 20.9 $\pm$ 1.7 G2: 21.3 $\pm$ 2.3 / 20.8 $\pm$ 1.9 Hand length (cm): G1: 20.2 $\pm$ 1.2 / 17.9 $\pm$ 1.3 G2: 19.1 $\pm$ 0.7 / 17.6 $\pm$ 1.6 Arm span (cm): G1: 185.1 $\pm$ 5.3 / 173.1 $\pm$ 5.2 G2: 182.5 $\pm$ 5.6 / 163.2 $\pm$ 8.2	Males / Females 25m butterfly time (s): G1: 13.57 $\pm$ 0.61 / 15.73 $\pm$ 0.98 G2: 14.29 $\pm$ 0.66 / 17.41 $\pm$ 0.91 25m backstroke time (s): G1: 14.66 $\pm$ 1.34 / 16.65 $\pm$ 1.06 G2: 16.22 $\pm$ 1.34 / 18.71 $\pm$ 1.21 25m breaststroke time (s): G1: 16.61 $\pm$ 0.89 / 18.31 $\pm$ 1.02 G2: 18.61 $\pm$ 1.66 / 21.66 $\pm$ 1.18 25m front crawl time (s): G1: 12.91 $\pm$ 0.38 / 14.43 $\pm$ 0.45 G2: 13.67 $\pm$ 1.29 / 16.35 $\pm$ 0.60	separate sexes and groups
Chatard et al., (1990)	84 - Males (57%) / Females (43%) 48 Males / 36 Females	Tier 3 Males / Females 16.1 $\pm$ 3.5 / 14.8 $\pm$ 2.0 years	400 m (maximal) front crawl	Males / Females Height (cm): 170 $\pm$ 12 / 165 $\pm$ 8 Body mass (kg): 60 $\pm$ 14 / 55 $\pm$ 9 Body surface area (m ²): 1.69 $\pm$ 0.25 / 1.59 $\pm$ 0.16	Males / Females 400 m front crawl v (m.s ⁻¹): 1.38 $\pm$ 0.18 / 1.31 $\pm$ 0.12	separate sexes
Costa et al., (2020)	12 - Males (100%)	Tier 4 and Tier 5 20.0 $\pm$ 3.54 years	200 m (maximal) front crawl	Height (m): 1.81 $\pm$ 0.07 Body mass (kg): 73.20 $\pm$ 5.33 Arm span (m): 1.87 $\pm$ 0.07	200 m front crawl time (s): 117.94 $\pm$ 4.88	all sample
Daly et al., (1988)	247 - Males (49%) / Females (51%) 121 Males / 126 Females	Tier 4 Males / Females 15.5 (range from 10.8 to 22.7) / 14.5 (range from 10.0 to 18.0) years	100 m (maximal) breaststroke	Males / Females Height (cm): 172.57 $\pm$ 11.35 / 163.60 $\pm$ 8.60 Height ² /Body mass: 493.68 $\pm$ 52.23 / 516.27 $\pm$ 52.44 Shoulder width (cm)/hip width (cm): 1.64 $\pm$ 0.11 / 1.57 $\pm$ 0.10 Hand surface (cm ²)/drag surface (cm ²): 0.20 $\pm$ 0.02 / 0.19 $\pm$ 0.03 Foot surface (cm ²)/drag surface: 0.31 $\pm$ 0.04 / 0.30 $\pm$ 0.05	Males / Females 100 m breaststroke time (s): 80.3 $\pm$ 7.3 / 85.3 $\pm$ 5.6	separate sexes

Table 1. (continued)

Authors (year)	Total sample - Females (%) / Males (%) G1 - n Males / n Females G2 - n Males / n Females ...	Tier Age (mean ± SD)	Test distance (intensity) Swimming techniques	Anthropometric domain Male / Female Group 1 / Group 2 / ... (mean ± SD)	Performance domain Male / Female Group 1 / Group 2 / ... Distance technique variable (unit): (mean ± SD)	Correlations (all sample or separate samples)
Demirkan et al., (2019)	22 - Males (45%) / Females (55%) 10 Males / 12 Females	Tier 3 Males / Females 11.9 ± 0.7 / 12.1 ± 0.9 years	50 m (maximal) butterfly backstroke breaststroke front crawl	Males / Females Height (cm): 154 ± 8.7 / 153 ± 7.6 Body mass (kg): 46.5 ± 6.1 / 47.9 ± 10.9 Upper body length (cm): 56.5 ± 3.1 / 57.9 ± 4.8 Chest circumference (cm): 75.4 ± 5.4 / 77.7 ± 7.0 Upper limb length (cm): 65.9 ± 4.6 / 63.2 ± 5.1 Arm span (cm): 158.1 ± 9.0 / 153.4 ± 9.8 Biceps circumference (cm): 25.0 ± 1.5 / 24.6 ± 3.0 Hand circumference (cm): 18.5 ± 0.7 / 17.9 ± 0.9 Hand width (cm): 9.8 ± 0.7 / 9.5 ± 0.9 Hand length (cm): 17.7 ± 1.4 / 17.2 ± 1.5 Hip circumference (cm): 82.2 ± 5.9 / 85.5 ± 10.4 Thigh circumference (cm): 48.5 ± 4.0 / 47.7 ± 6.0 Foot length (cm): 24.7 ± 1.1 / 23.6 ± 1.3 Foot circumference (cm): 21.7 ± 1.1 / 19.8 ± 2.7	Males/Females 50 m butterfly time (s): 42.32 ± 7.6 / 41.80 ± 4.0 50 m backstroke time (s): 41.30 ± 3.7 / 42.67 ± 4.2 50 m breaststroke time (s): 47.34 ± 3.0 / 48.58 ± 4.1 50 m front crawl time (s): 34.70 ± 2.6 / 35.61 ± 2.7	separate 4 techniques / both sexes together
Demirkan et al., (2023)	40 - Males (100%) G1: 20 Males G2: 20 Males	Tier 3 G1: 12.50 ±0.51 years G2: 14.35 ±0.48 years	50 m (maximal) front crawl breaststroke butterfly backstroke	G1 / G2 Height (cm): 161.6 ± 9.98 / 169.8 ± 6.53 Body mass (kg): 52.48 ± 7.17 / 61.45 ± 8.88 Body fat (%): 8.25 ± 3.61 / 5.76 ± 1.06 Lean body mass (kg): 48.08 ± 6.45 / 57.94 ± 8.66 Arm span (cm): 166.5 ± 12.05 / 174.0 ± 7.61 Hand length (cm): 18.68 ± 2.01 / 20.88 ± 2.45 Foot length (cm): 25.34 ± 1.37 / 27.45 ± 1.82 Biceps flexed circumference (cm): 26.47 ± 1.87 / 27.44 ± 2.10 Forearm circumference (cm): 23.74 ± 1.94 / 24.24 ± 2.14 Thigh circumference (cm): 46.20 ± 3.62 / 46.76 ± 4.07 Calf circumference (cm): 32.00 ± 2.28 / 34.01 ± 2.86 Chest circumference (cm): 80.02 ± 6.40 / 86.29 ± 6.64 Hip circumference (cm): 83.80 ± 7.63 / 86.89 ± 5.60 Waist circumference (cm): 69.25 ± 5.74 / 70.64 ± 3.52 Wrist diameter (cm): 5.12 ± 0.35 / 5.44 ± 0.46 Ankle diameter (cm): 6.02 ± 0.45 / 6.47 ± 0.45	G1 / G2 50 m front crawl time (s): 32.01 ± 2.50 / 29.71 ± 1.81 50 m butterfly time (s): - / 32.68 ± 2.06 50 m backstroke time (s): - / 33.06 ± 2.2	separate groups
do Bonfim et al., (2021)	25 - Females (100%) G1 pre-menarch: 16 Females G2 post-menarch: 9 Females	Tier 2 Total: 13.92 ± 2.05 years G1: 11.7 ± 0.63 years G2: 15.17 ± 1.36 years	100 m (maximal) front crawl	Total / G1 / G2 Height (cm): 158.20 ± 9.57 / 149.67 ± 8.53 / 163.00 ± 6.28 Body mass (kg): 51.22 ± 10.12 / 43.71 ± 11.47 / 55.45 ± 6.38 BMI (kg/m ²): (kg/cm ²): 20.44 ± 2.89 / 19.31 ± 3.84 / 21.08 ± 2.09 Skinfold thickness triceps + abdomen + thigh (tenth of a mm): 35.00 ± 10.00 / 41.33 ± 12.37 / 31.44 ± 6.39	Total / G1 / G2 100 m front crawl time (s): 67.38 ± 6.96 / 75.24 ± 4.2 / 62.94 ± 3.6	separate groups

Table 1. (continued)

Authors (year)	Total sample - Females (%) / Males (%) G1 - n Males / n Females G2 - n Males / n Females ...	Tier Age (mean $\pm$ SD)	Test distance (intensity) Swimming techniques	Anthropometric domain Male / Female Group 1 / Group 2 / ... (mean $\pm$ SD)	Performance domain Male / Female Group 1 / Group 2 / ... Distance technique variable (unit): (mean $\pm$ SD)	Correlations (all sample or separate samples)
Dopsaj et al., (2020)	82 - Males (56%) / Females (44%) 46 Males / 36 Females	Tier 4 Males / Females 22.9 $\pm$ 4.2 / 21.0 $\pm$ 4.7 years	50 and 100 m (maximal) front crawl backstroke breaststroke butterfly	Males / Females Height (cm): 186.3 $\pm$ 5.4 / 173.4 $\pm$ 5.8 Body mass (kg): 82.4 $\pm$ 6.5 / 62.8 $\pm$ 4.9 BMI (kg/m ²): (kg/m ²): 23.73 $\pm$ 1.35 / 20.88 $\pm$ 1.13 Body fat (kg): 8.12 $\pm$ 3.08 / 9.87 $\pm$ 3.01 Skeletal lean body mass (kg): 43.13 $\pm$ 3.55 / 29.52 $\pm$ 2.30 Lean body mass (kg): 74.29 $\pm$ 6.25 / 52.93 $\pm$ 5.18 Body fat (%): 9.82 $\pm$ 3.35 / 15.79 $\pm$ 4.84 Skeletal lean body mass (%): 52.36 $\pm$ 1.83 / 47.0 $\pm$ 2.93 Lean body mass (%): 90.18 $\pm$ 3.35 / 84.27 $\pm$ 4.83 Body fat Index (FMI) (kg/m ²): 2.35 $\pm$ 0.88 / 3.31 $\pm$ 1.11 Skeletal lean BMI (kg/m ²): (kg/m ²): 12.41 $\pm$ 0.63 / 9.80 $\pm$ 0.58 Lean BMI (kg/m ²): (kg/m ²): 21.38 $\pm$ 1.17 / 17.56 $\pm$ 0.99 Index of body composition: 2.80 $\pm$ 1.25 / 1.48 $\pm$ 0.48 Protein fat index (kg): 2.18 $\pm$ 1.08 / 1.21 $\pm$ 0.51 G1 / G2	Males / Females FINA score: 785 $\pm$ 71 / 727 $\pm$ 98	separate sexes
Douda et al., (2010)	72 G1 pre-pubertal: 30 G2 pubertal: 42	Tier 2 G1: 10.5 $\pm$ 0.5 years G2: 13.7 $\pm$ 1.5 years	50 m (maximal) front crawl	Height (cm): 146.5 $\pm$ 7.4 / 163.7 $\pm$ 10.3 Body mass (kg): 41.0 $\pm$ 6.8 / 55.5 $\pm$ 9.8 Arm span (cm): 145.9 $\pm$ 8.7 / 166.5 $\pm$ 12.7 Sitting/standing height ratio: 50.9 $\pm$ 1.6 / 50.9 $\pm$ 1.4 Biacromial diameter (mm): 32.6 $\pm$ 2.0 / 36.5 $\pm$ 3.1 Chest breadth (mm): 23.7 $\pm$ 1.2 / 26.9 $\pm$ 2.8 Shoulder circumference (cm): 85.7 $\pm$ 5.1 / 99.3 $\pm$ 8.6 Chest circumference (cm): 69.8 $\pm$ 4.6 / 82.1 $\pm$ 8.2 Arm circumference (cm): 20.6 $\pm$ 2.0 / 24.0 $\pm$ 2.4 Midthigh circumference (cm): 40.8 $\pm$ 3.9 / 45.8 $\pm$ 3.4 Calf circumference (cm): 29.7 $\pm$ 1.9 / 32.2 $\pm$ 2.1 BMI (kg/m ²): (kg/m ²): 19.0 $\pm$ 3.0 / 20.5 $\pm$ 2.0 Body fat (%): 8.3 $\pm$ 4.4 / 10.1 $\pm$ 4.9 Lean body mass (kg): 33.1 $\pm$ 5.3 / 44.4 $\pm$ 8.9	G1 / G2 / All 50 m front crawl time (s): 36.58 $\pm$ 3.79 / 31.58 $\pm$ 3.89 / 33.54 $\pm$ 4.67	separate groups
Duché et al., (1993)	25 - Males (100%)	Tier 2 11.3 $\pm$ 1.0 years	50, 100, 200 and 400 m (maximal) front crawl	Height (cm): 147.3 $\pm$ 9.7 Sitting height (cm): 77.3 $\pm$ 4.1 Body mass (kg): 38.3 $\pm$ 7.8 Body fat (%): 16.3 $\pm$ 4.9 Biacromial diameter (cm): 32.3 $\pm$ 2.0 Biliac diameter(cm): 22.6 $\pm$ 1.6 Thoracic section area (m ²): 0.042 $\pm$ 0.008 Body area (m ²): 1.26 $\pm$ 0.2 Upper Limb Length (cm): 63.3 $\pm$ 5.1 Arm Length (cm): 26.5 $\pm$ 3.9 Forearm Length (cm): 21.0 $\pm$ 2.3	50 m front crawl time (s): 40.6 $\pm$ 7.2 100 m front crawl time (s): 85.6 $\pm$ 14.7 200 m front crawl time (s): 187.7 $\pm$ 30.6 400 m front crawl time (s): 399.0 $\pm$ 78.5	all sample

Table 1. (continued)

Authors (year)	Total sample - Females (%) / Males (%) G1 - n Males / n Females G2 - n Males / n Females ...	Tier Age (mean $\pm$ SD)	Test distance (intensity) Swimming techniques	Anthropometric domain Male / Female Group 1 / Group 2 / ... (mean $\pm$ SD)	Performance domain Male / Female Group 1 / Group 2 / ... Distance technique variable (unit): (mean $\pm$ SD)	Correlations (all sample or separate samples)
Espada et al., (2023)	16 - Males (69%) / Females (31%) 11 Males / 5 Females	Tier 3 Males / Females 18.0 $\pm$ 4.0 / 16.8 $\pm$ 3.6 years	200, 400, 800 and 1500 m (maximal) front crawl	Total lean mass + bone mass content (kg): 56.8 $\pm$ 10.1 Body mass (kg): 68.4 $\pm$ 10.6 Total fat mass (%): 16.9 $\pm$ 6.8 Upper limb lean mass + bone mass content (kg): 6.7 $\pm$ 1.6 Upper limb mass (kg): 8.0 $\pm$ 1.5 Upper limb fat mass (%): 16.0 $\pm$ 8.6 Trunk lean mass + bone mass content (kg): 26.2 $\pm$ 4.6 Trunk mass (kg): 30.8 $\pm$ 5.1 Trunk fat mass (%): 14.8 $\pm$ 6.8 Lower limb lean mass + bone mass content (kg): 20.1 $\pm$ 3.8 Lower limb mass (kg): 25.1 $\pm$ 4.0 Lower limb fat mass (%): 19.6 $\pm$ 8.1	200 m front crawl v (m.s ⁻¹): 1.48 $\pm$ 0.13 400 m front crawl v (m.s ⁻¹): 1.34 $\pm$ 0.10 800 m front crawl v (m.s ⁻¹): 1.25 $\pm$ 0.12 1500 m front crawl v (m.s ⁻¹): 1.25 $\pm$ 0.09	all sample
Ferraz et al., (2020)	98 - Males (51%) / Females (49%) G1 u-13: 26 Males / 25 Females G2 u-12: 24 Males / 23 Females	Tier 3 Males / Females G1: 13.62 $\pm$ 0.25 / 12.48 $\pm$ 0.30 years G2: 12.69 $\pm$ 0.26 / 11.63 $\pm$ 0.28 years	50 and 400 m (maximal) front crawl	Males / Females Height (m): G1: 1.64 $\pm$ 0.07 / 1.60 $\pm$ 0.06 G2: 1.58 $\pm$ 0.08 / 1.52 $\pm$ 0.05 Body mass (kg): G1: 52.08 $\pm$ 7.68 / 47.25 $\pm$ 7.95 G2: 45.75 $\pm$ 6.70 / 42.7 $\pm$ 5.99 BMI (kg/m ²): (kg/cm ²): G1: 19.20 $\pm$ 1.81 / 18.31 $\pm$ 2.20 G2: 18.10 $\pm$ 1.45 / 18.26 $\pm$ 2.08 Arm span (m): G1: 1.67 $\pm$ 0.10 / 1.63 $\pm$ 0.07 G2: 1.60 $\pm$ 0.09 / 1.55 $\pm$ 0.06 Arm span/height index: G1: 1.01 $\pm$ 0.02 / 1.01 $\pm$ 0.01 G2: 1.01 $\pm$ 0.01 / 1.01 $\pm$ 0.02	Males / Females 50 m front crawl time (s): G1: 31.08 $\pm$ 1.69 / 34.48 $\pm$ 2.34 G2: 33.20 $\pm$ 1.98 / 36.52 $\pm$ 1.85 400 m front crawl time (s): G1: 310.52 $\pm$ 19.78 / 330.75 $\pm$ 25.92 G2: 326.48 $\pm$ 16.94 / 364.18 $\pm$ 26.36	separate distances / both sexes together
Geladas et al., (2005)	263 - Males (68%) / Females (32%) 178 Males / 85 Females	Tier 3 Males / Females 12.78 $\pm$ 0.047 / 12.68 $\pm$ 0.063 years	100 m (maximal) front crawl	Males / Females Height (cm): 165.5 $\pm$ 9.3 / 161.2 $\pm$ 5.53 Body mass (kg): 54.1 $\pm$ 9.3 / 48.3 $\pm$ 5.50 Total upper extremity length (cm): 74.9 $\pm$ 4.0 / 71.7 $\pm$ 3.69 Hand length (cm): 19.4 $\pm$ 1.3 / 18.6 $\pm$ 0.92 Foot length (cm): 26.1 $\pm$ 1.33 / 24.4 $\pm$ 0.92 Chest circumference (cm): 82.5 $\pm$ 6.67 / 80.6 $\pm$ 4.6 Biacromial diameter (cm): 37.2 $\pm$ 2.67 / 35.9 $\pm$ 1.84 Biiliac diameter (cm): 25.5 $\pm$ 1.33 / 25.3 $\pm$ 1.84 Body fat (%): 16.5 $\pm$ 4.0 / 20.8 $\pm$ 4.6	Males / Females 100 m front crawl time (s): 65.52 $\pm$ 3.33 / 68.10 $\pm$ 2.02	separate sexes

Table 1. (continued)

Authors (year)	Total sample - Females (%) / Males (%) G1 - n Males / n Females G2 - n Males / n Females ...	Tier Age (mean $\pm$ SD)	Test distance (intensity) Swimming techniques	Anthropometric domain Male / Female Group 1 / Group 2 / ... (mean $\pm$ SD)	Performance domain Male / Female Group 1 / Group 2 / ... Distance technique variable (unit): (mean $\pm$ SD)	Correlations (all sample or separate samples)
Ghouroghchi & Pahlevani, (2021a) / Ghouroghchi & Pahlevani, (2021b)	122 - Males (100%) G1 50m breaststroke: 31 Males G2 100m breaststroke: 29 Males G3 200m breaststroke: 23 Males G4 50m butterfly: 33 Males G5 100m butterfly: 24 Males	Tier 3 G1: 12.35 $\pm$ 0.49 years G2: 12.31 $\pm$ 0.47 years G3: 12.26 $\pm$ 0.45 years G4: 12.30 $\pm$ 0.47 years G5: 12.38 $\pm$ 0.50 years	50, 100 and 200 m (maximal) breaststroke butterfly	G1 / G2 / G3 / G4 / G5 Height (cm): 152.58 $\pm$ 9.28 / 151.83 $\pm$ 8.60 / 152.93 $\pm$ 8.56 / 153.28 $\pm$ 9.07 / 153.15 $\pm$ 9.06 Body mass (kg): 45.66 $\pm$ 8.15 / 46.09 $\pm$ 9.08 / 46.96 $\pm$ 7.14 / 46.61 $\pm$ 8.61 / 46.06 $\pm$ 9.06 BMI (kg/m ²): 19.51 $\pm$ 2.42 / 19.83 $\pm$ 2.47 / 19.60 $\pm$ 2.43 / 19.70 $\pm$ 2.34 / 19.49 $\pm$ 2.49 Sitting height (cm): 78.15 $\pm$ 5.16 / 78.42 $\pm$ 4.40 / 78.14 $\pm$ 5.06 / 78.08 $\pm$ 5.71 / 77.78 $\pm$ 4.99 Arm span (cm): 156.79 $\pm$ 9.42 / 156.17 $\pm$ 9.62 / 175.50 $\pm$ 9.74 / 158.94 $\pm$ 10.90 / 158.63 $\pm$ 9.30 Head circumference (cm): 54.06 $\pm$ 3.52 / 54.29 $\pm$ 3.43 / 54.33 $\pm$ 3.83 / 54.37 $\pm$ 2.55 / 52.80 $\pm$ 6.89 Trunk circumference at nipple height (cm): 74.09 $\pm$ 9.29 / 74.04 $\pm$ 9.91 / 74.08 $\pm$ 9.86 / 77.47 $\pm$ 6.84 / 76.01 $\pm$ 12.53 Trunk circumference at hip (cm): 72.06 $\pm$ 12.56 / 72.62 $\pm$ 13.44 / 72.21 $\pm$ 13.58 / 74.88 $\pm$ 9.11 / 75.15 $\pm$ 9.64 Forearm length (cm): 24.79 $\pm$ 4.97 / 24.59 $\pm$ 4.73 / 24.13 $\pm$ 2.75 / 24.78 $\pm$ 4.83 / 24.67 $\pm$ 4.68 Hand length (cm): 17.76 $\pm$ 2.63 / 17.88 $\pm$ 3.18 / 18.47 $\pm$ 3.39 / 17.67 $\pm$ 2.06 / 18.23 $\pm$ 2.78 Thigh length (cm): 43.67 $\pm$ 6.02 / 43.48 $\pm$ 6.37 / 43.71 $\pm$ 6.33 / 45.30 $\pm$ 5.09 / 45.55 $\pm$ 4.19 Tibia length (cm): 38.03 $\pm$ 5.90 / 38.51 $\pm$ 5.08 / 40.08 $\pm$ 4.30 / 37.92 $\pm$ 5.85 / 38.26 $\pm$ 4.75 Foot length (cm): 25.32 $\pm$ 4.02 / 24.50 $\pm$ 2.53 / 24.97 $\pm$ 2.53 / 25.89 $\pm$ 3.90 / 25.86 $\pm$ 3.93 Triceps skinfold (mm): 9.52 $\pm$ 3.97 / 10.84 $\pm$ 5.32 / 9.54 $\pm$ 4.31 / 9.09 $\pm$ 3.91 / 8.73 $\pm$ 3.42 Subscapularis skinfold (mm): 9.03 $\pm$ 3.58 / 9.64 $\pm$ 4.22 / 8.96 $\pm$ 3.71 / 8.80 $\pm$ 3.48 / 8.77 $\pm$ 3.61 Supraspinatus skinfold (mm): 9.27 $\pm$ 3.96 / 9.71 $\pm$ 4.05 / 8.98 $\pm$ 3.72 / 8.70 $\pm$ 3.61 / 8.40 $\pm$ 3.71	G1 50 m breaststroke time (s): 43.23 $\pm$ 5.30 G2 100 m breaststroke time (s): 98.31 $\pm$ 1 0.68 G3 200 m breaststroke time (s): 203.16 $\pm$ 16.67 G4 50 m butterfly time (s): 37.52 $\pm$ 4.56 G5 100 m butterfly time (s): 86.32 $\pm$ 9.90	separate groups

Table 1. (continued)

Authors (year)	Total sample - Females (%) / Males (%) G1 - n Males / n Females G2 - n Males / n Females ...	Tier Age (mean ± SD)	Test distance (intensity) Swimming techniques	Anthropometric domain Male / Female Group 1 / Group 2 /... (mean ± SD)	Performance domain Male / Female Group 1 / Group 2 /... Distance technique variable (unit): (mean ± SD)	Correlations (all sample or separate samples)
(cont.) Ghouroughchi & Pahlevani, (2021a) / Ghouroughchi & Pahlevani, (2021b)	122 - Males (100%) G1 50 m front crawl: 39 Males G2 100 m front crawl: 30 Males G3 200 m front crawl: 30 Males G4 400 m front crawl: 21 Males G5 50 m backstroke: 29 Males G6 100 m backstroke: 30 Males G7 200 m backstroke: 27 Males	Tier 3 G1: 12.49 ± 0.51 years G2: 12.47 ± 0.51 years G3: 12.50 ± 0.51 years G4: 12.48 ± 0.51 years G5: 12.41 ± 0.50 years G6: 12.50 ± 0.93 years G7: 12.57 ± 0.51 years	50, 100, 200 m (maximal) front crawl backstroke 400 m (maximal) front crawl	G1 / G2 / G3 / G4 / G5 / G6 / G7 Height (cm): 155.71 ± 8.48 / 154.58 ± 7.76 / 154.40 ± 8.32 / 154.50 ± 7.50 / 153.31 ± 11.39 / 153.48 ± 2.22 / 152.27 ± 12.15 Body mass (kg): 48.17 ± 7.94 / 48.62 ± 8.28 / 49.24 ± 8.74 / 48.82 ± 6.87 / 46.71 ± 11.69 / 46.99 ± 2.18 / 46.62 ± 2.18 BMI (kg/m ²): 19.77 ± 2.23 / 20.27 ± 2.69 / 20.53 ± 2.59 / 20.40 ± 2.13 / 19.62 ± 2.75 / 19.68 ± 0.49 / 19.68 ± 2.79 Sitting height (cm): 78.75 ± 5.42 / 78.96 ± 4.96 / 79.33 ± 4.28 / 79.40 ± 4.28 / 77.53 ± 5.85 / 77.97 ± 5.86 / 77.39 ± 5.80 Arm span (cm): 158.99 ± 10.69 / 159.65 ± 9.02 / 160.23 ± 10.17 / 161.90 ± 9.26 / 158.69 ± 12.13 / 159.08 ± 12.66 / 158.11 ± 12.69 Head circumference (cm): 52.91 ± 5.52 / 53.13 ± 6.94 / 54.11 ± 1.72 / 53.96 ± 1.53 / 73.55 ± 6.87 / 53.62 ± 6.82 / 53.19 ± 7.12 Trunk circumference at nipple height (cm): 76.84±9.90/ 75.81±11.62/ 78.87±6.29/ 77.29±10.07/ 74.82±11.55/ 74.83±11.57/ 72.91±13.59 Trunk circumference at hip (cm): 76.34±8.24 / 73.52±12.74 / 76.41±10.29 / 76.76±9.70 / 74.30±9.56 / 74.67±8.81/72.14±11.08 Forearm length (cm): 25.89 ± 5.87 / 25.10 ± 5.01 / 25.05 ± 5.06 / 46.68 ± 1.39 / 24.29 ± 3.89 / 24.50 ± 4.44 / 23.91 ± 2.44 Hand length (cm): 17.82 ± 1.88 / 17.82 ± 1.99 / 17.83 ± 2.00 / 18.21 ± 2.08 / 18.20 ± 2.84 / 18.10 ± 2.82 / 17.64 ± 2.50 Thigh length (cm): 46.47 ± 4.17 / 45.85 ± 4.45 / 45.82 ± 5.37 / 40.89 ± 4.56 / 44.43 ± 6.17 / 43.95 ± 6.40 / 43.42 ± 6.15 Tibia length (cm): 37.81 ± 6.69 / 38.50 ± 6.12 / 38.99 ± 6.29 / 40.86 ± 3.37 / 39.26 ± 5.79 / 39.23 ± 5.65 / 39.11 ± 5.77 Foot length (cm): 26.39 ± 4.18 / 25.00 ± 2.05 / 25.26 ± 1.83 / 25.13 ± 1.91 / 25.94 ± 3.82 / 25.67 ± 3.73 / 25.43 ± 4.02 Triceps skinfold (mm): 8.69 ± 2.93 / 9.10 ± 3.11 / 9.53 ± 3.98 / 10.17 ± 5.21 / 8.71 ± 2.92 / 8.47 ± 2.86 / 8.93 ± 4.11 Subscapularis skinfold (mm): 8.46 ± 2.58 / 9.00 ± 2.82 / 9.03 ± 3.13 / 9.21 ± 4.29 / 8.66 ± 3.18 / 8.77 ± 3.19 / 8.32 ± 3.28 Supraspinatus skinfold (mm): 8.08 ± 2.84 / 8.68 ± 2.39 / 8.63 ± 2.31 / 8.88 ± 3.59 / 8.90 ± 3.51 / 9.13 ± 3.43 / 09.15 ± 4.23	G1 50 m front crawl time (s): 33.06 ± 2.80 G2 100 m front crawl time (s): 72.43 ± 0.6 G3 200 m front crawl time (s): 176.27 ± 0.31 G4 400 m front crawl time (s): 365.71 ± 0.51 G5 50 m backstroke time (s): 39.59 ± 3.17 G6 100 m backstroke time (s): 86.00 ± 0.07 G7 200 m backstroke time (s): 186.22 ± 0.51	
Gomez-Bruton et al., (2015)	98 - Males (53%) / Females (47%) 52 Males / 46 Females	Tier 3 Males / Females 15.1 ± 2.0 / 13.37 ± 2.0 years	50 m (maximal) front crawl	Males / Females Height (cm): 169.7 ± 10.2 / 157.1 ± 10.7 Body mass (kg): 61.7 ± 12.0 / 47.5 ± 10.1 BMI (kg/m ²): 21.3 ± 3.0 / 19.1 ± 2.0 Lean body mass (kg): 50.6 ± 10.6 / 36.3 ± 7.2 Body fat (%): 16.2 ± 4.4 / 22.5 ± 3.5	Males / Females 50 m front crawl time (s): 29.5 ± 2.8 / 32.5 ± 2.7	separate sexes
Keskinen et al., (1989)	33 - Males (100%)	Tier 3 17.89 ± 3.69 years	10 m (maximal) front crawl	Height (cm): 176.9 ± 10.2 Arm span(cm): 182.8 ± 12.79 Total length (cm): 243.6 ± 14.69 Body mass (kg): 66.9 ± 13.17 Arm span/height ratio: 1.033 ± 0.022 Body fat (%): 6.35 ± 2.32	10 m front crawl max v (m.s ⁻¹): 1.76 ± 0.13	all sample

Table 1. (continued)

Authors (year)	Total sample - Females (%) / Males (%) G1 - n Males / n Females G2 - n Males / n Females ...	Tier Age (mean ± SD)	Test distance (intensity) Swimming techniques	Anthropometric domain Male / Female Group 1 / Group 2 / ... (mean ± SD)	Performance domain Male / Female Group 1 / Group 2 / ... Distance technique variable (unit): (mean ± SD)	Correlations (all sample or separate samples)
Lätt et al., (2009b) / Lätt et al., (2009a)	26 - Females (100%)	Tier 3 12.7 ± 2.2 years	400 m (maximal) front crawl	Height (cm): 160.9 ± 9.3 Body mass (kg): 50.3 ± 9.2 BMI (kg/m ²): 19.5 ± 2.9 Body fat (%): 20.7 ± 5.7 Body fat (kg): 10.0 ± 3.8 Lean body mass (kg): 37.2 ± 6.0 Bone mineral mass (kg): 2.0 ± 0.4 Total bone mineral density (g.cm ⁻²): 1.03 ± 0.08 Spine bone mineral density (g.cm ⁻²): 0.97 ± 0.15	400 m front crawl time (s): 373.9 ± 39.2	separate sexes
	29 - Males (100%)	Tier 3 13.0 ± 1.8 years	400 m (maximal) front crawl	Arm span (cm): 163.9 ± 9.4 Height (cm): 163.6 ± 11.9 Body mass (kg): 51.6 ± 13.0 BMI (kg/m ²): 18.9 ± 2.4 Body fat (%): 12.1 ± 5.3 Fat Mass (kg): 5.8 ± 2.9 Lean body mass (kg): 42.2 ± 11.2 Bone mineral mass (kg): 2.2 ± 0.7 Total bone mineral density (g.cm ⁻²): 1.0 ± 0.1 Spine bone mineral density (g.cm ⁻²): 0.9 ± 0.2	400 m front crawl time (s): 373.3 ± 53.5	
Lätt et al., (2010)	25 - Males (100%)	Tier 2 15.2 ± 1.9 years	100 m (maximal) front crawl	Arm span (cm): 168.8 ± 13.7 Height (cm): 176.0 ± 9.0 Body mass (kg): 63.3 ± 10.9 BMI (kg/m ²): (BMI (kg/m ²):) (kg.m ⁻²): 20.2 ± 2.2 Body fat (%): 12.8 ± 3.3 Body fat (kg): 8.0 ± 2.2 Lean body mass (kg): 54.7 ± 9.6 Bone mass (kg): 2.7 ± 0.6 Total bone mineral density (g.cm ⁻²): 1.12 ± 0.10 Spine bone mineral density (g.cm ⁻²): 1.06 ± 0.15	100 m front crawl time (s): 77.6 ± 9.1	all sample
Makar et al., (2022)	5 - Males (40%) / Females (60%) 2 Males / 3 Females	Tier 3 14.6 ± 0.89 years	200 m (maximal) front crawl	Arm span (cm): 182.8 ± 11.5 Height (cm): 172.80 ± 4.15 Body mass (kg): 65.40 ± 6.52 BMI (kg/m ²): 21.80 ± 2.33 Body fat (%): 20.10 ± 6.85 Body fat (kg): 13.40 ± 5.40 Lean body mass (kg): 52.00 ± 3.96 Total body water (kg): 38.10 ± 2.90	200 m front crawl v (m.s ⁻¹): 1.43± 0.05	all sample

Table 1. (continued)

Authors (year)	Total sample - Females (%) / Males (%) G1 - n Males / n Females G2 - n Males / n Females ...	Tier Age (mean ± SD)	Test distance (intensity) Swimming techniques	Anthropometric domain Male / Female Group 1 / Group 2 /... (mean ± SD)	Performance domain Male / Female Group 1 / Group 2 /... Distance technique variable (unit): (mean ± SD)	Correlations (all sample or separate samples)
Marinho et al., (2021a) / Marinho et al., (2021b)	92 - Females (100%) G1 U-16: 46 Females G2 U-15: 46 Females 184 - Males (50%) / Females (50%) G1 > 500 FINA points: 28 Males / 54 Females G2 < 500 FINA points: 64 Males / 38 Females	Tier 3 14.1 ± 0.6 years Tier 3 Males / Females 14.6 ± 0.8 / 14.1 ± 0.6 years	50 m (maximal) front crawl 50 and 400 m (maximal) front crawl	G1 / G2 Height (m): 1.64 ± 0.06 / 1.63 ± 0.05 Body mass (kg): 54.64 ± 4.51 / 52.11 ± 5.14 BMI (kg/m ²): (kg/m ²): 20.22 ± 1.47 / 19.63 ± 1.47 Arm span (m): 1.66 ± 0.07 / 1.65 ± 0.06 Arm span/height ratio: 1.01 ± 0.03 / 1.01 ± 0.03 Males / Females Height (m): G1: 1.75 ± 0.08 / 1.65 ± 0.05 G2: 1.75 ± 0.06 / 1.62 ± 0.06 Body mass (kg): G1: 64.73 ± 6.98 / 54.28 ± 4.74 G2: 63.76 ± 6.30 / 52.08 ± 5.07 BMI (kg/m ²): (kg/m ²): G1: 21.15 ± 1.26 / 19.93 ± 1.50 G2: 20.80 ± 1.41 / 19.91 ± 1.50 Arm span (m): G1: 1.80 ± 0.10 / 1.66 ± 0.06 G2: 1.81 ± 0.07 / 1.65 ± 0.08 Arm span/height: G1: 1.03 ± 0.02 / 1.01 ± 0.03 G2: 1.03 ± 0.02 / 1.02 ± 0.03	G1 / G2 50 m front crawl time (s): 30.98 ± 1.08 / 31.35 ± 1.25 Males / Females 50 m front crawl time (s): G1: 27.15 ± 0.65 / 30.88 ± 0.82 G2: 28.01 ± 0.82 / 31.58 ± 1.48 400 m front crawl time (s): G1: 262.10 ± 3.46 / 290.87 ± 4.17 G2: 277.49 ± 7.97 / 308.45 ± 8.83	all sample / all sample
Morais et al., (2012)	114 - Males (64%) / Females (36%) 73 Males / 41 Females	Tier 3 Males / Females 12.72 ± 1.03 / 11.47 ± 0.66 years	100 m (maximal) front crawl	Males / Females Height (cm): 157.20 ± 11.17 / 154.56 ± 8.26 Body mass (kg): 47.41 ± 10.09 / 45.79 ± 6.66 Arm span (cm): 161.56 ± 12.99 / 152.47 ± 9.26 Hand surface area (cm ²): 129.52 ± 20.16 / 112.23 ± 12.51	Males / Females 100 m front crawl time (s): 78.33 ± 12.07 / 85.25 ± 13.89	separate sexes
Morais et al., (2016)	100 - Males (49%) / Females (51%) 49 Males / 51 Females	Tier 3 All / Males / Females 12.3 ± 0.74 / 12.5 ± 0.76 / 12.2 ± 0.71 years	100 m (maximal) front crawl	Arm span (m): 1.66 ± 0.08	100 m front crawl time (s): 74.25 ± 8.80	all sample
Morales & Arellano, (2006)	21 - Males (43%) / Females (57%) 9 Males / 12 Females	Tier 3 Males / Females 12 / 19 years	50 m (maximal) front crawl	Body mass (kg): 50.01 ± 9.64 Height (cm): 160.07 ± 8.17 Arm Spam (cm): 163.09 ± 9.56	50 m front crawl time (s): 31.32 ± 1.90	all sample
Moreira et al., (2014)	25 - Males (48%) / Females (52%) 12 Males / 13 Females	Tier 3 Males / Females 12.8 ± 0.9 / 12.0 ± 0.9 years	25 m (maximal) front crawl	Males / Females Body mass (kg): 50.09 ± 10.13 / 49.42 ± 7.47 All Arm span: 167.9 ± 11.6 Hand surface (cm ²): 110.6 ± 10.5 Foot surface (cm ²): 136.1 ± 15.3 Height (cm): 160.2 ± 6.0	25 m front crawl v (m.s ⁻¹): 1.2 ± 0.25	separate groups/ both sexes together

Table 1. (continued)

Authors (year)	Total sample - Females (%) / Males (%) G1 - n Males / n Females G2 - n Males / n Females ...	Tier Age (mean $\pm$ SD)	Test distance (intensity) Swimming techniques	Anthropometric domain Male / Female Group 1 / Group 2 /... (mean $\pm$ SD)	Performance domain Male / Female Group 1 / Group 2 /... Distance technique variable (unit): (mean $\pm$ SD)	Correlations (all sample or separate samples)
Nasirzade, Ehsanbakhsh, Argavani, et al., (2014) / Nasirzade, Ehsanbakhsh, Ilbeygi, et al., (2014)	23 - Males (100%)	Tier 2 13.86 $\pm$ 0.86 years	50 m (maximal) front crawl	Height (cm): 171 $\pm$ 6 Body mass (kg): 58.9 $\pm$ 6.4 BMI (kg/m ²): (kg·m ⁻²): 20.1 $\pm$ 1.4 Arm span (cm): 1.77 $\pm$ 8.7 Shoulders width (cm): 36.5 $\pm$ 2.9 Arm length (cm): 37.3 $\pm$ 1.8 Thigh length (cm): 39.9 $\pm$ 1.9 Leg length (cm): 40.9 $\pm$ 2.1 Vastus lateralis fascicle length (cm): 7.46 $\pm$ 0.13 Gastrocnemius medialis fascicle length (cm): 5.31 $\pm$ 0.11 Gastrocnemius lateralis fascicle length (cm): 5.66 $\pm$ 0.11 Triceps brachii fascicle length (cm): 7.18 $\pm$ 0.14	50 m front crawl time (s): 35.07 $\pm$ 2.67 50 m front crawl v without gliding start and turnings (m.s-1): 1.38 $\pm$ 0.9	all sample
	23 - Males (100%) G1: 11 Males G2: 12 Males	Tier 2 G1: 13.86 $\pm$ 0.86 years G2: 13.86 $\pm$ 0.86 years	25 m (maximal) front crawl	G1 / G2 Height (cm): 171 $\pm$ 6 / 170 $\pm$ 6 Body mass (kg): 57.8 $\pm$ 6.3 / 59.9 $\pm$ 6.1 BMI (kg/m ²): (kg·m ⁻²): 19.6 $\pm$ 1.5/ 20.6 $\pm$ 1.2 Arm length (cm): 37.5 $\pm$ 1.6/ 36.9 $\pm$ 2.0 Thigh length (cm): 40.1 $\pm$ 2.2 / 39.8 $\pm$ 2.0 Lower Leg length (cm): 41.2 $\pm$ 2.3/ 40.6 $\pm$ 2.2 G1 Absolute fascicle length (cm) Vastus lateralis fascicle length (cm): 8.30 (1.1) 7.04 (1.2) Gastrocnemius medialis fascicle length (cm): 5.59 (1.0) 5.04 (1.1) Gastrocnemius lateralis fascicle length (cm): * 6.13 (.7) 5.23 (1.1) Triceps brachii fascicle length (cm): * 7.86 (1.4) 6.55 (1.1) Fascicle length/limb length (cm/cm) Vastus lateralis fascicle length (cm):* .21 (.03) Gastrocnemius medialis fascicle length (cm): .14 (.03) Gastrocnemius lateralis fascicle length (cm): .15 (.02) Triceps brachii fascicle length (cm): * .21 (.03)	G1 / G2 25 m front crawl time (s): 15.07 $\pm$ 0.37 / 16.31 $\pm$ 0.40	
Nasirzade et al., (2015)	22 - Males (100%)	Tier 2 14.52 $\pm$ 0.77 years	200 m (maximal) front crawl	Body height (cm): 173 $\pm$ 5 Body mass (kg): 60.5 $\pm$ 5.7 BMI (kg/m ²): 20.4 $\pm$ 1.1 Arm span (cm): 181 $\pm$ 8.2 Shoulders width (cm): 37.3 $\pm$ 2.7 Arm Length (cm): 38.1 $\pm$ 1.6 Thigh length (cm): 40.2 $\pm$ 1.8 Leg length (cm): 41.4 $\pm$ 2.3 Vastus Lateralis fascicle length (cm): 7.78 $\pm$ 0.14 Gastrocnemius Medialis fascicle length (cm): 5.42 $\pm$ 0.12 Gastrocnemius Lateralis fascicle length (cm): 6.08 $\pm$ 0.10 Triceps Brachii fascicle length (cm): 7.34 $\pm$ 0.14	200 m front crawl time (s): 162.66 $\pm$ 13.45	all sample

Table 1. (continued)

Authors (year)	Total sample - Females (%) / Males (%) G1 - n Males / n Females G2 - n Males / n Females ...	Tier Age (mean ± SD)	Test distance (intensity) Swimming techniques	Anthropometric domain Male / Female Group 1 / Group 2 / ... (mean ± SD)	Performance domain Male / Female Group 1 / Group 2 / ... Distance technique variable (unit): (mean ± SD)	Correlations (all sample or separate samples)
Noriega-Sánchez et al., (2015)	17 - Males (47%) / Females (53%) 8 Males / 9 Females	Tier 3 Males / Females 19.4 ± 0.7 / 16.9 ± 3.2 years	100 m (maximal) front crawl	Males / Females Height (cm): 181.2 ± 4.4 / 165.5 ± 2.1 Body mass (kg): 72.6 ± 6.5 / 55.0 ± 4.7 BMI (kg/m ²): 22.1 ± 1.6 / 20.1 ± 1.5 Skinfold thickness sum (mm): 61.7 ± 11.2 / 93.4 ± 17.6	Males / Females 100 m front crawl time (s): 56.1 ± 1.7 / 65.2 ± 4.2	separate sexes
Ozkadi et al., (2022)	40 - Males (50%) / Females (50%) 20 Males / 20 Females	Tier 3 Male: 16.50 ± 0.51 years Female: 16.50 ± 0.51 years	50 m (maximal) front crawl breaststroke butterfly backstroke	Males / Females Height (cm): 174.4 ± 5.81 / 164.9 ± 7.4 Body mass (kg): 67.00 ± 10.56 / 57.81 ± 7.23 Body fat (%): 7.58 ± 4.79 / 11.58 ± 2.47 Lean body mass (kg): 61.52 ± 6.54 / 51.06 ± 6.15 Ankle diameter (cm): 6.57 ± 0.51 / 5.88 ± 0.55 Arm span (cm): 179.3 ± 6.91 / 168.2 ± 10.0 Biceps flexion circumference (cm): 29.68 ± 3.20 / 28.27 ± 2.17 Calf circumference (cm): 35.16 ± 3.65 / 31.71 ± 3.67 Chest circumference (cm): 90.50 ± 6.87 / 84.57 ± 3.93 Forearm circumference (cm): 26.30 ± 1.81 / 26.97 ± 2.99 Foot length (cm): 26.44 ± 1.30 / 25.91 ± 2.14 Hip circumference (cm): 91.61 ± 5.60 / 84.05 ± 7.12 Hand length (cm): 20.60 ± 2.32 / 20.59 ± 3.42 Thigh circumference (cm): 50.07 ± 3.78 / 45.32 ± 5.40 Waist circumference (cm): 75.23 ± 7.46 / 67.85 ± 4.83 Wrist diameter (cm): 5.74 ± 0.70 / 6.00 ± 1.00	Males / Females 50 m front crawl time (s): 27.05 ± 2.32 / 29.48 ± 2.35 50 m backstroke time (s): 30.96 ± 2.33 / 32.18 ± 2.79 50 m breaststroke time (s): 32.92 ± 2.19 / 36.19 ± 2.92 50 m butterfly time (s): 29.79 ± 2.53 / 32.44 ± 3.49	separate sexes and distances
Pelayo et al., (1996)	173 - Males (51%) / Females (49%) G1: 21 Males / 20 Females G2: 20 Males / 21 Females G3: 23 Males / 22 Females G4: 24 Males / 22 Females	Tier 3, Tier 4 and Tier 5 Do not specify	50, 100, 200, 400, 800 and 1500 m (maximal) front crawl	Males / Females Height (cm): G1: 185.62 ± 6.01 / 172.25 ± 6.1 G2: 184.80 ± 4.82 / 173.43 ± 5.55 G3: 184.13 ± 4.14 / 169.16 ± 6.63 G4: 182.75 ± 4.00 / 168.80 ± 6.12 Arm span (cm): G1: 192.90 ± 6.59 / 178.90 ± 9.12 G2: 192.10 ± 6.15 / 179.76 ± 8.14 G3: 191.78 ± 5.11 / 172.27 ± 9.00 G4: 189.21 ± 6.23 / 170.27 ± 6.89 Body mass (kg): G1: 76.69 ± 1.40 / 61.22 ± 4.37 G2: 77.20 ± 5.01 / 62.29 ± 4.29 G3: 76.48 ± 3.17 / 58.31 ± 6.74 G4: 74.62 ± 5.75 / 57.03 ± 5.75 Foot size (French): G1: 43.8 ± 1.4 / 40.1 ± 1.5 G2: 43.7 ± 1.0 / 40.0 ± 1.6 G3: 43.8 ± 0.9 / 38.8 ± 1.2 G4: 43.6 ± 1.0 / 38.9 ± 1.1	Males / Females 50 m front crawl v (m.s ⁻¹): 1.97 ± 0.05 / 1.73 ± 0.04 100 m front crawl v (m.s ⁻¹): 1.85 ± 0.05 / 1.64 ± 0.05 200 m front crawl v (m.s ⁻¹): 1.70 ± 0.03 / 1.52 ± 0.03 400 m front crawl v (m.s ⁻¹): 1.57 ± 0.04 / 1.43 ± 0.04	separate sexes and distances

Table 1. (continued)

Authors (year)	Total sample - Females (%) / Males (%) G1 - n Males / n Females G2 - n Males / n Females ...	Tier Age (mean ± SD)	Test distance (intensity) Swimming techniques	Anthropometric domain Male / Female Group 1 / Group 2 / ... (mean ± SD)		Performance domain Male / Female Group 1 / Group 2 / ... Distance technique variable (unit): (mean ± SD)	Correlations (all sample or separate samples)
Perciavalle et al., (2014)	21 - Males (100%) G1 Front crawl: 12 Males G2 Backstroke: 4 Males G3 Medley: 3 Males G4.1 Breaststroke: 1 Male G4.2 Breaststroke: 1 Male	Tier 3 20.2 ± 2.3 years	100 (maximal) front crawl backstroke breaststroke medley	All Height (cm): 177.4 ± 7.9 Body mass (kg): 70.6 ± 9.1 BMI (kg/m²): (kg·m⁻²): 22.4 ± 1.7 All / G1 / G2 / G3 / G4.1 / G4.2 Ape Index: 1.04 ± 0.02 / 1.04 ± 0.03 / 1.05 ± 0.02 / 1.04 ± 0.01 / 1.04 / 1.02 2D:4D ratio: 0.96 ± 0.04 / 0.97 ± 0.02 / 0.93 ± 0.02 / 0.96 ± 0.07 / 0.93 / 0.90		All 100 m performance (% Italian record): 11.68 ± 1.48 All / G1 / G2 / G3 / G4.1 / G4.2 100 m time (s): 54.68 ± 4.14 / 51.71 ± 0.61 / 58.99 ± 0.13 / 58.5 ± 1.09 / 65.35 / 62.94	all sample
Pereira et al., (2010)	27 - Males (31%) / Females (69%) 11 Males / 16 Females	Tier 4 15.33 ± 1.0 years	FINA points (maximal)	Height (m): 1.73 ± 0.08 Body mass (kg): 63.15 ± 9.13		FINA points: 731.48 ± 46.26	all sample
Pessoa et al., (2016)	11 - Males (100%)	Tier 3 18.0 ± 4.0 years	200 m (maximal) front crawl	Lean body mass (kg): 61.7 ± 7.4 Lean upper limb mass (kg): 7.5 ± 1.1 Lean trunk mass (kg): 28.3 ± 3.7 Lean lower limb mass (kg): 22.1 ± 2.5 Height (cm): 180.2 ± 6.8 Body mass (kg): 71.8 ± 9.5		200 m front crawl v (m·s⁻¹): 1.52 ± 0.12	all sample
Rama et al., (2006)	494 - Males (64%) / Females (36%) G1: 97 Males / 125 Females G2: 219 Males / 53 Females	Tier 3 Males/Female s G1: 13-14 / 12- 13 years G2: 15-16 / 14 years	LEN points (maximal)	Males / Females Body mass (kg): G1: 55.5 ± 8.3 / 45.7 ± 5.9 G2: 62.1 ± 7.7/ 52.6 ± 6.1 Height (cm): G1: 166.9 ± 7.3 / 157.7± 6.4 G2: 172.3 ± 6.6/ 161.9 ± 5.5 Sitting height (cm): G1: 84.1 ± 4.3 / 80.6 ± 3.4 G2: 88.1 ± 3.7 / 83.5 ± 3.3 Arm span (cm): G1: 169.6 ± 7.6 / 158.9 ± 7.7 G2: 177.1 ± 7.3 / 164.3 ± 6.2 Hand length (cm): G1: 19.0 ± 1.0 / 17.5 ± 0.9 G2: 19.4 ± 0.9 / 18.0 ± 0.9 Hand width (cm): G1: 7.9 ± 0.5 / 7.1 ± 0.4 G2: 8.1 ± 0.4 / 7.4 ± 0.4	Males / Females Foot length (cm): G1: 25.4 ± 1.1 / 23.2 ± 1.0 G2: 25.8 ± 1.2 / 23.7 ± 1.1 Foot width (cm): G1: 9.3 ± 0.6 / 8.4 ± 0.5 G2: 9.4 ± 0.8 / 8.6 ± 0.5 Biacromial diameter (cm): G1: 37.9 ± 3.1 / 34.9 ± 2.0 G2: 39.0 ± 2.3 / 35.9 ± 1.8 Biiliac diameter (cm): G1: 25.4 ± 1.8 / 24.1 ± 1.8 G2: 25.7 ± 1.9 / 24.8 ± 2.2 Chest depth (cm): G1: 18.9 ± 1.8 / 17.1 ± 1.4 G2: 19.8 ± 1.8 / 18.3 ± 1.6 Skinfold sum (mm): G1: 66.7 ± 24.3 / 83.2 ± 18.1 G2: 59.1 ± 18.7 / 82.8 ± 24.1	Males / Females LEN points: G1: 460 ± 67 / 441 ±54 G2: 610 ± 79 / 595 ± 68	separate sexes and groups
Reis et al., (2012)	26 - Males (1000%) G1 100 m: 12 Males G2 200 m: 14 Males	Tier 3 G1: 18.6 ± 2.8 years G2: 17.1 ± 2.3 years	100 and 200 m (maximal) front crawl	G1 / G2 Body mass (kg): 67.8 ± 15.2 / 70.3 ± 6.6 Height (m): 1.77 ± 0.05 / 1.79 ± 0.06 Arm span (m): 1.84 ± 0.06 / 1.89 ± 0.05 Body fat (%): 10.7 ± 1.0 / 10.1 ± 0.6		G1 / G2 FINA points: 341.50 ± 88.14 / 356.31 ± 111.52	all sample

Table 1. (continued)

Authors (year)	Total sample - Females (%) / Males (%) G1 - n Males / n Females G2 - n Males / n Females ...	Tier Age (mean ± SD)	Test distance (intensity) Swimming techniques	Anthropometric domain Male / Female Group 1 / Group 2 / ... (mean ± SD)	Performance domain Male / Female Group 1 / Group 2 / ... Distance technique variable (unit): (mean ± SD)	Correlations (all sample or separate samples)
Rozi et al., (2018)	25 - Males (100%)	Tier 3 15 ± 1.5 years	100 m (maximal) front crawl	Height (cm): 169.9 ± 8.5 Body mass (Kg): 62.4 ± 9.8 Sitting height (cm): 85.2 ± 5.5 Arm span (cm): 173.7 ± 10.5 Shoulders width (cm): 39.1 ± 2.7 Pelvis width (cm): 32.7 ± 1.8 Chest depth (cm): 20.5 ± 2.0 Chest circumference (cm): 91.1 ± 6.9 Left arm length (cm): 74.04 ± 4.5 Breast skinfold (mm): 5.4 ± 2.8 Biceps skinfold (mm): 6.7 ± 4.3 Triceps skinfold (mm): 7.5 ± 3.7 Subscapular skinfold (mm): 8.7 ± 4.3 Iliac skinfold (mm): 9.5 ± 6.5 Gastrocnemius skinfold (mm): 14.2 ± 6.2	100 m front crawl time (s): 63.6 ± 6.3 100 m front crawl v (m.s ⁻¹): 1.58 ± 0.14	all sample
Saavedra et al., (2010)	133 - Males (49%) / Females (51%) 66 Males / 67 Females	Tier 3 Males / Females 13.6 ± 0.6 / 11.5 ± 0.6 years	100 and 200 m (maximal) front crawl backstroke butterfly breaststroke 400, 800 (females) and 1500 m (males) (maximal) front crawl	Males / Females Height (cm): 171.12 ± 7.50 / 154.75 ± 7.47 Body mass (kg): 57.95 ± 8.18 / 43.96 ± 7.17 Sitting height (cm): 80.46 ± 4.14 / 77.24 ± 4.10 Arm span (cm): 177.48 ± 8.77 / 158.86 ± 8.72 Hand length (cm): 17.55 ± 2.15 / 15.46 ± 0.99 Hand width (cm): 9.43 ± 0.62 / 8.08 ± 0.57 Foot length (cm): 24.89 ± 1.42 / 22.20 ± 1.62 Foot width (cm): 8.40 ± 0.61 / 7.22 ± 0.50 Biacromial diameter (cm): 37.77 ± 1.93 / 33.79 ± 1.62 Biiliac diameter (cm): 25.50 ± 1.75 / 23.03 ± 1.82 Bitrochanteric breadth (cm): 29.36 ± 2.12 / 27.06 ± 2.30 Knee breadth (cm): 9.74 ± 0.47 / 8.66 ± 0.41 Elbow breadth (cm): 6.87 ± 0.42 / 5.92 ± 0.32 Wrist diameter (cm): 5.45 ± 0.30 / 4.82 ± 0.25 Chest circumference (cm): 90.19 ± 5.05 / 82.78 ± 6.34 Biceps flexed circumference (cm): 28.46 ± 2.27 / 24.85 ± 2.12 Gluteal girth (cm): 84.92 ± 7.75 / 80.34 ± 7.23 Thigh circumference (cm): 51.20 ± 5.95 / 47.07 ± 7.27 leg circumference (cm): 34.00 ± 2.49 / 30.57 ± 2.03 Arm span/height index: 3.72 ± 2.04 / 2.64 ± 2.39 Biacromial diameter/height ratio: 20.96 ± 0.95 / 22.09 ± 0.99 Chest girth/height index: 52.72 ± 2.26 / 53.49 ± 3.18 Gluteal girth/height index: 49.68 ± 4.49 / 51.89 ± 3.59 BMI (kg/m ²): 19.66 ± 1.87 / 18.32 ± 1.91 Sum of six skinfolds: 61.76 ± 20.93 / 78.74 ± 22.38 Body fat (%): 9.08 ± 2.20 / 12.69 ± 2.21 Endomorphy: 2.57 ± 0.92 / 3.58 ± 1.01 Mesomorphy: 4.28 ± 1.08 / 3.67 ± 0.89 Ectomorphy: 3.92 ± 1.03 / 3.68 ± 1.04	Males /Females FINA points: 508.4 ± 70.7 / 476.0 ± 76.0	separate sexes

Table 1. (continued)

Authors (year)	Total sample - Females (%) / Males (%) G1 - n Males / n Females G2 - n Males / n Females ...	Tier Age (mean $\pm$ SD)	Test distance (intensity) Swimming techniques	Anthropometric domain Male / Female Group 1 / Group 2 / ... (mean $\pm$ SD)	Performance domain Male / Female Group 1 / Group 2 / ... Distance technique variable (unit): (mean $\pm$ SD)	Correlations (all sample or separate samples)
Seffrin et al., (2022)	60 - Males (73%) / Females (27%) G1: 16 Males / 6 Females G2: 17 Males / 6 Females G3: 11 Males / 4 Females	Tier 3 Males/ Females G1: 11.50 $\pm$ 0.52 / 11.67 $\pm$ 0.52 years G2: 13.53 $\pm$ 0.62 / 13.33 $\pm$ 0.52 years G3: 18.09 $\pm$ 2.12 / 16.25 $\pm$ 0.96 years	100 and 400 m (maximal) front crawl	Males/Females Height: G1: 151.70 $\pm$ 8.46 / 155.55 $\pm$ 4.58 G2: 164.74 $\pm$ 6.94 / 160.48 $\pm$ 4.53 G3: 175.62 $\pm$ 3.14 / 159.93 $\pm$ 5.59 Body mass (kg): G1: 42.08 $\pm$ 8.60 / 47.07 $\pm$ 9.76 G2: 53.19 $\pm$ 10.42 / 50.15 $\pm$ 5.41 G3: 67.49 $\pm$ 5.42 / 59.53 $\pm$ 6.59 Body fat (%): G1: 16.73 $\pm$ 8.60 / 23.05 $\pm$ 13.22 G2: 14.06 $\pm$ 6.49 / 21.58 $\pm$ 6.94 G3: 9.90 $\pm$ 2.42 / 29.15 $\pm$ 4.44 Lean body mass (kg): G1: 32.44 $\pm$ 5.87 / 32.78 $\pm$ 1.85 G2: 42.69 $\pm$ 7.64 / 36.40 $\pm$ 1.87 G3: 57.71 $\pm$ 4.02 / 39.26 $\pm$ 2.81	Males/Females 100 m front crawl time (s): G1: 84.73 $\pm$ 11.15 / 81.11 $\pm$ 8.45 G2: 67.54 $\pm$ 4.36 / 71.51 $\pm$ 3.64 G3: 59.82 $\pm$ 3.66 / 67.80 $\pm$ 2.91 400 m front crawl time (s): G1: 393.35 $\pm$ 62.93 / 376.65 $\pm$ 32.52 G2: 310.76 $\pm$ 14.40 / 329.05 $\pm$ 23.91 G3: 301.72 $\pm$ 22.72 / 322.13 $\pm$ 7.53	separate sexes and distances
Sekulić et al., (2007)	68 - Males (67%) / Females (33%) 40 Males / 28 Females	Tier 3 Males/ Females 15.2 $\pm$ 3 / 15.2 $\pm$ 3 years	50 and 400 m (maximal) front crawl	Males / Females Height (cm): 168.55 $\pm$ 5.18 / 160.70 $\pm$ 4.32 Body mass (kg): 56.45 $\pm$ 4.82 / 49.67 $\pm$ 3.82 BMI (kg/m ²): 19.57 $\pm$ 2.10 / 18.98 $\pm$ 1.38	Males / Females 50 m front crawl time (s): 30.23 $\pm$ 2.12 / 33.25 $\pm$ 1.96 400 m front crawl time (min:s): 5:21 $\pm$ 0:11 / 5:48 $\pm$ 0:14	separate sexes and distances
Shephard et al., (2014)	26 - Males (35%) / Females (65%) 9 Males / 17 Females	Tier 5 Males/ Females 22.7 $\pm$ 2.7 / 22.2 $\pm$ 2.8 years	FINA points (maximal)	All / Males / Females Height (m): 1.80 $\pm$ 0.08 / 1.88 $\pm$ 0.04 / 1.75 $\pm$ 0.05 Body mass (kg): 73.4 $\pm$ 10.1 / 82.3 $\pm$ 8.8 / 67.8 $\pm$ 6.1 Sum 7 skinfolds (mm): 64.0 $\pm$ 23.0 / 46.3 $\pm$ 6.9 / 75.4 $\pm$ 23.0 BMI (kg/m ²): (kg/m ²): 22.5 $\pm$ 2.0 / 23.2 $\pm$ 1.9 / 22.1 $\pm$ 2.0 dxa body mass (kg): 72.5 $\pm$ 10.1 / 81.3 $\pm$ 8.7 / 66.8 $\pm$ 6.0 Lean body mass (kg): 55.5 $\pm$ 9.7 / 65.9 $\pm$ 6.4 / 49.0 $\pm$ 3.8 Body fat (kg): 14.4 $\pm$ 3.2 / 12.4 $\pm$ 2.3 / 15.6 $\pm$ 3.1 Body fat (%): 20.1 $\pm$ 4.7 / 15.2 $\pm$ 1.6 / 23.2 $\pm$ 3.0	All / Males / Females FINA points: 893 $\pm$ 44 / 887 $\pm$ 48 / 897 $\pm$ 44	separate sexes
Siders et al., (1993)	74 - Males (42%) / Females (58%) G1 butterfly: 5 Males / 7 Females G2 backstroke: 8 Males / 5 Females G3 breaststroke: 3 Males / 4 Females G4 front crawl: 15 Males / 27 Females	Tier 3 and Tier 4 Males/ Females 20.5 $\pm$ 1.9 / 19.7 $\pm$ 1.4 years	100 yards (maximal) butterfly backstroke breaststroke front crawl	Males / Females Body mass (kg): 76.1 $\pm$ 5.0 / 63.8 $\pm$ 6.7 Body height (cm): 181.1 $\pm$ 5.1 / 168.3 $\pm$ 5.8 Body mass in water (kg): 3.9 $\pm$ 0.6 / 1.8 $\pm$ 0.6 Body fat (%): 14.1 $\pm$ 2.9 / 25.0 $\pm$ 5.3 Body fat (kg): 10.7 $\pm$ 2.3 / 16.1 $\pm$ 4.4 Lean body mass (kg): 65.3 $\pm$ 4.8 / 47.7 $\pm$ 4.7 Endomorphy: 2.2 $\pm$ 0.6 / 3.0 $\pm$ 0.9 Mesomorphy: 4.1 $\pm$ 1.0 / 2.9 $\pm$ 1.1 Ectomorphy: 2.6 $\pm$ 1.1 / 2.4 $\pm$ 0.9 Body mass (kg): 71.4 $\pm$ 7.1 Height (cm): 179.8 $\pm$ 6.4 Arm span (cm): 193.4 $\pm$ 7.7 Arm-hand length (cm): 81.6 $\pm$ 4.2	Males / Females 100 yards backstroke time (s): 62.4 $\pm$ 6.4 / 66.7 $\pm$ 4.3 100 yards breaststroke time (s): 68.2 $\pm$ 7.4 / 68.8 $\pm$ 3.3 100 yards butterfly time (s): 54.4 $\pm$ 2.9 / 68.5 $\pm$ 5.2 100 yards front crawl time (s): 53.4 $\pm$ 6.3 / 60.8 $\pm$ 4.1	separate sexes
Smith et al., (1988)	16 - Males (100%)	Tier 3 16 years or older	400 m (maximal) backstroke medley	Body mass (kg): 71.4 $\pm$ 7.1 Height (cm): 179.8 $\pm$ 6.4 Arm span (cm): 193.4 $\pm$ 7.7 Arm-hand length (cm): 81.6 $\pm$ 4.2	400 m v max (m.s ⁻¹): 1.28 $\pm$ 0.06 400 m v (m.s ⁻¹): 1.34 $\pm$ 0.06	all sample

Table 1. (continued)

Authors (year)	Total sample - Females (%) / Males (%) G1 - n Males / n Females G2 - n Males / n Females ...	Tier Age (mean ± SD)	Test distance (intensity) Swimming techniques	Anthropometric domain Male / Female Group 1 / Group 2 / ... (mean ± SD)	Performance domain Male / Female Group 1 / Group 2 / ... Distance technique variable (unit): (mean ± SD)	Correlations (all sample or separate samples)
Smith, (1978)	40 - Males (50%) / Females (50%) 20 Males / 20 Females	Tier 3 Males/ Females 21 / 19 years	25 yards (maximal) front crawl	Males / Females Height (cm): 180.21 ± 6.43 / 167.46 ± 6.68 Upper limb length (cm): 76.07 ± 5.22 / 67.36 ± 4.83 Leg length (cm): 85.55 ± 5.46 / 82.35 ± 4.52	Males/Females 25 yards front crawl time (s): 15.44 ± 1.96 / 17.03 ± 1.63	all sample
Sokołowski et al., (2021)	19 - Females (100%)	Tier 3 13.4 ± 0.26 years	100 m (maximal) front crawl	Height (m): 1.66 ± 0.07 Body mass (kg): 55.5 ± 9.3 Lean body mass (kg): 42.46 ± 5.54 Lean body mass (%): 76.94 ± 3.53 Total body water (kg): 31.10 ± 4.24 Total body water (%): 56.35 ± 2.65 Total Lean body mass of body segments (kg): 40.3 ± 5.50	100 m front crawl v (m.s ⁻¹): 1.50 ± 0.07	all sample
Strzala et al., (2005)	16 - Males (100%)	Tier 3 16.3 ± 0.73 years	100 and 400 m (maximal) front crawl	Height (cm): 177 ± 6.50 Body mass (kg): 65.6 ± 7.60 Body fat (%): 9.4 ± 3.20 Lean body mass (kg): 59.3 ± 6.30	100 m front crawl v (m.s ⁻¹): 1.68 ± 0.06 400 m front crawl v (m.s ⁻¹): 1.47 ± 0.07	separate distances
Strzala et al., (2015)	27 - Males (100%)	Tier 3 15.7 ± 1.98 years	200 m (maximal) breaststroke	Height (cm): 1.80 ± 0.02 Body fat percentage (%): 10.8 ± 2.48 Body mass (kg): 70.03 ± 9.35 Lean body mass (kg): 62.5 ± 8.3	FINA points: 399.3 ± 74.14 200 m breaststroke v (m.s ⁻¹): 1.22 ± 0.08 200 m breaststroke v surface swimming (m.s ⁻¹): 1.09 ± 0.08 200 m breaststroke v while the breaststroke turn zone speed (m.s ⁻¹): 1.27 ± 0.07	all sample
Strzala et al., (2017)	34 - Males (100%)	Tier 3 and Tier 4 19.3 ± 1.83 years	50 m (maximal) butterfly	Height (cm): 183.7 ± 5.93 Body mass (kg): 78.3 ± 5.00 Lean body mass (kg): 69.8 ± 4.59	50 m butterfly v (m.s ⁻¹): 1.64 ± 0.06 Second 25 m (of the 50 m butterfly) v (m.s ⁻¹): 1.74 ± 0.07	all sample
Strzala et al., (2019)	35 - Males (100%) G1 youth: 20 Males G2 junior: 15 Males	Tier 3 and Tier 4 G1: 17.3 ± 0.59 years G2: 20.6 ± 1.05 years	50 m (maximal) front crawl	G1 / G2 Body mass (kg): 80.3 ± 4.85 / 74.8 ± 4.40 Lean body Mass (kg): 71.4 ± 4.48 / 66.9 ± 4.29 Body height (m): 184.9 ± 5.97 / 181.1 ± 6.25 Total Body length (cm): 256.9 ± 7.81 / 251.2 ± 9.97 Arm span (cm): 191.4 ± 6.74 / 188.4 ± 6.63	G1 / G2 50 m front crawl v (m.s ⁻¹): 1.92 ± 0.06 / 1.82 ± 0.06	separate groups
Strzala et al., (2020)	26 - Males (100%)	Tier 3 19.8 ± 2.48 years	100 m (maximal) front crawl	Height (cm): 183.8 ± 6.44 Body mass (kg): 77.2 ± 9.51 BMI (kg/m ²): (kg/cm ²): 22.78 Lean body (kg): 68.7 ± 9.66 Lean body (%): 88.9 ± 3.54 Total body water (kg): 50.3 ± 7.08 Total body water (%): 65.1 ± 2.59	100 m front crawl v surface (m.s ⁻¹): 1.66 ± 0.07 100 m front crawl v (m.s ⁻¹): 1.74 ± 0.07	all sample
Strzala et al., (2022)	28 - Males (100%)	Tier 3 and Tier 4 19.6 ± 2.59 years	100 m (maximal) front crawl	Height (cm): 183.8 ± 6.32 Body mass (kg): 77.7 ± 9.60 BMI (kg/m ²): 23.09 ± 1.75 Total body length (cm): 253.80 ± 9.77 Hand surface area (cm ²): 159.89 ± 15.49 Hand surface area and forearm (cm ²): 425.13 ± 40.57	100 m front crawl v surface (m.s ⁻¹): 1.65 ± 0.07 100 m front crawl v 100 (m.s ⁻¹): 1.81 ± 0.08	all sample

Table 1. (continued)

Authors (year)	Total sample - Females (%) / Males (%) G1 - n Males / n Females G2 - n Males / n Females ...	Tier Age (mean $\pm$ SD)	Test distance (intensity) Swimming techniques	Anthropometric domain Male / Female Group 1 / Group 2 / ... (mean $\pm$ SD)	Performance domain Male / Female Group 1 / Group 2 / ... Distance technique variable (unit): (mean $\pm$ SD)	Correlations (all sample or separate samples)
Tijani et al., (2019)	40 - Males (55%) / Females (45%) 22 Males / 18 Females	Tier 3 12.2 $\pm$ 0.5 years	25 m (maximal) front crawl	Height (cm): 154.57 $\pm$ 7.32 Body mass (kg): 44.23 $\pm$ 7.68 BMI (kg/m ²): 18.4 $\pm$ 2.21 Arm span (cm): 158.22 $\pm$ 9.87 Arm span/height ratio: 1.02 $\pm$ 0.02 Body fat (%): 14.23 $\pm$ 3.74 Males / Females	25 m front crawl v (m.s ⁻¹): 1.61 $\pm$ 0.09 50 m front crawl time (s): 31.27 $\pm$ 1.1	all sample
Veliz et al., (2020)	27 - Males (52%) / Females (48%) 14 Males / 13 Females	Tier 4 Males / Females 15.6 $\pm$ 2.06 / 15.4 $\pm$ 1.93	50,100 and 200 m (maximal) front crawl backstroke breaststroke butterfly medley	Body mass (kg): 62.3 $\pm$ 9.51 / 56.8 $\pm$ 7.58 Height (cm): 170.9 $\pm$ 7.27 / 164.0 $\pm$ 4.84 BMI (kg/m ²): 21.2 $\pm$ 2.31 / 21.1 $\pm$ 2.51 Body fat (%): 23.5 $\pm$ 3.26 / 28.9 $\pm$ 4.37 Body fat (kg): 14.3 $\pm$ 1.73 / 16.4 $\pm$ 3.05 Lean body mass (%): 46.2 $\pm$ 3.63 / 43.6 $\pm$ 3.52 Lean body mass (kg): 29.2 $\pm$ 6.39 / 24.8 $\pm$ 4.30 Muscle-Bone index: 3.82 $\pm$ 0.46 / 3.89 $\pm$ 0.45 Bone mass (%): 12.3 $\pm$ 0.99 / 11.3 $\pm$ 1.02 Bone mass (kg): 7.87 $\pm$ 1.17 / 6.38 $\pm$ 0.82	males / females 50 m front crawl time (s): - / 31.33 $\pm$ 1.76 100 m front crawl time (s): 57.89 $\pm$ 5.02 / - 200 m front crawl time (s): 131.10 $\pm$ 9.77 / - 400 m front crawl time (s): 264.25 $\pm$ 37.52 / - 50 m backstroke time (s): 31.02 $\pm$ 2.41 / 34.17 $\pm$ 2.56 100 m backstroke time (s): 66.79 $\pm$ 6.08 / - 50 m breaststroke time (s): 34.58 $\pm$ 4.28 / 41.60 $\pm$ 5.71 100 m breaststroke time (s): - / 85.44 $\pm$ 7.60 200 m breaststroke time (s): - / 202.20 $\pm$ 35.96 50 m butterfly time (s): - / 32.17 $\pm$ 1.51 200 m individual medley time (s): 144.78 $\pm$ 13.00 / - 50 m front crawl time (s): 32.22 $\pm$ 2.51 100 m front crawl time (s): 82.37 $\pm$ 10.28	separate sexes and techniques
Yarar et al., (2021)	15 - Males (100%)	Tier 2 21.06 $\pm$ 2.52 years	50 and 100 m (maximal) front crawl	Height (cm): 176.73 $\pm$ 0.72 Body mass (kg): 75.35 $\pm$ 13.71 Body fat (%): 12.57 $\pm$ 7.04 Midstyliion-dactyliion (cm): 19.3 $\pm$ 1.51 Hand width (cm): 8.66 $\pm$ 0.48 Arm length (cm): 78.0 $\pm$ 4.61 Arm span (cm): 178.1 $\pm$ 10.32 Foot length (cm): 26.1 $\pm$ 2.02 Foot width (cm): 10.2 $\pm$ 0.47 Leg length (cm): 94.5 $\pm$ 5.18 Sitting height (cm): 93.7 $\pm$ 3.43 Biacromial diameters (cm): 40.8 $\pm$ 2.63 Length of shank (cm): 237.7 $\pm$ 12.34	50 m front crawl time (s): 32.22 $\pm$ 2.51 100 m front crawl time (s): 82.37 $\pm$ 10.28	all sample

Table 2. Participant and studies models characteristics.

Authors (year)	Total sample - Females (%) / Males (%) G1 - n Males / n Females	Tier Age (mean ± SD)	Test distance (intensity) Swimming techniques	Anthropometric domain Male / Female Group 1 / Group 2 / ... (mean ± SD)		Performance domain Male / Female Group 1 / Group 2 / ... Distance technique variable (unit): (mean ± SD)	Model output performance variable R square constant of model variables of model and Beta scores
Dos Santos et al., (2021)	... 85 - Males (59%) / Females (41%) 50 Males / 35 Females	Tier 3 Males / Females 13.56 ± 1.80 / 12.60 ± 1.88 years	50 m (maximal) front crawl	Males / Females Body mass (kg): 54.72 ± 10.08 / 47.63 ± 10.88 Height (cm): 165.07 ± 11.06 / 154.68 ± 8.82 Body Fat (%): 17.88 ± 6.76 / 27.94 ± 5.89 Body fat (kg): 9.86 ± 4.40 / 13.74 ± 5.66 Lean body mass (kg): 44.85 ± 8.68 / 33.92 ± 6.08 Arm span (cm): 169.35 ± 12.51 / 157.29 ± 11.23 Sitting height (cm): 80.90 ± 7.95 / 74.44 ± 8.49 Arm muscle area (cm²): 23.50 ± 2.66 / 21.27 ± 2.30 Leg length (cm): 84.17 ± 11.12 / 80.24 ± 7.12		Males / Females 50 m front crawl time (s): 30.68 ± 3.70 / 34.39 ± 5.20 s 50 m front crawl v (m.s ⁻¹): 1.65 ± 0.18 / 1.48 ± 0.21	all sample log-transformed 50 m swim speeds r ² = 0.548; r = 0.74* Parameters / β / SE / P-value Boys constant (Ln(a)): -0.557 / 1.062 / 0.602 Girls (ΔLn(a)): -4.304 / 1.527 / 0.006 Ln (Body fat %) (k3): -0.121 / 0.036 / 0.001 Ln (PFA) (k4): 0.108 / 0.033 / 0.001 Ln (Arm span) (k5): 0.205 / 0.211 / 0.333 Categorical Maturity b: 0.002 / 0.032 / 0.955 Interaction Girls* Ln (Arm span) (Δk5): 0.850 / 0.301 / 0.006
Nevill et al., (2020)	363 - Males (56%) / Females (44%) G1 breaststroke: 39 Males / 20 Females G2 butterfly: 103 Males / 64 Females G3 backstroke: 30 Males / 34 Females G4 front crawl: 30 Males / 44 Females	Tier 3 Males / Females G1: 11.5 ± 1.3 / 12.1 ± 1.0 years G2: 13.1 ± 2.8 / 13.6 ± 2.6 years G3: 14.0 ± 0.6 / 13.0 ± 1.2 years G4: 19.0 ± 3.8 / 15.9 ± 2.7 years	100 m (maximal) front crawl backstroke butterfly breaststroke	Males / Females Body Mass (kg): G1: 41.5 ± 9.5 / 46.0 ± 8.6 G2: 50.0 ± 14.2 / 49.3 ± 9.2 G3: 48.7 ± 12.3 / 49.1 ± 7.1 G4: 73.2 ± 9.7 / 62.5 ± 9.2 Height (cm): G1: 149.9 ± 10.4 / 155.9 ± 8.0 G2: 158.3 ± 12.7 / 157.9 ± 9.0 G3: 157.2 ± 11.6 / 158.8 ± 7.4 G4: 177.8 ± 6.5 / 168.9 ± 9.0 Body Fat (%): G1: 16.8 ± 5.5 / 19.0 ± 4.3 G2: 16.6 ± 5.2 / 18.6 ± 3.7 G3: 17.6 ± 5.7 / 18.2 ± 3.9 G4: 12.9 ± 2.8 / 18.0 ± 4.4 Sitting height (cm): G1: 74.4 ± 5.8 / 76.4 ± 7.9 G2: 78.6 ± 7.1 / 79.0 ± 6.6 G3: 77.8 ± 6.8 / 79.7 ± 3.9 G4: 90.7 ± 4.3 / 85.2 ± 5.0 Upper limb length (cm): G1: 69.3 ± 5.3 / 72.0 ± 4.4 G2: 73.3 ± 6.2 / 73.1 ± 4.5 G3: 72.6 ± 5.6 / 74.1 ± 4.4 G4: 82.6 ± 3.5 / 78.6 ± 5.0	Males / Females Leg length (cm): G1: 42.0 ± 3.4 / 43.4 ± 2.5 G2: 44.2 ± 3.5 / 43.7 ± 2.7 G3: 43.7 ± 2.8 / 44.1 ± 2.5 G4: 48.2 ± 2.7 / 46.1 ± 2.9 Foot length (cm): G1: 25.1 ± 2.2 / 25.5 ± 1.1 G2: 26.2 ± 1.8 / 25.2 ± 1.1 G3: 26.1 ± 1.6 / 25.3 ± 1.1 G4: 27.8 ± 1.3 / 26.3 ± 1.5 Arm relaxed Girth (cm): G1: 23.0 ± 3.0 / 23.8 ± 2.3 G2: 24.8 ± 3.8 / 24.6 ± 2.2 G3: 24.4 ± 3.2 / 24.1 ± 2.0 G4: 30.7 ± 2.9 / 28.1 ± 2.0 Forearm Girth (cm): G1: 21.1 ± 1.9 / 21.5 ± 1.5 G2: 22.7 ± 3.0 / 21.9 ± 1.6 G3: 22.2 ± 2.4 / 21.8 ± 1.5 G4: 27.5 ± 1.9 / 24.3 ± 2.0 Wrist Girth (cm): G1: 14.7 ± 1.1 / 15.4 ± 2.3 G2: 15.5 ± 1.4 / 15.0 ± 0.8 G3: 15.4 ± 1.3 / 15.2 ± 0.8 G4: 17.4 ± 0.9 / 16.8 ± 4.9 Thigh circumference (cm): G1: 43.9 ± 4.5 / 46.1 ± 5.6 G2: 46.8 ± 5.4 / 47.7 ± 4.4 G3: 46.5 ± 4.9 / 47.3 ± 3.8 G4: 52.9 ± 5.0 / 51.8 ± 4.3	Males / Females 100m breaststroke time (s): 97.7 ± 13.5 / 95.4 ± 9.5 100m butterfly time (s): 79.1 ± 13.2 / 81.8 ± 11.2 100m backstroke time (s): 77.2 ± 8.8 / 79.5 ± 5.0 100m front crawl time (s): 54.8 ± 3.3 / 62.0 ± 4.5 100m breaststroke v (m.s ⁻¹): 1.04 ± 0.14 / 1.06 ± 0.10 100m butterfly v (m.s ⁻¹): 1.30 ± 0.22 / 1.24 ± 0.16 100m backstroke v (m.s ⁻¹): 1.31 ± 0.17 / 1.26 ± 0.08 100m front crawl v (m.s ⁻¹): 1.83 ± 0.11 / 1.62 ± 0.12	all sample log-transformed 100 m swim speeds r ² = 0.883; r = 0.94* Variable / Beta coefficient / Std. Error / P speeds (Ln(SS)) using multilevel modelling (MLwin). Ln(Body Fat) -0.096 0.017 Ln(Lower arm length) -0.250 0.077 Ln(Arm relaxed girth) -0.195 0.094 Ln(Forearm girth) 0.324 0.112 Ln(Biacromial breadth) 0.465 0.092 Ln(Biiliac breadth) 0.142 0.051 Ln(Arm span) 0.338 0.091 Variable / Beta coefficient / Std. Error / P (Ln(SS)) given by Equation (2). Ln(Body Fat) -.089 .018 -4.891 .000 Ln(Lower arm length) -.247 .078 .002 Ln(Arm relaxed girth) -.272 .100 .007 Ln(Forearm girth) .409 .132 .002 Ln(Biacromial breadth) .434 .094 .000 Ln(Biiliac breadth) .171 .050 .001 Ln(Arm span) .327 .087 .000

Table 2. (continued)

Authors (year)	Total sample - Females (%) / Males (%) G1 - n Males / n Females ...	Tier Age (mean ± SD)	Test distance (intensity) Swimming techniques	Anthropometric domain Male / Female Group 1 / Group 2 / ... (mean ± SD)		Performance domain Male / Female Group 1 / Group 2 / ... Distance technique variable (unit): (mean ± SD)	Model output performance variable R square constant of model variables of model and Beta scores
(cont.) Nevill et al., (2020)				Males / Females Arm Length (cm): G1: 29.0 ± 2.2 / 30.4 ± 2.0 G2: 30.8 ± 2.9 / 31.0 ± 2.3 G3: 30.5 ± 2.5 / 31.2 ± 2.2 G4: 34.9 ± 2.1 / 33.3 ± 2.6 Lower arm length (cm): G1: 23.2 ± 1.9 / 23.7 ± 1.7 G2: 24.3 ± 2.1 / 24.2 ± 1.7 G3: 23.9 ± 1.6 / 24.3 ± 1.7 G4: 27.2 ± 1.8 / 25.7 ± 1.9 Hand length (cm): G1: 18.0 ± 1.6 / 18.7 ± 1.0 G2: 19.0 ± 1.6 / 18.9 ± 1.0 G3: 18.9 ± 1.3 / 19.0 ± 0.9 G4: 21.1 ± 1.1 / 19.9 ± 1.2 Lower limb length (cm): G1: 81.6 ± 6.1 / 85.0 ± 5.0 G2: 85.9 ± 6.6 / 86.4 ± 5.7 G3: 85.5 ± 5.6 / 86.9 ± 5.0 G4: 93.4 ± 4.2 / 92.1 ± 5.2 Thigh length (cm): G1: 38.9 ± 5.8 / 42.0 ± 2.2 G2: 41.4 ± 3.1 / 42.8 ± 3.4 G3: 41.6 ± 3.1 / 42.9 ± 3.0 G4: 44.3 ± 2.3 / 45.5 ± 3.9	Males / Females Calf circumference (cm): G1: 30.3 ± 3.1 / 30.7 ± 3.0 G2: 32.3 ± 3.4 / 31.9 ± 2.6 G3: 32.4 ± 3.1 / 32.4 ± 2.3 G4: 36.7 ± 2.0 / 34.9 ± 2.8 Grith ankle (cm): G1: 20.5 ± 1.8 / 20.5 ± 1.5 G2: 21.2 ± 1.8 / 20.7 ± 1.2 G3: 21.2 ± 2.1 / 20.9 ± 1.1 G4: 23.1 ± 1.3 / 22.4 ± 1.4 Biacromial breadth (cm): G1: 41.5 ± 3.9 / 43.3 ± 2.3 G2: 43.8 ± 3.5 / 43.7 ± 2.1 G3: 43.4 ± 2.6 / 43.9 ± 2.0 G4: 48.2 ± 2.4 / 45.3 ± 2.4 Biliac breadth (cm): G1: 24.4 ± 2.4 / 25.7 ± 2.4 G2: 26.2 ± 2.7 / 26.5 ± 2.3 G3: 25.7 ± 2.3 / 26.4 ± 2.2 G4: 29.0 ± 2.2 / 28.6 ± 2.3		
Rozi et al., (2019)	51 - Males (59%) / Females (41%) G1 13-15: 18 Males / 14 Females G2 16-18: 12 Males / 7 Females	Tier 2 Males / Females 15.08 ± 1.6 / 14.52 ± 1.5 years	100 m (maximal) front crawl	Males / Females Body height (cm): All: 169.5 ± 9.03 / 162.8 ± 7.9 G1: 165.1 ± 7.8 / 159.9 ± 6.9 G2: 176.1 ± 6.4 / 168.7 ± 6.9 Body mass (kg): All: 62.2 ± 9.6 / 54.1 ± 8.1 G1: 56.8 ± 7.8 / 51.1 ± 7.8 G2: 70.3 ± 5.4 / 60.1 ± 5.1 Sitting height (cm): All: 85.7 ± 5.8 / 83.8 ± 5.3 G1: 82.4 ± 4.6 / 81.3 ± 4.8 G2: 90.6 ± 3.5 / 88.7 ± 1.5	Males / Females Biceps brachii circumference in relaxation (cm): All: 27.5 ± 2.3 / 26.07 ± 2.6 G1: 26.6 ± 2.4 / 25.0 ± 2.5 G2: 28.8 ± 1.1 / 28.2 ± 1.3 Biceps brachii circumference in contraction (cm): All: 30.0 ± 2.5 / 28.07 ± 2.7 G1: 28.7 ± 2.3 / 27.03 ± 2.7 G2: 32.0 ± 1.1 / 30.1 ± 1.5	Males / Females 100m front crawl Performance time (s): All: 69.3 ± 6.4 / 61.3 ± 3.4 G1: 67.3 ± 6.1 / 59.8 ± 2.9 G2: 71.8 ± 6.1 / 63.9 ± 2.7	Time 100 m (male): 0.846; 2.61* Time 100 m (female): 0.544; 4.44* Time 100 m (16-18 yrs.): 0.717; 1.96* Time 100 m(13-15 yrs.): 0.727 3.49 0.000 Time 100 m (male): 125.700 – arm span • 0.182 + biceps skinfold • 0.597 – biceps bracchi circumference contracted • 1.129 Time 100 m (female): 143.427 – sitting height • 0.885 Time 100 m (16–18 yrs.): 109.360 – biceps bracchi circumference contracted • 1.104 – body weight • 0.202 Time 100 m(13–15 yrs.): 111.241 + triceps skinfold • 1.075 – biceps brachii circumference in contraction • 1.849

Table 2. (continued)

Authors (year)	Total sample - Females (%) / Males (%) G1 - n Males / n Females ...	Tier Age (mean ± SD)	Test distance (intensity) Swimming techniques	Anthropometric domain Male / Female Group 1 / Group 2 / ... (mean ± SD)	Performance domain Male / Female Group 1 / Group 2 / ... Distance technique variable (unit): (mean ± SD)	Model output performance variable R square constant of model variables of model and Beta scores
(cont.) Rozi et al., (2019)				Males / Females Arm span (cm): All: 173.0 ± 10.9 / 164.9 ± 8.9 G1: 168.2 ± 10.4 / 163.1 ± 10.01 G2: 180.3 ± 6.9 / 168.5 ± 5.1 Shoulder width (cm): All: 39.0 ± 2.7 / 36.8 ± 2.2 G1: 37.5 ± 2.2 / 36.3 ± 2.3 G2: 41.3 ± 1.5 / 37.8 ± 1.5 Pelvis width (cm): All: 32.7 ± 1.9 / 33.9 ± 2.6 G1: 32.05 ± 2.1 / 33.1 ± 2.8 G2: 33.6 ± 1.2 / 35.4 ± 1.4 Chest depth (cm): All: 20.5 ± 1.9 / 19.5 ± 1.6 G1: 20.05 ± 1.8 / 19.1 ± 1.8 G2: 21.2 ± 1.9 / 20.3 ± 0.7 Chest circumference (cm): All: 90.8 ± 6.9 / 87.04 ± 6.9 G1: 87.3 ± 5.8 / 83.8 ± 6.2 G2: 96.0 ± 5.02 / 93.4 ± 1.4	Males / Females Left arm length (cm): All: 73.8 ± 4.6 / 70.3 ± 3.8 G1: 71.5 ± 3.8 / 69.4 ± 4.1 G2: 77.2 ± 3.5 / 72.0 ± 2.6 Breast skinfold (cm): All: 5.3 ± 2.6 / 5.3 ± 1.7 G1: 5.8 ± 3.1 / 5.03 ± 1.4 G2: 4.6 ± 1.6 / 5.8 ± 2.4 Biceps skinfold (cm): All: 6.6 ± 4.02 / 8.1 ± 2.6 G1: 7.7 ± 4.8 / 7.6 ± 2.1 G2: 4.9 ± 1.3 / 9.2 ± 3.4 Triceps skinfold (cm): All: 7.4 ± 3.5 / 10.0 ± 2.6 G1: 8.5 ± 3.9 / 9.9 ± 2.3 G2: 5.8 ± 1.7 / 10.2 ± 3.2 Iliiac skinfold (cm): All: 8.5 ± 3.9 / 9.2 ± 2.4 G1: 9.1 ± 4.7 / 8.3 ± 1.9 G2: 7.8 ± 2.3 / 11.0 ± 2.5 Biacromial skinfold (cm): All: 9.4 ± 6.1 / 9.04 ± 3.1 G1: 9.7 ± 7.4 / 8.1 ± 3.1 G2: 8.8 ± 3.6 / 11.0 ± 2.3 Gastrocnemius skinfold (cm): All: 14.4 ± 5.7 / 14.4 ± 5.1 G1: 15.8 ± 6.5 / 14.7 ± 4.4 G2: 12.2 ± 3.5 / 13.7 ± 3.5 Abdominal skinfold (cm): All: 12.9 ± 6.7 / 14.6 ± 4.3 G1: 13.6 ± 7.5 / 12.9 ± 4.0 G2: 11.9 ± 5.3 / 17.9 ± 3.1	

Table 2. (continued)

Authors (year)	Total sample - Females (%) / Males (%) G1 - n Males / n Females ...	Tier Age (mean $\pm$ SD)	Test distance (intensity) Swimming techniques	Anthropometric domain Male / Female Group 1 / Group 2 / ... (mean $\pm$ SD)	Performance domain Male / Female Group 1 / Group 2 / ... Distance technique variable (unit): (mean $\pm$ SD)	Model output performance variable R square constant of model variables of model and Beta scores
Sammoud et al., (2019)	63 - Males (48%) / Females (52%) 30 Males / 33 Females	Tier 3 Males / Females 13.98 $\pm$ 0.58 / 13.02 $\pm$ 1.20 years	100 m (maximal) backstroke	Males / Females Body mass (kg): 48.70 $\pm$ 12.28 / 49.08 $\pm$ 7.08 Height (cm): 157.2 $\pm$ 11.6 / 158.8 $\pm$ 7.4 Sitting height (cm): 77.8 $\pm$ 6.8 / 79.8 $\pm$ 3.9 Body fat (%): 17.58 $\pm$ 5.69 / 18.24 $\pm$ 3.86 Body fat (kg): 8.74 $\pm$ 3.96 / 9.09 $\pm$ 2.87 Lean body mass (kg): 39.96 $\pm$ 9.96 / 39.98 $\pm$ 4.99 BMI (kg.m ⁻²): 19.45 $\pm$ 2.66 / 19.40 $\pm$ 1.90 Arm Length (cm): 30.5 $\pm$ 2.5 / 31.2 $\pm$ 2.2 Forearm length (cm): 23.9 $\pm$ 1.6 / 24.3 $\pm$ 1.7 Hand length (cm): 18.9 $\pm$ 1.3 / 19.0 $\pm$ 0.9 Thigh length (cm): 41.6 $\pm$ 3.1 / 42.9 $\pm$ 2.9 Leg length (cm): 43.7 $\pm$ 2.8 / 44.1 $\pm$ 2.5 Foot length (cm): 26.1 $\pm$ 1.5 / 25.3 $\pm$ 1.1 Arm relaxed girth (cm): 24.4 $\pm$ 3.2 / 24.1 $\pm$ 2.0 Forearm girth (cm): 22.2 $\pm$ 2.4 / 21.8 $\pm$ 1.4 Thigh circumference (cm): 46.5 $\pm$ 4.9 / 47.3 $\pm$ 3.8 Calf circumference (cm): 32.4 $\pm$ 3.2 / 32.4 $\pm$ 2.3 Biacromial breadth (cm): 43.4 $\pm$ 2.6 / 44.0 $\pm$ 2.0 Biiliocrystal breadth (cm): 25.7 $\pm$ 2.2 / 26.4 $\pm$ 2.2	Males / Females 100 m backstroke time (s): 77.16 $\pm$ 8.76 / 79.51 $\pm$ 5.00 100 m backstroke v (m.s ⁻¹): 1.31 $\pm$ 0.17 / 1.26 $\pm$ 0.08	all sample log-transformed 100 m backstroke swim speeds r ² = 0.75; r = 0.87* Variable / Beta coefficient / Std. Error Constant -4.400 / 0.468 / 0.001 Female -0.041 / 0.013 / 0.003 Biological age 0.037 / 0.008 / 0.001 Log (sitting height) 0.833 / 0.154 / <0.001 Log (leg-length) 0.258 / 0.132 / 0.057 Log (arm-relaxed girth) -0.627 / 0.141 / 0.001 Log (forearm girth) 0.519 / 0.183 / 0.006
Sammoud et al., (2023)	74 - Males (55%) / Females (45%) 41 Males / 33 Females	Tier 3 Males / Females 18.1 $\pm$ 3.5 / 15.9 $\pm$ 3.1 years	100 m (maximal) front crawl	Males / Females Body mass (kg): 72.7 $\pm$ 9.0 / 59.54 $\pm$ 8.0 Height (cm): 178.1 $\pm$ 6.5 / 165.53 $\pm$ 6.91 Sitting height (cm): 90.2 $\pm$ 4.2 / 83.95 $\pm$ 4.65 Body fat (%): 13.4 $\pm$ 3.2 / 19.0 $\pm$ 4.1 Body fat (kg): 9.7 $\pm$ 2.5 / 11.30 $\pm$ 2.8 Lean body mass (kg): 61.1 $\pm$ 8.7 / 46.6 $\pm$ 6.2 BMI (kg.m ⁻²): 22.9 $\pm$ 2.0 / 21.7 $\pm$ 1.8 Upper extremity length (cm): 82.9 $\pm$ 3.7 / 77.0 $\pm$ 4.2 Arm Length (cm): 34.9 $\pm$ 2.0 / 32.8 $\pm$ 2.6 Forearm length (cm): 27.2 $\pm$ 1.8 / 25.2 $\pm$ 1.8 Hand length (cm): 21.1 $\pm$ 1.1 / 19.44 $\pm$ 0.9 Lower extremity length (cm): 93.7 $\pm$ 4.1 / 91.4 $\pm$ 5.3 Thigh length (cm): 44.6 $\pm$ 2.7 / 45.5 $\pm$ 4.1 Leg length (cm): 48.4 $\pm$ 2.6 / 45.2 $\pm$ 2.5 Foot length (cm): 27.9 $\pm$ 1.3 / 25.75 $\pm$ 1.12 Arm relaxed girth (cm): 30.4 $\pm$ 2.7 / 27.60 $\pm$ 1.87 Forearm girth (cm): 27.2 $\pm$ 1.9 / 23.6 $\pm$ 1.7 Wrist girth (cm): 17.4 $\pm$ 0.9 / 16.5 $\pm$ 5.6 Thigh circumference (cm): 53.1 $\pm$ 4.7 / 51.30 $\pm$ 4.4 Calf circumference (cm): 36.7 $\pm$ 2.1 / 34.30 $\pm$ 2.7 Ankle girth (cm): 23.2 $\pm$ 1.3 / 22.0 $\pm$ 1.3 Biacromial breadth (cm): 48.1 $\pm$ 2.2 / 44.5 $\pm$ 2.1 Biiliocrystal breadth (cm): 28.9 $\pm$ 2.3 / 28.7 $\pm$ 2.3 Arm span (cm): 184.9 $\pm$ 9.3 / 169.2 $\pm$ 9.4	Males / Females 100 m front crawl time (s): 55.3 $\pm$ 3.1 / 63.9 $\pm$ 3.5 100 m front crawl v (m.s ⁻¹): 1.83 $\pm$ 0.11 / 1.62 $\pm$ 0.12	all sample log-transformed 100 m freestyle swim speeds Variable / Beta coefficient / Std. Error / P Constant -4.395 / 0.586 / 0.001 Gender boys (Da) 0.037 / 0.012 / 0.002 Ln (% body fat) -0.053 / 0.021 / 0.009 Ln (height) 0.789 / 0.200 / 0.001 Ln (leg length) -0.346 / 0.128 / 0.009 Ln (foot length) 0.264 / 0.123 / 0.035 Ln (ankle girth) -0.195 / 0.085 / 0.025 Ln (biacromial breadth) 0.537 / 0.115 / 0.000

Table 2. (continued)

Authors (year)	Total sample - Females (%) / Males (%) G1 - n Males / n Females ...	Tier Age (Mean ± SD)	Test distance (intensity) Swimming techniques	Anthropometric domain Male / Female Group 1 / Group 2 /... (Mean ± SD)	Performance domain Male / Female Group 1 / Group 2 /... Distance technique variable (unit): (Mean ± SD)	Model output performance variable R square constant of model variables of model and Beta scores
Thanopoulos et al., (2006)	25 - Males (52%) / Females (48%) 13 Males / 12 Females	Tier 3 Males / Females 15.3 ± 1.4 / 14.8 ± 1.2 years	50 and 100 m (maximal) front crawl	Males / Females BMI (kg/m ²): 20.7 ± 1.73 / 18.97 ± 2.17 Lean body mass (kg): 59.05 ± 5.62 / 41.37 ± 4.70 Body fat (%): 7.13 ± 1.83 / 15.23 ± 3.71 Leg-length index: 0.51 ± 0.014 / 0.531 ± 0.014 Arm-length index: 1.043 ± 0.035 / 1.040 ± 0.025 Index of the chest shape: 0.515 ± 0.035 / 0.510 ± 0.062 Index of the trunk shape: 0.810 ± 0.029 / 0.812 ± 0.081 Index of the body shape: 0.186 ± 0.054 / 0.183 ± 0.014	Males / Females 50 m front crawl critical velocity (m.s ⁻¹): 1.656 ± 0.106 / 1.516 ± 0.076 100 m front crawl critical velocity (m.s ⁻¹): 1.572 ± 0.084 / 1.445 ± 0.074	Male Vcri50 (Adjusted R ² = 0.5685, p = 0.026) index of the body shape (t = 3.09, p = 0.015) index of the trunk shape (t = - 1.43, p = 0.188) LBM (t = 3.73, p = 0.006) BMI (t = - 2.37, p = 0.045) The Critical velocity100 (Adjusted R ² = 0.5679; p = 0.024) index of the body shape (t = 1.32, p=0.224), index of the trunk shape (t = -1.52, p=0.168), LBM (t =2.18, p = 0.061) percentage of the body fat (t = -3.26, p = 0.012). Female Vcrr50 (Adjusted R ² = 0.5709, p = 0.009) arm-length index (t = -3.21, p = 0.011) LBM (t = 3.40, p = 0.008) Critical velocity100 (Adjusted R ² = 0.4729, p = 0.023) arm-length index (t = -3.03, p = 0.014) LBM (t 2.52, p = 0.033). Repeated measures correlation - all sample across the three moments (Males front crawl / Females breaststroke): 15 m time (s) - total body mass (kg): r = 0.05 15 m time (s) - body fat (kg): r = 0.52 (large effect) 15 m time (s) - lean body mass (kg): r = - 0.30 15 m time (s) - lower body lean mass (kg): r = -0.30
Thng et al., (2022)	5 - Males (60%) / Females (40%) 3 Males / 2 Females	Tier 3 Males / Females 22.1 ± 3.2 / 19.9 ± 2.5 years	100 and 200 m (maximal) Males front crawl Females breaststroke	Males / Females: Height (m): 1.95 ±0.08 / 1.75 ±0.04 Body mass (kg): 86.8 ±10.0 / 70.0 ±5.0 Male 1 / Male 2 / Male 3 / Female 1 / Female 2 Total body mass (kg): T1: 96.0 / 88.3 / 76.1 / 73.5 / 66.5 T2: 96.5 / 90.1 / 77.8 / 74.8 / 65.6 T3: 95.8 / 91.7 / 79.5 / 72.8 / 67.7 Body fat (kg): T1: 16.7 / 12.9 / 13.7 / 21.4 / 19.3 T2: 15.3 / 12.4 / 13.2 / 20.9 / 17.7 T3: 17.2 / 13.3 / 13.0 / 18.5 / 19.4 Lean body mass (kg): T1: 76.0 / 71.6 / 59.5 / 49.5 / 44.8 T2: 77.9 / 73.9 / 61.8 / 51.3 / 45.5 T3: 75.2 / 74.5 / 63.6 / 51.7 / 45.9 Lower body lean mass (kg): T1: 22.8 / 21.4 / 16.8 / 15.4 / 14.1 T2: 24.0 / 22.4 / 17.6 / 16.3 / 14.3 T3: 24.1 / 23.2 / 18.4 / 16.8 / 14.6	Males / Females FINA points: 861.7 ± 39.6 / 817.5 ± 44.6 Male 1 / Male 2 / Male 3 15 m front crawl time (s): T1: 5.97 / 6.14 / 6.41 T2: 6.03 / 6.37 / 6.36 T3: 6.00 / 6.22 / 6.21 Female 1 / Female 2 15 m breaststroke time (s): T1: 8.91 / 8.66 T2: 8.73 / 8.49 T3: 8.63 / 8.68	

Participant Classification and performance assessment

The most relevant participants tier found in the selected trials was tier 3 or national level swimmers and only ~16% (k = 11) used samples of swimmers of Tiers 4 and 5 (see Figure 4). Also, only 5 and 2 trials used separated samples of Tier 4 (Carvalho et al., 2023; Daly et al., 1988; Dopsaj et al., 2020; Pereira et al., 2010; Strzała et al., 2019) and tier 5 (A. C. Barbosa et al., 2019; Shephard et al., 2014) (respectively). More than half (> 50%) of the trials did not refer if the swimming performance test used was in their specialties regarding both swimming technique and distance. However front crawl was the most present swimming technique found in the studies (88%), what can be explained by the amount of front crawl that a swimmer normally performs during practice (more than 60%) (Stewart & Hopkins, 2000). Performance distances of 50 and 100 m were the most common swimming performance tests/events used to correlate with anthropometry. The number of registers were 82, superior to the original 67 trials, due to the studies that presented mixed samples and analysed them separated, counting as three or more entries (one in each tier present and one in the mixed columns).

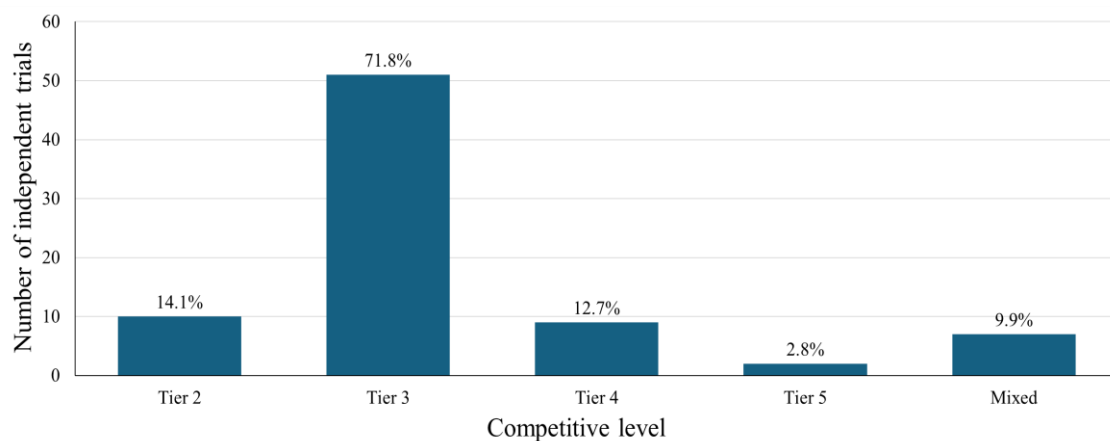


Figure 4. Distribution of participants classification in number of independent trials.

Anthropometric characteristics

It was observed the presence of 138 different physical variables assessed in the trials analysed in this review (see Figure 5). The ten most prevalent variables were body mass and height in more than 90% of the trials, arm span in 48%, body fat percentage, body mass index, lean body mass, hand length, foot length, body fat mass and sitting height. Only more 10 variables had prevalence in at least 10% of the trials, leaving more than 100 variables that appear in less than 7% of the trials ($k = 5$).

Risk of bias in studies

Figures 6 and 7 shows the risk of bias percentage distribution for the included trials or anthropometry and performance outcomes (respectively), with only 9 trials (i.e. 5% on average) presenting a high risk of bias on different domains, particularly due to the confounding variables (15%). However, the low risk of bias was predominant in the selection of participants (93%; information about age or sex was not available), confounding variables (70 and 63%; evaluations made in different time, some part of the evaluation is made with combined sexes or presenting only combined sexes outcomes) and incomplete outcome data (77%; unclear by only presents correlation values for the significant ones and high bias when not presenting even the significant outcomes, only the p-values). In addition, most trials (97%) presented an unclear risk of bias have in the blinding of outcome assessments, but as they are observational studies with anthropometric and performance tests the evaluations were likely not influenced by knowledge of the interventions. Also, most trials presented an unclear risk of bias in selective outcome reporting (93%; did not present a preregistered protocol or duplicated studies separating samples). Figure 8 shows the risk of bias percentage distribution for the included trials that only presented complete anthropometric models without individual correlation values. For further detail, the reader can see Table S4 in the Supplementary Material.

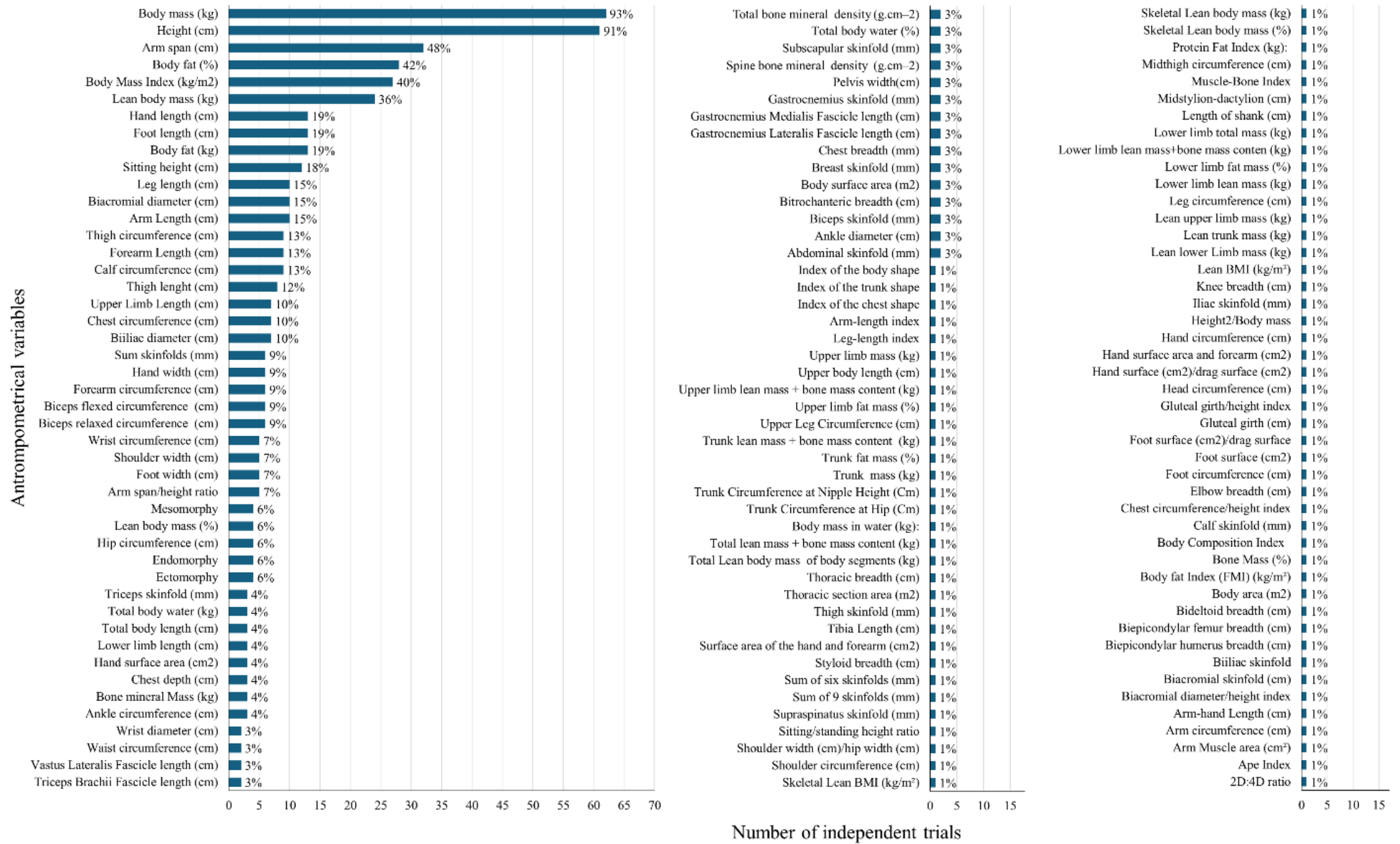


Figure 5. Distribution of anthropometrical variables in number of independent trials.

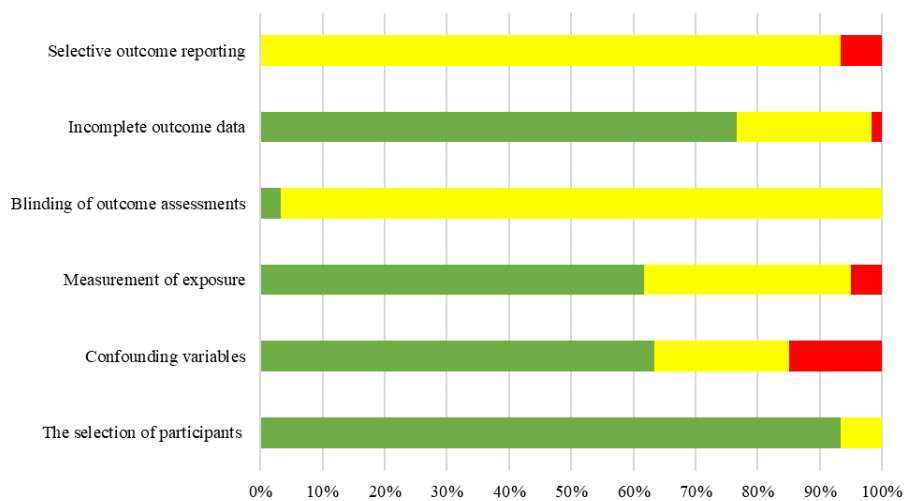


Figure 6. Risk of Bias for performance outcome with 60 individual trials.

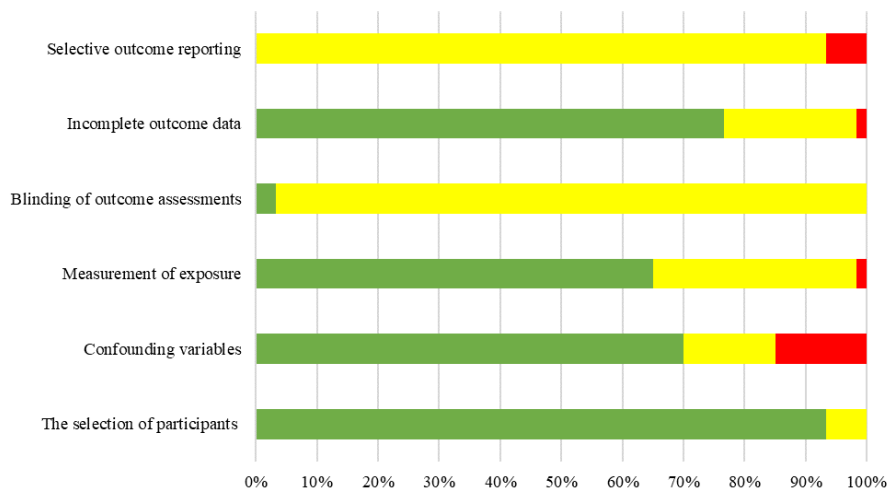


Figure 7. Risk of Bias for anthropometry outcome with 60 individual trials.

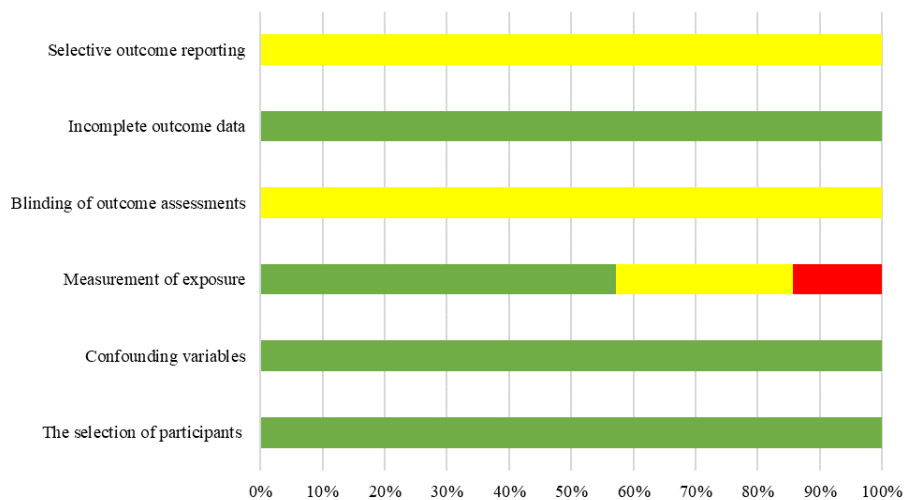


Figure 8. Risk of Bias for the 7 individual trials that present anthropometrical models to predict performance.

Results of individual trials

Most trials (> 80%) showed that existed an advantage of swimmers with higher lengths and diameters and disadvantage of higher body fat mass to achieve better swimming performance regardless of the type of performance output chosen, distance and swimming techniques. However, more than half of the trials studied relationships of anthropometry and performance in young or youth swimmers (mean ages between 10 and 17 years old) without controlling the effect of maturation where the biological and chronological ages can present different effects on this analysis and maturation presents a source of heterogeneity. In the elite categories, with the lower number of trials ($k = 11$), the results showed contradictory results, where sometimes the same anthropometrical characteristic (e.g., body fat mass) had positive and negative significant correlations/associations depending on the sex or swimming performance used (Dopsaj et al., 2020; Shephard et al., 2014).

Results of syntheses

Were selected seven principal meta-analyses in total based on the number of studies present, sample size, and possibility of performing subgroup analysis. The selected meta-analyses corresponded to relationships between distances up to 100 m in front crawl and height, arm span, body fat mass and body lean mass. With all the trials analysed it were computed other 20 meta-analysis that can be found in S5 in the Supplementary Material. After Bonferroni corrections (for 27 meta-analysis) the p value assumed for significant effects was ≤ 0.002 .

Female swimmers, front crawl times (s) in distances up to 100 m and arm span (cm)

The meta-analysis presented in Figure 9 was performed between three trials ($K = 3$) totalizing 148 female swimmers ($N = 148$). Significant association was noted between outcomes (Fisher's $Z = -0.276$, 95% CI -0.444 to -0.108, $p = 0.001$). Tests for the magnitude of the impact of heterogeneity were identified as non-significant ($p = 0.400$) and low ($I^2 = 0.0\%$). The higher arms span favours better performances in front crawl distances up to 100m for female swimmers.

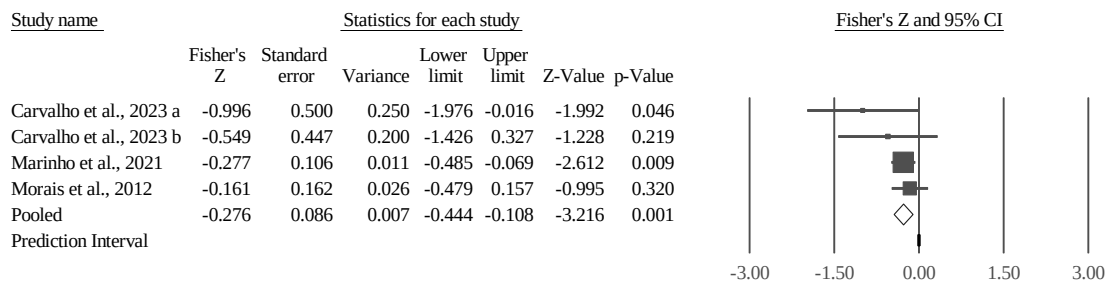


Figure 9. Forest plot outlining the association between females front crawl times (s) in distances up to 100 m and arm span (cm). Plotted black squares denote trials effect sizes (Fisher's Z), with 95% confidence intervals, and their area (size) represents trials relative weights. The white rhomboid represents the overall result. Trials with letter "a" and "b" denotes different groups in a single study.

Female swimmers, front crawl times (s) in distances up to 100 m and body height (cm)

The meta-analysis presented in Figure 10 was performed between six trials ($k = 6$) totalizing 255 female swimmers ($N = 255$). Non-significant association was noted between outcomes (Fisher's $Z = -0.212$, 95% CI -0.463 to 0.040 , $p = 0.099$). Tests for the magnitude of the impact of heterogeneity were identified as significant ($p < 0.001$) and moderate ($I^2 = 54.1\%$). The body height does not show a specific effect in front crawl distances up to 100m for female swimmers.

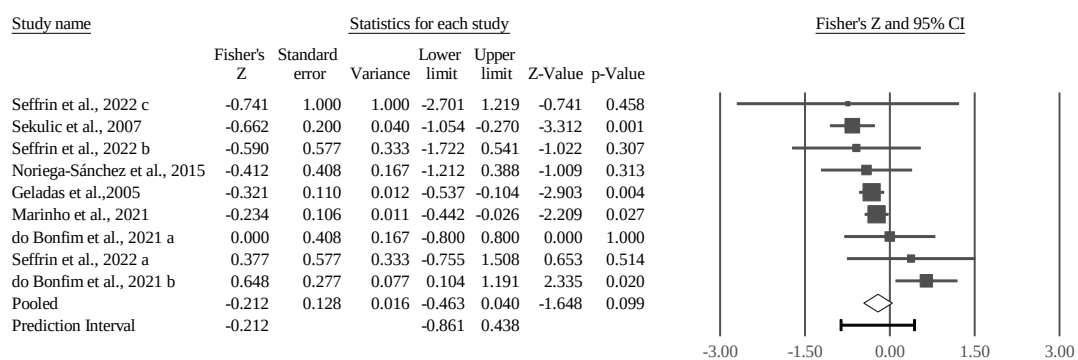


Figure 10. Forest plot outlining the association between females front crawl times (s) in distances up to 100 m and body height (cm). Plotted black squares denote trials effect sizes (Fisher's Z), with 95% confidence intervals, and their area (size) represents trials relative weights. The white rhomboid represents the overall result. Trials with letter "a", "b" and/or "c" denotes different groups in a single study.

Female swimmers, front crawl times (s) in distances up to 100 m and body fat mass (%)

The meta-analysis presented in Figure 11 was performed between six trials (k = 5) totalizing 203 female swimmers (N = 203). Non-significant association was noted between outcomes (Fisher's Z = 0.394, 95% CI 0.034 to 0.755, p = 0.032). Tests for the magnitude of the impact of heterogeneity were identified as significant (p < 0.001) and moderate ($I^2 = 73.2\%$). The body fat mass does not show a specific effect in front crawl distances up to 100m for female swimmers.

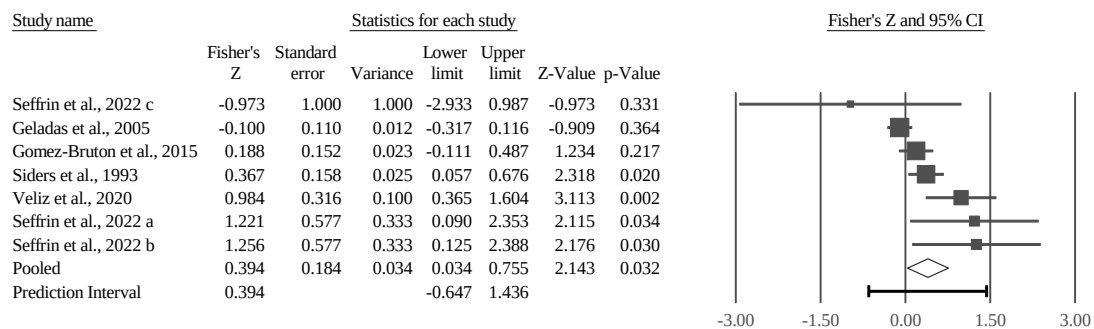


Figure 11. Forest plot outlining the association between females front crawl times (s) in distances up to 100 m and body fat mass (%). Plotted black squares denote trials effect sizes (Fisher's Z), with 95% confidence intervals, and their area (size) represents trials relative weights. The white rhomboid represents the overall result. Trials with letter "a", "b" and/or "c" denotes different groups in a single study.

Male swimmers, front crawl times (s) in distances up to 100 m and arm span (cm)

The meta-analysis presented in Figure 12 was performed between eight trials (K = 8) totalizing 247 male swimmers (N = 247). Significant association was noted between outcomes (Fisher's Z = -0.666, 95% CI -0.957 to 0.-375, p < 0.001). Tests for the magnitude of the impact of heterogeneity were identified as significant (p < 0.000) and high ($I^2 = 77.2\%$). A sub-group analysis as per the athlete's tier level indicated a significant correlation for tier 3 (N = 184, Z = -0.704, p = 0.001), and tier 2 (N = 63, Z = -0.601, p < 0.001), although without reaching significance for the between sub-groups comparison (p = 0.690). The higher arms span favours better performances in front crawl distances up to 100m for male swimmers independently the Tier level 2 and 3.

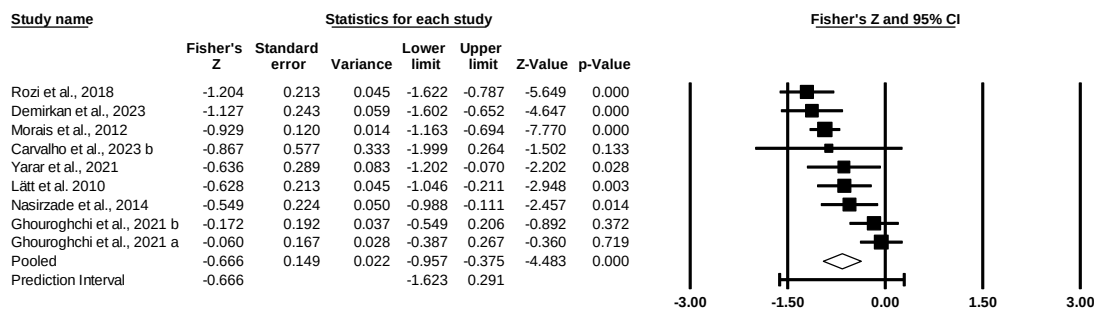


Figure 12. Forest plot outlining the association between males front crawl times (s) in distances up to 100 m and arm span (cm). Plotted black squares denote trials effect sizes (Fisher's Z), with 95% confidence intervals, and their area (size) represents trials relative weights. The white rhomboid represents the overall result. Trials with letter "a" and "b" denotes different groups in a single study.

Male swimmers, front crawl times (s) in distances up to 100 m and body fat mass (%)

The meta-analysis presented in Figure 13 was performed between six trials (K = 6) totalizing 330 male swimmers (N = 330). Non-significant association was noted between outcomes (Fisher's Z = -0.016, 95% CI -0.128 to 0.096, $p = 0.782$). Tests for the magnitude of the impact of heterogeneity were identified as non-significant ($p = 0.529$) and low ($I^2 = 0.0\%$). A sub-group analysis as per the athlete's tier level indicated a non-significant correlation for tier 3 (N = 274, Z = -0.02, $p = 0.831$), and tier 2 (N = 56, Z = 0.12, $p = 0.424$), without significant difference for the between sub-groups comparison ($p = 0.422$). The body fat mass does not show a specific effect in front crawl distances up to 100m for male swimmers independently the Tier level 2 and 3.

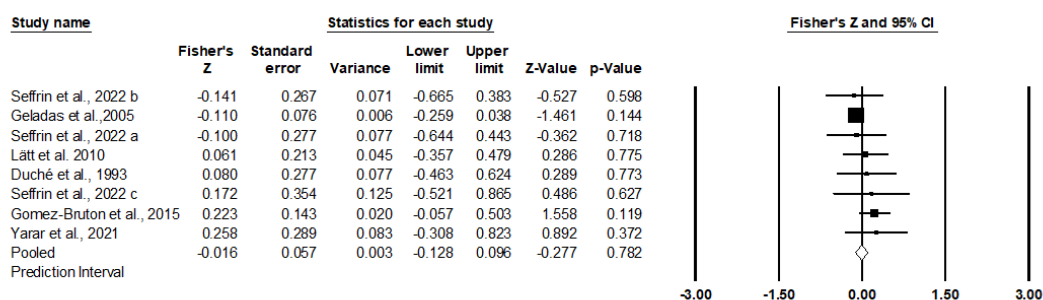


Figure 13. Forest plot outlining the association between males front crawl times (s) in distances up to 100 m and body fat mass (%). Plotted black squares denote trials effect sizes (Fisher's Z), with 95% confidence intervals, and their area (size) represents trials relative weights. The white rhomboid represents the overall result. Trials with letter "a", "b" and/or "c" denotes different groups in a single study.

*Male swimmers, front crawl times (s) in distances up to 100 m and
body lean mass (kg)*

The meta-analysis presented in Figure 14 was performed between four trials (K = 4) totalizing 141 male swimmers (N = 141). Significant association was noted between outcomes (Fisher's Z = -0.712, 95% CI -0.916 to -0.508, $p < 0.001$). Tests for the magnitude of the impact of heterogeneity were identified as non-significant ($p = 0.291$) and low ($I^2 = 18.8\%$). The higher body lean mass favours better performances in front crawl distances up to 100m for male swimmers.

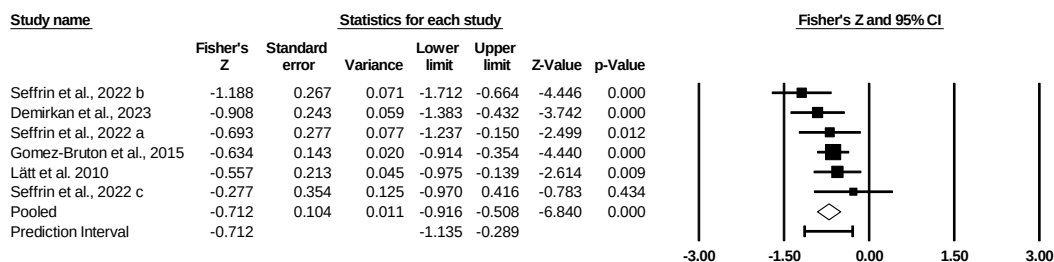


Figure 14. Forest plot outlining the association between males front crawl times (s) in distances up to 100 m and body lean mass (kg). Plotted black squares denote trials effect sizes (Fisher's Z), with 95% confidence intervals, and their area (size) represents trials relative weights. The white rhomboid represents the overall result. Trials with letter "a", "b" and/or "c" denotes different groups in a single study.

*Male swimmers, front crawl times (s) in distances up to 100 m and
body height (cm)*

The meta-analysis presented in Figure 15 was performed between eleven trials (k = 11) totalizing 446 male swimmers (N = 446). Significant association was noted between outcomes (Fisher's Z = -0.736, 95% CI -0.847 to -0.625, $p < 0.001$). Tests for the magnitude of the impact of heterogeneity were identified as non-significant ($p = 0.348$) and low ($I^2 = 9.8\%$). A sub-group analysis as per the athlete's tier level indicated a significant correlation for tier 3 (N = 367, Z = -0.77, $p < 0.001$), and for tier 2 (N = 79, Z = -0.59, $p < 0.001$), without significant difference for the between sub-groups comparison ($p = 0.210$). A sub-group analysis as per the year of articles publication indicated a significant correlation for articles published up to 2009 (Z = -0.74, $p < 0.001$) and after 2009 (Z = -0.71, $p < 0.001$), with no significant difference for the between sub-groups comparison ($p = 0.724$). The meta-regression analysis indicated that Tier level and year of

articles publication did not significantly explain the correlation, either as isolated or combined factors in the model ($p > 0.208$). No risk of reporting bias was noted (Egger's test, 2-tailed p -value = 0.418). The higher body height favours better performances in front crawl distances up to 100m for male swimmers independently of the tiers 2 and 3 and year of publication.

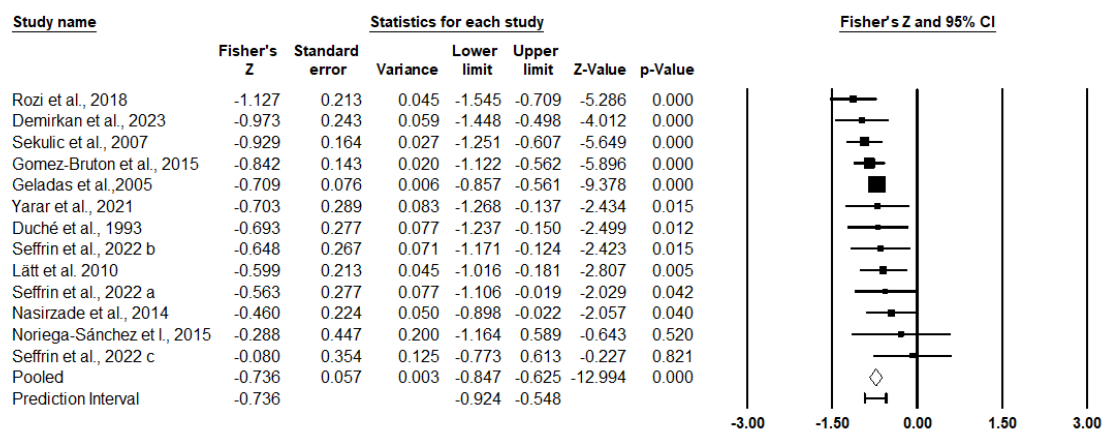


Figure 15. Forest plot outlining the association between males front crawl times (s) in distances up to 100 m and body height (cm). Plotted black squares denote trials effect sizes (Fisher's Z), with 95% confidence intervals, and their area (size) represents trials relative weights. The white rhomboid represents the overall result. Trials with letter "a", "b" and/or "c" denotes different groups in a single study.

Subgroup analysis

Tier and year were the only subgroups eligible for meta-analysis. Similar effects of anthropometry on front crawl swimming performance (s) in distance up to 100 m were verified for Tier 2 and 3 before and after 2009. No sufficient data existed to define associations based only on Tiers 4 and 5.

Certainty of evidence

We found a low and very low level of certainty of evidence, due to an analysis with moderate risk of bias in trials, and low number of participants included in the analyses and/or the confidence interval crossed the small effect size in main analyses (Table 3).

Table 3. Certainty of evidence (GRADE).

Outcomes	Trials (k) and PSS	Risk of bias in trials	Risk of publication bias	Inconsistency	Imprecision	Certainty of evidence
Front crawl time in distances up to 100 m and arm span (female)	k=3, n=148	Downgrade by one level (some concerns).	Not assessed ($k \leq 10$)	No downgrading ($I^2=0.0\%$)	Downgrade by one level: (i) <800 participants; (ii) moderate mean effect favouring longer arm spans.	⊕⊕, Low
Front crawl time in distances up to 100 m and body height (female)	k=6, n=255	Downgrade by one level (some concerns).	Not assessed ($k \leq 10$)	Downgrade by one level ($I^2=54.1\%$)	Downgrade by two levels: (ii) <800 participants; (ii) unclear direction of effects and very large 95% CIs in several of the included trials.	⊕, Very low
Front crawl time in distances up to 100 m and % body fat mass (female)	k=5, n=203	Downgrade by one level (some concerns).	Not assessed ($k \leq 10$)	Downgrade by one level ($I^2=73.2\%$)	Downgrade by two levels: (ii) <800 participants; (ii) unclear direction of effects and very large 95% CIs in several of the included trials.	⊕, Very low
Front crawl time in distances up to 100 m and arm span (male)	k=8, n=247	Downgrade by one level (some concerns).	Not assessed ($k \leq 10$)	Downgrade by two levels ($I^2=77.2\%$)	Downgrade by one level: (i) <800 participants; (ii) large mean effect favouring longer arm spans.	⊕, Very low
Front crawl time in distances up to 100 m and body height (male)	k=11, n=446	Downgrade by one level (some concerns).	No suspected risk of publication bias.	No downgrading ($I^2=9.8\%$)	Downgrade by one level: (i) <800 participants; (ii) large mean effect favouring greater body height.	⊕⊕, Low
Front crawl time in distances up to 100 m and % body fat mass (male)	k=6, n=330	Downgrade by one level (some concerns).	Not assessed ($k \leq 10$)	No downgrading ($I^2=0.0\%$)	Downgrade by two levels: (ii) <800 participants; (ii) unclear direction of effects and very large 95% CIs in several of the included trials.	⊕, Very low
Front crawl time in distances up to 100 m and body lean mass (male)	k=4, n=141	Downgrade by one level (some concerns).	Not assessed ($k \leq 10$)	No downgrading ($I^2=18.8\%$)	Downgrade by one level: (i) <800 participants; (ii) large mean effect favouring greater absolute body lean mass.	⊕⊕, Low

i) Risk of bias in trials: downgraded by one level if there were some concerns (technically assessed as unclear using RoBANS) in at least 50% of trials, or by two levels if high risk bias was suspected in at least 50% of trials.

ii) Indirectness: considered low by default due to eligibility criteria.

iii) Risk of publication bias: assessed when ≥ 10 trials were available; in case of suspected risk of publication bias, the cell was flagged, but no downgrading was implemented due to potential alternative explanations for the performed statistical tests [cf., (Afonso et al., 2023)].

iv) Inconsistency: downgraded by one level when the impact of statistical heterogeneity (I^2) was moderate (25-75%) and by two levels if it was large ($> 75\%$).

v) Imprecision: downgraded by one level when <800 participants were available for a comparison or if there was no clear direction of the effects; downgraded by two levels in case both applied (Guyatt et al., 2021).

GRADE: Grading of Recommendations Assessment, Development and Evaluation.

PSS: pooled sample size.

Discussion

The aims of this systematic review with meta-analysis were to assess the existing literature and examine the association between anthropometric factors and swimming performance across various swimming specialty and distance and competitive levels in both male and female swimmers. Additionally, we provide an in-depth analysis of the evolution in swimmers' anthropometric characteristics between specific time mark, such as the super suits prohibitions and Covid pandemic. From the 138 assessed anthropometric variables only a small set of the anthropometrical variables used in the meta-analysis. The latter ones, with influence on front crawl swimming performances technique in distances up to 100 m, included characteristics that are largely genetic, such as height and arm span, as well as modifiable traits like body fat percentage and lean mass. This finding suggests that while genetic factors play a significant role in swimming proficiency, certain physical attributes can be developed or optimized to enhance or offset innate bodily features. However, the certainty of evidence of these meta-analyses are low to very low, underlying that further research, particularly in increasing the number of swimmers evaluated and diminishing the confounding factors (e.g. chronicle/biological ages, sex and tiers combinations) should be considered. It was also found that there is insufficient evidence yet to describe how anthropometry can affect swimming performance in Tiers 4 and 5.

Swimming speed can be calculated by multiplying stroke frequency (the rate of upper limb cycles per time unit) with stroke length (the distance covered during a full cycle of upper limb movements, measured by the ratio of speed to stroke frequency) (Craig & Pendergast, 1979). Gaining a clearer understanding of these essential kinematic parameters and how they relate to swimming speed has been a focus of interest in the field (Figueiredo, Morais, et al., 2013; Pelarigo et al., 2016; Toussaint et al., 2006). Changes in swimming velocity are the result of either an increase or decrease in stroke frequency and stroke length (Craig & Pendergast, 1979; Toussaint et al., 2006). This relationship can be affected by various factors, including anthropometric characteristics. Somatic attributes,

which are largely inherited, play a significant role in shaping swimming technique (Issurin, 2017; Lätt et al., 2009a, 2009b) and optimal performance in swimming is traditionally associated with advanced technical skills and advantageous anthropometric dimensions (J. E. Morais, T. M. Barbosa, et al., 2021). However, for young and adolescent swimmers (based on ages of peaking performances), the impact of growth and development on their anthropometric characteristics can greatly influence technical indexes and, as a result, their overall performance (Barzdukas et al., 1992; Ferraz et al., 2020).

Potential heterogeneity sources: age, competitive levels, sex, rules changes, swimming technique and distance

It is widely acknowledged that swimmers sharing the same chronological age may exhibit notable differences in biological maturation, training experience, and overall development (Abbott et al., 2021). While chronological age itself may not independently forecast swimming performance, it is intricately connected to critical determinants (Lobato et al., 2023). For instance, athletes with a longer chronological age are more likely to have completed adolescence, achieved peak bone mass, and possessed advantageous anthropometric and physical attributes (Lobato et al., 2023; Dos Santos et al., 2021). Additionally, older athletes tend to showcase advanced cognitive development, including decision-making skills, as well as heightened mental and emotional factors like motivation, self-efficacy, and self-esteem. The likelihood of having undergone more specialized training and competition in a specific sport also increases with higher chronological age. Thus, although chronological age is not a singular predictor, its association with key performance influencers is evident.

Sex differences regarding body composition can introduce significant heterogeneity when examining the relationship between anthropometry and performance. Body composition, particularly buoyancy, is an important distinction between men and women. Generally, women have a higher proportion of fatty tissue and a different distribution compared to men, potentially resulting in higher net buoyancy (Zamparo et al., 1996). Exists a difference in added mass between

men and female that seems to be more influenced by body size parameters than by fineness ratio based on linear regression calculations (Caspersen et al., 2010). Also, differences when comparing swimming technique and distance related anthropometry traits are expected (Nevill et al., 2020; Shaw & Mujika, 2018).

Other important aspect is the competitive level, and probably the biggest influence on heterogeneity, since comparing low level swimmers with elite level, particularly Tiers 4 and 5 will have the effect of firstly natural selection and the effect of training experience and hour spending in swimming (Carvalho et al., 2023; Mallett et al., 2020; J. E. Morais, T. M. Barbosa, et al., 2021). Swimming specialty regarding technique or distance is a major factor when relating anthropometric traits and gains in performance due to mechanical advantages, since it is needed a minimum of expertise (Carvalho et al., 2023). The prohibition of high-tech swimsuits partly explains the increased interest in exploring the relationship between anthropometric traits and swimming performance (Neiva et al., 2011; Partridge, 2011). In 2009, these suits were banned from all official swimming competitions, including early development categories, to encourage swimmers to focus on technical improvements rather than relying on technological textiles for performance enhancement.

The COVID-19 pandemic can also partially account for the subsequent surge in research on anthropometric characterization and its association with performance (Haddad et al., 2021). During the pandemic, swimmers were compelled to train at home for almost a year, replacing water training with indoor and strength training (Arsoniadis et al., 2022). Interestingly, many swimmers began to perform better after this period, contrary to expectations (Costa et al., 2021; Demarie et al., 2022; Tsalis & Mougios, 2022). Nevertheless, the scientific research shows a typical trend of exponential growth in the number of publications along the year independently of the field (McLaren et al., 2021).

Main analysis

Front crawl swimming and height

For female swimmers no effect of height was found with a moderate magnitude of the impact of heterogeneity was observed, however it was not possible to further explore its sources in the moderators analyses. Male it was found a positive effect but with low certainty of evidence due principally to the lower pooled sample and confounding variables. The positive effects of height in male might be justified due to longer bodies be more streamlined, being able to 'glide' more effectively through water (Geladas et al., 2005). The slenderness of the body affects the Reynolds number, causing the boundary layer separation to occur farther back, which creates a smaller wake and less wave drag compared to shorter bodies (Toussaint & Truijens, 2005). However, the lack of a height-performance relationship in females explanations rather than the sources of heterogeneity, could be justified by the advantage of having longer limbs being specific to particular body parts rather than a whole-body benefit (Figueiredo et al., 2016). Furthermore, if an increase in height does not come with a proportional increase in muscle mass (less evident in female athletes), the added length might not be very beneficial, as the swimmer cannot use their height (longer levers) to produce a greater force effectively.

Front crawl swimming and arm span

A consistent higher arms span favoured better performances in front crawl effects of the meta-analysis for female and male swimmers in distances up to 100m and the moderators analysis showing that the results are similar independently the Tiers level 2 and 3. When swimmers larger arm span linked to height it has been associated with longer stroke length and, subsequently improved swimming economy (Kennedy et al., 1990; Lätt et al., 2010; Saavedra et al., 2010). Moreover, both height and arm span are associated with the ability to generate greater propulsive forces during swimming (Kjendlie & Stallman, 2011). Consequently, it is reasonable to suggest that taller swimmers associated with larger arm span may appear more frequently in final races compared to their shorter counterparts (Mallett et al., 2020).

Front crawl swimming and body fat mass

In athletes, body mass often reflects active muscle mass, so an increase could indicate more muscle mass. However, increased body mass might also signify higher body fat mass. Since muscle mass contributes to a swimmer's strength, low values could lead to reduced performance. It's important to note that body mass alone doesn't differentiate between lean body mass and body fat mass, so for a more precise assessment, these should be measured separately. Higher fat mass may require swimmers to have more lean body mass and muscle strength for faster propulsion in water. Increased fat mass also potentially raises the body's cross-sectional area, leading to more total drag. However, higher values of fat mass can also be advantageous in longer distance swimming (400-800 and 1500 m) or open water (due to extreme distance and temperature of water), particularly in female swimmers (Knechtle et al., 2020).

The non-significant effect of body fat mass observed in the meta-analyses both for male and female in distances up to 100 m was unexpected but underline that dichotomy in response depending on context. Since the studies included in the meta-analyses were mainly research performed with young swimmers and as they do not present a proper specialization regarding swimming technique or distance, the results regarding the performance can be misled. Also, is likely that a threshold value be the response when looking into body fat mass rather slight differences between subjects implying better or worse performances (around 10% for male and 15% for female; Dopsaj et al., 2020).

Front crawl swimming and body lean mass

The body lean mass was only possible to be evaluated in male swimmers where higher values favoured better performances in distances up to 100m. A greater lean body mass, indicating more muscle mass, can positively impact biomechanical values by increasing the force exerted in each upper limb cycle and enhancing the ability to maintain a good stroke index even under exhaustion (da Silva et al., 2022; Pelayo et al., 1996). Nevertheless, it is important to address that the level of evidence provided by this meta-analysis was low and do not allow

moderator analysis. This emphasizes the need for additional research, particularly studies that involve a larger sample of swimmers and address potential confounding variables, such as chronological/biological age, sex, and competitive level discrepancies, to better inform future investigations (Knechtle et al., 2020).

Elite swimming

Due to the limited number of studies that used samples of elite swimmers and analysed the relationships as a separated group it still we are left to their characterization of (Mallett et al., 2020) more than confidently understanding properly how specific anthropometric variables can influence the performance in due to the number of subjects included in the studies. (Carvalho et al., 2023; Perciavalle et al., 2014). It remains dubious if the anthropometrics can distinguish proper within the elite group or in other hand if the swimming techniques can and should be manipulated based on the swimmers anthropometry and transform some less advantageous characteristics in specific modifications and still be able to perform at the highest level.

Anthropometry assessment

There existed an issue with certain variables being presented in different forms, either as a percentage of body mass or in kilograms, which reduced the number of studies in the meta-analyses of the respective variables. Another challenge is that body fat, lean body mass and muscle mass are usually obtained through bioimpedance, that are known to present substantial errors (Lee et al., 2018; Svantesson et al., 2008; Wang et al, 2013). Within the limited set of anthropometric variables analysed in the meta-analysis a combination of more genetically determined (height and arm span) but also trainable traits (body fat and lean mass) were included. This suggests that while a substantial genetic influence exists for enhanced swimming performance, certain traits are malleable and can be manipulated to accentuate or compensate for inherent genetic predispositions (Issurin, 2017). However, it is crucial to note that our findings are associated with a low and very low level of certainty of evidence.

Performance assessment variables

Using time, velocities and FINA/World Aquatics points as performance variables in studies selected in the review lead reduced number of studies entering in each meta-analyses reduce the power and certainty of the results, particularly by reducing the pooled sample and capability of performing moderator analysis and meta-regressions. While FINA/World Aquatics points eliminate the need to select a specific swimming technique or distance for computation (Saavedra et al., 2010), they also eliminate the ability to moderate these factors in the relationship being assessed in studies. Using FINA/World Aquatics points likely requires similar precautions as other metrics, including adding information and separating samples to gain further insights. Nonetheless, it can be a valuable metric in complex models such as artificial intelligence models. The main advantage of using FINA/World Aquatics points is that as they are related to the current best performance in the world it allows to understand how different determinant factors of swimming performance interact in specific years, allowing to compare same competitive levels of distinct eras.

Models of anthropometry

Six studies included in the review did not provide individual correlations for each anthropometrical variable but combine them to elaborate predictive models only with anthropometrical parameters and moderators (Dos Santos et al., 2021; Nevill et al., 2020; Rozi et al., 2019; Sammoud et al., 2023; Sammoud et al., 2019; Thanopoulos et al., 2006) and one presented a particularly statistical approach called repeated measures correlation (Thng et al., 2022). In the studies that compute the models, a mix of inherent and trainable anthropometric traits was found to influence outcomes.

Height and arm span, which are largely genetically determined, consistently showed positive associations with swimming velocity across studies (Dos Santos et al., 2021; Nevill et al., 2020; Rozi et al., 2019; Sammoud et al., 2023). Modifiable factors such as body fat percentage were generally linked to decreased performance (Nevill et al., 2020; Sammoud et al., 2023), while lean

body mass was positively associated with critical velocity in front crawl for both genders (Thanopoulos et al., 2006). The limb proportions and girths, including biacromial and biiliac breadths, were positively related to swimming efficiency (Nevill et al., 2020).

The repeated measures correlation showed a significant correlation between body fat and performance time, with higher body fat linked to slower times (Thng et al., 2022). Conversely, lean body mass and lower body lean mass were negatively correlated with performance time, indicating that greater muscle mass in these areas is associated with faster swimming times (Thng et al., 2022). That results aligned perfectly with the results observed in the models, suggesting that while a swimmer's body composition can be optimized through training to enhance performance, certain favourable physical characteristics can offer a natural advantage in competitive swimming.

Strengths and limitations

Some limitations of this meta-analysis should be mentioned. Firstly, we performed analyses separately for each sex due to bias and misinterpretation that could arise from combining data from both sexes. This caution was necessary since males are typically faster than female swimmers in the pool events and differ in terms of height, body mass, lean and fat mass (Knechtle et al., 2020). Other important limitation was the forced division of meta-analyses by swimming techniques and groups of distances instead of using them to the moderator analyses. Several researchers used the same sample of subjects to test different swimming techniques (Ghouroghchi & Pahlevani, 2021a, 2021b; Siders et al., 1993) or distances (Nasirzade, Ehsanbakhsh, Argavani, et al., 2014; Nasirzade, Ehsanbakhsh, Ilbeygi, et al., 2014), making it impossible to address them in the same metanalyses without needing to choose one specific event. That is especially difficult when using young swimmers, based on they not presenting a proper specialization (most swimming probably front crawl in practice) or when using adult swimmers, the lack of clarification of the best technique or distance of the swimmers evaluated.

Lastly, considering age as a continuous variable and the meta-analysis predominantly focusing on competitive levels Tier 2 and 3, primarily comprising young swimmers, amplifies the influence of factors such as maturation or training experience on the relationships between anthropometry and performance. The strengths of this meta-analysis should also be acknowledged, where to our knowledge, this is the first meta-analysis to investigate the moderation of competitive level and year ("super suits" prohibition) in the relationships between anthropometry traits and swimming performance.

Conclusion

The findings on this review contribute to a comprehensive understanding of the anthropometric characteristics of swimmers, shedding light on key factors that may influence their performance and the limitations existent in the current evidence. It was only possible to identify positive effects of anthropometric traits in front crawl swimming in distances up to 100m for swimmers corresponding to Tiers 2 and 3 but with low to very low certainty of evidence. Does not exist sufficient information yet to describe how anthropometry can affect the swimming performance in Tiers 4 and 5. Also, more studies should be conducted using tests that are tailored to the best technique and distance of the swimmers being evaluated, since mechanical advantages require a minimum level of technical quality to be effectively utilized.

Chapter 3

Anaerobic Threshold Biophysical Characterization of the Four Swimming Techniques

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Abstract

The anaerobic threshold (AnT) seems to be not only a physiologic boundary but also a transition after which swimmers technique changes, modifying their biomechanical behaviour. We expanded the AnT concept to a biophysical construct in the four conventional swimming techniques. Seventy-two elite swimmers performed a 5 x 200 m incremental protocol in their preferred swimming technique (with a $0.05 \text{ m}\cdot\text{s}^{-1}$ increase and a 30 s interval between steps). A capillary blood samples were collected from the fingertip and stroke rate (SR) and length (SL) determined for the assessment of $[\text{La}^-]$, SR and SL vs. velocity inflexion points (using the interception of a pair of linear and exponential regression curves). The $[\text{La}^-]$ values at the AnT were 3.3 ± 1.0 , 3.9 ± 1.1 , 2.9 ± 1.34 and $4.5 \pm 1.4 \text{ mmol}\cdot\text{L}^{-1}$ (mean $\pm$ SD) for front crawl, backstroke, breaststroke and butterfly, and its corresponding velocity correlated highly with those at SR and SL inflection points ($r = 0.91\text{-}0.99$, $p < 0.001$). The agreement analyses confirmed that AnT represents a biophysical boundary in the four competitive swimming techniques and can be determined individually using $[\text{La}^-]$ and/or SR/SL. Blood lactate increase speed can help characterise swimmers' anaerobic behaviour after AnT and between competitive swimming techniques.

Keywords: physiology, biomechanics, biophysics, anaerobic threshold, elite swimmers

Introduction

In swimming, competitive success can be compromised by high volume and indiscriminate training loads. Indeed, accurate and dedicated exercise prescription is required, reinforcing the importance of regular training control and pool-based testing of biophysical measures (Almeida-Coelho et al., 2016; Nugent et al., 2017; Thanopoulos, 2010). From the complex group of swimming determinants, the physiological variables have been studied extensively using established testing procedures (e.g., Gonjo et al., 2018). The most field-applicable procedure is the anaerobic threshold concept (AnT; [Mader et al., 1978; Wasserman et al., 1973]) allowing determination of the boundary after which the rise of swimming velocity leads to the loss of body homeostasis, as aerobic metabolism alone does not support energy requirements (Faude et al., 2009).

AnT can be assessed as the break point on the blood lactate concentration ($[La^-]$) vs. workload curve during incremental swimming (Mader et al., 1978; Fernandes et al., 2011), identifying the individual exercise intensity after which lactate production exceeds its reduction, and swimming velocity is no longer sustainable for a long time period (Wasserman et al., 1973; Olbrecht et al., 1985; Pelarigo et al., 2016). Occurring in the transition from moderate to heavy exercise intensity domains (de Jesus et al., 2016; Ribeiro et al., 2017), AnT is considered as one of the most consistent predictors of performance in cyclic and individual sports, particularly in swimming (Olbrecht et al., 1985; Pelarigo et al., 2016; Sousa et al., 2015). However, the fixed $[La^-]$ $4 \text{ mmol}\cdot\text{L}^{-1}$ value proposed by Mader et al. (1978) does not consider inter-individual differences, overestimating the real aerobic capacity of aerobically trained athletes (Faude et al., 2009; Fernandes et al., 2011; Stegmann & Kindermann, 1982).

Biomechanics is of growing importance in swimming training diagnosis, leading to a biophysical approach to training prescription and evaluation. In fact, combining the physiologic and biomechanical areas of expertise allows better

control of the complexity of training loads and increase swimming performance (Ribeiro et al., 2017; Barbosa et al., 2008). Some studies already reported technical changes as swimming intensity rises, particularly identifying a stroke rate (SR) increase and stroke length (SL) deterioration after the AnT (Mader et al., 1978; Barbosa et al., 2008). Therefore, AnT is purportedly not only a physiologic boundary, but also decisively influences the behaviour of biomechanical and coordinative variables (de Jesus et al., 2016; Figueiredo et al., 2013). However, probably due to the complexity of the motor task and constraints of the aquatic environment, these findings were only evident for front crawl swimming (with backstroke, breaststroke and butterfly being negatively discriminated) and using samples close to 10 subjects.

Our main aim was to confirm the AnT as the boundary above which $[La^-]$, SR and SL exhibit significant changes. This will be done for the four conventional swimming techniques and using a representative cohort of trained swimmers using adequately powered sample size. We hypothesized that $[La^-]$ at AnT ($[La^-]_{AnT}$) in front crawl and backstroke will be lower than the standard $4 \text{ mmol} \cdot \text{L}^{-1}$ value (leading to relevant practical differences between corresponding swimming velocities) and that in breaststroke and butterfly it will be higher than that fixed value (as they are less economical swimming techniques; Barbosa et al., 2006). It is also expected that SR will rise and SL decrease after the AnT intensity due to changes in coordination strategies. Complementary, given that the anaerobic energy systems contribute substantially to short duration swimming events (and the majority of competitions lasts less than 2 min), we have also assessed the swimmers' anaerobic behaviour in different techniques (Ribeiro et al., 2017).

Materials and Methods

Seventy-two international level swimmers (47 males and 25 females), specialists in front crawl ($n = 38$), backstroke ($n = 15$), butterfly ($n = 11$) and breaststroke ($n = 8$), volunteered to participate. Their main physical characteristics were: 20.3 ± 3.1 vs. 18.4 ± 2.5 y, 73.9 ± 7.3 vs. 58.9 ± 5.7 kg body mass, 1.80 ± 0.06 vs.

1.70 ± 0.04 m height, 8.0 ± 2.5 vs. 16.0 ± 5.7 percentage of fat mass and 811 ± 32 vs. 808 ± 39 FINA points of best competitive performance for male and female swimmers (respectively). Swimmers were informed about the purpose of the evaluations and provided individual consent for participation in accordance with this journal (Harris et al., 2019), the local research ethics committee (code nº CEFAD 28 2019) and the Declaration of Helsinki.

In a 25 m indoor pool with water temperature of 27° C, after an 800 m standardised low intensity warm-up, each subject performed a 5 x 200 m intermittent incremental protocol, with 0.05 m·s⁻¹ increase per step and a 30 s rest interval (de Jesus et al., 2016; Ribeiro et al., 2017; Fernandes et al., 2010). In-water starts were used and initial velocities were established by the swimmer's current individual 400 m performance less five velocity increments (first step: velocity at 400 m - 0.20 m·s⁻¹). Performance was measured using a Seiko stopwatch and controlled through auditory signals. Each step represented the same relative intensity for all swimmers, independent of the swimming technique, who were verbally encouraged to reach their maximal exertion during the last 200 m step.

Capillary blood samples for [La⁻] analysis were collected from the fingertip at rest, in the intervals between steps and 1, 3, 5 and 7 min after the protocol using a Lactate Pro 2 analyser (Arkay, Inc, Kyoto, Japan) (Ribeiro et al., 2017). SR was determined as the number of cycles per min (using a Seiko stopwatch with a base 3 upper limb cycles frequency meter function) and SL was calculated by dividing the mean velocity by SR (both were assessed as the mean value of each 50 m per 200 m step) (Fernandes et al., 2010). By computing the [La⁻], SR, and SL vs. velocity, linear and exponential curves were determined using the least square method (Fernandes et al., 2011; Figueiredo et al., 2013). After a visual inspection of the plots, and considering the respective residue value, the inflection points were assumed to be the intersection at the maximal fit situation, of a combined pair of linear and exponential regressions. In addition, linear inter- or extrapolation

of the $[La^-]$ /velocity curve allowed the determination of v_4 and $v_{3.5}$ (Fernandes et al., 2010), as displayed (Figure 1).

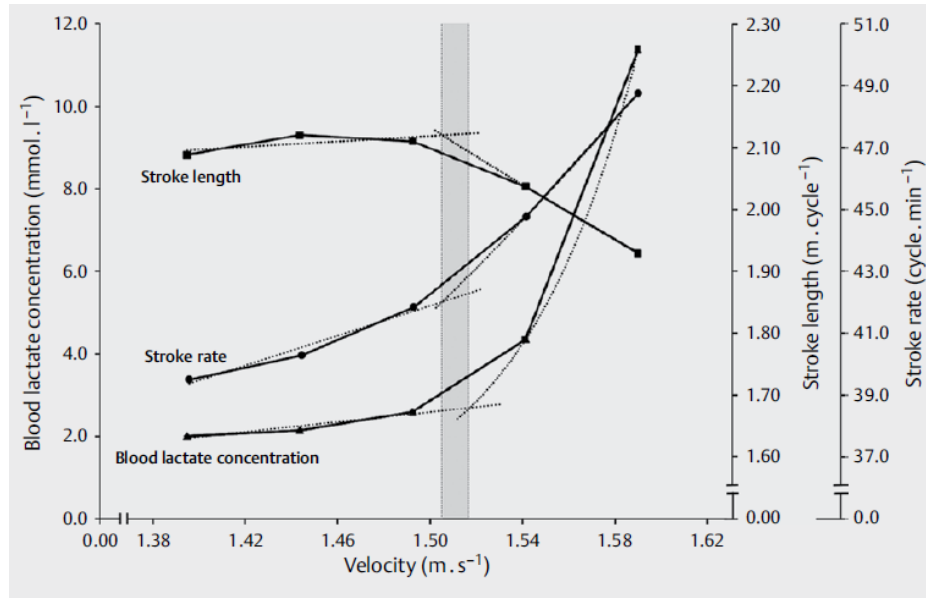


Figure 1. Determination of the inflection points of blood lactate concentrations, stroke rate and stroke length vs. velocity of one swimmer.

Each swimmer's anaerobic profile was established with two derived indicators: (i) the blood lactate increase rate ($[La^-]_{rate}$; adapted from (Holroyd & Swanwick, 1993)), as the ratio between the net $[La^-]$ and velocities ($\Delta[La^-]$ and Δv , respectively) of the two last protocol steps; and (ii) the blood lactate increase speed (BLIS) of 4th and 5th steps, as the time rate of net $[La^-]$ per step (difference between the $[La^-]$ obtained after the current step and the previous one, and the time needed to accomplish the 200 m step; adapted from (Almeida-Coelho et al., 2016)). Swimming techniques were analysed individually and by alternated (front crawl and backstroke) and simultaneous (breaststroke and butterfly) upper and lower limb-action groups, given the obvious dichotomy between them (Gonjo et al., 2018; Barbosa et al., 2006). Mean and standard deviation of measures were computed, and data were checked for distribution normality with the Shapiro-Wilk test. One-way independent and repeated measures ANOVA were performed to compare velocities, $[La^-]$, SR and SL between swimming techniques and along the incremental protocol. Where a significant F-value was obtained, a Bonferroni post hoc was conducted to identify the pairwise differences and partial eta-

squared (η^2) used for computing the effect size. A paired samples Student's t-test was used to assess the differences between v_{AnT} and v_4 , $v_{3.5}$, v_{SRinf} and v_{SLinf} . Intraclass correlation and Pearson's r correlation coefficients quantified the degree of reliability and association between v_{AnT} , v_{SRinf} and v_{SLinf} (respectively; Hopkins, 2002). Agreement analysis between the inflexion points was also performed (using v_{AnT} as the reference) through both Passing-Bablok (Passing & Bablok, 1983) regression and Bland-Altman (Bland & Altman, 1986) plot analysis (MedCalc Software, version 17.3, Mariakerke, Belgium) to assess the absence of systematic differences between measurements ($p \leq 0.05$).

Results

In Figure 2, the $[La^-]$ vs. velocity curves are presented for each conventional swimming technique, displaying similar shapes although with diverse values. Velocity of 5th step corresponded to ~96% of the swimmers 200 m best performance and 99-100% of 400 m front crawl best performance. Increases in swimming velocity along the 5 x 200 m protocol in all swimming techniques ($p < 0.001$; $\eta^2 = 0.88-0.95$) implied, between first and last step of 200 m, higher $[La^-]$ (front crawl 288-845%; backstroke 162-700%; butterfly 163-650%; breaststroke 193-910%) higher SR (front crawl 112-170%; backstroke 125-241%; butterfly 115-170%; breaststroke 119-207%), and lower SL (front crawl 1-14%; backstroke 8-36%; butterfly 1-22%; breaststroke 5-30%), all for $p < 0.001$ and $\eta^2 = 0.83-0.99$. When analysing alternated and simultaneous upper and lower limb-action swimming techniques, we observed the same biophysical behaviour, i.e., the rise in swimming velocity ($F_{4.208} = 219.66$, $\eta^2 = 0.95$ vs. $F_{4.76} = 25.71$, $\eta^2 = 0.87$) implied, between first and last step of 200 m, higher $[La^-]$ ($F_{4.208} = 133.06$, $\eta^2 = 0.92$ vs. $F_{4.76} = 71.63$, $\eta^2 = 0.95$) higher SR ($F_{4.208} = 118.27$ $\eta^2 = 0.91$; and $F_{4.76} = 40.52$, $\eta^2 = 0.91$), and lower SL ($F_{4.208} = 68.08$, $\eta^2 = 0.85$; and $F_{4.76} = 16.07$, $\eta^2 = 0.80$), all for $p < 0.001$. The evolution of SR and SL along the incremental protocol for all analysed swimming techniques can be observed in Figure 3.

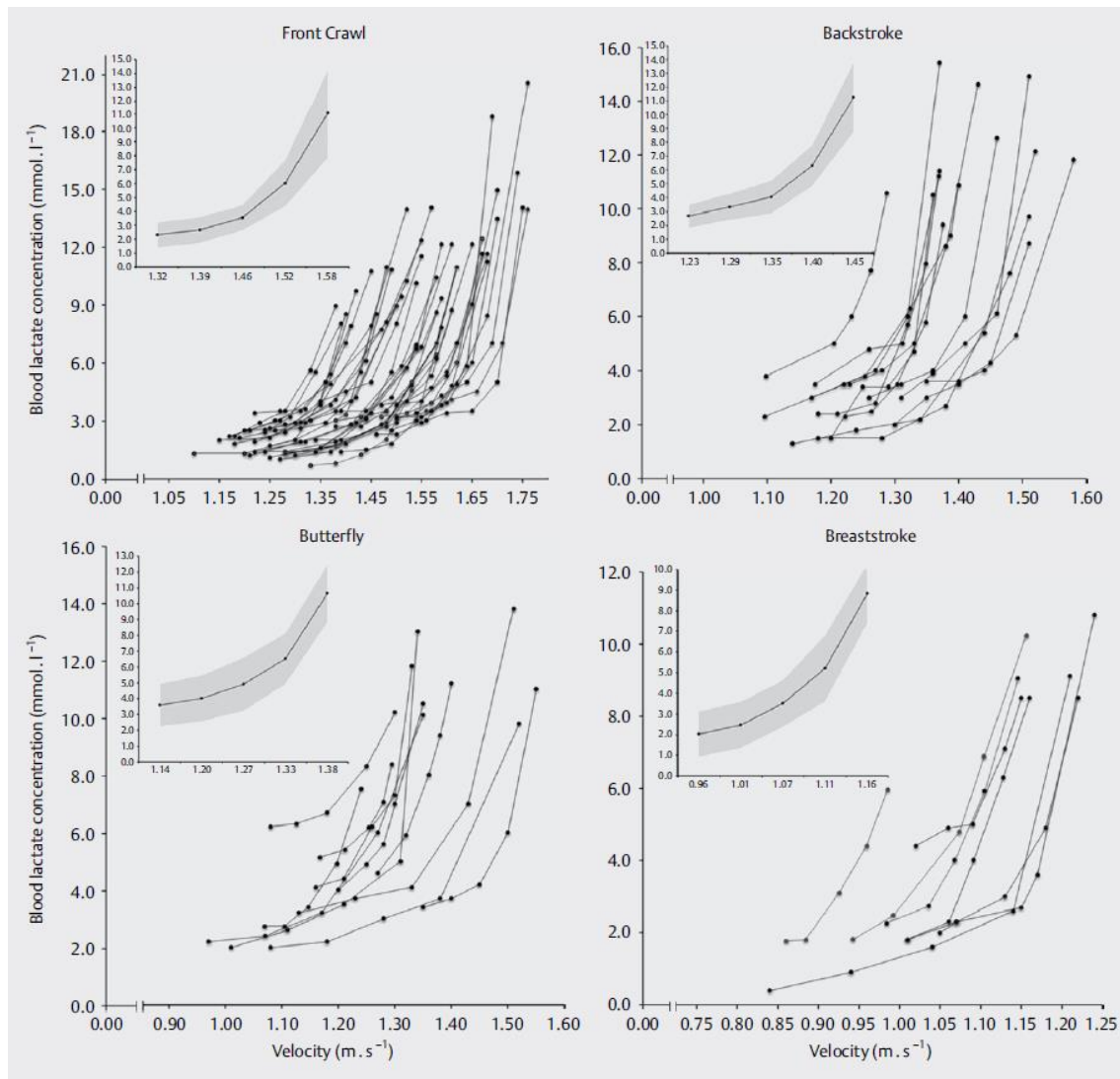


Figure 2. Individual and mean $\pm$ standard deviation envelope blood lactate concentrations vs velocity curves for individual anaerobic threshold assessment in each conventional swimming technique.

Table 1 presents mean and SD of $[La^-]_{AnT}$, v_{AnT} , v_{SRinf} , v_{SLinf} , $v_{3.5}$, v_4 , $[La^-]_{rate}$ and 4th and 5th BLIS for the four conventional swimming techniques and the alternated and simultaneous techniques. $[La^-]_{AnT}$ and $[La^-]_{rate}$ ranged from 1.3 to 5.6 mmol·L⁻¹ and 28 to 258 (mmol·L⁻¹).(m·s⁻¹) in front crawl, 1.5 to 5.4 mmol·L⁻¹ and 18.6 to 193.3 (mmol·L⁻¹).(m·s⁻¹) in backstroke, 2.5 to 6.8 mmol·L⁻¹ and 37.6 to 266.7 (mmol·L⁻¹).(m·s⁻¹) in butterfly and 1.8 to 5.4 mmol·L⁻¹ and 60.4 to 102.9 (mmol·L⁻¹).(m·s⁻¹) in breaststroke, exhibiting highly interindividual variability.

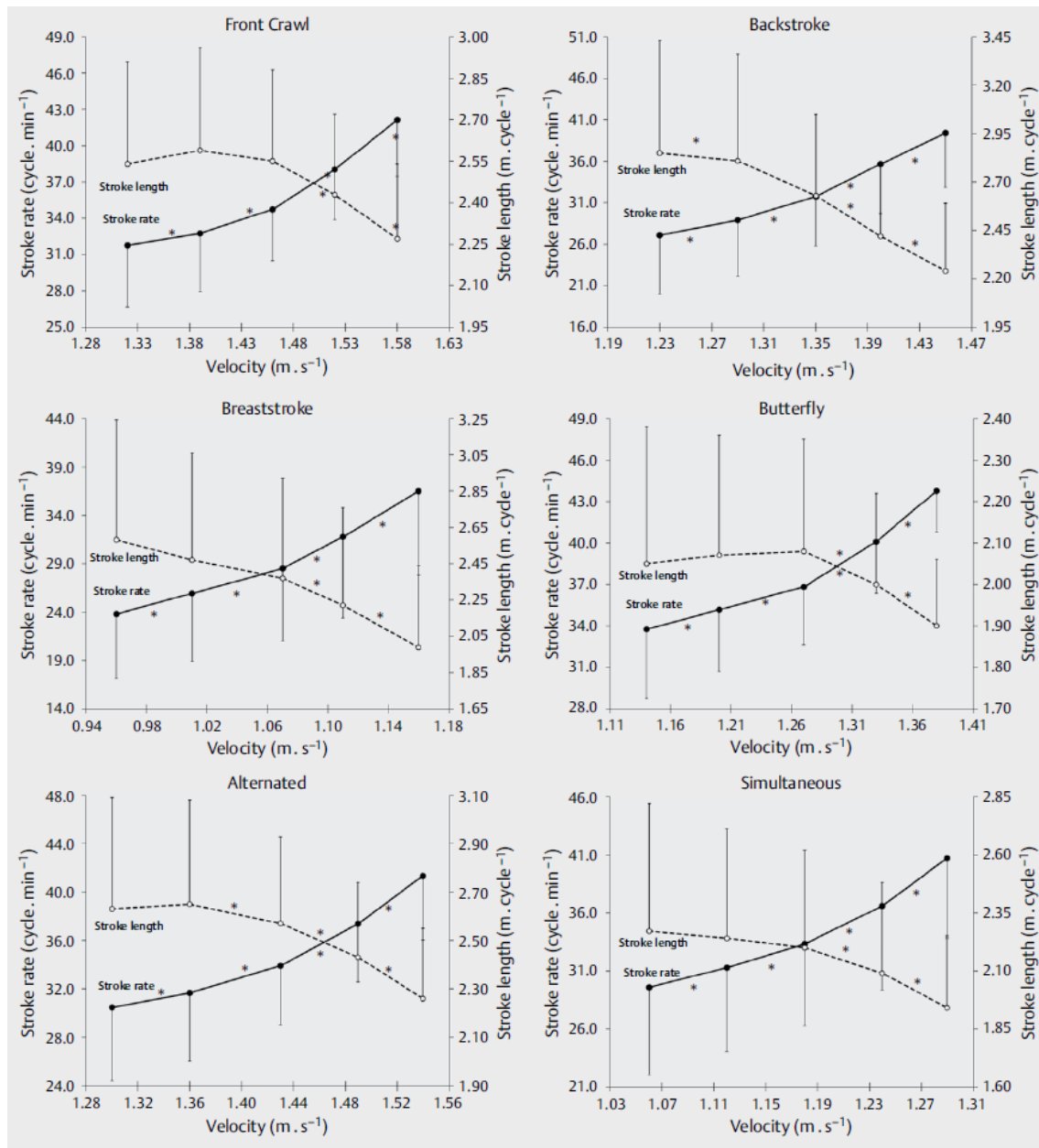


Figure 3. Mean and standard deviations for stroke rate and length along the incremental protocol for assessment of individual anaerobic threshold for each competitive swimming techniques and by alternated and simultaneous upper and lower limb-action groups.

When the swimming techniques were analysed individually, results showed that: (i) v_{AnT} was lower than v_4 (but similar to the $v_{3.5}$) in front crawl; (ii) v_{AnT} was similar to the v_4 (but higher than the $v_{3.5}$) in backstroke and butterfly; and (iii) v_{AnT} was not different from both v_4 and $v_{3.5}$ in breaststroke. When analysed between groups, results showed that: (i) v_{AnT} was lower than v_4 and $v_{3.5}$ in alternated swimming techniques; and (ii) v_{AnT} was similar to v_4 (but higher than $v_{3.5}$) in

simultaneous techniques. In addition, the four swimming techniques v_{AnT} corresponded to ~92% of v_{200} at the 5th step (92 ± 3 , 93 ± 3 , 93 ± 4 and $92 \pm 3\%$, for front crawl, backstroke, butterfly and breaststroke, respectively), with front crawl presenting higher v_{AnT} than butterfly, and breaststroke the lowest v_{AnT} value.

Analyses of both physiological and biomechanical inflection points showed that the v_{AnT} , vSR_{inf} and vSL_{inf} were coincident for front crawl, backstroke, butterfly and breaststroke. In all the swimming techniques, intraclass correlation between physiological and biomechanical inflection points was excellent (ICC: 0.947 to 0.996; 95% CI: 0.861 to 0.998), v_{AnT} showed a strong direct relationship with vSR_{inf} (r : 0.948 to 0.995) and vSL_{inf} (r : 0.953 to 0.995), all for $p < 0.001$. Passing-Block regressions between physiological and biomechanical inflection points are presented in Figure 4, the 95% confidence intervals of the slope and intercept included or were very close to 1 and zero, respectively. Similar results were observed in Bland-Altman plot reports (Figure 5), where estimations were almost unbiased and between the 95% limits of agreement. In addition, the slope of the Bland Altman regression showed evidence of a proportional error in the v_{AnT} vs. vSR_{inf} comparison in the breaststroke technique.

In relation to swimmers' anaerobic characteristics, we observed that: (i) $[La^-]_{rate}$ is similar in all four swimming techniques; (ii) BLIS is higher in the 5th 200 m step for all swimming techniques; (iii) front crawl presents higher BLIS in the 4th and 5th step compared to breaststroke and butterfly, but similar compared to backstroke, and (iv) alternated swimming techniques present higher BLIS than simultaneous ones. Combining BLIS with the AnT assessment in the incremental protocol is very relevant allowing researchers and coaches to evaluate both aerobic and anaerobic behaviours in a single test session.

Table 1. Mean and SD values of all assessed variables in the 5 x 200 m incremental protocol.

Variables	Front crawl (n = 38)	Backstroke (n = 15)	Breaststroke (n = 8)	Butterfly (n = 11)	Alternated techniques (n = 53)	Simultaneous techniques (n = 19)
$[La^-]_{AnT}$ (mmol·L ⁻¹)	3.3 ± 1.0 ⁺	3.9 ± 1.1	2.9 ± 1.1 ⁺	4.9 ± 1.5	3.4 ± 1.1	4.0 ± 1.7
v_{AnT} (m·s ⁻¹)	1.45 ± 0.13 ^{+, ++}	1.35 ± 0.09 ⁺⁺	1.06 ± 0.09	1.29 ± 0.10 ⁺⁺	1.43 ± 0.13	1.19 ± 0.15
v_4 (m·s ⁻¹)	1.48 ± 0.10 [*]	1.35 ± 0.12	1.08 ± 0.08	1.22 ± 0.16	1.44 ± 0.12 [*]	1.16 ± 0.15
$v_{3.5}$ (m·s ⁻¹)	1.45 ± 0.10	1.30 ± 0.12 [*]	1.07 ± 0.09	1.17 ± 0.17 [*]	1.41 ± 0.12 [*]	1.13 ± 0.15 [*]
vSR_{inf} (m·s ⁻¹)	1.45 ± 0.13	1.35 ± 0.10	1.07 ± 0.07	1.28 ± 0.08	1.42 ± 0.13	1.19 ± 0.13
vSL_{inf} (m·s ⁻¹)	1.45 ± 0.13	1.35 ± 0.10	1.07 ± 0.08	1.28 ± 0.08	1.42 ± 0.13	1.20 ± 0.13
$[La^-]_{rate}$ [(mmol·L ⁻¹)·(m·s ⁻¹)]	93.5 ± 44.2	118.7 ± 49.7	71.8 ± 11.6	89.5 ± 69.8	99.6 ± 46.3	82.4 ± 54.0
4 th BLIS [(mmol·L ⁻¹)·s ⁻¹]	0.02 ± 0.01 ^{+, ++}	0.02 ± 0.01	0.01 ± 0.00	0.01 ± 0.01	0.02 ± 0.01 [#]	0.01 ± 0.00
5 th BLIS [(mmol·L ⁻¹)·s ⁻¹]	0.04 ± 0.02 ^{+, ++, ##}	0.04 ± 0.02 ^{##}	0.02 ± 0.01 ^{##}	0.03 ± 0.02 ^{##}	0.04 ± 0.02 ^{#, ##}	0.03 ± 0.02 ^{##}

Abbreviations: $[La^-]_{AnT}$, blood lactate concentration at individual anaerobic threshold; v_{AnT} , v_4 and $v_{3.5}$, velocities corresponding to individual anaerobic threshold, 4 and 3.5 mmol·L⁻¹ of blood lactate concentrations; vSR_{inf} and vSL_{inf} , velocities corresponding to stroke rate and length inflexion points; $[La^-]_{rate}$, blood lactate increase rate between last two steps of the protocol; 4th and 5th BLIS, blood lactate increase speed of 4th and 5th steps. ^{*}, ⁺, ⁺⁺, [#], ^{##} differences from v_{AnT} , butterfly, breaststroke, simultaneous techniques and 4th BLIS, respectively ($p \leq 0.05$).

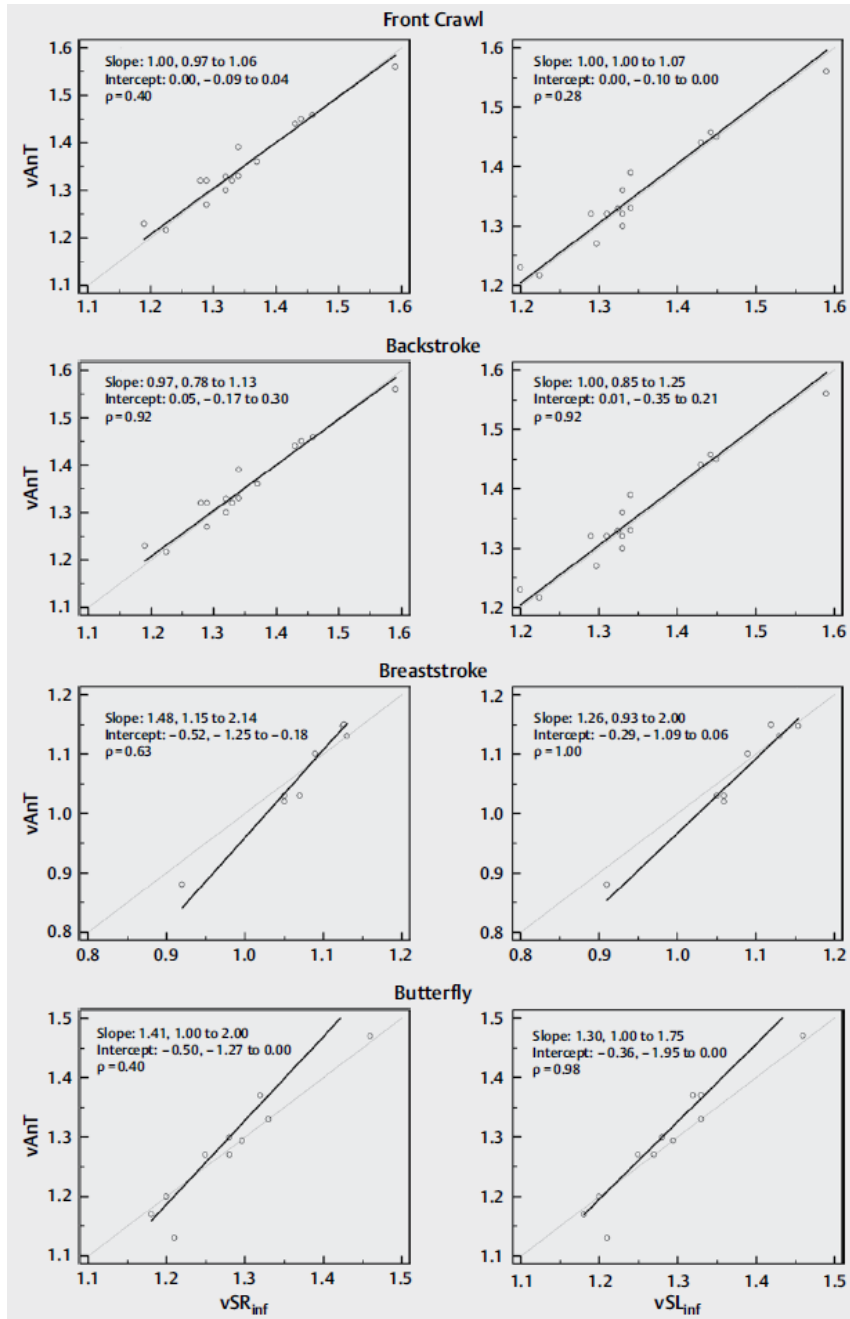


Figure 4. Passing-Bablok regression of velocities at individual anaerobic threshold and at stroke rate inflexion points (left panels), and stroke length (right panels). The regression equation and the identity are represented by the solid and dotted lines, respectively. Regression equation ($y = ax + b$) evidences existence of proportional (slope: a) and systematic (intercept: b) differences and respective 95% confidence intervals (CIs). If zero is in the 95% CIs of the intercept, and one in the 95% CIs of the slope, the two methods are comparable. If zero is not in the 95% CIs of the intercept there is a systematic difference and if one is not in the 95% CIs of the slope exists a proportional difference between the two methods. Passing-Bablok method deemed applicable if the relationship between the two measurements is linear ($p > 0.05$). Abbreviations: v_{AnT} , velocity corresponding to individual anaerobic threshold; $v_{SR_{inf}}$ and $v_{SL_{inf}}$, velocities corresponding to stroke rate and length inflexion points.

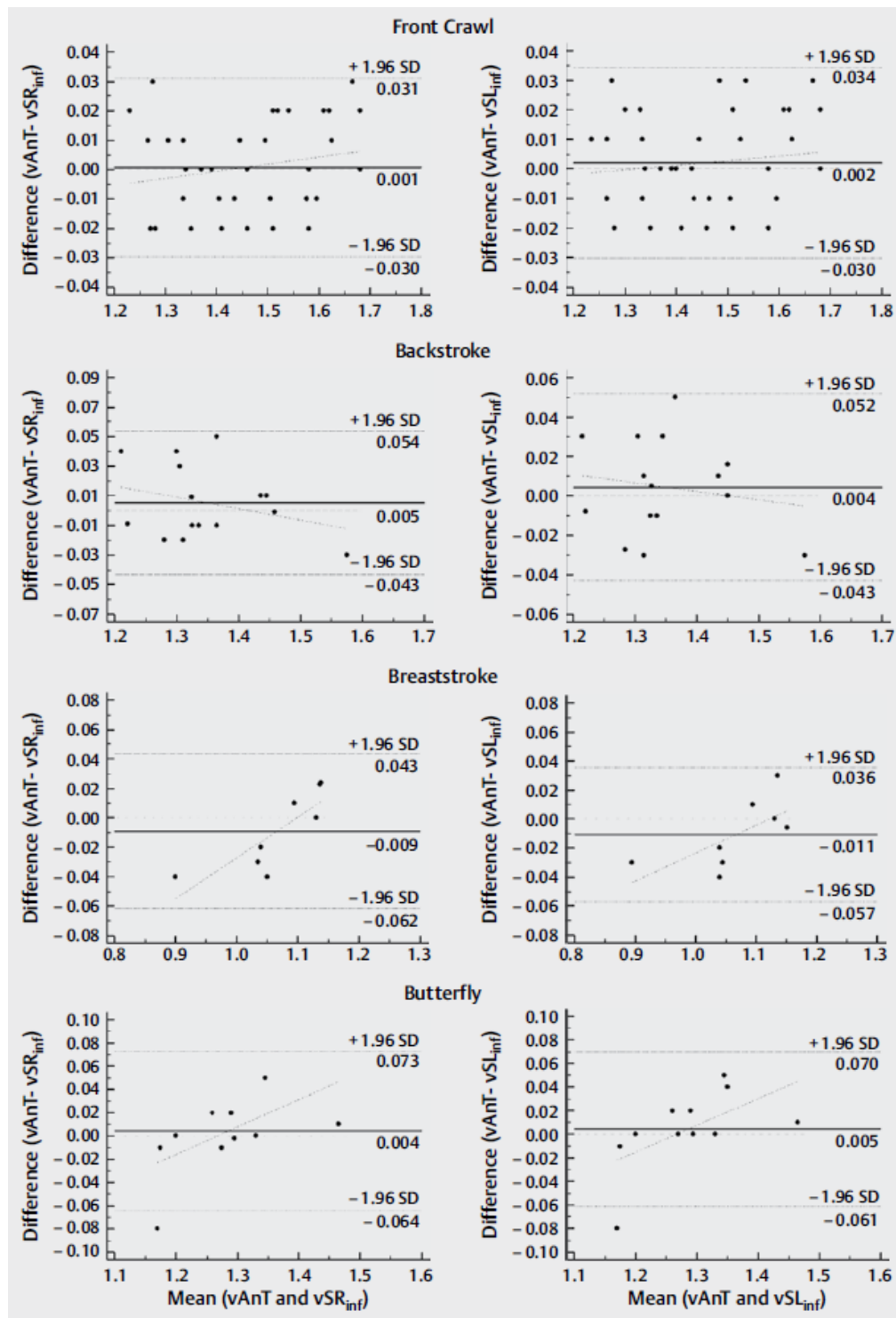


Figure 5. Bland Altman analyses between velocity corresponding to individual anaerobic threshold and velocity of stroke rate (left panels), and stroke length (right panels) inflection points. Black dotted lines representing 95% limits of agreement and black dashed lines bias and linear regression of physiological and biomechanical variables. Abbreviations: vAnT, velocity corresponding to individual anaerobic threshold; vSR_{inf} and vSL_{inf}, velocities corresponding to stroke rate and length inflexion points.

Discussion

One of the main purposes of AnT assessment is to evaluate the adequacy of aerobic training. As its development is one of the most important targets in competitive swimming, we assessed the AnT through a biophysical approach for all four conventional swimming techniques. Despite a variety of different AnT testing procedures in swimming, the majority are not regularly used, since: (i) the non-invasive 30 min and 2000 m tests (Faude et al., 2009; Pyne & Touretski, 1993) are monotonous and not motivational, possibly leading to an underestimation of the final result; (ii) the maximal lactate steady state test (Pelarigo et al., 2016; Heck et al., 1985), although still considered the gold standard for assessing aerobic capacity requires, at least, 3 consecutive days of testing; (iii) the critical velocity test, composed by, at least, two maximal intensity bouts, can lead to an overestimation of the final result if a distance of ~15 min is not used (Wright & Smith, 1994); (iv) the long duration tests probably are not performed at constant velocities, reflecting different intensities levels, and are difficult to apply using simultaneous swimming techniques (Smith et al., 2002); (v) the two speed test has the limitation inherent to the $[La^-]$ $4 \text{ mmol}\cdot\text{L}^{-1}$ average value (Stegmann & Kindermann, 1982; Fernandes et al., 2010).

To overcome the above referred constrains, we have adapted one of the most used swimming intermittent incremental protocols (Fernandes et al., 2011; Anderson et al., 2008; Pyne et al., 2001) to assess the AnT in the four conventional swimming techniques. This 5 x 200 m incremental protocol was already used for front crawl (Thanopoulos, 2010; Fernandes et al., 2010) and appears to be a useful procedure to determine the exact exercise intensity corresponding to the beginning of an exponential $[La^-]$ rise in the four competitive swimming techniques. In addition, as it is shorter in duration comparing to other incremental protocols (e.g., Fernandes et al., 2011), it might be more frequently implemented in swimming training cycles, particularly at elite level, allowing a more regular and systematic training control and swimmers evaluation.

In front crawl, $[La^-]_{AnT}$ was lower than the fixed $4 \text{ mmol}\cdot\text{L}^{-1}$ value, in accordance with the literature (Pelarigo et al., 2016; Figueiredo et al., 2013; Fernandes et al., 2010), but similar to the $3.5 \text{ mmol}\cdot\text{L}^{-1}$ value proposed by Heck et al. (1985) for highly aerobically trained athletes. This reinforces the idea that v_4 does not represent the v_{AnT} and should be used with caution for training prescription. Backstroke and butterfly v_{AnT} were similar to v_4 and higher than $v_{3.5}$, but no differences were observed for breaststroke (probably due to small sample size). After the $[La^-]$ evidencing an exponential behaviour, a small increase in swimming velocity will imply a high increment in $[La^-]$, justifying the similarity between the v_{AnT} , v_4 and $v_{3.5}$ values, even with $[La^-]_{AnT}$ lower than $3.5 \text{ mmol}\cdot\text{L}^{-1}$.

In fact, the mean $[La^-]_{AnT}$ values differ between swimming techniques, with a range from < 2 to $> 5 \text{ mmol}\cdot\text{L}^{-1}$, showing a high inter-variability. This may be justified by the high specialized training process of elite swimmers (in advanced moments of their sporting career the training load is increasingly anaerobic), particularly for non-front crawl specialists, as their competitive events lasts from 50 to 200 m in opposition to the typical non-oriented and high-volume training (Nugent et al., 2017). This underlines the importance of determining the individual AnT instead of using the 4 or $3.5 \text{ mmol}\cdot\text{L}^{-1}$ averaged values that do not take into consideration the inter-individual variability or technique and event specificity (Faude et al., 2009; Stegmann & Kindermann, 1982; Fernandes et al., 2010).

The higher $[La^-]_{AnT}$ found for butterfly compared to front crawl and backstroke was expected, since the higher butterfly intracycle velocity variations leads to an increased energy cost and anaerobic contribution to reach the energy demands of that specific swimming technique (Barbosa et al., 2006; Vilas-Boas et al., 2011). However, the lower $[La^-]_{AnT}$ in breaststroke comparing to backstroke was not anticipated, conflicting with our previous hypothesis. As the v_{AnT} in breaststroke was also considerably lower than all other swimming techniques, the possible lower energy output requirement of this simultaneous swimming technique (Barbosa et al., 2006; Hellard et al., 2018) could justify these results.

The above-referenced comparisons between swimming techniques were made possible since v_{AnT} occurred at ~92% of the velocity of the last protocol step in all four of them, a similar value to that found in the literature (Fernandes et al., 2008; Zacca et al., 2016). However, $[\text{La}^-]_{\text{AnT}}$ assessment were not reliable when analysing swimming techniques between upper and lower limb-action groups, since a $[\text{La}^-]_{\text{AnT}}$ lower than $3.5 \text{ mmol}\cdot\text{L}^{-1}$ corresponded to a higher velocity than $v_{3.5}$, confirming the assertion that swimming techniques are not equal biophysical terms (Gonjo et al., 2018; Barbosa et al., 2006; Vilas-Boas et al., 2011). Moreover, we observed that front crawl presented higher velocities in all five steps of the incremental protocol. Therefore, AnT assessment should be undertaken in each swimmer's specialist technique.

Regarding the general biomechanical parameters, low SR and high SL values were constant within the steps swum at low to moderate intensities (below and at the AnT), in which the aerobic system is predominant (for all techniques; Fernandes et al., 2011; Barbosa et al., 2008; Figueiredo et al., 2013). Above the AnT, at heavy and severe intensities (de Jesus et al., 2016; Ribeiro et al., 2017), where the anaerobic contributions start to increase, SR and SL showed an opposite behaviour in response to the metabolic imbalance (Pelarigo et al., 2016; de Jesus et al., 2016; Figueiredo et al., 2013) and an increased hydrodynamic drag (Komar et al., 2012; Seifert et al., 2014). These changes were not strictly linear and a critical turning point was identified for both physiological and biomechanical variables, in accordance with front crawl literature (Pelarigo et al., 2016; de Jesus et al., 2016; Figueiredo et al., 2013). In some cases, SL presented an inverted “U shape” justifying the close values between the first and last step. However, the same SL behaviour after AnT was evident for all swimmers. Good agreement was also observed between v_{AnT} , v_{SRinf} and v_{SLinf} , corroborating the above-referenced previous findings.

Since most competitive swimming events have a short duration (from ~20 s to 5 min), $[\text{La}^-]_{\text{rate}}$ and BLIS were determined to complement the AnT assessment to explore the anaerobic capability of highly trained swimmers. $[\text{La}^-]_{\text{rate}}$ assessment

was adapted from Holroyd & Swanwick (1993) lactate tolerance rating (differential velocity between $[La^-]$ of 5.0 and 10.0 mmol·L⁻¹) since that methodology could not be used in our entire sample because some swimmers have their AnT higher 5 mmol·L⁻¹ and others presented values lower 10 mmol·L⁻¹ in the last step of the incremental protocol. No differences were observed in $[La^-]_{rate}$ between swimming techniques, probably related to the non-regular velocity differential between the last two steps of the incremental protocol (the last 200 m were done at maximal effort). However, the use of the $[La^-]_{rate}$ in consecutive evaluations may be useful for identification of swimmers strengths and weakness regarding the use of anaerobic energy.

Higher anaerobic contribution at the end of the incremental protocol was indicated by a higher BLIS of the 5th step than the 4th 200 m stage (as the last step was conducted at maximal exertion; Figueiredo et al., 2013). Another contributing evidence was the fact that swimmers with a higher SR, at the final of the incremental protocol, could not maintain their SL (Ribeiro et al., 2017; Barbosa et al., 2008). The higher BLIS values observed on the alternated swimming techniques can be justified by the higher velocities achieved at the 4th and 5th step (comparing to simultaneous techniques) and consequent increased metabolic demands. Curiously, BLIS of the last butterfly step was lower than a previous study using an all-out 200 m butterfly effort (Ferreira et al., 1997), evidencing the effect of previous exercise on the energetic pathways behaviour during the incremental protocol (indicating a progressive decrease in glycolytic power). These data may also indicate that the aerobic system is potentiated at submaximal exertions, allowing a higher blood lactate metabolization during exercise at maximal effort (Brooks, 2009), particularly during the last step of the 5 x 200 m intermittent incremental protocol.

Conclusion

The widely used 5 x 200 m intermittent incremental protocol allowed a specific and precise AnT assessment in the four conventional swimming techniques.

Although it appears that the $3.5 \text{ mmol}\cdot\text{L}^{-1}$ threshold value (rather than $4.0 \text{ mmol}\cdot\text{L}^{-1}$) is more suitable for front crawl, an individual assessment is the better option. It was also possible to establish the AnT as a biophysical boundary for all competitive swimming techniques, allowing very practical information for coaches. Although it may be easier to determine the AnT using biomechanical variables, it is important to initially analyse the swimmers' AnT through a physiological approach, to determine whether the difference between the two approaches is significant in actual practice. The BLIS indicator was useful for assessing swimmers anaerobic behaviour and training exercises above AnT.

Chapter 4

Swimming sprint performance depends on upper/lower limbs strength and swimmers level

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Abstract

Swimming performance is likely influenced by strength but differences between butterfly, backstroke, breaststroke and front crawl, as well as between novice and expert swimmers are unclear. We have examined the associations between sprint performances, upper and lower limbs strength, and anthropometric characteristics in 14 (six males and eight females) non-elite and 16 (nine males and seven females) elite level swimmers). After an anthropometric characterisation, participants performed four 25 m maximal swims (one per technique) with 10 min intervals, right and left shoulder flexion/extension isokinetic testing at 90 and 300°/s angular velocities and three countermovement jumps. Pearson correlation analysis showed that sprint times were moderate-largely negatively correlated with upper and lower limb strength and power ($r \pm 95\% \text{ CI} = 0.39 \pm 0.26 - 0.77 \pm 0.13$, $p < 0.05$). Elite swimmers higher strength levels were associated with longer stroke length in butterfly and front crawl, and with higher stroke rate in backstroke and breaststroke ($r \pm 95\% \text{ CI} = 0.37 \pm 0.32 - 0.68 \pm 0.21$; $p < 0.05$). Butterfly, backstroke and front crawl sprint times were moderate-largely negatively related with arm span ($r \pm 95\% \text{ CI} = 0.37 \pm 0.26$, 0.39 ± 0.25 and 0.69 ± 0.17 , $p < 0.05$). The predictive model indicated that higher dry-land strength values distinguished elite from non-elite swimmers ($r^2 = 0.67 - 0.81$; $p < 0.001$). This association was not observed per performance level and per sex, confirming that sprint swimming performance levels can be differentiated by dry-land strength testing.

Keywords: force; torque; power; anthropometry; performance

Introduction

The constant search for improvement in sports requires a systematic evaluation of physical, technical and energetic demands (Gola et al., 2014; Figueiredo et al., 2013), with swimming performance depending on the direct and indirect interaction of biomechanical, physiological, psychological, genetic and contextual factors (Barbosa et al., 2010; Ribeiro et al., 2017). Biomechanical evaluation has a particular fundamental role to enhance swimmers performance and prevent injuries imposed by systematic cyclic movements (Batalha et al., 2010; Figueiredo et al., 2016). Muscle strength and power should be closely monitored given they are important motor qualities influencing both swimming propulsion (Hawley et al., 1992) and performance (Gola et al., 2014).

Swimmers shoulder complex is largely responsible for propulsive power in the four competitive swimming techniques, with shoulder extension crucial during most propulsive phases (Heinlein & Cosgarea, 2010; Wanivenhaus et al., 2012). Lower limbs strength and power are largely associated with both start and turn swimming skills (West et al., 2011; Cuenca-Fernández et al., 2019), as well as with overall performance, contributing decisively to sprint events success (Keiner et al., 2021). The contribution of lower limbs propulsion contribution in front crawl swimming remains ambiguous (Ribeiro et al., 2015; Bartolomeu et al., 2018), likely increasing at higher velocity (Silveira et al., 2017) and differs between swimming techniques (Bartolomeu et al., 2018). Therefore, new data are required to clarify the contributions and relationships between swimming sprint performance and swimmers upper and lower limbs strength and power.

Increments in swimmers muscular strength in dry-land condition should translate into increased ability to generate swimming propulsive force, with the technical aspects of upper and lower limbs mechanics largely determining the degree of transfer into faster performances (Hawley et al., 1992; Garrido et al., 2012, Ruiz-Navarro, Gay, et al., 2022). However, the use of different methodologies for strength assessment and their inherent limitations makes the data difficult to

interpret (Kwok et al., 2021). Since most studies examining swimmers upper and lower limb strength have focused on the front crawl technique (Amaro et al., 2019; Kwok et al., 2021; Keiner et al., 2021), researchers and coaches would benefit from a better understanding on how upper and lower limbs strength and power influence the four competitive swimming techniques.

As it remains uncertain how the competitive level of a swimmer influences the relationships between strength and power with swimming performance (Amaro et al., 2019; Tan et al., 2021), we sought to examine the linear associations of the four conventional swimming techniques sprint performance and upper and lower limbs strength. This approach is justified within and between swimming competitive levels, given that muscle strength capability is influenced by limbs length (Stanelle et al., 2021). The relationships between sprint performance and anthropometric characteristics will also be taken into consideration. This information will assist swimming coaches, scientists and academics interested in identifying, developing and applying new strategies for enhancing sprint swimming performances.

Material and Methods

Participants

Sixteen elite and fourteen non-elite level swimmers (six and nine males, respectively) voluntarily participated in the current study presenting the following characteristics: 20.7 ± 3.3 vs. 15.9 ± 1.7 years of age, 11.7 ± 2.8 vs. 7.3 ± 1.6 years of practice, 10.5 ± 0.6 vs. 7.1 ± 1.0 in-water sessions/week, 4 ± 1 vs. 1 ± 1 dry-land sessions/week and 817 ± 34 vs. 491 ± 77 World Aquatics (FINA) points of best competitive performance. The elite and non-elite swimmers, classified as levels 2 and 4 (respectively; Ruiz-Navarro, López-Belmonte, et al., 2022), were front crawl specialists (50 and 90%, respectively) and of those four were sprinters. All swimmers were healthy (with no serious injury or illness in the last six months), familiar with the testing apparatus and informed about the evaluations purpose and known risks. They provided individual consent for participation after being

informed about the study purpose, procedures, benefits and risks (parental consent for the swimmers under 18 y) in accordance with the local research ethics committee (CEFADE 28 2019) and the Declaration of Helsinki.

Experimental protocol

After an anthropometric characterization (obtained in duplicate and recorded to the nearest 0.1 cm or kg) and a 1000 m low-to-moderate intensity warm-up (Neiva et al., 2014), an observational cross sectional study design was employed (Figure 1). In a 1.90 m deep 25 m indoor swimming pool (with 27° C water temperature) and randomized order, swimmers performed four 25 m sprints in butterfly, backstroke, breaststroke and front crawl (with a 10 min interval in-between). An acoustic signal was used for in-water starts and a manual Seiko stopwatch (S141, Tokyo, Japan) was used to measure performance time. Stroke rate was determined manually as the number of cycles/min (using the base 3 upper limbs cycles frequency meter function of the same stopwatch), stroke length calculated by dividing the mean velocity by stroke rate and stroke index assessed as the product of the mean stroke length and 25 m velocity.

At least 2 h after, in an isokinetic dynamometer (Biodex System 4-Biodex Medical Systems, Inc., Carrollton, TX, USA) configured with a 100 Hz sampling rate, swimmers were positioned with a supinated forearm (similar to hand position during swimming) and performed five submaximal (warm-up) and 10 maximal right and left shoulder extension/flexions (with 5 min intervals) contractions at 90 and 300°/s. These actions represented the 180° range of motion (ROM) that can occur during propulsive phases of swimming upper limbs actions, and the low and high angular velocities are specific to obtain force ratios and similar to the angular velocities observed during competitive sprint swimming (Zamparo et al., 2005). Corrections were made to account for the effect of gravity, with the relaxed arm in the neutral starting position and alignment of joints in accordance with Biodex's recommendations. During each isokinetic evaluation, the absolute and relative (to body mass) peak torque, mean absolute peak torque, total work, mean power of shoulder extension and ROM were determined.

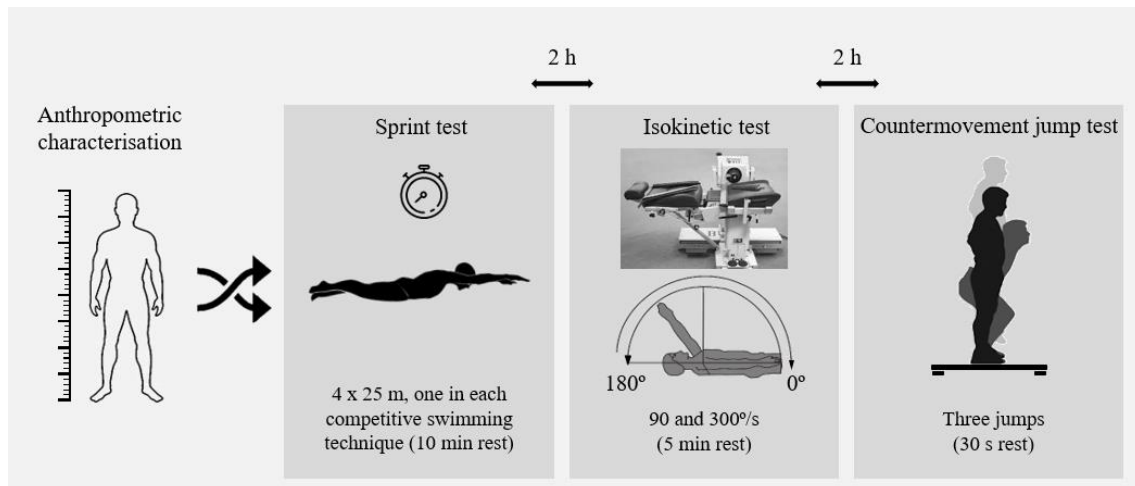


Figure 1. Testing anthropometrics, sprint swimming performance, shoulder isokinetic strength and countermovement jump in a randomized order.

Three countermovement jumps were performed on a portable force platform (OR6-WP, AMTI, Watertown, USA) with 30 s rest between trials. The following variables were measured: total time, eccentric and concentric phases times, peak force time, peak power time, flight time, eccentric and concentric peak forces, mean force, concentric phase peak and mean power, total impulse, maximum velocity and jump height (calculated by the impulse-momentum method; Linthorne 2001). Variables were computed from the force-velocity, -time and -acceleration traces using a custom-made MATLAB routine (MATLAB, MathWorks, Natick, MA, USA; Rago et al., 2018).

Statistical analysis

Descriptive analyses were obtained for all variables and data were checked for distribution normality with the Shapiro-Wilk test. A student's T-test for independent samples with effect size estimation (Cohen, 1988) was used for comparing performance levels. Pearson correlation coefficients controlling for sex were calculated between swimming performance and anthropometric, isokinetic and countermovement jump related variables (and presented as absolute values). The threshold used to qualitatively assess the correlation values was based on the following criteria (Hopkins, 2009): < 0.1 (trivial), 0.1-0.3 (small), 0.3-0.5 (moderate), 0.5-0.7 (large), 0.7-0.9 (very large) and > 0.9 (nearly perfect).

Magnitude-based inference and precision of estimation were calculated to assess practical significance with 95% confidence intervals (CI; Hopkins et al., 2009), and correlations are presented as $r \pm 95\%$ CI. The correlated variables were then explored for predicting performance using Automatic Linear Modelling. The models were created without discriminating elite and non-elite groups, and without trimming for outliers, to establish a more realistic model. The possibility of collinearity between the predictive variables was examined using the variance inflation factor, and only one variable per test (the higher predicting coefficient) entered the models. A sample size of 30 swimmers was deemed sufficient to identify large correlations (effect size = 0.5; minimum power = 0.85; and $\alpha = 5\%$) using G*Power software (v.3.1.9.7, University of Düsseldorf, Düsseldorf, Germany). The data were analysed using IBM SPSS Statistics 27 software and used a 5% significance level.

Results

Anthropometric and Swimming Performance

Anthropometrics and sprint performances of swimmers from different competitive levels are presented in Table 1. The only observed differences were the elite females exhibiting higher height and arm span comparing to non-elite counterparts. Elite swimmers presented higher stroke lengths in butterfly and front crawl, and higher stroke rates in backstroke and breaststroke than non-elite swimmers. In terms of upper limbs strength, elite swimmers had ~10% higher isokinetic torque, power and work, but lower range of motion both at 90 and 300°/s, than non-elite swimmers (see in Table 2). In addition, elite swimmers generated higher countermovement jump flight time, jump height and impulse than their non-elite counterparts, and male elite swimmers showed higher maximum velocity, absolute and relative eccentric peak force and concentric mean power, than their peers (Table 3).

Table 1. Anthropometric characteristics and swimming sprint performances in elite and non-elite male and female swimmers.

Variables (mean±SD)		Elite male (n=9)	Non-elite male (n=6)	Effect size (95% CI)	Elite female (n=7)	Non-elite female (n=8)	Effect size (95% CI)
Anthropometry	Body mass (kg)	76.1±8.9	68.8±9.0	0.8 (-0.3 to 1.9)	60.0±4.2	54.9±7.0	0.9 (-0.2 to 1.9)
	Height (cm)	180.4±4.8	179.5±2.7	0.2 (-0.8 to 1.3)	169.6±5.3*	162.5±7.3	1.1 (-0.1 to 2.2)
	Body mass index (kg·m ⁻²)	23.3±2.0	21.3±2.3	1.0 (-0.2 to 2.1)	20.9±1.7	20.8±1.9	0.1 (-0.9 to 1.1)
	Hand length (cm)	20.2±1.2	19.1±0.7	1.1 (0.0 to 2.2)	17.9±1.3	17.6±1.6	0.23 (-0.8 to 1.3)
	Arm span (cm)	185.1±5.3	182.5±5.6	0.5 (-0.6 to 1.5)	173.1±5.2*	163.2±8.2	1.4 (0.3 to 2.4)
Butterfly	Time of 25 m (s)	13.57±0.61*	14.29±0.66	-1.1 (-2.2 to 0.0)	15.73±0.98*	17.41±0.91	-1.8 (-2.9 to -0.5)
	Stroke rate (cycle·min ⁻¹)	54.7±3.8	57.3±5.9	-0.6 (-1.6 to 0.5)	51.1±6.4	50.1±4.8	0.2 (-0.8 to 1.2)
	Stroke length (m·cycle ⁻¹)	2.03±0.08*	1.85±0.20	1.3 (0.1 to 2.4)	1.89±0.16	1.74±0.22	0.8 (-0.3 to 1.8)
	Stroke index (m ² ·s ⁻¹ ·cycle ⁻¹)	3.74±0.14*	3.25±0.41	1.8 (0.5 to 3.0)	3.00±0.28*	2.51±0.43	1.3 (0.2 to 2.4)
Backstroke	Time of 25 m (s)	14.66±1.34*	16.22±1.34	-1.2 (-2.3 to -0.2)	16.65±1.06*	18.71±1.21	-1.8 (-3.0 to 0.6)
	Stroke rate (cycle·min ⁻¹)	49.8±3.7	46.8±3.6	0.8 (-0.3 to 1.9)	47.5±3.6*	41.0±3.7	1.8 (0.5 to 3.0)
	Stroke length (m·cycle ⁻¹)	2.07±0.15	2.00±0.21	0.4 (-0.6 to 1.5)	1.91±0.15	1.97±0.15	-0.4 (-1.4 to 0.6)
	Stroke index (m ² ·s ⁻¹ ·cycle ⁻¹)	3.56±0.46	3.11±0.51	0.9 (-0.2 to 2.0)	2.88±0.35	2.64±0.28	0.8 (-0.3 to 1.8)
Breaststroke	Time of 25 m (s)	16.61±0.89*	18.61±1.66	-1.6 (-2.8 to -0.4)	18.31±1.02*	21.66±1.18	-3.0 (-4.5 to -1.5)
	Stroke rate (cycle·min ⁻¹)	53.4±5.4*	46.0±8.1	1.1 (0.0 to 2.2)	52.8±5.2*	44.1±6.9	1.4 (0.2 to 2.5)
	Stroke length (m·cycle ⁻¹)	1.71±0.15	1.79±0.21	-0.5 (-1.5 to 0.6)	1.56±0.09	1.60±0.18	-0.2 (-1.3 to 0.8)
	Stroke index (m ² ·s ⁻¹ ·cycle ⁻¹)	2.58±0.25	2.41±0.21	0.7 (-0.4 to 1.8)	2.14±0.14*	1.84±0.14	2.2 (0.8 to 3.4)
Front crawl	Time of 25 m (s)	12.91±0.38	13.67±1.29	-0.9 (-2.0 to 0.2)	14.43±0.45*	16.35±0.60	-3.6 (-5.3 to -1.9)
	Stroke rate (cycle·min ⁻¹)	54.5±4.4	54.0±5.2	0.1 (-0.9 to 1.1)	50.5±4.1	49.0±2.4	0.4 (-0.6 to 1.5)
	Stroke length (m·cycle ⁻¹)	2.14±0.13	2.05±0.16	0.6 (-0.4 to 1.7)	2.07±0.18*	1.88±0.10	1.4 (0.2 to 2.5)
	Stroke index (m ² ·s ⁻¹ ·cycle ⁻¹)	4.15±0.16	3.78±0.50	1.1 (-0.1 to 1.8)	3.59±0.36*	2.87±0.22	2.5 (1.1 to 3.8)

Abbreviations: SD, Standard deviation; CI, Confidence interval. * Differences between swimmers competitive level ($p \leq 0.05$).

Table 2. Upper limb strength related variables in elite and non-elite male and female swimmers.

Variables (mean±SD)		Elite male (n=9)	Non-elite male (n=6)	Effect size (95% CI)	Elite female (n=7)	Non-elite female (n=8)	Effect size (95% CI)
Right upper limb 90°	Absolute peak torque (N·m ⁻¹)	122.64±18.89*	80.17±7.74	2.7 (1.2 to 4.2)	60.64±9.30*	44.53±6.19	2.1 (0.8 to 3.3)
	Relative peak torque (%BM)	159.67±18.89*	117.40±15.89	2.4 (1.0 to 3.7)	101.66±14.45*	77.95±11.44	1.8 (0.6 to 3.0)
	Mean peak torque (N·m ⁻¹)	110.56±16.71*	70.60±14.61	2.5 (1.1 to 3.9)	56.54±8.99*	40.74±6.59	2.0 (0.7 to 3.3)
	Total work (J)	2131.1±344.4*	632.1±161.6	5.2 (3.0 to 7.4)	1128.0±209.7*	338.9±87.3	5.1 (2.9 to 7.2)
	Mean power (W)	127.62±16.72*	75.45±20.18	2.9 (1.4 to 4.4)	64.49±13.33*	36.19±9.13	2.5 (1.1 to 3.9)
	ROM (°)	137±4*	148±3	-3.4 (-5.0 to -1.7)	137±1*	146±6	-2.1 (-3.4 to -0.8)
Right upper limb 300°	Absolute peak torque	115.06±18.49*	53.28±12.93	3.7 (2.0 to 5.5)	76.21±13.77*	27.31±6.30	4.7 (2.6 to 6.7)
	Relative peak torque (%BM)	149.48±18.65*	77.17±14.30	4.2 (2.3 to 6.1)	129.03±30.39*	47.13±9.01	3.8 (2.0 to 5.5)
	Mean peak torque	105.24±17.25*	43.00±13.76	3.9 (2.1 to 5.7)	68.26±13.77*	20.81±5.43	4.7 (2.6 to 6.7)
	Total work (J)	1633.9±235.3*	842.8±440.3	2.4 (1.0 to 3.8)	746.0±216.8*	317.6±150.6	2.3 (1.0 to 3.7)
	Mean power (W)	248.82±45.32*	77.25±43.28	3.9 (2.0 to 5.6)	99.63±37.19*	23.11±12.86	2.8 (1.3 to 4.3)
	ROM (°)	135±4*	147±1	-4.1 (-5.9 to -2.2)	134±1*	145±3	-5.0 (-7.2 to -2.9)
Left upper limb 90°	Absolute peak torque (N·m ⁻¹)	111.34±21.09*	71.83±11.04	2.2 (0.9 to 3.5)	62.11±10.75*	40.80±7.92	2.3 (0.9 to 3.6)
	Relative peak torque (%BM)	146.88±21.22*	104.25±12.29	2.3 (0.9 to 3.7)	104.03±15.85*	71.15±11.51	2.4 (1.0 to 3.7)
	Mean peak torque (N·m ⁻¹)	103.18±22.43*	65.95±13.88	1.9 (0.6 to 3.1)	56.69±10.26*	36.15±8.39	2.2 (0.9 to 3.5)
	Total work (J)	2106.6±338.5*	607.0±188.5	5.2 (2.9 to 7.4)	1160.8±221.3*	317.9±86.9	5.2 (2.9 to 7.4)
	Mean power (W)	118.49±22.64*	65.03±21.07	2.4 (1.0 to 3.8)	62.10±13.34*	30.44±8.86	2.8 (1.3 to 4.3)
	ROM (°)	143±3*	154±3	-3.3 (-4.9 to -1.7)	144±3*	156±3	-4.1 (-5.9 to -2.2)
Left upper limb 300°	Absolute peak torque (N·m ⁻¹)	114.97±22.82*	48.43±14.80	3.1 (1.7 to 4.9)	86.80±9.43*	24.45±6.45	7.8 (4.7 to 10.9)
	Relative peak torque (%BM)	151.26±23.91*	70.10±17.49	3.8 (2.0 to 5.5)	146.49±22.13*	42.50±9.07	6.3 (3.7 to 8.9)
	Mean peak torque (N·m ⁻¹)	104.67±20.27*	37.87±14.92	3.6 (1.9 to 5.3)	79.77±9.21*	19.14±5.87	8.0 (4.8 to 11.2)
	Total work (J)	1641.9±293.6*	767.1±461.4	2.4 (1.0 to 3.7)	879.0±207.0*	297.3±140.9	3.3 (1.7 to 4.9)
	Mean power (W)	238.96±56.15*	64.62±43.72	3.4 (1.7 to 5.0)	111.21±38.87*	18.65±9.03	3.4 (1.7 to 5.0)
	ROM (°)	141±3*	155±5	-4.4 (-6.3 to -2.4)	141±3*	153±3	-4.2 (-6.0 to -2.3)

Abbreviations: SD, Standard deviation; CI, Confidence interval; BM, Body mass; ROM, Range of motion. * Differences between competitive level ($p \leq 0.05$).

Table 3. Lower limb strength related variables in elite and non-elite male and female swimmers.

Variables (mean±SD)		Elite male (n=9)	Non-elite male (n=6)	Effect size (95% CI)	Elite female (n=7)	Non-elite female (n=8)	Effect size (95% CI)
Countermovement (s)		0.99±0.16	0.97±0.15	0.1 (-0.9 to 1.5)	0.88±0.15	0.84±0.18	0.3 (-0.7 to 1.3)
Flight time (s)		0.54±0.05*	0.47±0.04	1.4 (0.2 to 2.6)	0.47±0.06*	0.41±0.03	1.4 (0.2 to 2.5)
Jump Height (cm)		33.94±5.38*	24.70±2.55	1.4 (0.3 to 2.6)	25.19±6.12*	19.75±3.26	1.7 (0.5 to 2.9)
Peak power time (s)		0.93±0.16	0.89±0.15	0.2 (-0.8 to 1.2)	0.82±0.15	0.77±0.18	0.3 (-0.7 to 1.4)
Peak force time (s)		0.83±0.18	0.85±0.15	-0.2 (-1.2 to 0.9)	0.61±0.14	0.62±0.19	0.0 (-1.1 to 1.0)
Eccentric phase time (s)		0.70±0.15	0.67±0.12	0.3 (-0.8 to 1.3)	0.60±0.14	0.53±0.10	0.6 (-0.5 to 1.6)
Concentric phase time (s)		0.28±0.04	0.30±0.05	-0.4 (-1.4 to 0.7)	0.28±0.02	0.30±0.08	-0.4 (-1.4 to 0.7)
Mean force (N)		950±118	834±105	1.0 (-0.1 to 2.1)	741±51	671±81	1.0 (-0.1 to 2.1)
Mean force (N·kg ⁻¹)		12.48±0.51	12.15±0.47	0.7 (-0.4 to 1.7)	12.35±0.35	12.25±0.48	0.2 (-0.8 to 1.3)
Maximum velocity (m·s ⁻¹)		2.72±0.20*	2.42±0.12	1.7 (0.5 to 2.9)	2.37±0.24	2.17±0.17	1.0 (-0.1 to 2.1)
Impulse (N·s ⁻¹)		196±25*	151±19	2.0 (0.7 to 3.2)	133±17*	108±18	1.4 (0.2 to 2.5)
Peak force	Eccentric (N)	1539±182*	1214±215	1.7 (0.4 to 2.9)	1277±149	1116±194	0.9 (-0.2 to 2.0)
	Eccentric (N·kg ⁻¹)	20.28±1.76*	17.64±2.19	1.4 (0.2 to 2.5)	21.25±1.69	20.40±3.04	0.3 (-0.7 to 1.4)
	Concentric (N)	1693±300	1500±210	0.7 (-0.4 to 1.8)	1282±147	1167±169	0.7 (-0.4 to 1.8)
	Concentric (N·kg ⁻¹)	22.14±1.90	21.89±2.39	0.1 (-0.9 to 1.2)	21.33±1.70	21.39±2.89	0.0 (-1.0 to 1.0)
Mean power concentric (W·kg ⁻¹)		27.04±3.16*	21.47±3.56	1.7 (0.4 to 2.9)	22.55±3.40	19.28±2.73	1.1 (0.0 to 2.1)
Peak power concentric (W·kg ⁻¹)		49.78±6.34	44.39±5.64	0.9 (-0.2 to 2.0)	39.81±6.20	36.52±4.05	0.6 (-0.4 to 1.7)

Abbreviations: SD, Standard deviation; CI, Confidence interval. * Differences between competitive level ($p \leq 0.05$).

Clear significant relationships were observed between sprint performance for the four swimming techniques, anthropometric, isokinetic and countermovement jump variables (Figure 2). Anthropometric measures were moderate-largely negatively correlated with butterfly, backstroke and front crawl sprint times (particularly arm span, $0.34 \pm 0.32 - 0.69 \pm 0.20$, $p < 0.05$). Front crawl had the strongest relationships between sprint time and anthropometrics, and breaststroke showed no linear relationships with any anthropometric characteristic. Arm span was moderately positively correlated with stroke length in butterfly and front crawl (0.38 ± 0.31 , $p = 0.044$ and 0.47 ± 0.29 , $p = 0.010$) and stroke rate in backstroke (0.41 ± 0.31 , $p = 0.029$).

Isokinetic strength measures of upper and lower limbs

Moderate to very large negative correlations were observed between the four swimming techniques sprint times and all the assessed isokinetic variables ($0.39 \pm 0.31 - 0.77 \pm 0.16$; $p < 0.05$), with faster sprints associated with higher upper limbs strength levels. Faster butterfly and front crawl performances and higher upper limbs strength values were associated with higher stroke lengths, while quicker backstroke and breaststroke sprint times and higher upper limbs strength values were associated with higher stroke rates ($0.37 \pm 0.32 - 0.67 \pm 0.21$; $p < 0.05$). With countermovement jump variables, there were moderate to large negative correlations between the four sprint times and flight time, jump height, max velocity, peak and mean power concentric and impulse ($0.43 \pm 0.30 - 0.69 \pm 0.20$; $p < 0.01$). Faster butterfly performances and lower limb strength (expressed by countermovement jump impulse) values were also directly related with stroke lengths (0.43 ± 0.30 , $p = 0.02$). Faster backstroke and breaststroke performances and lower limb strength variables were associated with higher stroke rates, and better front crawl sprint times and higher lower limb strength variables were associated with higher stroke lengths (when expressed by absolute mean force) and with higher stroke rates ($0.37 \pm 0.32 - 0.68 \pm 0.21$; $p < 0.05$; Figure 2).

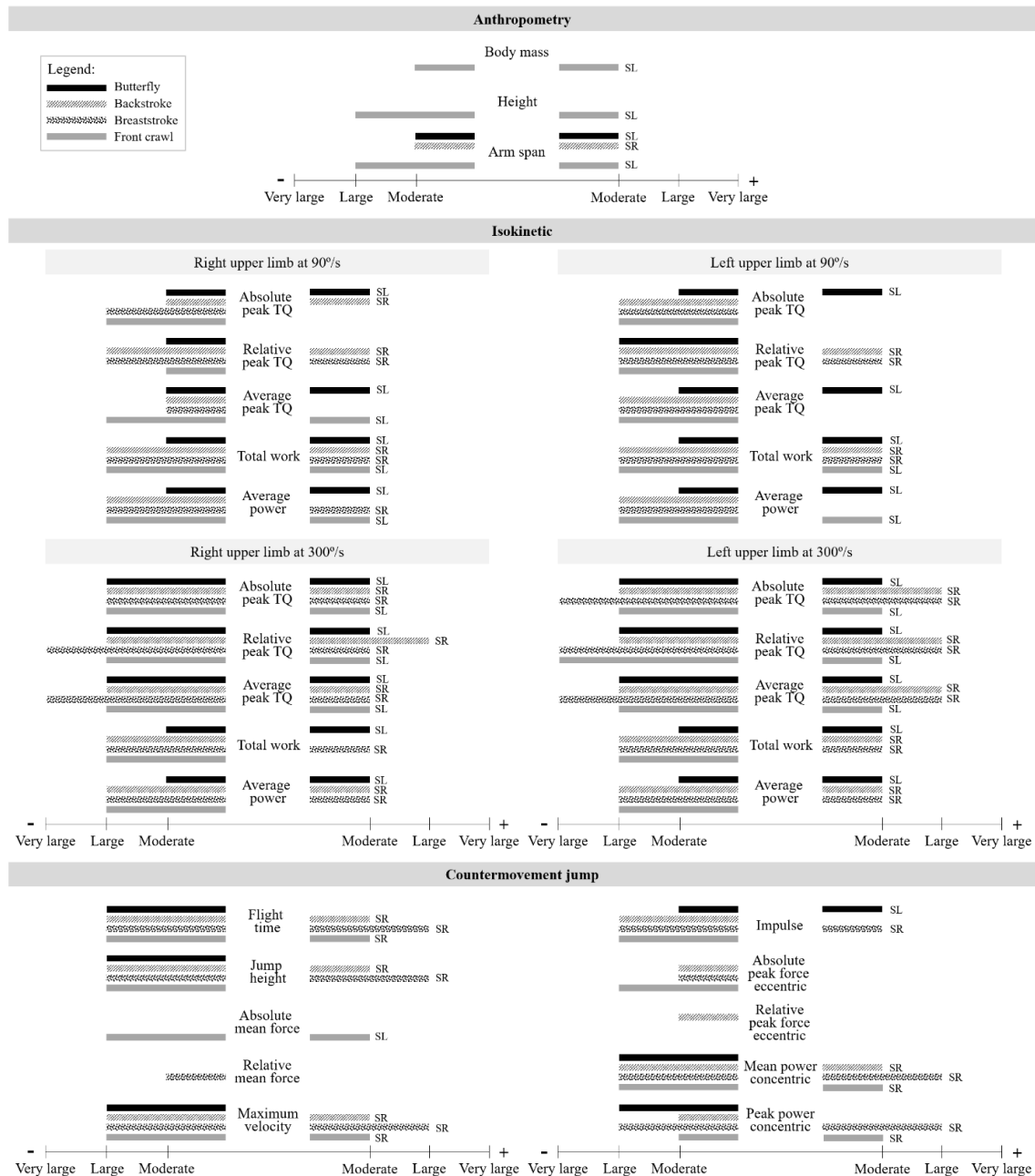


Figure 2. Associations between swimming sprint time and stroke rate (SR) or length (SL) and anthropometric, isokinetic and countermovement jump variables, for the 30 swimmers. Relationships between test measures and swimming performance are presented in ordinal (categorical) format, and presented as trivial, moderate, large or very large according to the criteria of Hopkins et al. (2009). The negative and positive sides represent 25 m time and stroke rate and stroke length (respectively). Abbreviations: TQ, Torque.

In Elite swimmers, shorter backstroke sprint time was associated with body mass (0.60 ± 0.35 , $p = 0.018$) and body mass index (0.61 ± 0.34 , $p = 0.015$), and faster front crawl performance was associated with arm span (0.51 ± 0.39 , $p = 0.050$).

Breaststroke sprint times were associated with selected isokinetic variables, particularly the right upper limb relative peak torque and total work and left upper limb mean peak torque, all at 300°/s (0.63 ± 0.33 , $p = 0.012$; 0.57 ± 0.36 , $p = 0.027$ and 0.61 ± 0.34 , $p = 0.015$; respectively). In contrast, the four swimming techniques sprint times showed large negative correlations with countermovement jump variables, particularly the flight time, jump height and maximum velocity (0.52 ± 0.39 - 0.67 ± 0.30 , $p \leq 0.05$). In addition, butterfly and breaststroke sprint times presented clear relationships with upper limbs peak and mean power (0.51 ± 0.39 - 0.61 ± 0.33 , $p \leq 0.05$).

In non-elite swimmers, faster front crawl and backstroke performances were associated with body mass index (0.55 ± 0.40 , $p = 0.049$ and 0.55 ± 0.37 , $p = 0.047$). The front crawl sprint times were inversely related to isokinetic variables, particularly the right upper limb mean peak torque (0.58 ± 0.39 , $p = 0.039$), total work (0.55 ± 0.40 , $p = 0.050$), mean power (0.64 ± 0.35 , $p = 0.019$), left upper limb mean peak torque (0.61 ± 0.37 , $p = 0.028$) and mean power (0.57 ± 0.39 , $p = 0.041$), all at 90°/s. Backstroke and front crawl swimming techniques performances showed inverse relationships with countermovement jump variables, particularly with absolute peak force in concentric and eccentric phases, and mean force (0.56 ± 0.37 - 0.71 ± 0.28 ; $p < 0.05$).

Regression models of sprint swimming performance

In Figure 3 the associations of models variables and their corresponding 95% CIs with swimming performance are shown. The best model for each of the studied techniques with importance of the independent variables in order was the following: (i) butterfly - peak power concentric, arm span and relative peak torque of right upper limb at 300°/s ($r = 0.87$, adjusted $r^2 = 0.73$; $F = 26.96$, $p < 0.001$; equation 1), with a standard error of estimation of ± 0.90 s; (ii) backstroke - maximum velocity of countermovement jump, relative peak torque of right upper limb at 300°/s and arm span ($r = 0.84$, adjusted $r^2 = 0.67$; $F = 20.30$, $p < 0.001$; equation 2), with a standard error of estimation of ± 1.13 s; (iii) breaststroke - flight time and absolute peak torque of right upper limb at 300°/s without any

anthropometric variable ($r = 0.87$, adjusted $r^2 = 0.74$; $F = 41.14$, $p < 0.001$; equation 3), with a standard error of estimation of ± 1.16 s; (iv) front crawl - arm span, mean power of right upper limb at 90°/s and flight time ($r = 0.91$, adjusted $r^2 = 0.81$; $F = 43.15$, $p < 0.001$; equation 4), with the lower standard error of estimation of the models (± 0.66 s).

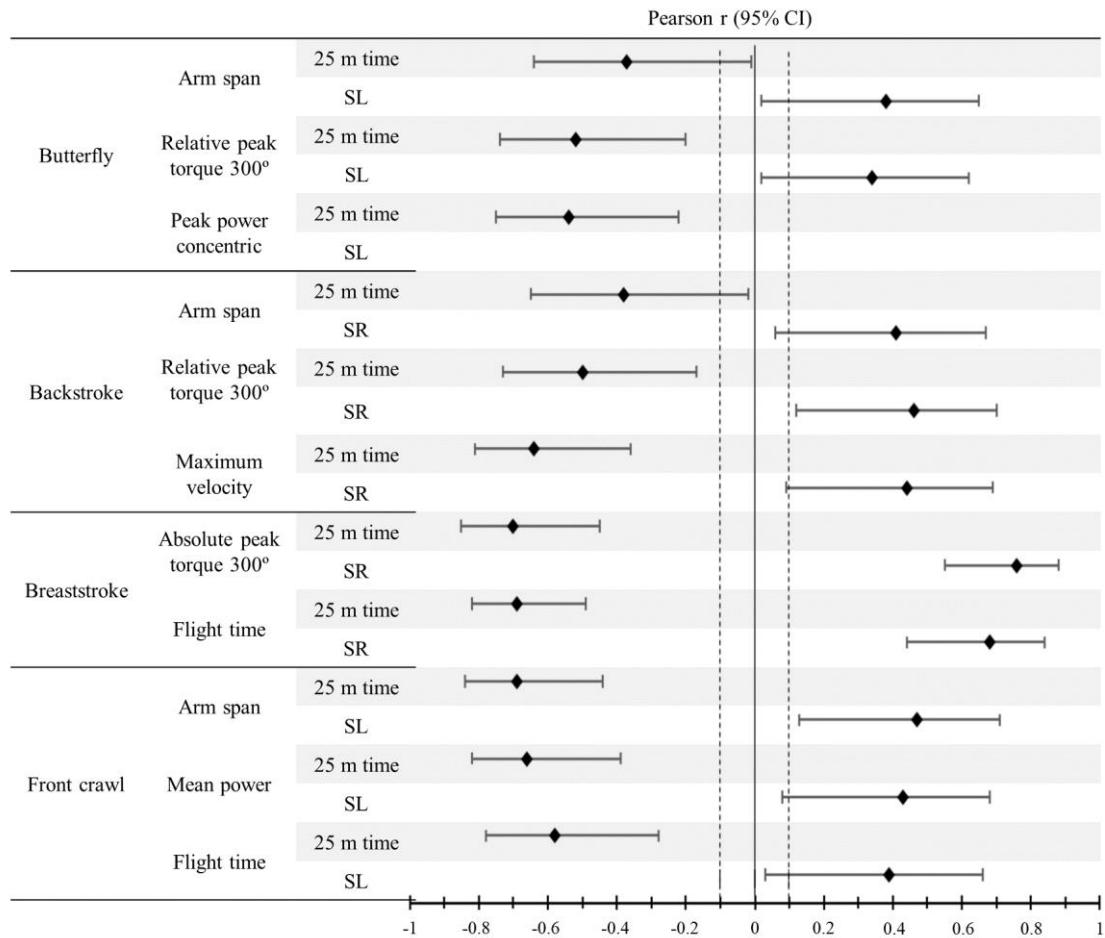


Figure 3. Correlations values and 95% confidence intervals (CI) controlled for sex effect between swimming techniques sprint times and stroke rate (SR) or length (SL) and arm span and the lower limbs strength and power measures selected by the regression models. Dashed lines represent the smallest clinically (practically) important correlation (± 0.1).

The models equations for each swimming technique were:

$$\text{Butterfly 25 m time (s)} = -0.06 \cdot \text{arm span} - 0.01 \cdot \text{relative peak torque of right upper limb at } 300^\circ/\text{s} - 0.09 \cdot \text{peak power concentric} + 30.81 \quad (1)$$

$$\text{Backstroke 25 m time (s)} = -0.04 \cdot \text{arm span} - 0.01 \cdot \text{relative peak torque of right upper limb at } 300^\circ/\text{s} - 3.02 \cdot \text{maximum velocity of countermovement jump} + 32.48 \quad (2)$$

$$\text{Breaststroke 25 m time (s)} = -0.03 \cdot \text{absolute peak torque of right upper limb at } 300^\circ/\text{s} - 16.35 \cdot \text{flight time} + 28.51 \quad (3)$$

$$\text{Front crawl 25 m time (s)} = -0.07 \cdot \text{arm span} - 0.01 \cdot \text{mean power of right upper limb at } 90^\circ/\text{s} - 5.54 \cdot \text{flight time} + 30.52 \quad (4)$$

In Figures 4 and 5 the dispersion of the variables used in each of the four above-referred models, with their magnitude are displayed depending on the swimmers sex and performance level. The degree of dispersion indicates a substantial uncertainty in the relationships between the sprint performances and upper and lower limbs strength and power when analysed within the groups. The exceptions were lower limb strength for butterfly, backstroke and front crawl sprints in male elite group and for breaststroke sprint in female elite group.

Discussion

We have shown that sprint performances were moderately to largely correlated with upper and lower limbs strength (independently of the swimming technique). However, the performance determinants within each of the elite and non-elite swimmers groups were unclear. As an example, there was a clear relationship between front crawl sprint performance and arm span but only for the elite swimmers group. We developed models explaining 70-80% of the variance observed in sprint swimming performance, even in the presence of high relative

error of estimations (typically ~1.0 s for 25 m performance). Butterfly and front crawl sprint performance primarily depended on stroke length, and backstroke and breaststroke performance on stroke rate.

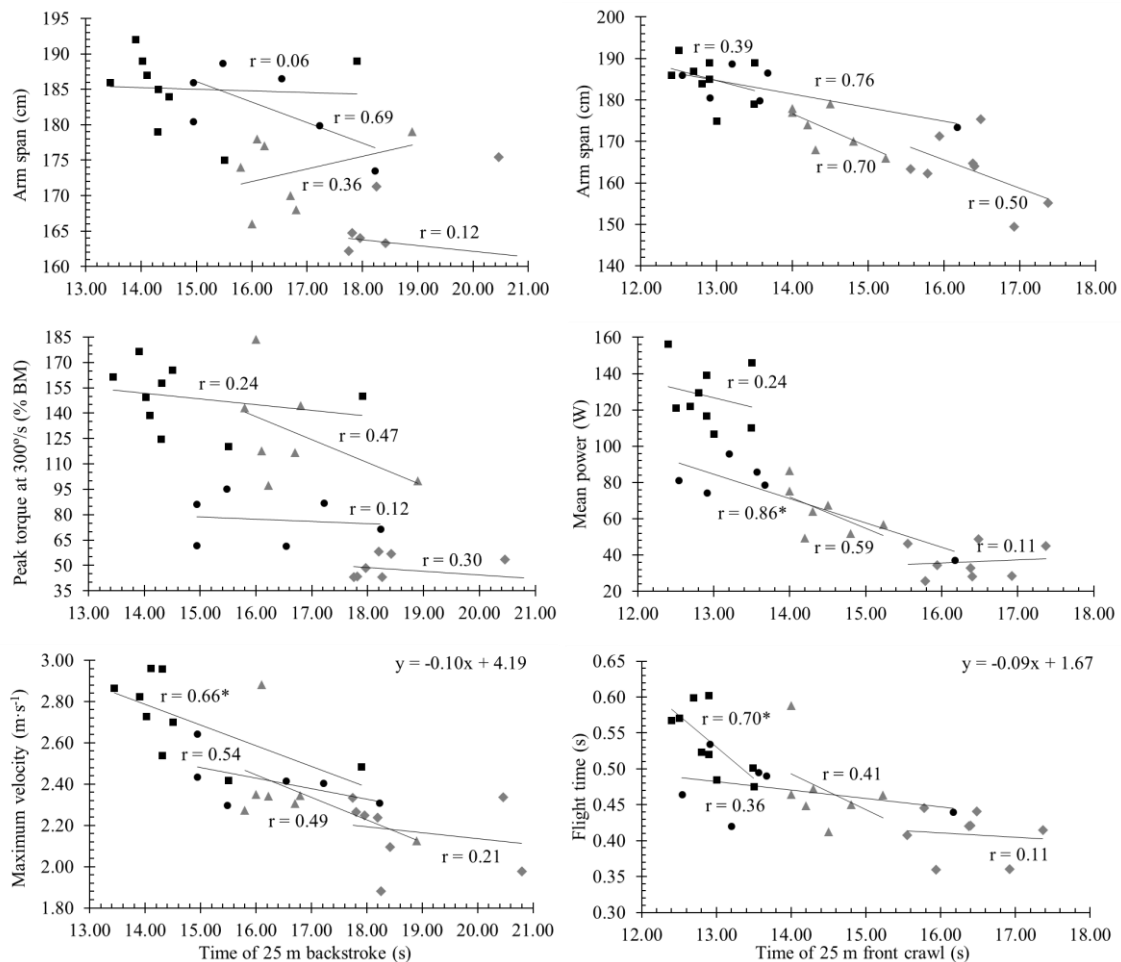


Figure 4. Dispersion of the predictive models selected variables for the 25 m time for backstroke and front crawl with correlation values and linear regression lines. ■ ▲ ● ◆ represents male elite and non-elite, and female elite and non-elite swimmers (respectively). Displayed equations of the linear regression for the significant correlations in elite male group (bottom panels). * Significant correlations ($p \leq 0.05$).

Isokinetic dynamometry is considered the gold standard method for measuring muscle strength of dynamic movements of discrete joints (Downson et al. 1998), but direct comparisons across the strokes in swimmers are lacking. Moreover, when conducting muscle strength laboratory evaluations, to approximate to real world swimming (by adjusting upper limbs placement and/or angular velocities),

very strong relationships with in-water force production of elite swimmers were obtained (Carvalho et al, 2019). The countermovement jump is also a commonly used test to evaluate lower limbs explosive power (West et al., 2011; Strzala et al., 2020) and is valid to assess the capability of in-water lower limb force exertion (Morouço, Neiva, et al., 2011). Our results highlighted the utility of these tests to differentiate swimmers of lower and high sprint swimming ability.

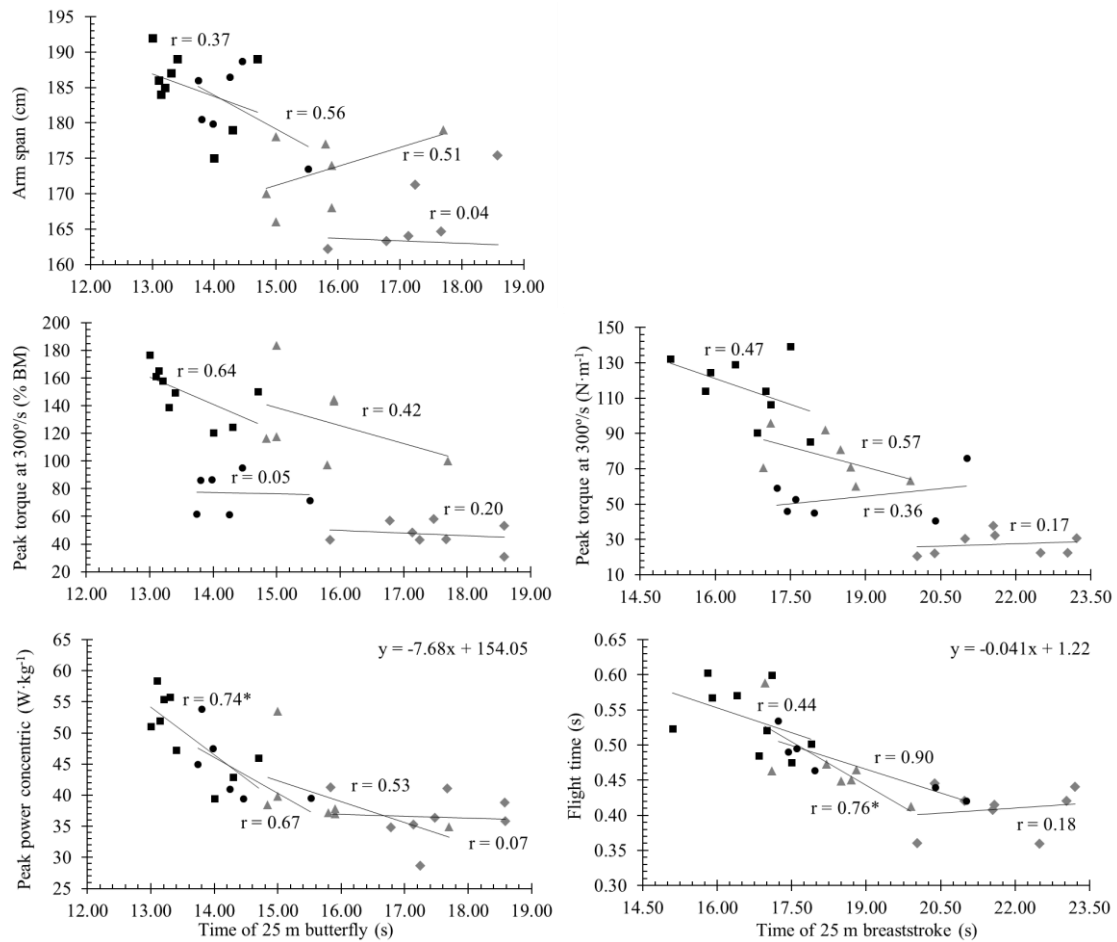


Figure 5. Dispersion of the predictive models selected variables for the 25 m time for butterfly and breaststroke with correlation values and linear regression lines. ■ ▲ ● ◆ represents male elite and non-elite, and female elite and non-elite swimmers (respectively). Displayed equations of the linear regression for the significant correlations in elite male and female groups, (lower left and right panels, respectively). *Significant correlations ($p \leq 0.05$).

Sprint swimming is normally associated with high stroke rates (between 50-60 cycles·min⁻¹; Ribeiro et al., 2017; Gonjo et al., 2020), with our non-elite group struggling to reach these levels in backstroke and breaststroke. This shortcoming

might reflect that their training was mainly composed of front crawl training (for warming-up, conditioning, perfecting their technique and recovering; Stewart & Hopkins, 2000), and/or they completed few non-front crawl sprint sets. Our elite swimmers sprint mean velocities were comparable to the competitive levels and 50 m performances (Morouço, Keskinen, et al., 2011) likely as our trials started in-water, (i.e., without a dive start). The mean gap of ~ 0.7 s lacks statistical relevance when comparing the front crawl sprint performance of elite and non-elite male swimmers. However, this magnitude of difference is associated with a large effect size that, due to the small size of the groups, can be assumed as practically important.

It is common knowledge that taller and longer arm span swimmers typically have better sprint performances (Strzała et al., 2020). We observed that arm span was the strongest anthropometric predictor of butterfly, backstroke (only with relationships) and front crawl sprint performances (higher correlation magnitude), in agreement with reports for younger front crawl swimmers (Lätt et al., 2010). The dominance of front crawl training may have elicited better technical levels (given by higher stroke index values) independent of the performance group, with longer limb levers providing higher propulsive forces (Strzała et al., 2020; Stanelle et al., 2021). The absence of substantial relationships between breaststroke sprint performance and anthropometry can be explained partially by the absence of specialists in this swimming technique. A lower swimming efficiency (i.e., reduced stroke index values) appears to have limited underlying mechanical advantages.

Elite swimmers produced higher upper limbs torques, power and work than the non-elite counterparts, presenting similar values to the literature (Carvalho et al., 2019). Furthermore, independently of the swimming techniques, we showed that upper limbs strength and power testing can be used to allocate swimmers in different performance groups. These results are in accordance with a recent study that employed the FINA points scale as a swimming performance indicator and similar strength related variables (Wiażewicz & Eider, 2021). However, within

the same performance level, our data was not consistent, with unclear relationships between sprint swimming performance and upper limbs strength and power.

Our elite group swimmers presented the higher shoulder torque and power at 300°/s, while the non-elite swimmers produced the higher torque at 90°/s and higher power at 300°/s. These results indicate that elite swimmers have greater ability to produce force under conditions closer to the real practice. An unexpected outcome of the study was the elite swimmers exhibiting lower range of motion compared to the non-elite counterparts. This result likely reflects that the most advanced swimmers selected an optimal amplitude to replicate the upper limbs actions during the in-water horizontal phases (without trunk rotation). Complementary, the elite swimmers also demonstrated a higher upper limbs strength contralateral symmetry when performing at 300 compared to 90°/s (i.e., at similar angular velocities than those used on sprint events; Carvalho et al., 2019). The non-elite swimmers exhibited substantial asymmetries in the two tested velocities ($\geq 10\%$, $p < 0.05$).

The elite swimmers presented higher countermovement jump flight time, height and impulse values than the non-elite counterparts, permitting swimmers to be differentiated by performance levels. In addition, our male elite swimmers presented lower values for the jump height than swimmers from analogous competitive levels (Morouço, Neiva, et al., 2011), but with different assessment methods. Moreover, our female elite swimmers presented higher jump height and maximum velocity than other elite swimmers (Benjanuvatra et al., 2007). The relationships between sprint performance and the lower limbs strength and power were evident for the four techniques in the elite group and for front crawl and backstroke in the non-elite group. This outcome for the lower limbs is contrary to what was observed in the associations with the upper limbs strength variables. The importance of the lower limb strength and power assessment for the understanding of sprint performance is corroborated data showing positive relationships between countermovement jump work and both tethered swimming

force exertion (Morouço et al., 2015) and sprint performance (Keiner et al., 2019). In addition, lower limbs strength and power assessment can be used to understand the positive plyometric training effects on swimming performance (Potdevin et al., 2011).

Swimming velocity can be manipulated by changing stroke rate or length, and both can benefit from high levels of maximum strength (Gola et al., 2014; Ribeiro et al., 2017; Silveira et al., 2017). Our results add to this body of knowledge that faster sprint performance in butterfly and front crawl reflects higher lower limbs strength and power, as well as greater stroke lengths. In contrast, backstroke and breaststroke performance appeared to be mainly influenced by the higher upper limb strength/power and stroke rates. Those results are in line with the previously observed positive relationships between front crawl stroke length and lower limbs propulsive work (Silveira et al., 2017), and between breaststroke stroke rate and upper limbs strength (Invernizzi et al., 2014).

The butterfly, backstroke and front crawl sprint performance prediction linear models combined anthropometric measures and upper and lower limbs strength/power variables. The breaststroke sprint model detailed here did not involve an anthropometric measure given the likelihood of the swimmers weaker technique level (evidenced by the lowest stroke index values), since only two elite and one non-elite swimmers were breaststroke specialists. Moreover, the selected anthropometric variables did not include any measures related to the lower limbs girths or lengths, which might be more relevant for breaststroke (Sekulic et al., 2007). The observed relative high error of estimations could be explained by the characteristics of the linear approach (Maszczyk et al., 2012) and by the unclear relationships between sprint performance and upper and lower limbs strength/power related variables within elite and non-elite groups. The lower error of estimations of front crawl could be supported by most of the swimmers were front crawl specialists and ~50% of their training are performed with this swimming technique (Stewart & Hopkins, 2000).

Analysing the variables selected for entering the predictive models (within performance and sex groups) indicated the relationships between sprint performance and arm span and upper limbs strength/power fade away. Only in elite males (for front crawl, backstroke and butterfly) and elite females (for breaststroke) sprint performances and lower limbs strength/power sustained their relationships and prediction capability. Swimming dry-land strength programs normally employ exercises to improve the strength of the upper limbs and trunk (Garrido et al., 2012; Amaro et al., 2019), neglecting the lower limbs, justifying why sprint performances exhibited large relationships with countermovement jump within the elite group. With only 16 elite swimmers, a limitation of the current study is that the within-group analysis was centred on a small number of subjects, constraining the opportunity to confidently identify worthwhile relationships between sprint performance and upper and lower limbs strength and power. Future research should analyse a wider range of swimmers divided by swimming technique specialty and level to clarify the effect of upper and lower limbs strength and power on sprint performance.

In conclusion, elite swimmers exhibited higher upper and lower limbs strength and power levels than the non-elite counterparts, with these attributes moderately to largely correlating with sprint swimming. Upper and lower limbs variables clearly discriminated top and low tier sprint performances (independent of the swimming technique). Isokinetic and countermovement jump testing are useful for distinguishing differences in strength and power attributes between elite and non-elite swimmers. Given the consistent relationships with sprint performance, its easy application, fast data analysis and general acceptance as a valid predictor of lower limbs power, we recommend the use of the countermovement jump for sprint performance training control. The current outcomes provide practical insight on how physical contributors to sprint performance can be used by swimming and strength and conditioning coaches to tailor the swimmers short- and long-term development.

Chapter 5

In-water and on-land swimmers' symmetry and force production

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Abstract

Although performance and biomechanical evaluations are becoming more swimming-specific, dry-land testing permits monitoring of a larger number of performance-related variables. However, as the degree of comparability of measurements conducted in-water and on land conditions is unclear, we aimed to assess the differences between force production in these two different conditions. Twelve elite swimmers performed a 30 s tethered swimming test and four isokinetic tests (shoulder and knee extension at 90 and 300°/s) to assess peak force, peak and average torque, and power symmetry index. We observed contralateral symmetry in all the tests performed, e.g., for 30 s tethered swimming and peak torque shoulder extension at 90°/s: 178 ± 50 vs. 183 ± 56 N ($p = 0.38$) and 95 ± 37 vs. 94 ± 35 N x m ($p = 0.52$). Moderate to very large direct relationships were evident between dry-land testing and swimming force production ($r = 0.62$ to 0.96 ; $p < 0.05$). Swimmers maintained similar symmetry index values independently of the testing conditions ($r = -0.06$ to -0.41 and 0.04 to 0.44 ; $p = 0.18$ - 0.88). Asymmetries in water seems to be more related to technical constraints than muscular imbalances, but swimmers that displayed higher propulsive forces were the ones with greater force values on land. Thus, tethered swimming and isokinetic evaluations are useful for assessing muscular imbalances regarding propulsive force production and technical asymmetries.

Keywords: biomechanics; isokinetic; tethered swimming; asymmetry; swimming

Introduction

Biomechanical characteristics are important swimming performance determinants, fundamental in understanding propulsion mechanics in the highly specific hydrodynamic environment. Analysing swimmers' force production should be a priority in their training control and research, as an effective propulsion is fundamental for competitive success (Sharp & Troup, 1982; Girolld et al., 2006; Ribeiro et al., 2017). For this purpose, tethered swimming has been one of the most frequently used methods, yielding substantial associations between tethered forces and swimming performance in sprint events (Yeater et al., 1981; Morouço et al., 2014; Santos et al., 2016). These studies underpin the notion that movements used in training and testing should be mechanically similar to those used in competition (Barbosa et al., 2010).

Complementarily, it is known that similar force application from both right and left body sides can positively affect swimming performance, particularly by reducing drag, promoting better body alignment and lowering intracycle velocity variations (Sanders et al., 2011). In fact, ~96% of the human population present a perceptible asymmetry level (Annett, 1998), which may negatively influence exercise performance, mainly in cyclic and continuous sports (Sanders et al., 2012; Toubekis et al., 2010). Since elite swimmers spend a huge number of hours in-water and land workouts, they are more vulnerable to overuse injuries, particularly if they present muscular and technical imbalances (Batalha et al., 2015). Furthermore, if hydrodynamic and inertial limitations are also considered, swimmers need to be as symmetrical as possible when propelling through the water.

The isokinetic dynamometer is the laboratorial gold standard to evaluate asymmetries and imbalances in force production, permitting analysis of specific muscle groups and movements (Batalha et al., 2015; Rupp et al., 1995; Secchi et al., 2011). However, even if its use is common in muscular symmetry analysis, it does not allow evaluating specific swimming movements. For this reason,

tethered swimming has been conducted to quantify and analyze both force production and asymmetries during swimming (Toubekis et al., 2010; dos Santos et al., 2013; Morouço et al., 2015). Surprisingly, it is unclear if measurements obtained from tethered swimming and isokinetic dynamometer are related, and whether swimmers generate a similar level of force production symmetry in-water and dry-land conditions.

Using an innovative approach, with closer approximation to real-world swimming characteristics, of assessing shoulder and knee extension force values (hand placement, angular velocities, isolated and combined analysis), the aim of the current study was to determine the degree of association between tethered swimming peak propulsive forces and dry-land isokinetic torque and power. We also sought to determine whether there is a similar contralateral symmetry regarding force production in both the above referred conditions and the nature of their symmetry index (SI) relationships. Finally, we determined whether swimming symmetry can be identified by using only the first 10 upper limb cycles during tethered swimming.

Material and Methods

Participants

Twelve elite swimmers (seven males and five females) voluntarily participated in the current study, presenting the following physical and competitive characteristics (respectively): 20.9 ± 3.4 vs. 19.0 ± 2.2 years of age, 77.1 ± 8.9 vs. 59.6 ± 5.0 kg of body mass, 1.82 ± 0.04 vs. 1.69 ± 0.06 m of height, 23.3 ± 2.1 vs. 20.8 ± 1.8 of body mass index and 841 ± 37 vs. 816 ± 38 Fédération Internationale De Natation points of best competitive performance. Eight swimmers presented right lateral preference and four were left-handed. The experimental moment comprised a tethered swimming test in an indoor 25 m pool and four laboratory isokinetic evaluations, performed in randomized order on consecutive days. Subjects were familiarized with the two apparatus, informed about the purpose of the evaluations and any known risks, providing individual

consent for participation in accordance with the local research ethics committee (CEFADE 28 2019) and Declaration of Helsinki.

Design and Procedures

After a 1000 m low-to-moderate intensity warm-up, swimmers performed a 30 s maximal front crawl ($n = 6$) and backstroke ($n = 6$) tethered swimming test using a belt attached to a steel cable (5 m length and 5.7° angle with the water surface) (Morouço et al., 2011). Its beginning and end were indicated by an acoustic signal, with swimmers adopting a horizontal position with the cable fully extended just before the starting signal. The data collection only commenced after the first upper limbs cycle was completed. A load-cell connected to a Globus Ergometer data acquisition system (Globus, Codognè, Italy) obtained force measurements at a rate of 100 Hz (Morouço et al., 2014). Tests were recorded using one surface video camera (50 Hz, Sony® Handycam HDR-CX160E, Tokyo, Japan) placed in the sagittal plane, with video acquisition synchronized with force data to better identify the beginning and end of each upper limb cycle.

In isokinetic dynamometer (Biodex System 4-Biodex Medical Systems, Inc., Carrollton, TX, USA), after freely warmed-up without constraint of velocity, swimmers performed a shoulder and knee extension/flexion (representing the front crawl and backstroke upper limb action with 180° range of motion and leg movement during the lower limb actions with 90° range of motion, respectively) at 90 and $300^\circ/\text{s}$ and a sampling rate of 100 Hz. These angular velocities represented a low (used for construct ratios of forces in a clinical point-of-view) and a high (similar to competitive swimming). Swimmers were positioned in the dynamometer chair with a forearm supination similar to hand positioning during swimming (Figure 1). The tests consisted in five sub-maximal repetitions at each pre-defined angular velocity, 10 maximal repetitions with 90 s and 10 min of rest permitted between side trials and movements, respectively. Swimmers were instructed to generate maximal one-way force during the phase of knee and shoulder extension to form a more realistic simulation of the aquatic environment motion.

Measures

Tethered swimming peak forces of each upper limb action were extracted from individual force vs. time curves synchronized with the video recording to associate each peak force value to one upper limb cycle body side (Morouço et al., 2015), involving a two-stage process; (i) characterizing the initial 10 upper limb cycles, i.e., the time duration associated with changings in energetic system dominance and muscle recruitment (Gastin, 2001; Soares et al., 2014); (ii) characterizing all upper limbs cycles performed during the entire 30 s, representing the gold standard test to quantify the anaerobic capacity, the Wingate test (Morouço et al., 2015; Bar-Or, 1987). During each isokinetic evaluation, the peak torque (the highest value observed in the 10 repetitions), mean peak torque (mean of the 10 peaks obtained) and mean power values were determined. Shoulder and knee isokinetic force variables were analysed individually and in combination to represent the group muscles used during front crawl and backstroke swimming.



Figure 1. Initial and final positioning of the hand (white circle) during upper limb simulated action isokinetic test ((a) and (b) panels, respectively).

SI was calculated for all force variables according to the following equation:

$$SI (\%) = \frac{(\text{preferred} - \text{nonpreferred})}{0.5 \times (\text{preferred} + \text{nonpreferred})} \times 100 \quad (1)$$

in which values between $-10 < SI < 10\%$ and $-10 > SI > 10\%$ indicate symmetry and asymmetry, respectively (Robinson et al., 1987). SI values were made positive, obtaining means without a zero-central tendency to compute absolute asymmetries between tethered swimming and isokinetic dry-land testing. This approach permitted comparisons of overall level of asymmetry values irrespective of the preferred side.

Statistical Analysis

Descriptive analyses (mean and standard deviation) were obtained for all variables and data checked for distribution normality with the Shapiro-Wilk test. Spearman correlation coefficients were calculated between isokinetic and tethered swimming force related variables and correspond SI. Intraclass correlation coefficients (ICC) were assessed to quantify the degree of reliability between repetitions of each body side in isokinetic and tethered swimming. Correlations were interpreted as follows (Bilkman et al., 2013): 0-0.25 (little), 0.26-0.49 (weak), 0.50-0.69 (moderate), 0.70-0.89 (strong) and 0.90-1.0 (very strong). The Wilcoxon signed-rank test was used to compare the forces produced by the preferred and the non-preferred body side and the mean absolute SI obtained with isokinetic and tethered swimming tests.

Effect size was calculated using the ratio of z score and square root of the number of observations, and interpreted as 0-0.09 (trivial), 0.1-0.29 (small), 0.3-0.49 (medium), 0.5-0.69 (large) and ≥ 0.7 (very large; Cohen, 1988). A Bland-Altman plot analysis (Bland & Altman, 1986) was also performed to characterize the differences between SI of tethered swimming and isokinetic evaluations, and between SI of the first 10 upper limb cycles and 30 s in the tethered swimming (the last one used as reference method). A $p \leq 0.05$ level of significance was accepted.

Results

Tethered swimming and force production isokinetic variables were moderately to very largely directly related, with correlation values ranging from $r = 0.62$ to 0.96 . The peak torque, mean torque, mean power and mean peak forces values of the first 10 upper limb cycles and 30 s of front crawl and backstroke tethered swimming, for both preferred and nonpreferred body sides, are presented in Table 1. When analysed as combined isokinetic forces, the relationships ranged from $r = 0.65$ to 0.94 . In most of the evaluated variables, the non-preferred side presented higher absolute correlations than the preferred side. Values obtained during the first 10 s of tethered swimming presented similar correlation to the isokinetic forces when compared to the 30 s data.

Table 1. Correlation coefficients between tethered swimming and isokinetic variables for preferred and non-preferred upper body sides. All associations were significant ($p < 0.05$).

Isokinetic variables	Front Crawl and Backstroke Tethered Swimming			
	10 Upper Limb Actions		30 s	
	Preferred	Nonpreferred	Preferred	Nonpreferred
Upper limbs simulated action				
Peak torque 90°/s	0.83	0.92	0.82	0.90
Mean peak torque 90°/s	0.80	0.94	0.79	0.91
Mean power 90°/s	0.80	0.96	0.79	0.93
Peak torque 300°/s	0.62	0.67	0.66	0.66
Mean peak torque 300°/s	0.64	0.72	0.68	0.71
Mean power 300°/s	0.81	0.94	0.83	0.92
Knee extension				
Peak torque 90°/s	0.68	0.90	0.68	0.81
Mean peak torque 90°/s	0.80	0.90	0.78	0.84
Mean power 90°/s	0.79	0.91	0.78	0.85
Peak torque 300°/s	0.73	0.92	0.71	0.86
Mean peak torque 300°/s	0.72	0.93	0.69	0.89
Mean power 300°/s	0.71	0.96	0.69	0.94
Combined				
Peak torque 90°/s	0.79	0.91	0.78	0.85
Mean peak torque 90°/s	0.69	0.84	0.72	0.84
Mean power 90°/s	0.79	0.94	0.78	0.89
Peak torque 300°/s	0.65	0.87	0.69	0.87
Mean peak torque 300°/s	0.83	0.92	0.83	0.87
Mean power 300°/s	0.76	0.83	0.72	0.85

No substantial differences were evident between SI of isokinetic and tethered swimming force production or between first 10 upper limb cycles and 30 s of tethered swimming (Figure 2). Only in two swimmers, an asymmetrical force production in tethered swimming ($SI > 10\%$) was identified. However, in the isokinetic evaluations, eight swimmers presented asymmetrical force production (at least in one of the studied variables), reduced to three swimmers when the shoulder and knee extension combined variables were evaluated. Absolute values of SI obtained from tethered swimming and isokinetic force variables showed no substantial differences, but a high variability was evident between subjects (Figure 2). The correlation analyses showed that only the SI of 10 upper limb cycles had a moderate inverse relationship with SI of power of knee extension at $300^\circ/s$ ($r = -0.66$) and combined average power SI ($r = -0.60$). No substantial relationships in the other SI ($r = -0.06$ to -0.41 and 0.04 to 0.44 with $p = 0.18$ to 0.88).

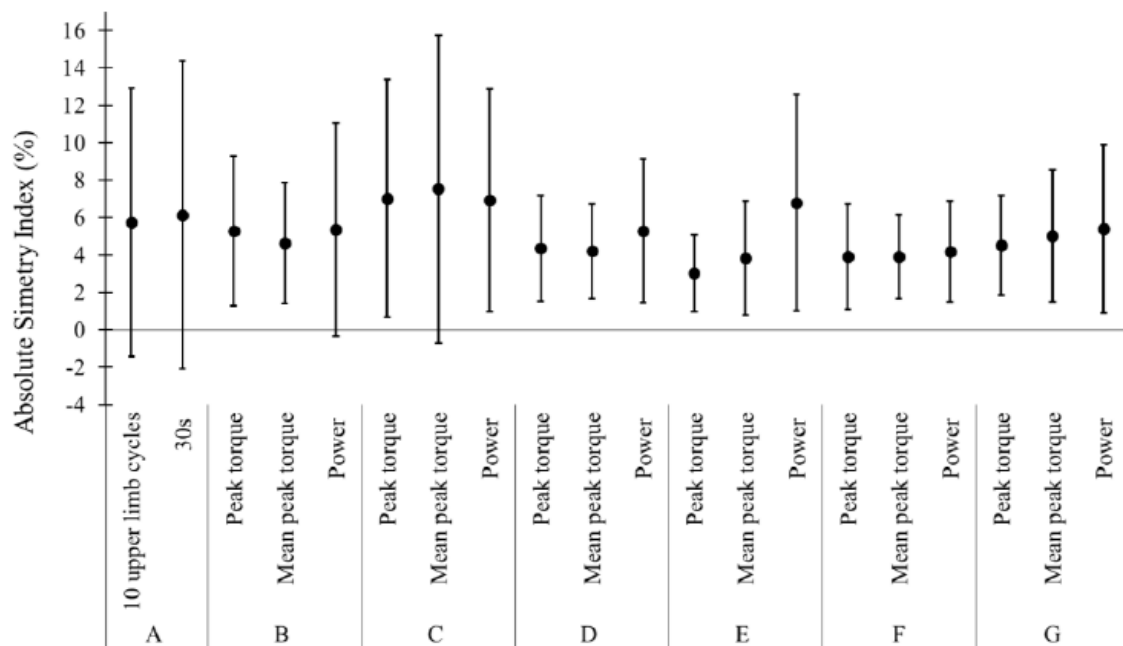


Figure 2. Mean and SD values of absolute symmetry index of tethered swimming (A), upper limb simulated action ($90^\circ/s$ and $300^\circ/s$: B and C), knee extension ($90^\circ/s$ and $300^\circ/s$: D and E), combined upper limb simulated action and knee extension ($90^\circ/s$ and $300^\circ/s$: F and G).

Swimmers showed a similar force production between preferred and nonpreferred body sides (both in tethered front crawl and backstroke swimming) and isokinetic tests (Table 2; $p = 0.18$ to 0.97). In the tethered swimming and isokinetic tests, intraclass correlation between repetitions for both preferred and nonpreferred side were excellent (ICC: 0.989 to 0.997 ; 95% CI: 0.963 to 0.999 with $p < 0.001$). Agreement analyses between SI's of isokinetic evaluations and 30 s tethered swimming presented a bias standard deviation $> 9\%$ and the 95% limits of agreement higher than 19% , demonstrating that the SI were independent from each other (see Table 2). The SI of the first 10 upper limb cycles and 30 s in tethered swimming test showed a very strong relationship ($r = 0.99$). In addition, comparison between the SI calculated with the first 10 upper limb cycles and 30 s of tethered swimming showed a good agreement with a bias of $-0.7 \pm 1.2\%$ and 95% limits of agreement of -3.0 and 1.6% , resulting in a consistent behaviour of SI during the 30 s effort.

Discussion

Our results indicate moderate to very strong relationships between in-water and dry-land conditions force production, which supports the first hypothesis that forces produced in land condition are closely related with the capability to apply force in-water. We also identified similar force production between preferred and nonpreferred body sides, showing that elite swimmers, as a consequence of their training, exhibit upper and lower body symmetry. Our swimmers presented similar but independent contralateral symmetry during swimming and dry-land testing. The very strong relationship between isokinetic and tethered forces supports the assertion that isokinetic ones are related to swimming performance and reinforced that the 30 s tethered swimming test is a good predictor of swimming performance (Santos et al., 2016; Morouço, Keskinen, et al., 2011).

The above outcomes are in accordance with the study that reported an inverse relationship between isokinetic knee extension force and mono-fin swimming 100 m time (Kunitson et al., 2015). However, some studies indicated that isokinetic

Table 2. Isokinetic and tethered swimming variables mean $\pm$ SD for preferred and nonpreferred body side and effect size. Bias and 95% limits of agreement of estimations between symmetry indexes of isokinetic evaluations and 30 s tethered swimming.

Variables	Preferred	Nonpreferred	Effect Size	Bias	95% CI
Upper limb simulated action					
Peak torque 90°/s (N x m)	95.10 $\pm$ 36.69	93.89 $\pm$ 35.14	-0.14	1.5 $\pm$ 13.4	-25-28
Mean peak torque 90°/s (N x m)	87.78 $\pm$ 33.92	86.19 $\pm$ 31.72	-0.15	1.9 $\pm$ 10.8	-19-23
Mean power 90°/s (W)	99.72 $\pm$ 38.46	98.47 $\pm$ 36.89	-0.13	-2.0 $\pm$ 9.8	-17-21
Peak torque 300°/s (N x m)	100.92 $\pm$ 23.76	105.22 $\pm$ 22.93	-0.28	-1.8 $\pm$ 16.9	-35-31
Mean peak torque 300°/s (N x m)	93.63 $\pm$ 23.46	95.64 $\pm$ 20.50	-0.03	-0.6 $\pm$ 18.5	-37-36
Mean power 300°/s (W)	186.55 $\pm$ 90.21	192.69 $\pm$ 86.71	-0.11	-1.6 $\pm$ 12.7	-26-23
Knee extension					
Peak torque 90°/s (N x m)	185.60 $\pm$ 50.06	186.86 $\pm$ 50.30	-0.08	0.6 $\pm$ 10.7	-20-22
Mean peak torque 90°/s (N x m)	171.25 $\pm$ 47.09	170.72 $\pm$ 44.29	-0.03	1.0 $\pm$ 10.5	-20-22
Mean power 90°/s (W)	173.51 $\pm$ 51.67	177.41 $\pm$ 47.48	-0.16	-0.6 $\pm$ 10.6	-21-20
Peak torque 300°/s (N x m)	124.36 $\pm$ 39.95	127.34 $\pm$ 38.57	-0.27	-0.9 $\pm$ 11.8	-24-22
Mean peak torque 300°/s (N x m)	114.33 $\pm$ 36.98	116.48 $\pm$ 35.02	-0.18	-0.7 $\pm$ 12.7	-26-24
Mean power 300°/s (W)	306.94 $\pm$ 110.05	307.93 $\pm$ 91.57	-0.02	-0.1 $\pm$ 15.0	-29-29
Combined					
Peak torque 90°/s (N x m)	280.70 $\pm$ 85.52	280.75 $\pm$ 83.84	-0.02	0.9 $\pm$ 11.3	-21-23
Peak torque 300°/s (N x m)	225.28 $\pm$ 61.35	232.56 $\pm$ 58.45	-0.30	-1.3 $\pm$ 13.7	-28-26
Mean peak torque 90°/s (N x m)	259.03 $\pm$ 79.99	265.91 $\pm$ 75.01	-0.03	-0.6 $\pm$ 14.7	-29-28
Mean peak torque 300°/s (N x m)	207.97 $\pm$ 57.93	212.12 $\pm$ 53.12	-0.16	1.3 $\pm$ 10.4	-19-22
Mean power 90°/s (W)	273.23 $\pm$ 87.72	275.88 $\pm$ 82.97	-0.10	0.2 $\pm$ 9.7	-19-19
Mean power 300°/s (W)	493.79 $\pm$ 197.05	500.62 $\pm$ 175.73	-0.05	-0.8 $\pm$ 13.0	-26-25
Tethered swimming					
10 upper limb actions (N)	183.20 $\pm$ 46.41	186.68 $\pm$ 56.17	-0.10	-	-
30 s (N)	177.71 $\pm$ 49.55	183.44 $\pm$ 56.31	-0.19	-	-

force variables were not associated with swimming performance (Miyashita & Kanehisa, 1983; Reily et al., 1990; Dalamitros et al., 2015). Regarding not only isokinetic variables, other studies showed strong relationships (e.g., $r = 0.78-0.94$) between force variables in dry-land exercises (bench press and squad jumps) and force produced during tethered swimming (Morouço, Neiva, et al., 2011; Loturco et al., 2016). Taken together, these data reinforce the notion that forces produced in dry-land testing can be transferred to water when patterns of movement angular velocities and amplitude are similar.

The biomechanical asymmetries are useful both for clinical and research purposes, permitting the characterization of the functional imbalances between contralateral limbs (Evershed et al., 2014). Theoretically, the front crawl and backstroke intracycle velocity variation can be enhanced by this functional imbalance, increasing the energy cost of swimming (Figueiredo et al., 2012; Gonjo et al., 2018) and deteriorating body postures with increasing hydrodynamic drag (Sanders et al., 2012) at a given swimming speed. The current results demonstrate that elite swimmers are more symmetrical than lower level swimmers (data from Morouço et al., 2015), since we did not observe considerable differences between the force production of contralateral body sides.

However, the mean values of the SI need to be considered with caution, as asymmetry measurements are direction-dependent and a tendency for both preferred and non-preferred predominance will make the mean values tend towards zero. Therefore, comparing absolute values between conditions (in-water and dry-land) is preferred. The similar SI in-water and in-dry-land conditions observed in this study likely reflects the technical training to build a balanced and efficient swimming technique. This process typically involves a combination of pool-based dry-land training enhance bilateral symmetry and muscular proficiency.

Despite similar tethered and isokinetic force production SI, the correlation analyses show the few substantial relationships between almost all tethered and isokinetic SI. The agreement analyses presented a bias of ~ 10 and 95% limits of agreement $\sim 20\%$ indicating why SI values were not underpinning the change of SI direction in almost all swimmers evaluated. These data indicate that during swimming, one upper limb is typically used for propulsion and the other for control and support. In addition, it appears that the preferred upper limb is the limb of control and support during swimming, while the non-preferred limb is used mainly for propulsion. This pattern of limb control and propulsion explains the higher correlation values on the non-preferred body side.

This outcome highlights that the explanations of asymmetry observed in-water are more related to swimming technique adaptations consequent of the aquatic environment and to a lesser extent to muscular imbalances (Seifert et al., 2005). We expected changes on SI across 30 s test in response to the change of energetic system and muscular recruitment (Gastin, 2001; Soares et al., 2014). However, when examined the force (a)symmetry development along the maximal test, very strong direct relationships ($r = 0.98$) and similar values between the SI from the first 10 upper limb cycles and 30 s were found. The behaviour of SI during the first 10 cycles showed high agreement with the 30 s data, enhancing the capability of 10 cycles to indicate likely patterns during the overall effort. These results can be justified by the adaptations of swimming technique during the test being more important than the capacity of force production for SI behaviour. However, this outcome is contrary to that shown in a previous study (Morouço et al., 2015) using only front crawl tethered swimming in low-level swimmers. These outcomes indicate that high-level swimmers can maintain symmetry during the effort even when the absolute force produced is diminishing.

Conclusions

There is a direct relationship between forces produced in isokinetic and tethered swimming conditions for both front crawl and backstroke. We also confirmed similar force production symmetry in these swimming techniques. Coaches and swimmers may use isokinetic and tethered swimming evaluations to determine muscular and swimming technical imbalances, and track training-induced changes in these measures within and between swimming seasons. The first 10 cycles in tethered swimming should be sufficient to define the behaviour/patterns of the symmetry index during an all-out testing.

Chapter 6

Explaining swimming performance through artificial intelligence modelling and interpretability

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Abstract

Artificial neural network models with Shapley additive explanations (SHAP) values allow representation of movement performance with high generalization interpreted similarly to human intuition. We evaluated swimming performance (FINA points) predictability of combination of demographic, training, anthropometric and biomechanical variables (inputs) using an artificial neural network model. Forty-seven swimmers (15 males and 27 females) after training background and anthropometric assessment performed, in a randomised order, 25 m front crawl and three countermovement jumps, at maximal intensity. The predicted 516 ± 159 FINA points were highly correlated ($r^2 = 0.93$) with the 529 ± 158 actual ones. The duration of swimming training was the most important variable (95SHAP), followed by the countermovement jump impulse (37SHAP), both with a positive effect on FINA points. In contrast, a higher percentage of fat mass (21SHAP) corresponded to lower FINA points. Impulse when interpreted together with dry-land training duration and stroke rate shows the positive effects of upper and lower limbs power on swimming performance. Swimmers with higher FINA points had the highest dry-land training duration (4h/week), and height and body mass should be interpreted together with arm span and hand length. The artificial intelligence model interpreted with SHAP highlights the importance of specific training, technical, physical testing, and anthropometric factors for swimmers.

Keywords: performance prediction, anthropometry, countermovement jump force

Introduction

Artificial neural networks can be employed to form a simplified model of the brain cells cooperation performing a desired function in human movement based on recognition and patterns classification. This type of network uses a series of non-linear interconnected mathematical equations to calculate an output variable (e.g., swimming performance) based on independent input variables (Linder et al., 2003; Chainok et al., 2021; Yang, 2022). These models can be used for different tasks (e.g., classification, data noise reduction and prediction; Petrakova et al., 2015) with interpretation and translation important for implementation in practical settings. Artificial neural network complexity and difficulty in understanding the interaction between input variables (the so-called “black box” effect; Zhang et al., 2018), for example the hidden layers where computations performed on the input data extract increasingly abstract features and patterns, has limited applications in sports performance prediction, particularly in swimming (Pearl, 2001; Edelmann-Nusser et al., 2002). Studies that used these models in swimming prediction typically combined them with correlation and/or regression analysis for data interpretation (Silva et al., 2007; Maszczyk et al., 2012), potentially limiting the power of artificial neural networks.

Nevertheless, swimming performance prediction using simpler models (e.g., linear and non-linear regression) remains commonplace given their easy to interpret results (Morais et al., 2016; Demarie et al. 2022). However, their lack of generalization power and the likelihood of substantial prediction errors should be considered. Artificial neural network interpretation can be as simple as the outputs obtained from correlations and regressions models in combination with the Shapley additive explanations values (SHAP; Lundberg et al., 2020). Shapley values are a useful visualization tool that make a machine learning model more explainable by visualizing its output as they present a similar interpretation to human intuition (Lundberg et al., 2020). The artificial neural network and Shapley additive explanations values permits more accurate and interpretable predictive models (presenting lower error than traditional statistical methods), with better

generalization and representation of the non-linear systems behavior like human athletic performance (Pearl, 2001; Lundberg et al., 2020). This approach has started to be applied in team sports related research (Garnica-Caparrós & Memmert, 2021) but to our knowledge only one technical study has applied the SHAP interpretation method to swimming performance prediction, particularly backstroke to breaststroke turns performance in age-group (Chainok et al., 2021).

Given the multifactorial nature of swimming performance, and that a predicting model should be as practical as possible (Silva et al., 2007), the input data selection should be derived from the literature (biomechanical, physiological, psychological, genetical and contextual; Barbosa et al, 2010), and integrate data easy to collect and apply in the training context (Post et al. 2022). Since the variables that influence swimming performance are not independent of the underlying subjects (Silva et al., 2007; West et al., 2011; Morais et al., 2016; Strzala et al., 2020), the predictive models should separate taxonomically homogenous groups, like swimmers of different performance levels.

Using a three hidden layers deep artificial neural network model with Shapley additive explanations values, the aim of the current study was to assess the prediction capability and relationships strength of age, training background and duration, anthropometric, countermovement jump, and general biomechanical related variables (stroke rate and length) on swimming performance (FINA points). We hypothesized that when artificial neural network models are employed (by not forcing linear or nonlinear relationships), simple and training specific evaluations should be capable of explaining variations in competitive swimming performance. We hypothesized that the model could differentiate elite and non-elite junior swimming groups.

Methods

Participants

Forty-seven swimmers (males, $n = 15$, age 16.6 ± 1.2 y; females, $n = 27$, 15.2 ± 1.8 y) voluntarily participated in the current study. The total sample was divided into 17 elite/subelite (five male) and 30 national/regional level (11 male) swimmers with 718 ± 41 and 423 ± 84 World Aquatics (FINA) points (respectively). All swimmers were healthy (without serious injuries or illnesses in the last six months) and familiar with the testing experiments and apparatus. Swimmers provided individual consent for participation after being told the purpose, procedures, benefits and risks of the study, in accordance with the local research ethics committee (CEFADE 28 2019) and the Declaration of Helsinki.

Testing protocol

Using an observational cross sectional study design, after a brief training background questionnaire and conducting an anthropometric characterisation, the experimental protocol was applied in a randomised order (with 2 h apart between evaluations; Figure 1). After a 1000 m low-to-moderate intensity warm-up in a 27°C water temperature and 1.90 m deep 25 m indoor swimming pool, swimmers performed a maximal 25 m front crawl. An acoustic signal was used for in-water starts and time measured using a manual stopwatch (S141, Seiko, Tokyo, Japan). The 25 m were performed with a controlled push-off, and without an underwater phase to reduce the effect of pushing on the free swim velocity. The swimmers also performed three countermovement jumps on a portable force platform (OR6-WP, AMTI, Watertown, USA) with 30 s rest in-between. Each jump was initiated while standing on the platform with the lower limbs extended and hands on hips for weight calibration. Then, the lower limbs were flexed to 90° and explosively extended in a coordinated manner aiming for maximum height (Linthorne, 2001), with the ground contact made with the toes first.

Data collection

Swimrankings.net data base was used to assess each swimmer's best competitive swimming performance (FINA points; output) and performance level (regional, national or elite), based on the events closest to the experimental protocol (Figure 2). Swimming and dry-land training duration (h spend in each

type of training) were assessed by a short questionnaire administered to both the swimmers and coaches. The anthropometric data were obtained in duplicate and recorded to the nearest 0.1 cm or kg. Body mass and fat mass were assessed using a bio-impedance scale (InBody 720; InBody, CA, USA), height measured using a stadiometer (Holtain Ltd., Crymych, UK), arm-spam with an anthropometer and hand length using a sliding caliper (Sibe-Hegner, GPM, Zurich, Switzerland).

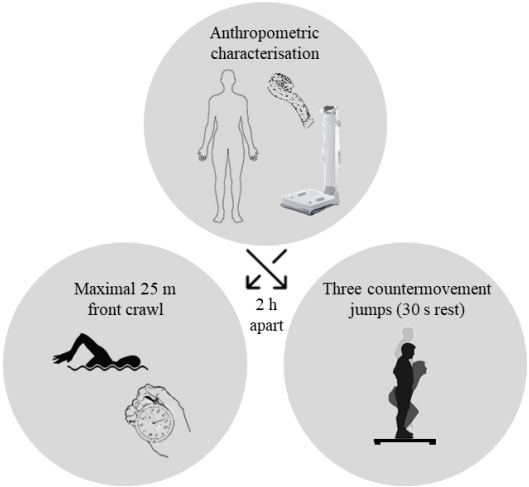


Figure 1. Representation of the swimmers experimental evaluations.

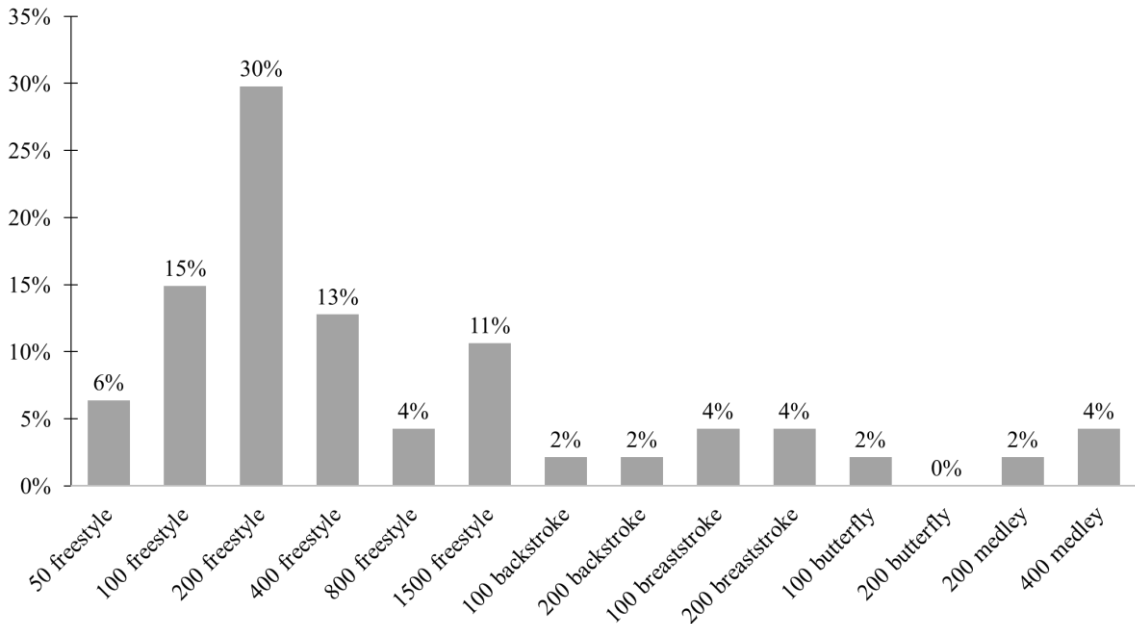


Figure 2. Distribution of swimming events used to assess competitive swimmers performance (model output) based on FINA points.

Stroke rate was determined during the 25 m front crawl manually as the number of upper limb cycles per min (using a Seiko stopwatch with a base 3 frequency meter function), and stroke length calculated by dividing the mean velocity by stroke rate (Carvalho et al., 2020). The countermovement jump related variables were computed from the force-velocity, -time and -acceleration traces using a custom-made MATLAB routine (MATLAB, MathWorks, Natick, MA, USA; Rago et al., 2018) to quantify flight time and total impulse.

Statistical analysis

A sample size of 47 participants was deemed adequate based on a 0.95 statistical power (β), a 0.50 large effect size and a 5% level of significance (G*Power 3.1.9.7, Heinrich-Heine-Universität Düsseldorf, Düsseldorf, Germany). The post-hoc (correlation: bivariate normal model) power analysis showed that correlations between the variables selected and FINA points presented a statistical power from 0.93 to 1.00. Normality distribution and variance homogeneity were confirmed using Shapiro-Wilk and Levene tests (respectively), and descriptive analysis (mean and standard deviation) were obtained for all variables. A student's T-test for independent samples with effect size estimation was used for comparing swimmers performance levels. Pearson correlation coefficients and 95% confidence intervals controlling for sex were calculated between age, training background and duration, anthropometric, countermovement jump and general biomechanical related variables and FINA Points.

After inferential procedures, we developed a predictive deep artificial neural network model to assess the relationship between the dependent variables and FINA points. The structure was developed in Python (version 3.9.2) using the TensorFlow© library (Google), had one input layer with 16 variables, three hidden layers (hyperbolic tangent, sigmoid and linear rectified activation functions, respectively) with 1000 neurons each and the output layer with one variable (FINA points; Figure 3).

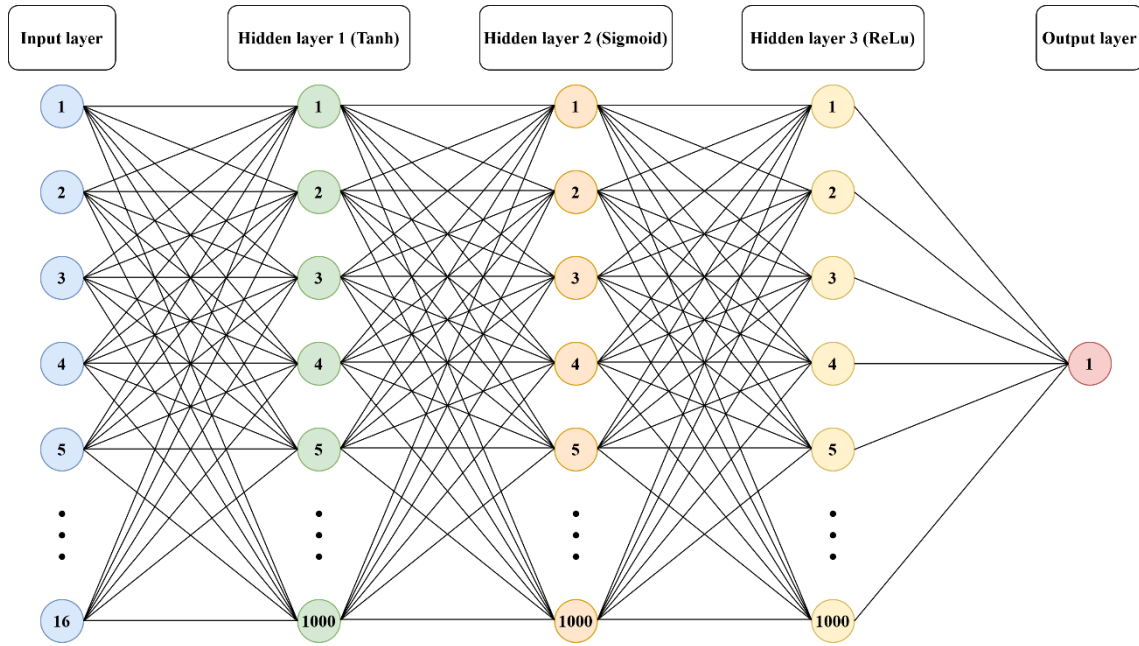


Figure 3. Artificial neural network model structure displayed as input layer with 16 variables, three hidden layers (hyperbolic tangent, sigmoid and linear rectified activation functions, respectively) with 1000 neurons each and the output layer with one variable (FINA points).

The sample was then divided randomly into data sets for the model training and testing (70 and 30% of the sample, respectively). In the model training, the root mean square propagation adaptive learning algorithm was used, with a loss function based on the mean square error and a learning rate of 0.001. A limit of 200000 epochs was established for training, and a checkpoint function used to store the information of the best weight configuration (by monitoring the root mean square error) avoiding overtraining. The final model reached a value of 0.0001 of the latter error after 25640 epochs. The model training, test and total sample sets were measured using the coefficient of determination of linear regressions between targets and output values (Figure 4), and interpretation of the model performed by computing Shapley additive explanations values (Lundberg et al., 2020).

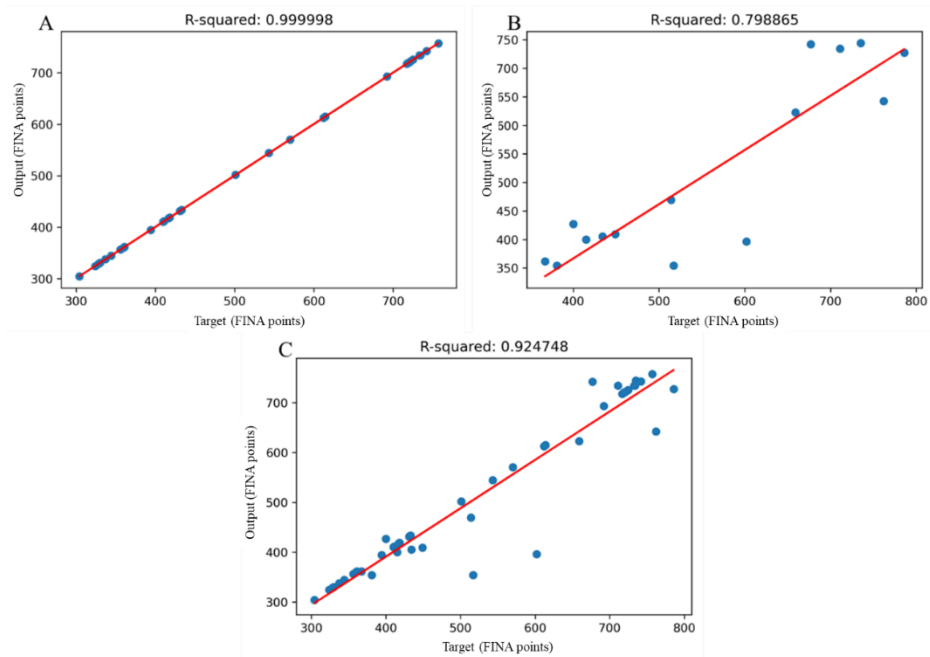


Figure 4. Coefficient of determination of the linear regressions between targets (real FINA points) and output (estimated FINA points) values in training, testing and total sample sets (panel A, B and C, respectively).

Results

The age, training background and duration, anthropometric, countermovement jump, general biomechanical variables and swimming performance for both performance groups are presented in Table 1. The elite swimmers were older than the non-elite, but only elite female swimmers had a greater training background. The elite swimmers also presented higher swimming and dry-land training durations, but the training ratio of 90-10% (for swimming and dry-land, respectively) was similar between the two groups. Correlational analysis showed that all the assessed variables had moderate to high direct relationships with swimming performance, except the inverse relationship for fat mass, and the trivial correlations for body mass and body mass index (Table 2). In addition, when the correlations were computed for the elite and non-elite level groups separately, none of the variables in the elite group correlated positively with swimming performance, and in the non-elite group only swimming training and arm spam showed direct relationships with performance ($r = 0.630$, $p < 0.001$ and $r = 0.453$, $p = 0.014$, respectively).

Table 1. Comparison of elite and non-elite swimmers age, training background and duration, anthropometry, swimming performance, countermovement jump and swimming biomechanics.

	Elite male (n=5)	Non-elite male (n=11)	p-value	Effect size (95% CI)	Elite female (n=12)	Non-elite female (n=19)	p- value	Effect size (95% CI)
Age (years)	17.6 ± 0.6	16.1 ± 1.1	0.015	1.5 (0.3 - 2.7)	16.2 ± 0.7	14.5 ± 1.9	0.003	1.0 (0.3 - 1.8)
Training background (years)	8 ± 0.7	6.2 ± 2.4	0.119	1.4 (0.3 - 2.5)	7.5 ± 1.0	5.5 ± 2.3	0.002	1.1 (0.3 - 1.8)
Swimming training (h·week ⁻¹)	19.2 ± 1.1	10.9 ± 1.1	< 0.001	7.4 (4.5 - 10.3)	18.5 ± 1.2	10.5 ± 1.0	< 0.001	7.4 (5.4 - 9.4)
Dry-land training (h·week ⁻¹)	1.8 ± 0.4	0.9 ± 0.2	< 0.001	3.0 (1.5 - 4.5)	1.8 ± 0.9	0.7 ± 0.2	< 0.001	1.9 (1.0 - 2.7)
Swimming performance (FINA points)	706 ± 31	445 ± 108	< 0.001	2.8 (1.3 - 4.3)	723 ± 44	409 ± 66	< 0.001	5.3 (3.8 - 6.9)
Height (cm)	176.9 ± 3.5	177.8 ± 4.5	0.717	-0.2 (-1.3 - 0.9)	167.5 ± 4.0	162.0 ± 5.6	0.006	1.1 (0.3 - 1.2)
Body mass (kg)	66.6 ± 5.2	66.2 ± 8.9	0.924	0.1 (-1.0 - 1.1)	57.9 ± 4.0	55.4 ± 6.3	0.216	0.5 (-0.3 - 1.2)
Body mass index (kg·m ²⁻¹)	21.3 ± 1.1	20.9 ± 3	0.743	0.2 (-0.9 - 1.2)	20.7 ± 1.2	21.1 ± 2.1	0.528	-0.2 (-1.0 - 0.5)
Hand length (cm)	18.7 ± 0.5	18.7 ± 0.8	0.789	0.1 (-1.0 - 1.1)	18.2 ± 0.5	17.2 ± 1.3	0.012	1.0 (0.2 - 1.8)
Arm span (cm)	179.5 ± 3.0	178.1 ± 4.5	0.686	0.2 (-0.8 - 1.3)	172.1 ± 5.2	161.7 ± 6.9	< 0.001	1.7 (0.8 - 2.5)
Waist-hip ratio	0.85 ± 0.01	0.80 ± 0.03	0.001	1.6 (0.4 - 2.8)	0.78 ± 0.03	0.75 ± 0.03	0.026	0.9 (0.1 - 1.6)
Fat mass (%)	7.1 ± 1.6	12.9 ± 2.8	< 0.001	-2.3 (-3.6 - -0.9)	15.6 ± 3.2	22.8 ± 5.3	< 0.001	-1.6 (-2.4 - -0.7)
Flight time (s)	0.55 ± 0.04	0.48 ± 0.04	0.005	1.8 (0.5 - 3.0)	0.48 ± 0.03	0.40 ± 0.04	< 0.001	2.2 (1.3 - 3.1)
Impulse (N·s ⁻¹)	177.3 ± 20.6	148.6 ± 22.8	0.032	1.3 (-0.1 - 2.4)	133.0 ± 13.7	108.6 ± 16.7	< 0.001	1.6 (0.7 - 2.4)
Stroke rate (cycle·min ⁻¹)	54.4 ± 12.0	54.0 ± 5.6	0.875	0.1 (-1.0 - 1.1)	52.9 ± 4.6	47.5 ± 4.2	0.002	1.2 (0.4 - 2.0)
Stroke length (m·cycle ⁻¹)	2.20 ± 0.14	2.00 ± 0.19	0.055	1.1 (0.0 - 2.2)	2.04 ± 0.17	1.91 ± 0.15	0.026	0.9 (0.1 - 1.6)

Table 2. Relationships between swimming performance and age, training background, anthropometry, countermovement jump, stroke rate and length.

Variables	Pearson r (FINA points)	95% CI	p-value
Age (years)	0.512	(0.208 - 0.840)	< 0.001
Training background (years)	0.482	(0.237 - 0.690)	0.001
Swimming training (h·week ⁻¹)	0.920	(0.883 - 0.952)	< 0.001
Dry-land training (h·week ⁻¹)	0.695	(0.583 - 0.842)	< 0.001
Body mass (kg)	0.232	(-0.032 - 0.458)	0.122
Height (cm)	0.429	(0.169 - 0.643)	0.003
Body mass index (kg·m ² ⁻¹)	-0.025	(-0.302 - 0.262)	0.871
Hand length (cm)	0.435	(0.223 - 0.676)	0.003
Arm span (cm)	0.620	(0.459 - 0.749)	< 0.001
Waist-hip ratio	0.519	(0.294 - 0.740)	< 0.001
Fat mass (%)	-0.614	(-0.728 - -0.495)	< 0.001
Flight time (s)	0.714	(0.545 - 0.837)	< 0.001
Impulse (N·s ⁻¹)	0.625	(0.438 - 0.767)	< 0.001
Stroke rate (cycle·min ⁻¹)	0.695	(0.240 - 0.651)	0.001
Stroke length (m·cycle ⁻¹)	0.695	(0.174 - 0.595)	0.005

The artificial neural network model predicted average scores of 515 ± 161 , 519 ± 155 and 516 ± 159 FINA points (based on the coefficients of determination; see Figure 4), while the true average scores were 515 ± 161 , 560 ± 145 and 529 ± 158 FINA points for the training, test and all sets (respectively). In the Figure 5 the relative importance of each variable to swimming performance are presented, where the hours of swimming training appear as the most important variable followed by the countermovement jump impulse and fat mass percentage (95, 37 and 21 Shapley additive explanations values, respectively). In contrast, stroke length, flight time and waist-to-hip ratio only showed marginal effects in explaining the swimming performance, but were important for the model construction (0.24, 0.03 and 0.02 Shapley additive explanations values, respectively).

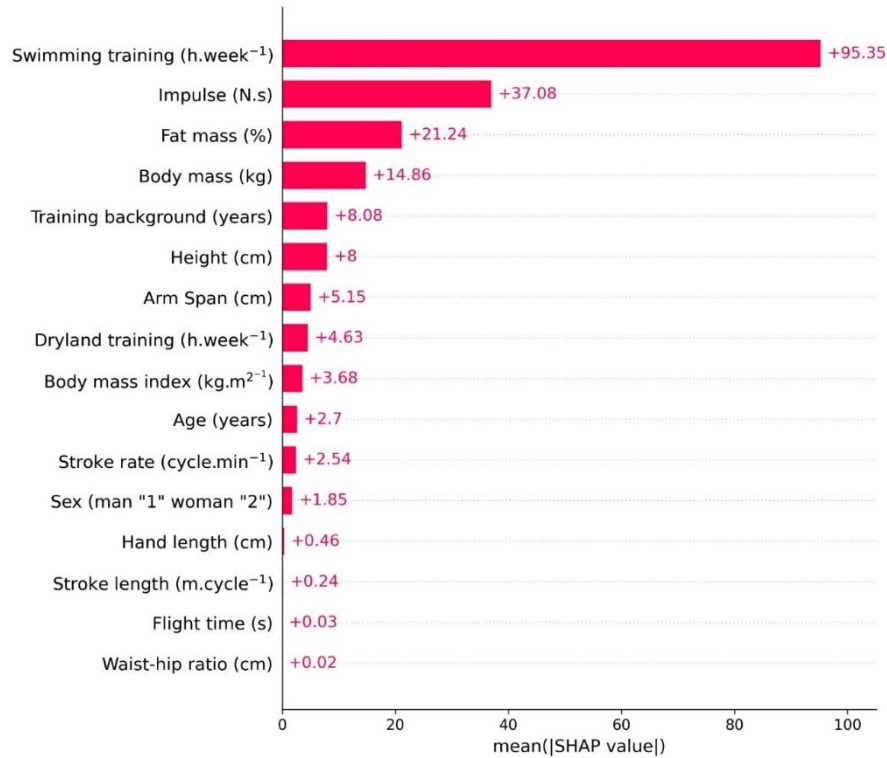


Figure 5: Hierarchical average impact magnitude on swimming performance for the 16 input variables used on the artificial model expressed by Shapley additive explanations (SHAP) values.

The direction (positive or negative) of the variables impact on swimming performance is presented in Figure 6. Swimming training and impulse contributed positively to swimming performance, where more hours of swimming training and impulse were associated with higher FINA points. In contrast, fat mass contributes negatively to swimming performance. In Figure 7, the importance of variables was altered when the model was exposed only to elite or non-elite swimmers separately. For example, the impulse went to the first place of importance in both groups, and swimming training duration went to the eighth and seventh place in elite and non-elite groups, respectively. In the elite group, the duration of dry-land training explains more of the changes in competitive swimming performance than the swimming training duration.

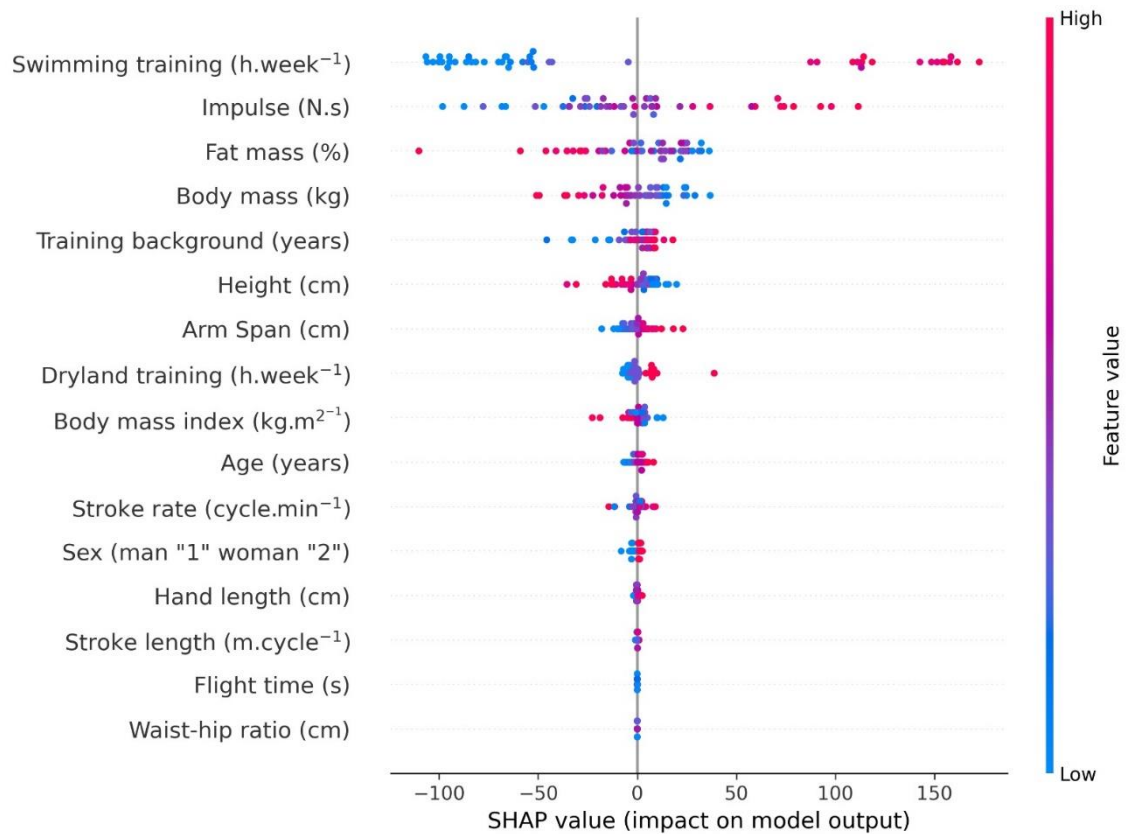


Figure 6. Shapley additive explanations (SHAP) values summary plot with the 16 input variables ordered by feature importance. Colour bar on right used to interpret the direction (red) of the relationship between one individual variable and the competitive swimming performance. The strength of the relationships is defined by the amplitude of the SHAP values. When red colour is presented in both positive and negative sides of the graphic (e.g., stroke rate) indicates that this variable is important for the model as a cooperative variable and need to be interpreted combined with other variables.

Discussion and implications

We investigated relationships between swimming performance and a suite of demographic measures, training background and duration, anthropometry and easily applicable training tests in junior swimmers. We employed artificial neural network model with Shapley additive explanations values to interpret the importance of these relationships. The model interpretation showed that the swimming training duration, lower-body impulse from the countermovement jump, and fat mass were the principal variables that explain differences in swimming performance. However, when exploring separately the cohorts of elite or non-elite swimmers, the differences in swimming performance were principally related to impulse generated during the countermovement jump.

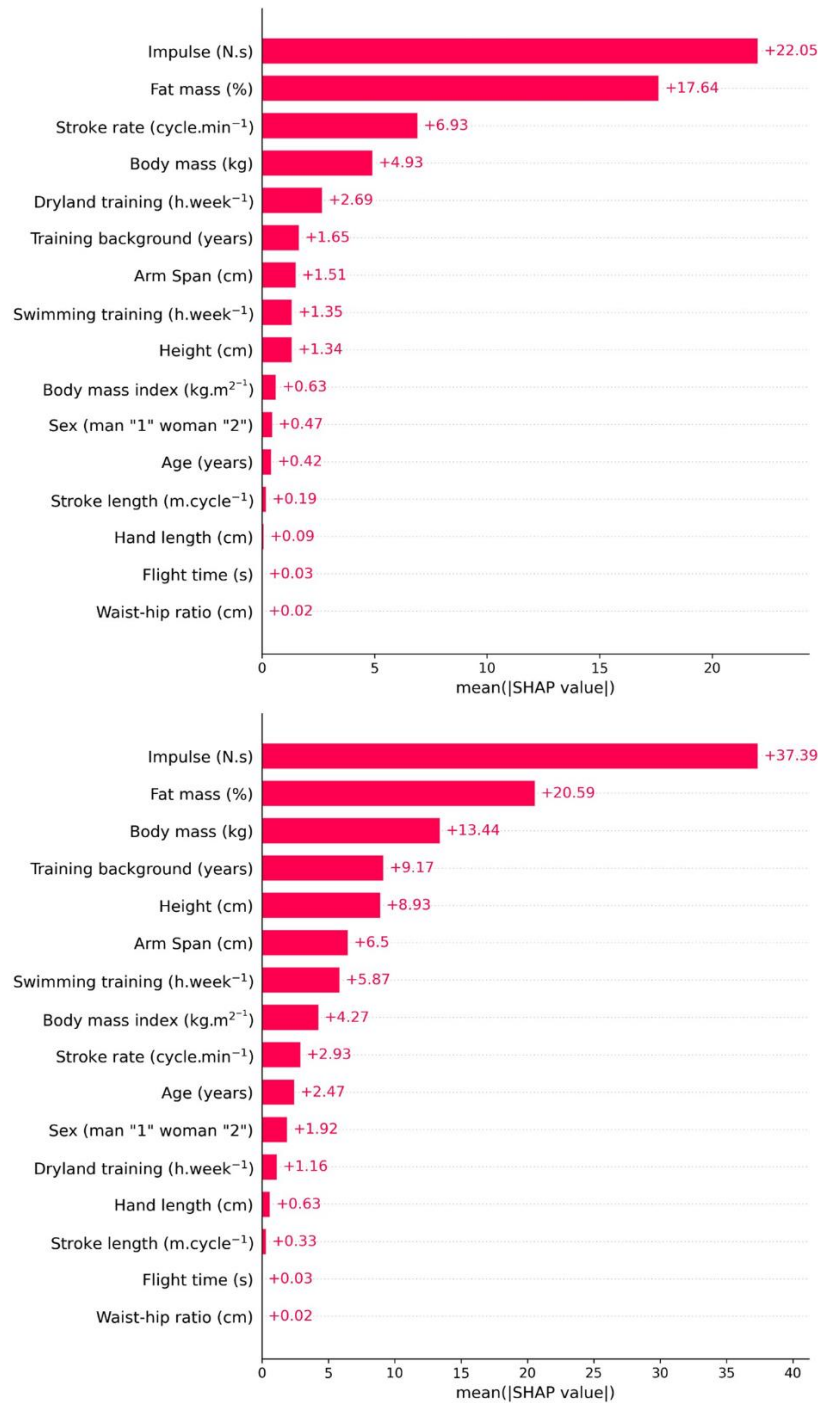


Figure 7. Hierarchical average impact magnitude on swimming performance for the 16 input variables used on the artificial model for elite and non-elite (top and bottom panels, respectively) expressed by Shapley additive explanations (SHAP) values.

The utility of the model permits simple physical fitness tests and swimming training background to predict swimming performance. Artificial neural networks do not force the variables into a linear or nonlinear relationship, with the benefit

of reducing the possibility misinterpreting how that variable interacts with the outcome. On this basis, neural networks are an attractive alternative to statistical methods computing quantitative measurements of confidence and correlation (Pearl, 2001; Lundberg et al., 2020). Moreover, when regressions are used, the input variables are deemed independent from each other which may not always be the case in real life settings. This shortcoming of regression analysis can increase the error of estimation and diminish the strength of the relationships and interpretations. In contrast, an artificial neural network works in an unsupervised and unbiased way (Pearl, 2001), getting closer to the real-world context.

The selection of the variables included in predictive models normally depends on the determinant factors of the underlying event. In swimming, the selection should follow the concepts of energetic performance determinants (e.g., Di Prampero et al., 1974; Figueiredo et al., 2013) and studies detailing predictive models (e.g., Silva et al., 2007; Carvalho et al., 2019). However, even variables that present contradictory results in literature, given the inevitable heterogeneity in methodologies and subjects, should also be explored using artificial models. If a variable needs to be removed from a model it will be identified by the high predictive error during the model training. The redundant information problem is easily solved by the model that uses that information to control the model, instead of diminishing its predictive capability.

Machine learning approaches have been proposed as a beneficial approach to modelling and interpreting human (athletic) performances (Maszczyk et al., 2014). In our results the duration of swimming training, a simple characteristic easily measured and understood by coaches and swimmers, was the highest contributor to swimming performance when both competitive levels were analyzed together. The model showed that the second most important variable was lower-body countermovement jump impulse, that only presented the fifth higher correlation value. Height of the swimmer presents a positive correlation but, in the model, had a negative effect on swimming performance, showing this measure should be combined with other anthropometric variables. Linear

correlation analysis must be used with caution to interpret the relations of the variables included in the neural network to avoid contentious interpretations (Silva et al., 2007), eliminating the main quality of the artificial intelligence of not forcing one type of relationships between the input and output.

Our results support the widely held but untested assertion that the time swimmers have in contact with the water environment is fundamental to achieving better performances (Post et al., 2022). The importance of an extensive period of training is widely acknowledged (Post et al., 2022), improving the responses to underlying swimming constraints (Seifert et al., 2007). Our elite and non-elite swimmers completed more (Nugent et al., 2017) and similar (Post et al., 2022) swimming training than previous studies. Importantly, training duration is different than volume, where the numerous hours of swimming training can be associated with high volumes (Nugent et al., 2017) or with high intensities with increased resting periods (Toubekis et al., 2005).

The impulse (power test) appearance as the second most important variable, while stroke rate is a useful explanatory variable (with mainly positive effect) to interpret the higher the swimmer's training and higher intensity quality work. The two tests where the impulse and stroke rate were computed are related with explosive and high intensity training, while low intensity training can also elicit reductions in stroke rate (Costill et al., 1991; Termin & Pendergast, 2000) and a negative effect on performance. Even with similar distribution of the swimming and dry-land training durations, the elite group completed almost twice the number of total hours of training, exemplified by the dedication of the elite group to swimming practice. The ratio of dry-land/swimming training (10%) was substantially higher than a previous study (0.2%; Hellard et al., 2005), mainly explained by the different methodologies used.

The impulse positive effect on swimming performance with a dispersion parallel to the range of FINA points (see Figure 6) showed that the lower limb power capability is important. This result can open an old discussion of the role (balance

of swimming technique) and importance of lower limbs to the overall swimming velocity (possibly more than the 10% previously identified; Deschodt et al., 1999). Our results are in line with other data indicating the importance of lower limb strength and power in dry-land capability to apply force in-water (Morouço et al., 2015; Carvalho et al., 2019). Moreover, the lower limb actions contribution to the force production in front crawl (~31%; Morouço et al., 2015) and velocities performed only using the lower limbs actions (from 57-86% of full technique; Bartolomeu et al., 2018), justifies further explorations using new mathematical approaches.

The countermovement jump is used frequently to train and evaluate lower limb explosive power in swimming (West et al., 2011; Strzała et al., 2020). The results of jump testing help to explain why the dry-land training duration elicited a positive effect on swimming performance in our model (Dopsai et al., 2020). Notably, the swimmer with higher FINA points was the individual with the most dry-land training duration (4 h/week). Collectively the results confirm the utility of dry-land training in promoting the generation of force in water (Morouço et al., 2011) and why dry-land training should be part of the daily practice of the swimmers (Wirth et al., 2022).

Our swimmers present similar anthropometric profiles to previous studies of swimmers of different performance levels (Pyne et al., 2006; Lätt et al., 2010; Dopsai et al., 2020). In swimming, the taller and longer arm span swimmers typically have biomechanical advantages (Lätt et al., 2010; Strzała et al., 2020). On this basis our results showing that height presented negative effects on swimming performance was unexpected. In early ages an anthropometric advantage is related with early maturational development (Lätt et al., 2009), however in adult swimmers the main anthropometric variables (such as height, weight and body mass index) are less likely to distinguish the higher performance level swimmers (Lätt et al., 2010; Dopsai et al., 2020). Nevertheless, the outcome that arm span presented positive effects on swimming performance conforms with existing data (Strzała et al., 2020), and is more important in terms of

biomechanical advantage than height. It is important to understand that anthropometry is only one of the determinants that influence swimming performance (Barbosa et al., 2010), and being tall alone is not sufficient to swim at a high standard.

The negative effects of body fat and weight on swimming performance need to be interpreted together, since heavier swimmers normally present higher muscle mass but also body fat (Pyne et al., 2006; Lätt et al., 2010). In competitive swimming, elite swimmers typically present lower body fat values than non-elite counterparts (Lätt et al., 2010; Dopsai et al., 2020; Strzała et al., 2020) likely a consequence of a higher level of training and lean mass values. The small but positive effect of the hand length is justified by increased propelling surface (Toussaint & Beek, 1992). Given that height, arm span or hand length are largely inherited, and interrelated due to scaling effects (Lätt et al., 2010), talent identification processes should be implemented until the swimmers are fully developed. After maturation is completed, changes in these variables are no longer expected, and may not be influenced by the training process. The exception here might body weight that is sensitive to strength training and dietary practices.

Power capability in the water is associated with sprint swimming and high stroke rates (Ribeiro et al., 2017), and the 25 m test allows us to determine the highest stroke rates that swimmers are able to perform (Craig & Pendergast et al., 1979). Moreover, swimming velocity can be manipulated by changing stroke rate or length, and these factors represent a swimmer's technical ability in water (Figueiredo et al., 2013). Elite swimmers exhibit higher stroke lengths than non-elite for the same stroke rates, and higher stroke rates for the same stroke length (Craig et al., 1985; Hellard et al., 2008). The front crawl test was chosen as > 50% of the swimmers training is performed with this technique (Stewart & Hopkins, 2000), and 80% of this cohort presented their best performance in freestyle events (see Figure 2). However, the unexpected lack of stroke length having a substantial effect on the FINA points can be justified by stroke

parameters being assessed from a maximal 25 m front crawl test (Craig & Pendergast et al., 1979). The swimmers in this cohort typically specialized in longer distances.

The positive effects of training background together with age on swimming performance were expected, since a constant progression in swimmers performance, is evident between subsequent Olympic Games and within the pre-Olympic year (Pyne et al., 2004). The elite swimmers were older than their non-elite counterparts, and consequently presenting a larger training background. When the swimmers reach the junior and senior ages group but not an elite level, they normally have more tendency to drop out from competitive swimming, instead of progressing further in competitiveness (Monteiro et al., 2018).

The duration of swimming training loses most of its performance explanation capability when the model is interpreted on elite and non-elite groups separately. This effect mainly relates to the homogeneous training durations within each performance group. Interestingly, lower-body jump impulse appears as the most important explanatory variable in both groups, highlighting the importance of lower limbs power on competitive swimming performance. In elite group even the dry-land training duration climbed to fifth place showing that strength training is an important part of competition preparation. One limitation of the study was that our sample was composed of approximately 35 and 65% of elite and non-elite swimmers (respectively), and training duration were based only on estimated time spent in each activity/training sets. Future research should include in the model both training intensity and internal and external load metrics. When analyzed in separate performance level groups, our model can be used to generalize the interpretation of non-elite swimmers given a relatively heterogeneous distribution of performances within this group.

Conclusion

The artificial neural network model combined with Shapley additive explanations values showed that training background and duration, anthropometry, impulse and stroke rate are fundamental variables that explain competitive performance in junior swimmers. Dry-land training was more beneficial for achieving higher FINA points in the elite group. The lower limb power (expressed by lower-body countermovement jump impulse) is highly important irrespective of the level of the swimmer. A test battery of countermovement jumping and anthropometric measures is simple to use in the field which increases the practical relevance of our study protocol. The application of this approach can assist swimming coaches, scientists and researchers interested in identifying, developing and applying new strategies to improve junior swimmer performance.

Pre-competition overload period in elite swimming: impact of daily training loads on heart rate variability, sleep quality, motivation, and performance

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Abstract

Understanding the impact of training sessions on physiological, psychological and immunological responses is crucial for adequate training periodization and preventing negative influences on health, training and performance. We characterized the responses of heart rate variability (HRV), sleep time and quality, motivation, dry-land strength and swimming performance to an overload period of three consecutive seven-day cycles with different training intensity and volume dynamics (cycles 1, 2 and 3). We also tested the capability of HRV to interpret daily variation in training loads. Fourteen elite swimmers (4 males and 10 females, age 17.5 ± 1.5 years) were monitored via an orthostatic test, Hooper index and sleep questionnaires and rating of perceived exertion (RPE) of each training session. The self-reported and prescribed training loads were compared. At the beginning of each cycle and at the end of cycle 3, swimmers completed anthropometric testing, countermovement jumps, hand-grip strength tests and a 5 x 200 m incremental protocol. Elite swimmers accurately perceived their daily training loads. However, differences between the training and RPE loads emerged on weekends, indicating that physiological and psychological loads have different influences and should be considered simultaneously when characterizing training loads. The overload period was characterized by an increase in both training (27 %) and RPE (20 %) loads without eliciting a negative effect on sleep quantity and quality, fundamental to interpret effects on HRV. During the overload period, supine ($F_{2,18} = 3.448$, $\eta^2 = 0.28$; $p = 0.05$) and standing ($F_{2,18} = 3.809$, $\eta^2 = 0.30$; $p = 0.04$) mean heart rate (HR) increased and supine log root mean square of the successive differences (LnRMSSD; $F_{2,18} = 4.379$, $\eta^2 = 0.33$; $p = 0.028$) and maximal blood lactate ($F_{3,27} = 3.441$, $\eta^2 = 0.28$; $p = 0.03$) decreased during and after cycle 3 (respectively). Dry-land and swimming performances were maintained, indicating that the autonomic nervous system appears to be more sensitive to changes in acute/short-term training load. In addition, HRV indices reflected changes in training loads, with a decrease in supine RMSSD and increases in mean HR and time to achieve peak HR corresponding to higher loads imposed on swimmers. A combination of vagally-

mediated biomarkers, psychological and performance monitoring tools should be used to define and evaluate training loads in competitive swimmers.

Keywords: Orthostatic test, HRV, Swimming, Training, Physiology, Performance

Introduction

In competitive sports such as swimming, training stimuli are commonly quantified through the measurement of intensity, volume and frequency (Mujika et al., 2018). The aim is to boost swimming performance through short-term and cumulative adaptive responses across a range of physiological systems. However, incorrect prescription of training loads, poor tolerance, or insufficient recovery can heighten the risk of overreaching and overtraining (Halsen & Jeukendrup, 2004). Regardless of the training periodization approach (traditional or alternative), dividing the season plan into smaller phases is beneficial, enabling better management of the training program and achieving optimal peaking for major competitions (Clemente-Suárez et al., 2017; Zacca et al., 2020). A microcycle is the shortest prescribed period of training, usually one week in duration, and its arrangement directly influences load, recovery management and performance enhancement (Mujika et al., 2018; Zacca et al., 2020). However, the swimming training community has been engaged in an ongoing debate regarding the relative merits of two training types, namely high volume-low intensity and low volume-high intensity (Clemente-Suárez et al., 2017).

Understanding the impact of training sessions on physiological, psychological and immunological responses is critical for adequate training periodization, with the goal of avoiding negative impacts on performance and health (Clemente-Suárez et al., 2021; Mujika et al., 2018). Consequently, regular monitoring of biomarkers, including diverse and validated indicators of stress/fatigue (e.g. heart rate [HR] patterns and heart rate variability [HRV]), recovery (e.g. sleep quality and duration) and performance (e.g. anaerobic threshold and maximal oxygen uptake) can be employed. Despite the challenge of observing overall performance shifts in daily swimming practice, stress/fatigue and recovery indicators should be tracked daily to mitigate chronic stress (Clemente-Suárez et al., 2021; Lee et al., 2017). Intentional periods of intensive overload training are incorporated into elite swimmers training regimens to induce a state of functional overreaching (Halsen & Jeukendrup, 2004; Zacca et al., 2020), which is marked

by a transient performance declines and acute fatigue sensations. When followed by a proper period of reduced training, these can elicit performance enhancement(s) beyond prior levels (Fry et al., 1991; Mujika et al., 2004). Precise and consistent exercise prescription is key, emphasizing the importance of regular training control and in-pool testing of biophysical measures (Carvalho et al., 2020). Among the multifaceted determinants of swimming performance, physiological variables have received significant attention through established testing procedures (Carvalho et al., 2020).

Blood samples, although informative and often considered the gold standard biomarkers, are costly and can be inconvenient for frequent monitoring (Oppliger & Bartok, 2002). Saliva sampling (still expensive) is a friendly and non-invasive method to monitoring physiological responses like cortisol or immunoglobulin A levels and immune biomarkers, as well as for monitoring stress and recovery (Mujika et al., 2004; O'Connor et al., 1989). However, inconsistencies in saliva collection methods, diurnal variations in hormonal concentrations and the potential influence of dehydration and oral health conditions on salivary parameters can introduce variability, potentially affecting the reliability and usefulness of the results (Justino et al., 2017). Measurement of HRV has been proposed as a practical non-invasive and inexpensive means of monitoring individual adaptations to training (Plews et al., 2013) and to help predict changes in immune function (Luo et al., 2019). When monitoring physical load in practical and research settings HR and HRV measurements are employed to calibrate their training load and detect early signs of overtraining (Buchheit, 2014; Uusitalo et al., 2000). HRV changes have been suggested to indicate adaptations to endurance training regimens but, probably due to the lack of consensus, HR monitoring is still not accepted as a gold standard, despite its common use (Buchheit, 2014; Sixsmith et al., 2023; Wallace et al., 2009).

The autonomic nervous system has attracted extensive interest given its vital role in homeostatic regulation, enabling functional adaptation to environmental demands, like sports (Bourdillon et al., 2017; Fu & Levine, 2013). An orthostatic

test offers a practical method to study overload and overtraining, assessing this system's responses to training (Atlaoui et al., 2007; Buchheit, 2014; Schneider et al., 2019). Changes in body position can elicit specific HR responses, offering more detailed insights into autonomic regulation patterns (Clemente-Suárez et al., 2021; Hottenrott et al., 2021). During an orthostatic tolerance test, HRV patterns in both supine and standing positions are influenced by varying involvement of cardiopulmonary receptors, cardiac preload, and consequently, shifts in plasma volume and/or peripheral vasomotor tone. These factors may underpin alterations in autonomic patterns and HRV during different training loads and phases (Schmitt et al., 2015).

Sleep quantity and quality must be addressed when interpreting HRV data given the likelihood that they might elicit short-term fluctuations (Oliver et al., 2020; Stein & Pu, 2012). Moreover, the daily effects of training on swimmers physiological and psychological traits remain underexplored, as do reference values for biomarkers and their responses to various training combinations. Although each biomarker provides information about one or more physiological systems, insights are limited if only a single data point is available (Lee et al., 2017). Since the effects of training loads require close scrutiny (Buchheit, 2014; Clemente-Suárez et al., 2021; Hellard et al., 2013) we aimed to characterize HRV, sleep quality, motivation, dry-land strength and performance responses and patterns/behaviours during an overload period of three consecutive seven-day cycles of swimming training. Secondly, we aimed to evaluate the capability of HRV, as an internal biomarker, to evaluate the effects of variations in daily training load (based on the two most common training load assessment methods applied in swimming) variations in elite swimmers. We hypothesize that the autonomic nervous system response to daily training loads reflects the underlying training load and changes may explain in part modifications in swimming and strength performances during an overload period.

Methods

Participants

Fourteen elite swimmers (four male and ten female) with 17.5 ± 1.5 years of age and 703 ± 47 FINA/World Aquatics points of best competitive performance, voluntarily participated for the study. Swimmers were classified as level 3 (Ruiz-Navarro et al., 2023) and their physical characteristics are presented in Table 1. The swimrankings.net data base was used to assess each swimmer's best competitive swimming performance (FINA/World Aquatics points) and performance level (regional, national or elite), based on the events closest to the monitoring period. All the participants were from the same swimming team to ensure similar training conditions and feeding and rest exposures. The female participants reported regular menstrual cycles for at least the four months prior to the participation in this study.

Table 1. Swimmers physical characteristics at the first performance assessment day.

Variables (mean $\pm$ SD)	First assessment		
	Male (n = 4)	Female (n = 10)	Effect size (95% CI)
Body mass (kg)	74.1 $\pm$ 9.4*	60.6 $\pm$ 2.1	3.0 (1.1 to 4.7)
Height (cm)	183 $\pm$ 11*	169 $\pm$ 3	2.7 (0.9 to 4.3)
Arm span (cm)	194 $\pm$ 7*	174 $\pm$ 5	1.7 (0.3 to 3.0)
Body fat (%)	12.2 $\pm$ 2.0	17.3 $\pm$ 4.0	-1.4 (-2.8 to 0.1)
Free fat mass (kg)	65.2 $\pm$ 7.9*	50.1 $\pm$ 2.2	3.2 (1.3 to 5.0)
Body mass index (kg.m ²)	22.0 $\pm$ 0.6	21.3 $\pm$ 1.4	0.5 (-0.8 to 1.8)

*Differences compared to female ($p < 0.05$).

Before the study took place, all swimmers underwent a physical examination by a physician, and each swimmer was cleared of any underlying medical disorder(s) that might limit their participation (e.g., muscle or joint injuries or cardiovascular/respiratory conditions that could impede high intensity training). The clinical consultation also ensured that exogenous anabolic-androgenic steroids, drugs, or other supplements that could affect physical performance or hormonal balance were not taken during the study period (swimmers were affiliated with a performance centre that operates under the federation's control).

Swimmers, coaches and parents were informed about the purpose and potential risks of the evaluations and provided individual consent for participation in accordance with the local research ethics committee (code nº CEFADE 28 2019) and the Declaration of Helsinki. Parental/guardian consent was obtained from all participants under 18 years old involved in this investigation.

Study design

The single group longitudinal study design in the first macrocycle of the 2022/2023 season (from November 7th until December 4th) encompassed three seven-day cycles in a four-week training period involving different training dynamics (see Figure 1), with one or two daily swimming training sessions (from 8-10 sessions per week), consisting in a period of overload. The training sessions were individualized according to each swimmer preferential technique and distance, with the participants being nutritionally controlled and supported to avoid energy deficits during this overload period. Cycles 1, 2 and 3 featured a controlled training load, an increased in both intensity and volume, and an increase in intensity while maintaining the volume of previous cycle (respectively). Swimmers monitoring started immediately after a competition weekend and was maintained for 28 days, with a set of daily tests and four dry-land and swimming performance assessments performed in the beginning and at the end of each cycle (Figure 1). The training sessions before the performance assessment days (24 h) were similar in volume and intensity to avoid acute fatigue effects on the evaluations.

Training program

The swimmers followed the training program prescribed by their head coach, and training volume, intensity and dry-land work times were recorded daily by the head coach and assistant for each swimmer and averaged per cycle. The different swimming intensities ranged from 1-5 and were defined after the first performance assessment, using the 5 x 200 m incremental protocol to determine the velocities corresponding to the anaerobic threshold and the maximal oxygen uptake (Carvalho et al., 2020; Monteiro et al., 2020; Mujika et al., 1996). Dry-land

training equivalents were calculated (each hour corresponding to 1, 0.5 and 0.5 km of intensities 1, 4 and 5, respectively) and expressed in km according to the recommendations (Mujika et al., 1996). The total training load in arbitrary units (A.U.) was then assessed by the sum of the volumes multiplied by each intensity (equation 1) and training intensity was assessed by dividing the total training load by the total volume (equation 2).

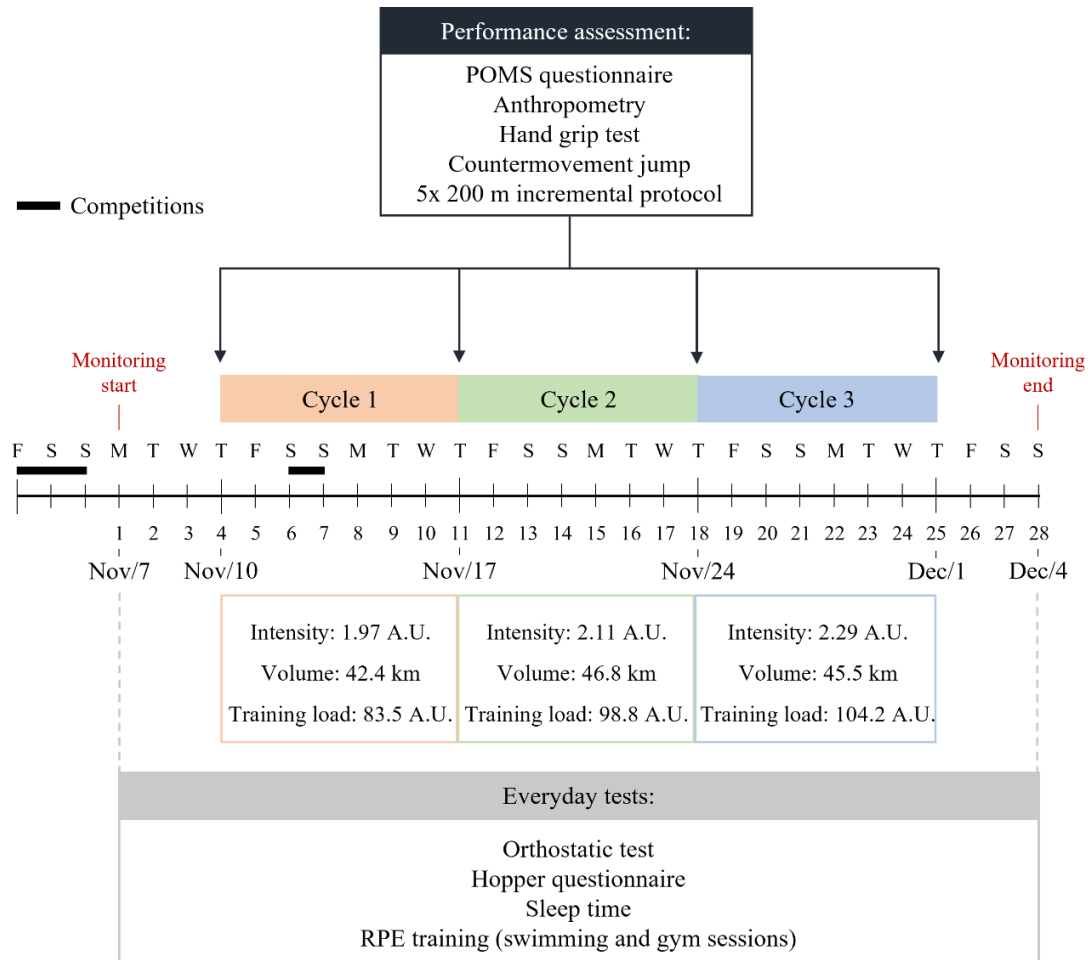


Figure 1. Representation of the swimmers experimental evaluations and planned intensity, volume and training load. Profile of mood state (POMS), rate of perceived exertion (RPE).

$$\text{Training load (A.U.)} = 1 \times \text{km}_1 + 2 \times \text{km}_2 + 3 \times \text{km}_3 + 4 \times \text{km}_4 + 5 \times \text{km}_5 + \text{dry-land equivalent} \quad (1)$$

$$\text{Training intensity (A.U.)} = \frac{1 \times \text{km}_1 + 2 \times \text{km}_2 + 3 \times \text{km}_3 + 4 \times \text{km}_4 + 5 \times \text{km}_5 + \text{dry-land equivalent}}{\text{training volume (km)}} \quad (2)$$

After each training session, swimmers were asked to report their rate of perceived exertion (RPE: 0-10). The magnitude of the global training load (RPE load) was then calculated by multiplying training RPE and the training session duration (RPE load [A.U.] = RPE x session duration [min]). When swimmers performed more than one training session per day, the RPE load was calculated as the sum of each training sessions RPE loads (Foster et al., 2001).

Heart rate variability and sleep time and quality assessment

During the 28-day monitoring period, a daily (after a night's sleep) orthostatic test was performed with 5min in the supine and 5min in the standing position (Bourdillon et al., 2017; Hottenrott et al., 2021). All swimmers were familiarized with the test, which was performed several times during the previous year. The HR continuous beat-to-beat recordings were taken in the supine and standing positions without a given breathing rhythm after the morning visit to the restroom (two consecutive R-waves intervals [RR intervals] with a H10 sensor, Polar Electro GmbH, Finland, (Gilgen-Ammann et al., 2019)). The calculated orthostatic test parameters included the mean HR in the supine and standing positions and the vagal time-domain HRV parameters: the root mean-square difference of successive normal RR intervals (RMSSD) in the supine and standing positions, the differences between supine and standing mean HR and RMSSD, peak HR and time to peak HR in the standing position. In addition, the natural logarithm of the RMSSD (Ln RMSSD) was computed (Schneider et al., 2019).

Calculations of the RR data from the orthostatic test were performed using the Kubios HRV Premium Software (Version 3.4.1) (Tarvainen et al., 2014). The RMSSD was calculated for 3 min in the supine and 3 min in standing position. The first 2 min in the supine position was not used for data analysis but served for physiological stabilization (Bourdillon et al., 2017; Hottenrott et al., 2021). The HRV data was analysed each day individually, computed to a mean of each temporal cycle (pre cycles, cycle 1, 2 and 3 and post cycles) and on the specific performance assessment days. During the four-week monitoring period the swimmers completed a questionnaire regarding their sleep duration and the

Hooper questionnaire (Hooper et al., 1995) with a 0-7 scale in four categories (quality of sleep, fatigue, muscle and stress level), where higher values corresponded to the worst sensations.

Performance testing days

At the beginning and at the end of each cycle the swimmers performed anthropometric characterization, countermovement jump (CMJ) and hand grip tests (in a randomized order), and after a 30 min rest the 5 x 200 m incremental protocol in their best swimming technique.

Incremental protocol

In a 50 m indoor pool with water temperature of 27° C and, after a 1200 m standardized low to moderate intensity warm-up (Neiva et al., 2014), swimmers performed a 5 × 200 m intermittent incremental protocol in their best swimming technique (two backstroke, two butterfly, two breaststrokes, two medley and six front crawl swimmers), with 0.05 m·s⁻¹ increase per step and a 30 s rest interval (Carvalho et al., 2020). In-water starts were used and initial velocities established by the swimmer's current individual 400 m performance less (5-1) velocity increments (e.g. first step: velocity at 400 m - 0.20 m·s⁻¹) for front crawl and medley. For the other swimming techniques, the final velocity was defined by the swimming coach based on their 200 m competitive performance, and initial velocities corresponding to all swimmers to 200 m performance less (5+1) velocity increments (e.g., first step: velocity at 200 m - 0.30 m·s⁻¹). Performance was measured using a Seiko stopwatch and pace controlled through auditory signals at each 25 m. Each step represented the same relative intensity for all swimmers, independent of the swimming technique, who were verbally encouraged to reach their maximal exertion during the last 200 m step (Carvalho et al., 2020). Capillary blood samples for blood lactate ([La⁻]) and glucose concentrations ([Glu⁻]) analysis were collected from the fingertip at rest, in the intervals between steps and 1, 3, 5, 7 and 9 min after the protocol using a Lactate Pro 2 analyser (Arkay, Inc, Kyoto, Japan) and a Glucose analyser (Accu-Check, Roche Diabetes Care, USA; Carvalho et al., 2020; Simões et al., 2003).

By computing the $[La^-]$ vs. velocity curve, linear and exponential regression curves were determined using the least square method. After a visual inspection of the plots and considering the respective residue value, the inflection points were assumed to be the intersection at the maximal fit, of a combined pair of linear and exponential regressions (Carvalho et al., 2020). Heart rate was measured continuously using a Polar OH1+ (Polar Electro GmbH, Finland) and RPE (CR10 Borg scale) was employed after each step and 30 min after the protocol. Based on the secondary criteria for achieving maximal oxygen uptake it was assumed that the swimming velocity performed in the 5th step would correspond to the velocity that elicits maximal oxygen uptake if swimmers also presented elevated heart rate ($HR > 90\%$ of $[220 - \text{age}]$), high $[La^-]$ levels ($\geq 8 \text{ mmol}\cdot\text{L}^{-1}$), high $[Glu^-]$ levels ($\geq 6 \text{ mmol}\cdot\text{L}^{-1}$) and exhaustive RPE (at least 8, controlled visually and case-by-case; Howley et al., 1995; Monteiro et al., 2022; Simões et al., 2003; Sousa et al., 2015). Each swimmer's anaerobic profile was established with two derived indicators (Carvalho et al., 2020): (i) the blood lactate increase rate, as the ratio between the net $[La^-]$ and velocities ($\Delta[La^-]$ and Δv , respectively) of the two last protocol steps; and (ii) the blood lactate increase speed of 5th step, as the time rate of $\Delta[La^-]$ per step (difference between the $[La^-]$ obtained after the current step and the previous one, and the time needed to accomplish the 200 m step).

Dry-land testing

The anthropometric data were obtained in duplicate and recorded to the nearest 0.1 cm or kg. Body mass, free fat mass and fat mass were assessed using a bioimpedance scale (Tanita BC 418 Body Composition Analyzer; Tanita Corporation, Tokyo, Japan). Height was measured using a stadiometer (Holtain Ltd., Crymch, UK) and arm span using an anthropometer (Sibe-Hegner, GPM, Zurich, Switzerland). After the anthropometric assessment, swimmers performed three countermovement jumps using Optojump photocells (Microgate, Bolzano, Italy; Glatthorn et al., 2011) with a 30 s rest between trials (Carvalho et al., 2023) and CMJ height was extracted. Afterwards, hand grip isometric strength was

measured using an adjustable mechanical hand dynamometer (Lafayette Instrument, Lafayette, IN). After a 10 min warm-up, a familiarization session was conducted after providing instructions about proper handgrip technique. The swimmers were then instructed to exert their maximal grip with the upper limb in extension in three trials for both the right and left (all swimmers were right-handed dominant), with 2 min intervals (Garrido et al., 2012). The mean result was used for the analysis (Garrido et al., 2012; Innes, 1999) and hand grip symmetry was -computed as $([\text{right-left/right}]*100)$.

Profile of mood state questionnaire

The performance assessment also included the French version of the profile of mood state questionnaire (POMS-f). The questionnaire is composed by a series of 65-adjectives measuring six mood states (tension, depression, anger, vigour, fatigue, confusion) on a five-point Likert scale from 0 (not at all) to 4 (extreme), in relation to the context (Cayrou et al., 2000). The test takes approximately 5-15 min to administer in a paper and pencil form. Swimmers were also asked to state how they felt during testing using the RPE. The total mood disturbance (the sum of tension, depression, anger, fatigue and confusion minus vigour) was calculated. The raw scores for each item were analysed to further investigate changes in mood states. Lower scores indicate more stable mood profiles and a constant of 100 was added to the final score to eliminate negative values.

Statistical procedures

Statistical analysis was performed using the software SPSS version 29.0 (IBM Statistics, USA) for Windows with the level of significance set at 0.05 ($p < 0.05$). Data normality and homogeneity of distribution were checked using the Shapiro-Wilk test and mean $\pm$ SD values were calculated. A single factor repeated measures ANOVA was used to test whether there were differences of the variables mean values between cycle 1, 2 and 3 and between the four measurement points (start cycle 1, after cycle 1, 2 and 3). Partial eta-squared (η^2) values were computed for effect size calculation: 0.05-0.25 small, 0.25-0.64 moderate and > 0.64 strong (Ferguson, 2016). Post-hoc pairwise comparisons

with Bonferroni correction were applied and sphericity was determined in advance using the Mauchly test. Intraclass correlation coefficients (ICC) and Pearson's correlation coefficients were used to assess the reliability and stability of performance assessments. The thresholds used to qualitatively assess the ICC and autocorrelation values were based on the following criteria: < 0.5 poor, 0.5-0.75 moderate, 0.75-0.9 good and > 0.9 excellent (Koo & Li, 2016); and < 0.1 trivial, 0.1-0.3 small, 0.3-0.5 moderate, 0.5-0.7 large, 0.7-0.9 very large and > 0.9 nearly perfect (Hopkins et al., 2009). Statistical Parametric Mapping was used to compare the training load methods (physiological and RPE based training loads) in MATLAB (MATLAB R2023a, The MathWorks Inc., Natick, MA, USA) employing the open-source code SPM1d (v.M0.1, www.spm1d.org), with load data series being normalized based on their maximal value (Pataky, 2010).

After inferential procedures, two predictive deep artificial neural network models were developed to assess the relationship between the dependent variables (extracted from HRV) and training load or RPE load (output). The structure was developed in Python (version 3.9.2) using the TensorFlow© library and was composed of one input layer with 277 data points, 11 variables, three hidden layers (hyperbolic tangent, sigmoid and linear rectified activation functions) with 1000 neurons each and the output layer with one variable (load A.U., Figure 2). Then, the sample was divided randomly into data sets for the model training and testing (70 and 30% of the sample, respectively). In the model training, the root mean square propagation adaptive learning algorithm was used, with a loss function based on the mean square error and a learning rate of 0.0001. A limit of 50,000 epochs was established for training, and a checkpoint function was used to store the information of the best weight configuration (by monitoring the root mean square error) avoiding overtraining. The final models reached a value of 0.0243 and 0.0848 of the latter error after 41,396 and 44,254 epochs for the training RPE loads (respectively). The model training, test and total sample sets were measured using the coefficient of determination of the linear regressions between the targets and output values (Figure 3), and the model was interpreted by computing the Shapley additive explanations values (Lundberg et al., 2020).

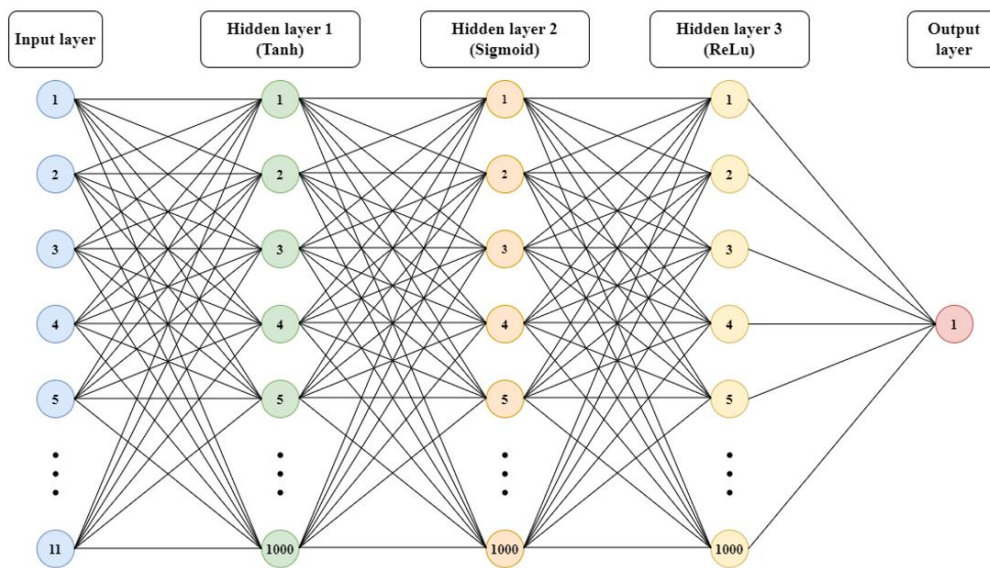


Figure 2. Artificial neural network model structure displayed as input layer with 11 variables, three hidden layers (hyperbolic tangent, sigmoid and linear rectified activation functions, respectively) with 1000 neurons each and the output layer with one variable (training load / RPE load).

Results

For the fourteen swimmers, the training load behaviours (training load and RPE load) during the monitoring period (without Sundays after cycle 1) and their comparison are presented in Figure 4. The training load and RPE load showed a similar behaviour in most of the monitoring period, with only differences in the competition that occurred in cycle 1 and during the weekends ($p < 0.05$), particularly on Saturdays of cycles 2, 3 and at the off end of the monitoring period (see Figures 1 and 4). On competition days and on the last Saturday of the monitoring period (after three cycles), the training load was lower than the RPE load. However, on weekends in cycles 2 and 3, the training load surpassed the RPE load (see Figure 4). Four of the fourteen swimmers did not complete all the training sessions during the monitoring period (three experienced illness and one swimmer underwent a medical procedure). Consequently, the analysis between cycles was conducted with only ten swimmers (three males and seven females) who did not miss any training sessions, ensuring comparable (within-subject) cumulative effects of the loads.

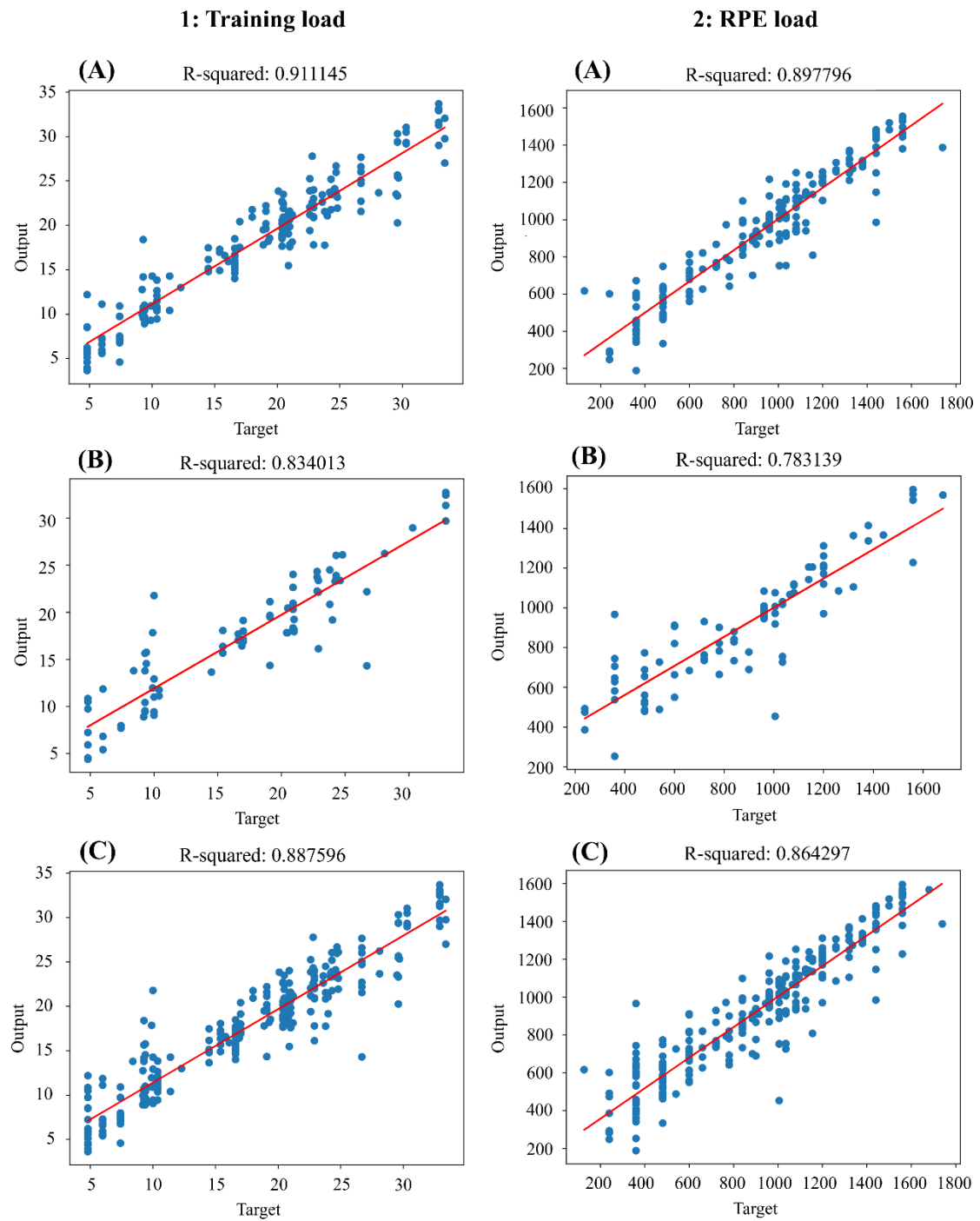


Figure 3. Coefficients of determination values of the linear regressions between targets (real training load [1]) and rate of perceived exertion load [2]) and output (estimated loads) for the training, testing and total sample sets (panels A, B and C, respectively).

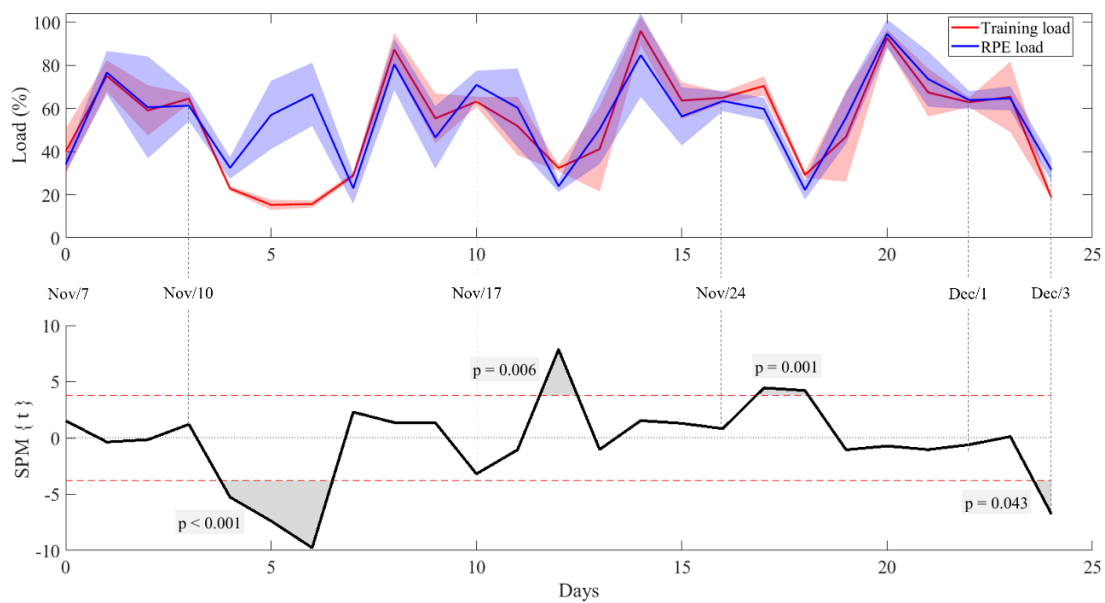


Figure 4. Comparisons of training load and RPE load behaviours along the monitoring period (28 days less 3 Sundays) based on Statistical Parametric Mapping (SPM), with day zero corresponding to the beginning of the monitoring period.

The mean values of training characteristics, HR, HRV time domain and sleep time and quality related variables and comparisons of cycles 1, 2 and 3 are shown in Table 2. The intensity ($F_{2,18} = 43.717$, $\eta^2 = 0.829$; power = 1.00; $p < 0.001$), swimming volume ($F_{2,18} = 19.351$, $\eta^2 = 0.683$; power = 1.00; $p < 0.001$) total volume ($F_{2,18} = 20.881$, $\eta^2 = 0.699$; power = 1.00; $p < 0.001$), training load ($F_{2,18} = 71.723$, $\eta^2 = 0.889$; power = 1.00; $p < 0.001$) and RPE load ($F_{2,18} = 15.473$, $\eta^2 = 0.632$; power = 0.997; $p < 0.001$) increased from cycle 1-3. From cycle 1-2 the intensity, volume and load increased by 7, 17 and 24% (respectively) and from cycle 2-3 only intensity presented a marked mean increase of 5% ($p < 0.01$). The overall mean increase of training load and RPE load from cycle 1-3 were 27 and 20% (respectively). The training loads observed during the training cycles were higher than initially prescribed for all the three cycles and the sleep time and quality were stable throughout the monitoring period. Regarding the HRV variables, supine and standing mean HR increased ($F_{2,18} = 3.448$, $\eta^2 = 0.28$; power = 0.57; $p = 0.05$; $F_{2,18} = 3.809$, $\eta^2 = 0.30$; power = 0.62; $p = 0.04$) and supine LnRMSSD decreased from cycle 1-3 ($F_{2,18} = 4.379$, $\eta^2 = 0.33$; power = 0.68; $p = 0.028$).

Table 2. Mean values of training characteristics, heart rate variability time domain and sleep time and quality variables and comparisons between cycles 1, 2 and 3.

Variables (mean $\pm$ SD)	Pre-cycles (3 days)	Cycle 1 (7 days)	Cycle 2 (7 days)	Cycle 3 (7 days)	Post-cycles (4 days)
Intensity (A.U.)	-	2.00 $\pm$ 0.03	2.14 $\pm$ 0.07*	2.24 $\pm$ 0.06* [#]	-
Swimming volume (km)	-	42.9 $\pm$ 2.2	49.0 $\pm$ 4.0*	48.6 $\pm$ 4.0 [#]	-
Total volume (km)	-	45.9 $\pm$ 2.2	53.4 $\pm$ 4.7*	52.2 $\pm$ 4.7 [#]	-
Training load (A.U.)	-	92.0 $\pm$ 5.1	113.9 $\pm$ 7.9*	116.9 $\pm$ 10.8 [#]	-
RPE load (A.U.)	-	804 $\pm$ 96	956 $\pm$ 101*	946 $\pm$ 65 [#]	-
Supine mean HR (beats·min ⁻¹)	62 $\pm$ 6	59 $\pm$ 8	60 $\pm$ 8	61 $\pm$ 9 [#]	58 $\pm$ 8
Supine RMSSD (ms)	93.02 $\pm$ 63.99	101.44 $\pm$ 61.71	92.47 $\pm$ 57.80	93.37 $\pm$ 63.57	94.66 $\pm$ 49.04
Supine LnRMSSD (ms)	4.29 $\pm$ 0.89	4.35 $\pm$ 0.89	4.16 $\pm$ 0.94* [#]	4.17 $\pm$ 0.97 [#]	4.23 $\pm$ 0.82
Standing mean HR (beats·min ⁻¹)	91 $\pm$ 10	85 $\pm$ 8	89 $\pm$ 7	89 $\pm$ 8 [#]	86 $\pm$ 7
Standing RMSSD (ms)	19.04 $\pm$ 13.57	24.97 $\pm$ 15.41	20.89 $\pm$ 8.66	21.75 $\pm$ 11.28	26.54 $\pm$ 12.32
Standing LnRMSSD (ms)	3.05 $\pm$ 0.77	2.98 $\pm$ 0.71	2.91 $\pm$ 0.48	2.84 $\pm$ 0.75	2.65 $\pm$ 0.62
Standing mean HR - supine mean HR (beats·min ⁻¹)	30 $\pm$ 9	27 $\pm$ 9	30 $\pm$ 8	28 $\pm$ 10	28 $\pm$ 7
Standing RMSSD - supine RMSSD (ms)	-73.99 $\pm$ 65.33	-75.99 $\pm$ 62.40	-72.54 $\pm$ 58.41	-71.82 $\pm$ 61.74	-68.12 $\pm$ 44.89
Standing LnRMSSD - Supine LnRMSSD (ms)	-1.24 $\pm$ 0.43	-1.38 $\pm$ 0.79	-1.26 $\pm$ 0.77	-1.34 $\pm$ 0.69	-1.57 $\pm$ 0.88
Peak HR (beats·min ⁻¹)	107 $\pm$ 9	105 $\pm$ 5	107 $\pm$ 6	108 $\pm$ 5	106 $\pm$ 4
Time to peak HR (s)	21.07 $\pm$ 5.61	21.19 $\pm$ 3.69	23.88 $\pm$ 6.37	21.07 $\pm$ 5.61	23.25 $\pm$ 4.27
Sleep time (min)	486 $\pm$ 38	505 $\pm$ 58	497 $\pm$ 46	507 $\pm$ 38	526 $\pm$ 59
Hopper scale total (0- 28)	13 $\pm$ 3	12 $\pm$ 3	12 $\pm$ 4	11 $\pm$ 3	10 $\pm$ 3
Quality of sleep (0-7)	3 $\pm$ 1	3 $\pm$ 2	3 $\pm$ 2	3 $\pm$ 2	3 $\pm$ 2
Fatigue (0-7)	4 $\pm$ 1	4 $\pm$ 1	4 $\pm$ 1	3 $\pm$ 1	3 $\pm$ 1
Muscle soreness (0-7)	4 $\pm$ 1	3 $\pm$ 1	4 $\pm$ 1	4 $\pm$ 1	3 $\pm$ 1
Stress level (0-7)	3 $\pm$ 2	2 $\pm$ 1	2 $\pm$ 1	2 $\pm$ 1	2 $\pm$ 1

Abbreviations: HR, heart rate. *[#] differences compared to the previous moment and to the cycle 1, respectively, ($p \leq 0.01$).

The mood state profile of the ten swimmers in the four performance assessment days before initiating the physical testing is presented in Figure 5, where the iceberg profile was maintained during all the monitoring period. The physiological responses and comparisons between the four performance assessment days (in which HRV variables corresponded to the values observed in the morning of the same day) are presented in Tables 3 and 4. Anger perception ($F_{3,27} = 4.512$, $\eta^2 = 0.334$; power = 0.83; $p = 0.01$) decreased between first and the third and fourth assessments ($p = 0.01$ and 0.004 , respectively). The RPE of 5th step ($F_{3,27} = 3.857$, $\eta^2 = 0.70$; power = 0.76; $p = 0.02$) increased between first and second assessments and decreased between second and third assessments² ($p = 0.037$ and 0.004 , respectively). The $[La^-]$ of 5th step ($F_{3,27} = 3.441$, $\eta^2 = 0.28$; power = 0.71; $p = 0.03$) decreased between the third and fourth assessments ($p = 0.013$). All HRV, POMS and performance variables presented high stability and reliability of results with good to excellent ICC between all assessments, except for hand grip symmetry and anxiety. No substantive relationships were observed between HRV time domain indexes and swimming performance during the monitoring period.

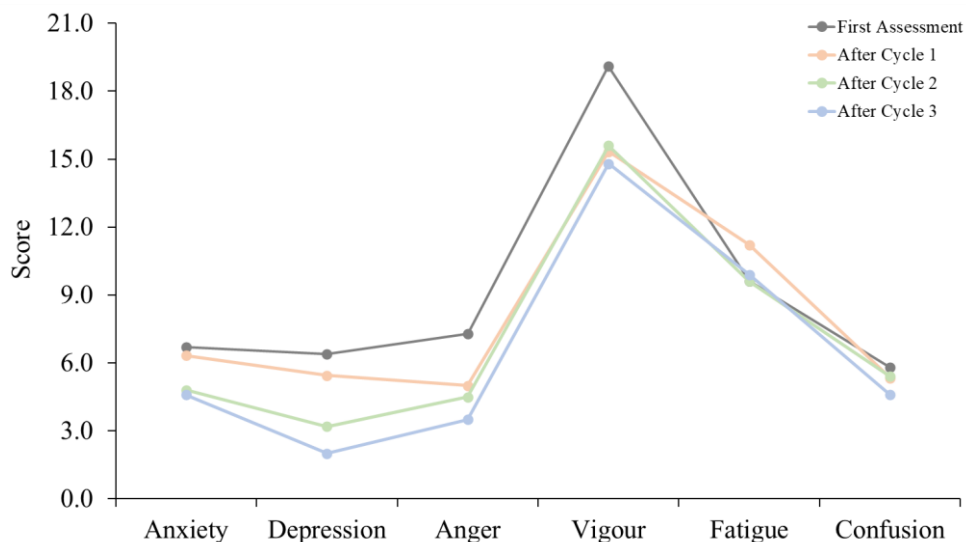


Figure 5. Profile of mood state graphical representation of the four performance assessment days.

Table 3. Anthropometric, heart rate variability and profile of mood state (POMS) variables in the performance assessment days, autocorrelation values between initial moment and after cycle 3 and intraclass correlation coefficients with correspondent p values.

Variables (mean $\pm$ SD)	First assessment (Start cycle 1)	Second assessment (After cycle 1)	Third assessment (After cycle 2)	Fourth assessment (After cycle 3)	Autocorrelation (Pearson r)	ICC of four moments (95% CI)	P value
Body mass (kg)	64.55 $\pm$ 8.18	64.47 $\pm$ 8.18	64.33 $\pm$ 8.28	65.47 $\pm$ 11.16	0.993	0.992 (0.978 – 0.998)	0.000
Height (cm)	172.5 $\pm$ 9.4	172.5 $\pm$ 9.4	172.5 $\pm$ 9.4	172.6 $\pm$ 9.6	0.994	0.999 (0.998 – 1.000)	0.000
Arm span (cm)	179.85 $\pm$ 11.27	-	-	180.45 $\pm$ 11.21	0.997	0.998 (0.993 – 1.000)	< 0.001
Body fat (%)	15.72 $\pm$ 4.63	14.48 $\pm$ 4.48	16.32 $\pm$ 4.68	16.19 $\pm$ 5.07	0.705	0.943 (0.854 – 0.984)	< 0.001
Free fat mass (kg)	54.56 $\pm$ 9.02	55.30 $\pm$ 8.97	54.02 $\pm$ 9.20	55.12 $\pm$ 11.79	0.970	0.990 (0.974 – 0.997)	0.000
Body mass index (kg·m ²)	21.65 $\pm$ 1.14	21.60 $\pm$ 1.16	21.57 $\pm$ 1.11	21.85 $\pm$ 1.72	0.871	0.965 (0.910 – 0.990)	< 0.001
Supine mean HR (beats·min ⁻¹)	57.9 $\pm$ 7.0	56.2 $\pm$ 8.1	58.8 $\pm$ 8.4	61.1 $\pm$ 7.9	0.794	0.882 (0.697 – 0.967)	< 0.001
Supine RMSSD (ms)	109.01 $\pm$ 65.23	96.88 $\pm$ 61.11	95.96 $\pm$ 65.41	92.17 $\pm$ 52.74	0.967	0.981 (0.952 – 0.995)	< 0.001
Supine LnRMSSD (ms)	4.44 $\pm$ 0.87	4.33 $\pm$ 0.86	4.30 $\pm$ 0.84	4.28 $\pm$ 0.89	0.980	0.989 (0.972 – 0.997)	0.000
Standing mean HR (beats·min ⁻¹)	85.4 $\pm$ 7.9	87.3 $\pm$ 7.6	87.87 $\pm$ 9.63	90.04 $\pm$ 9.33	0.151	0.772 (0.412 – 0.936)	0.001
Standing RMSSD (ms)	21.90 $\pm$ 11.40	20.47 $\pm$ 13.13	18.45 $\pm$ 8.98	18.70 $\pm$ 10.70	0.585	0.882 (0.697 – 0.967)	< 0.001
Standing LnRMSSD (ms)	2.89 $\pm$ 0.75	2.79 $\pm$ 0.81	2.79 $\pm$ 0.58	2.72 $\pm$ 0.77	0.682	0.937 (0.837 – 0.982)	< 0.001
Standing mean HR - Supine mean HR (beats·min ⁻¹)	27.48 $\pm$ 9.38	30.59 $\pm$ 9.69	29.09 $\pm$ 8.58	28.98 $\pm$ 9.06	0.536	0.822 (0.541 – 0.950)	< 0.001
Standing RMSSD - Supine RMSSD (ms)	-87.11 $\pm$ 68.03	-73.90 $\pm$ 57.72	-77.51 $\pm$ 65.43	-73.48 $\pm$ 53.51	0.934	0.975 (0.937 – 0.993)	< 0.001
Standing LnRMSSD - Supine LnRMSSD (ms)	-1.55 $\pm$ 0.93	-1.55 $\pm$ 0.82	-1.52 $\pm$ 0.74	-1.56 $\pm$ 0.84	0.691	0.932 (0.826 – 0.981)	< 0.001
Peak HR (beats·min ⁻¹)	103.90 $\pm$ 7.85	102.90 $\pm$ 4.28	104.20 $\pm$ 7.41	107.50 $\pm$ 4.84	0.303	0.742 (0.335 – 0.928)	0.002
Time to peak (s)	20.60 $\pm$ 6.19	23.80 $\pm$ 7.45	25.00 $\pm$ 6.55	25.30 $\pm$ 6.86	0.778	0.810 (0.510 – 0.946)	< 0.001
Anxiety	7.00 $\pm$ 3.50	6.40 $\pm$ 4.06	4.60 $\pm$ 1.78	4.50 $\pm$ 2.42	-0.329	0.479 (-0.340 – 0.854)	0.087
Depression	6.40 $\pm$ 8.38	5.20 $\pm$ 6.09	3.10 $\pm$ 2.51	1.70 $\pm$ 1.57	0.695	0.746 (0.347 – 0.929)	0.002
Anger	7.60 $\pm$ 4.48	6.80 $\pm$ 6.34	3.90 $\pm$ 2.33 [#]	3.40 $\pm$ 2.50 [#]	0.631	0.697 (0.220 – 0.915)	0.007
Vigour	18.90 $\pm$ 4.82	15.20 $\pm$ 4.18	15.30 $\pm$ 4.37	15.30 $\pm$ 3.77	0.271	0.664 (0.134 – 0.906)	0.012
Fatigue	9.10 $\pm$ 4.70	11.70 $\pm$ 5.68	8.70 $\pm$ 5.40	8.60 $\pm$ 4.35	0.741	0.721 (0.281 – 0.922)	0.004
Confusion	5.60 $\pm$ 3.20	5.30 $\pm$ 2.87	4.90 $\pm$ 2.92	4.50 $\pm$ 1.84	0.490	0.725 (0.292 – 0.923)	0.004
POMS Global score	116.80 $\pm$ 21.05	120.20 $\pm$ 23.20	109.90 $\pm$ 11.89	107.40 $\pm$ 10.76	0.417	0.759 (0.378 – 0.932)	0.002

Abbreviations: HR, heart rate; RMSSD, root mean square of the successive differences. [#] differences compared to the previous moment and to the first assessment, respectively, (p < 0.05). Values correspond to significant autocorrelation values in bold.

Table 4. Dry-land testing and 5 x 200 m incremental protocol variables in the performance assessment days, autocorrelation values between initial moment and after cycle 3 and intraclass correlation coefficients with correspondent p values.

Variables (mean $\pm$ SD)	First assessment (Start cycle 1)	Second assessment (After cycle 1)	Third assessment (After cycle 2)	Fourth assessment (After cycle 3)	Auto-correlation (Pearson r)	ICC of four moments (95% CI)	P value
Countermovement jump height (cm)	29.41 $\pm$ 6.61	29.52 $\pm$ 6.68	29.54 $\pm$ 6.71	28.87 $\pm$ 6.24	0.991	0.997 (0.991 – 0.999)	0.000
Hand grip right (kg)	33.48 $\pm$ 5.54	33.90 $\pm$ 6.95	34.02 $\pm$ 6.08	33.24 $\pm$ 5.79	0.925	0.987 (0.966 – 0.996)	0.000
Hand grip left (kg)	31.37 $\pm$ 6.04	32.26 $\pm$ 7.34	32.25 $\pm$ 6.13	31.98 $\pm$ 5.54	0.896	0.972 (0.929 – 0.992)	0.000
Hand grip symmetry (%)	9.6 $\pm$ 6.1	8.4 $\pm$ 5.1	5.8 $\pm$ 3.0	7.3 $\pm$ 5.2	-0.024	0.275 (-0.866 – 0.796)	0.241
Velocity at anaerobic threshold (m·s ⁻¹)	1.29 $\pm$ 0.09	1.28 $\pm$ 0.09	1.28 $\pm$ 0.09	1.28 $\pm$ 0.11	0.984	0.993 (0.982 – 0.998)	0.000
Lactate at anaerobic threshold (mmol·L ⁻¹)	3.1 $\pm$ 0.9	3.1 $\pm$ 1.1	2.8 $\pm$ 0.6	2.7 $\pm$ 0.7	0.659	0.837 (0.581 – 0.954)	< 0.001
Glucose at anaerobic threshold (mmol·L ⁻¹)	4.9 $\pm$ 1.0	4.9 $\pm$ 0.8	4.7 $\pm$ 1.0	4.7 $\pm$ 0.8	0.489	0.905 (0.754 – 0.973)	< 0.001
Heart rate at anaerobic threshold (beats·min ⁻¹)	176 $\pm$ 8	177 $\pm$ 7	178 $\pm$ 7	176 $\pm$ 10	0.608	0.893 (0.725 – 0.970)	0.000
RPE at anaerobic threshold (0-10)	5.2 $\pm$ 1.1	5.5 $\pm$ 1.0	5.2 $\pm$ 1.2	5.7 $\pm$ 1.3	0.360	0.822 (0.541 – 0.950)	< 0.001
Velocity of 5 th step (m·s ⁻¹)	1.38 $\pm$ 0.10	1.37 $\pm$ 0.10	1.37 $\pm$ 0.10	1.36 $\pm$ 0.10	0.970	0.995 (0.986 – 0.999)	0.000
Lactate concentration of 5 th step (mmol·L ⁻¹)	9.9 $\pm$ 3.6	10.3 $\pm$ 3.7	9.6 $\pm$ 4.3	8.6 $\pm$ 3.2 ^{#,+}	0.865	0.960 (0.898 – 0.989)	< 0.001
Glucose concentration of 5 th step (mmol·L ⁻¹)	7.8 $\pm$ 1.3	7.4 $\pm$ 1.3	7.7 $\pm$ 1.8	7.2 $\pm$ 1.3	0.818	0.931 (0.823 – 0.981)	< 0.001
Heart rate of 5 th step (beats·min ⁻¹)	192 $\pm$ 10	193 $\pm$ 9	192 $\pm$ 10	190 $\pm$ 11	0.839	0.970 (0.923 – 0.992)	< 0.001
RPE of 5 th step (0-10)	8.8 $\pm$ 1.0	9.6 $\pm$ 0.5 [*]	8.7 $\pm$ 1.0 [*]	9.0 $\pm$ 1.2	0.652	0.765 (0.394 – 0.934)	0.001
Relative velocity at anaerobic threshold (%)	93.5 $\pm$ 1.5	93.0 $\pm$ 1.4	93.1 $\pm$ 1.9	93.4 $\pm$ 2.0	0.440	0.749 (0.354 – 0.929)	0.002
Relative HR at anaerobic threshold (%)	91.7 $\pm$ 3.1	91.8 $\pm$ 3.1	92.4 $\pm$ 2.5	92.6 $\pm$ 2.5	0.118	0.781 (0.435 – 0.938)	< 0.001
Relative lactate at anaerobic threshold (%)	32.5 $\pm$ 9.1	31.4 $\pm$ 8.7	33.2 $\pm$ 12.6	33.6 $\pm$ 10.0	0.468	0.844 (0.599 – 0.956)	< 0.001
Relative glucose at anaerobic threshold (%)	63.2 $\pm$ 7.2	66.5 $\pm$ 9.4	60.8 $\pm$ 9.0	65.8 $\pm$ 9.1	0.331	0.847 (0.607 – 0.957)	< 0.001
Blood lactate increase speed of 5 th step [(mmol·L ⁻¹)·s ⁻¹]	0.03 $\pm$ 0.02	0.04 $\pm$ 0.02	0.03 $\pm$ 0.02	0.03 $\pm$ 0.01	0.749	0.942 (0.851 – 0.984)	< 0.001
Lactate increase rate of 5 th step [(mmol·L ⁻¹)·(m·s ⁻¹)]	98.2 $\pm$ 58.8	112.4 $\pm$ 110.1	81.1 $\pm$ 61.2	75.4 $\pm$ 49.8	0.744	0.898 (0.737 – 0.971)	< 0.001

Abbreviations: HR, heart rate; RPE, rate of perceived exertion. ^{*,#,+} differences compared to the previous moment, to the first assessment and to after cycle 1, respectively, (p < 0.05). Values correspond to significant autocorrelation values in bold

Despite the absence of substantial changes in the group mean swimming performance across the assessment days, individual variations were noted among the ten evaluated swimmers. Specifically, five swimmers exhibited an impairment ranging from 1.1-4.1% in the maximal velocity reached during the 5 x 200 m protocol (see Figure 6). Additionally, seven swimmers displayed an impairment ranging from 0.7-3.2% in their velocity corresponding to the individual anaerobic threshold. The artificial neural network models, as indicated by the coefficients of determination in Figure 3, predicted mean training load and RPE load values of 17.6 ± 7.9 and 896 ± 364 A.U. (respectively). These predictions were closely aligned with the true mean values of 17.6 ± 6.9 and 919 ± 316 A.U. as shown in Figure 7. The figure illustrates the relative importance of each variable in determining the loads, with the difference between standing and supine RMSSD, supine RMSSD, peak HR, and supine mean HR emerging as the most crucial variables for interpreting the training loads, with Shapley additive explanation values of 3.14, 2.95, 2.76, and 2.56 (respectively).

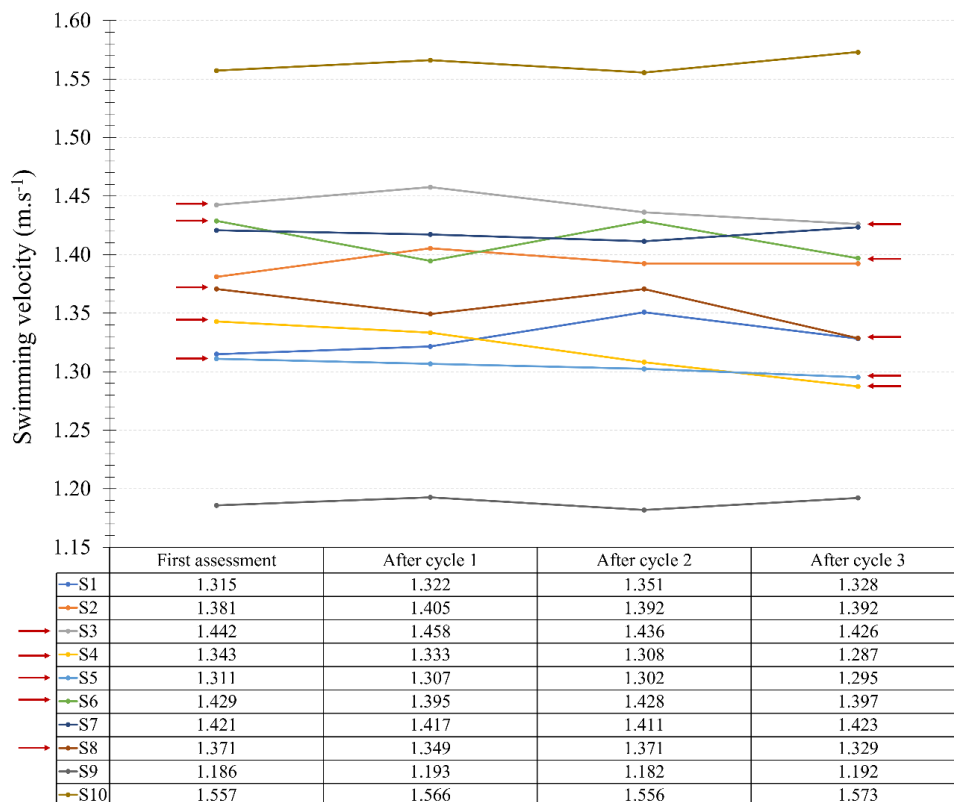


Figure 6. Individual patterns of the maximal velocity achieved during the 5 x 200 m incremental protocol in the four performance assessment days. Red arrows corresponding to swimmers with practical performance impairments.

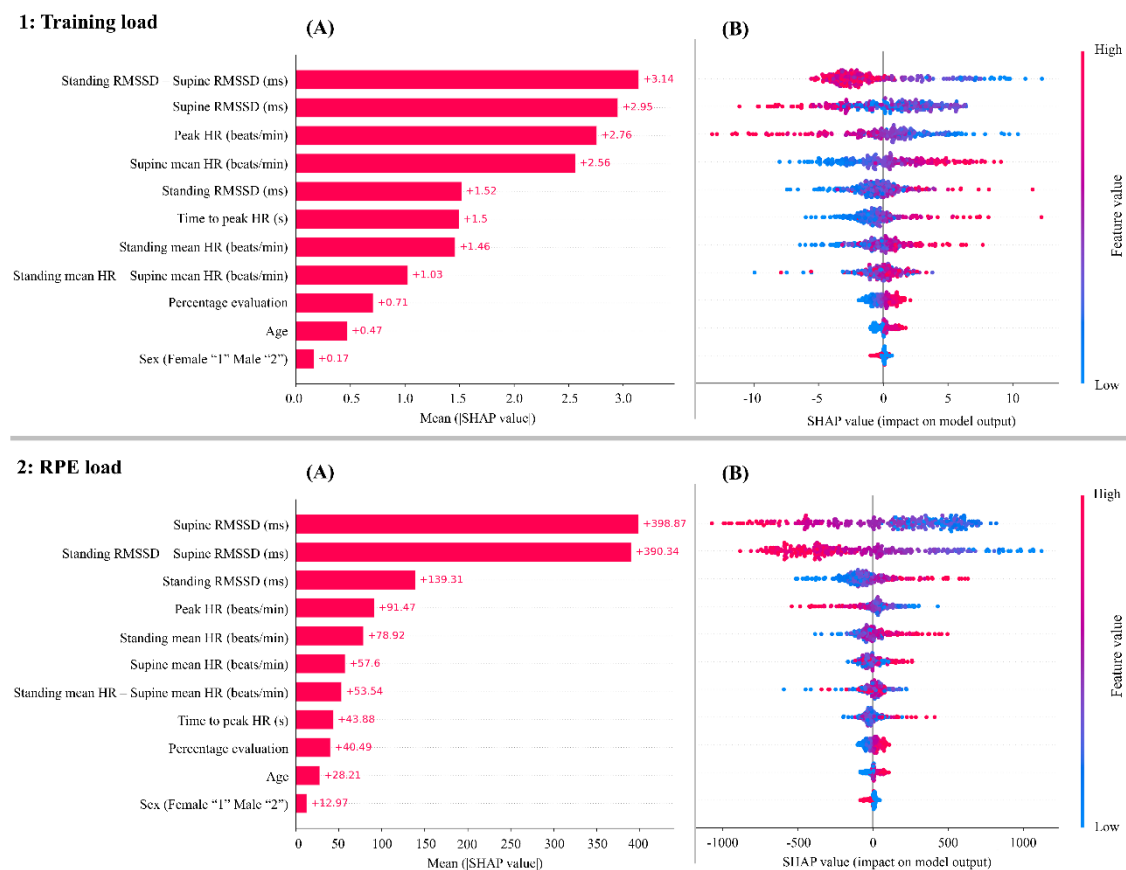


Figure 7. Shapley additive explanations (SHAP) values summary plots with the 11 input variables ordered by feature importance. (A) panels: hierarchical average impact magnitude on targets (real training load [1] and RPE load [2]) for the 11 input variables used on the artificial model expressed by SHAP values. (B) panels: colour bar on right used to interpret the direction of the relationship between one individual variable and the competitive swimming performance. The strength of the relationships is defined by the amplitude of the SHAP values, where larger magnitudes mean a greater influence. When red colour is presented in both positive and negative sides of the graphic indicates that this variable is important for the model as a cooperative variable and needs to be interpreted combined with other variables.

In the model related to RPE load, the Shapley additive explanation values highlight the significance of supine RMSSD and the difference between standing and supine RMSSD, with respective values of 399 and 390 to interpret the variations in load. Surprisingly, supine mean HR did not emerge as one of the most crucial variables in explaining RPE load. Figure 7 also illustrates the direction (positive or negative) of the variables' impact on training/RPE load. Notably, the difference between standing and supine RMSSD, supine RMSSD, and peak HR increases indicated a lower external training load, while higher

supine mean HR corresponded to higher training loads. The difference between standing and supine RMSSD values should be interpreted as absolute values due to the model transformations. The direction of the impact of all variables on the RPE load remained consistent to the training load model.

Discussion

We examined the effect of three consecutive seven-day cycles (like a microcycle) with different intensity and volume dynamics on HRV, mood profile, dry-land and swimming performance. HRV time domain variables and HR were used to interpret the training loads imposed on elite swimmers. We also examined the daily differences between the two methods of training load assessments. It seems that elite swimmers accurately perceive the loads imposed on them in daily training indicating that physiological and psychological loads have different influences and should be considered in parallel when characterizing external loads. The autonomic nervous system response, defined mainly as changes in HRV behaviour, are sensitive to acute/short term overload periods and could reproduce the training loads (independently of the assessment method) that the elite swimmers were undertaking. The lack of a consistent impairment in performance after a training overload period, characterized by an increase of 27% in training load and 20% in RPE load and negative effects on supine and standing mean HR and supine LnRMSSD, implies that even with changes in vagal activity, not all swimmers respond similarly to training loads in terms of performance.

Although the monitoring of each training week started on a Monday, the cycles were defined from Thursday-Wednesday so that all swimmers had a less intense training on the previous sessions (both Wednesday afternoon and Thursday morning sessions were similar for all swimmers). The 28 days permitted evaluation of the daily changes in the training load dynamics (intensity and volume) and how they affect HRV measurements and dry-land strength and swimming performance. We chose morning resting HRV recordings given the practicability of the measurement and the focus on vagal activity based on HRV

time domain parameters, such as RMSSD. Using the time-domain measure including RMSSD leads to more reliable outcomes in longitudinal analysis, as opposed to frequency-domain analysis of HRV, which necessitates a minimal level of control over the breathing rate in the context of training and health status (Hottenrott et al., 2021; Nakamura et al., 2015; Saboul et al., 2014). Paced breathing is also not recommended for highly trained athletes (Saboul et al., 2014) due to their normally reduced breathing frequency. The evaluated swimmers self-determined breathing frequency ranged from 7-14 breaths·min⁻¹ (where half of the swimmers presented ≤ 9 breaths·min⁻¹) which can negatively influence the interpretation of vagal activity based on HRV frequency domains (Saboul et al., 2014; Shaffer et al., 2014). RMSSD related variables were transformed by taking the natural logarithm to have stronger effects when performing parametric statistical comparisons that assumed a normal distribution (Javaloyes et al., 2020).

Even swimmers being familiarized with all the tests performed during the monitoring period, the first performance assessment day served to define basal values for comparisons of the different load dynamics effects and to eliminate the learning effect between testing days. The use of CMJ (frequently used to train and evaluate lower limb explosive power) and hand grip strength in dry-land testing is supported by a series of studies (Carvalho et al., 2023; Garrido et al., 2012; Glatthorn et al., 2011; West et al., 2011; Zampagni et al., 2008) that showed good relationships with different swimming performances and high reliability. Our CMJ and hand grip strength results obtained in the first performance assessment day correlated positively with the FINA/World Aquatics points obtained in the competition during cycle 1 ($r = 0.58$ and 0.66 [$0.08 - 0.95$ 95% CI], $p = 0.015$ and 0.05).

RPE load method has been shown to be reliable and useful in the field (Foster et al., 2001; Halson, 2014). This method takes into consideration the intensity perceived by the swimmer (as a normalization method) and the duration of training session or competition to calculate training or competition loads (Haddad

et al., 2017). However, it is well known that physiological and neural determinants do not fully explain the variation in RPE as other factors can also influence it (Clemente-Suárez et al., 2021; Sixsmith et al., 2023). Furthermore, weak relationships between the coaches' prescribed intensity and the individual swimmers' perceived intensity are often evident (Clemente-Suárez et al., 2021; Stewart & Hopkins, 1997), particularly in well-trained swimmers who perceive high and low-intensity training sessions as harder and easier than prescribed sessions, respectively (Wallace et al., 2009). Therefore, it is of great importance to compare daily the training load (intensity based on physiological parameters) with the RPE load to identify and account for observed differences.

The differences between training load (physiological) and RPE load (psychophysiological) observed during the competition of cycle 1, can be explained by the contrast of low training load (low-volume and low-to-moderate intensity warm-ups and cool-downs and one to two swimming events per session) (Anderson et al., 2008; Neiva et al., 2014) and the swimmers exposure to a high psychological stresses (e.g. coach's expectations, personal commitment to continuous improvement, aspirations for future event qualification and adherence to race strategy (McDonough et al., 2013). The lower RPE load recorded during the Saturdays of cycles 2 and 3 was most likely related to be the last training of the week, where swimmers were aware that the previous training was the hardest from the week and that the next day they will rest. Taken together, these findings corroborate that both physiological and psychological loads have different influences and should be considered when exploring training loads (Anderson et al., 2008; Clemente-Suárez et al., 2021).

The increase in training load from cycles 1-2 was related to the increase in intensity and volume. However, the intensity increase from cycles 2-3, despite the maintenance of volume, was not enough to elevate the overall training load in a substantive way. These results, demonstrate that methods developed in swimming to discriminate between volume and intensity (Mujika et al., 1996), need to evolve so that they are more sensitive to small changes in each training

load factor (Javaloyes et al., 2020; Mujika et al., 2018). In addition, the increase in training load and RPE load presented similar behaviours but with different magnitudes (mean increase from cycle 1-3 of 27 and 20%, respectively). This outcome aligns with long-held assertions that training loads based on RPE are more sensitive to the psychological stresses that affect the perception of each training session without distinguishing whether the changes in load are a consequence of changes in intensity or volume (Foster et al., 2001).

The multiple cycles of increased load did not lead to any significant changes in the mean weekly Hooper index, which is a noteworthy observation. Additionally, the sleep duration remained consistent throughout all monitoring periods, which is crucial for evaluating the potential effects of daily training on HRV. The higher supine and standing mean HRs during cycle 3 and the lower LnRMSSD during cycles 2 and 3 compared to cycle 1 caused by the training load increase in cycle 2 and its maintenance during cycle 3 (with increase in intensity), are usually described as a marker of overtraining condition, associated with an increased sympathetic or decrease in parasympathetic activity during supine rest (Uusitalo et al., 2000). Similar decreases in vagally mediated biomarkers were observed after one week of high intensity training (Schneider et al., 2019) and after three weeks of intensive training (Garet et al., 2004). However, without corresponding impairments in performance we cannot determine whether swimmers reached an overtraining condition after the overload period.

The similar values found between HRV measurements assessed in the morning of the four performance assessment days are corroborated by other studies that observed stability in HRV time domain variables after an overload/intensive training periods in elite swimmers using the HRV of the testing day (Atlaoui et al., 2007; Hedelin et al., 2000). Beat-to-beat variations in HR represent the continuous interaction between the sympathetic and parasympathetic branches (Shaffer et al., 2014), where increases and decreases in HR are associated with heightened sympathetic and parasympathetic activity (respectively). During rest, the heart is under tonic inhibitory control, demonstrating parasympathetic

dominance over sympathetic influences (Shaffer et al., 2014) and, for an accurate monitoring, it should be evaluated in the supine and standing positions (Hottenrott et al., 2021; Schmitt et al., 2015). The absence of an increase in supine mean HR and a decrease in supine LnRMSSD between the four performance assessment days contrasts with the mean of each cycle (see Tables 2 and 3). This sequence can be probably explained by the low intensity training of the previous day and justifies the need of using mean values instead of discrete one-day values when describing effects on HRV. Moreover, in elite swimmers, this intensity reduction can be sufficient to recover from previous accumulated fatigue (Hellard et al., 2013; Mujika et al., 2018). Conflicting results depending on the data point or interval used to analyse HRV changes have been observed when analysing high-level swimmers, explaining the difficulty of confidently interpreting the existence or lack of changes in HRV (Plews et al., 2013).

The iceberg POMS maintenance profile, typical in high-level athletes, and the decrease in Anger category between the first and the third and fourth assessments showed that the overload period did not have a negative effect on the swimmers psychological profile (Urhausen & Kindermann, 2002). Similarly, dry-land strength and swimming performances were conserved with high stability, showing that elite swimmers were able to adapt to the short-term overload, without losing their physical performance ability. Other studies have reported similar outcomes with different overload periods (Atlaoui et al., 2007; Garet et al., 2004). The swimming incremental protocol facilitated trustworthy estimates of training intensities given the swimmers velocities corresponded to the anaerobic threshold and maximal oxygen uptake (based on the secondary criteria) (Howley et al., 1995; Monteiro et al., 2022; Simões et al., 2003; Sousa et al., 2015).

The observed $[La^-]$ and $[Glu^-]$ concentrations were similar to those reported earlier at the intensity of both the anaerobic threshold and maximal oxygen uptake (Carvalho et al., 2020; Simões et al., 2003). The observed lower $[La^-]$ of the 5th step might be evidence of an early overreaching stage (Halsen & Jeukendrup, 2004; Urhausen & Kindermann, 2002). Our results on anaerobic behavior

regarding $[La^-]$ increase speed and rate of 5th step were in similar ranges of swimmers with same competitive level (Carvalho et al., 2020). The anaerobic capability was conserved during the overload period, contrasting with the reduced maximal $[La^-]$, probably explaining the achievement of similar maximal velocities in the last step of the incremental protocol even with lower $[La^-]$ (Carvalho et al., 2020).

We used the Bonferroni correction to be as conservative as possible and limiting the likelihood of a type 1 error. However, when analysing elite, where the success is based on the smallest of margins close to their genetic ceiling, it is more important to reduce false-negatives and thus potential opportunities that may stimulate positive adaptations (Turner et al., 2021). Exploring the results using the Hochberg-Bonferroni (step-up) correction, a viable approach to our sample and study design (repeated measures and lower number of subjects and comparisons), we verified a decrease in supine RMSSD from cycle 1-2 ($p = 0.027$) and an increase in peak HR from cycle 2-3 ($p = 0.033$). When comparing the four performance assessment days with that approach, we observed a decrease in supine RMSSD between first-fourth ($p = 0.024$), an increase in peak HR between third-fourth ($p = 0.030$) and in time to peak HR between first-fourth ($p = 0.008$), a decrease in $[Glu^-]$ of 5th step between third-fourth ($p = 0.041$) and a decrease in HR of 5th step between second-fourth ($p = 0.018$) assessments. The decrease in supine RMSSD reflects a decrease in parasympathetic activity mediated by the vagal nerve and the increase in peak HR and time to peak HR may be a potential indicator of training-induced fatigue (Hottenrott et al., 2021; Shaffer et al., 2014).

In addition, using the mean HRV values of each cycle, seven from the 10 swimmers presented in response to the overload period, either reduced supine mean HR together with decrease in supine RMSSD or one of the responses, and two swimmers presented augmented time to peak HR ($p < 0.05$), all reflecting a possible negative effect on the autonomic nervous system response. The different patterns of change in performance between the four assessments need

to be carefully considered. During a season, the performance improvement of elite swimmers is typically between 0.6-1.1% (Costa et al., 2010; Pyne et al., 2004) and Olympic swimmers should seek improvements of approximately 1% within the year leading up to the Olympics (Pyne et al., 2004). The consistent impairments on swimming performance of the five swimmers (see Figure 6) align with these expectations (1.1-4.1%) and corresponded to an increase in the 200 m time of 1.5-5.5 s. This analysis allowed us to understand that the incremental protocol is sensitive to individual responses to changes in training load (Anderson et al., 2008).

After the monitoring period, swimmers started a tapering phase of two weeks (14 days) until the main competition, with a progressive weekly volume and intensity reduction of ≥ 30 and 20% (respectively) from previous week (Hellard et al., 2013; Mujika & Padilla, 2003). From the 10 swimmers, four reported illness during the tapering period, but without a direct cause to the overload. Among the six remaining swimmers, three presented a loss in competitive performance of 0.3, 2.4 and 3.2%, after having presented consistent impairments in the swimming velocity after the cycle 3, combined with negative HRV indexes responses. One swimmer, who had a decrease in performance after the overload period but did not present changes in HRV responses, improved in the final competition by 3%. The other two swimmers had stable training performance combined with negative HRV indexes responses during the overload period but were able to improve their competitive performances by 0.5 and 3%.

Based on our results, it appears that acute cardiac autonomic adaptations do not reflect impairments in swimming performance in incremental protocols and derived physiological parameters during short periods of overloading (Buchheit, 2014; Garet et al., 2004). However, our predictive models showed a high sensitivity of the vagally-mediated biomarkers responses to the changes in training/RPE loads. Two important aspects of the models interpretation are that prediction of loads from HRV measurements is sufficiently robust to assess training loads (based on the correlation values) and that the direction of each

HRV time domain indices were maintained regardless of the training load calculation method (see Figure 7). Taken together these results indicate elite swimmers ability to perceive accurately the loads imposed on them during daily training.

Different studies have used training loads prescription based on HRV measurements (Garet et al., 2004; Javaloyes et al., 2020; Nakamura et al., 2015; Vesterinen et al., 2016). However, a lack of consistency with the methods used for assessing its sensitivity is evident (Manresa-Rocamora et al., 2021). The sensitivity should be defined on HRV capability to predict the changes evident in training loads, since the changes in performance are dependent on cardiac autonomic activity and other physiological parameters (Halsen & Jeukendrup, 2004; Mujika et al., 2018). Raw RMSSD data was used for the model, based on the need to preserve the real variability within the parameter and the non-dependence of the specific data distribution for artificial neural network models.

In the current study, the models created with HRV time domain variables and HR to interpret training loads and RPE loads showed the supine RMSSD and difference between standing and supine RMSSD presented the higher predictive power and should be interpreted together. Our results align with earlier data (Shaffer et al., 2014) showing decreases on supine RMSSD, increases in supine and standing mean HR and time to peak HR when predicting higher loads imposed to the swimmers (Bosquet et al., 2008). However, in this model the increase in standing RMSSD and decrease in peak HR is aligned with higher training loads, previously presented as a readiness to perform (Buchheit, 2014; Hottenrott et al., 2021). This effect partly explains why a mean impairment of swimmers ability to perform both in dry-land and swimming testing between cycles was not observed.

One limitation of the study was that only 10 out of 14 swimmers completed the entire training period, that combined with the observed variations in the individual responses to overload impacted the consistency of the anticipated performance

decline (Atlaoui et al., 2007; Hellard et al., 2013). Implementing standardized rest intervals and practical organization of training sessions likely limited cumulative fatigue and impairments in swimming performance. Given the individual differences in fatigue thresholds among swimmers, the prescription, monitoring, and management of training load increases should be personalized (Garet et al., 2004; Hellard et al., 2013; Javaloyes et al., 2020). Combining daily HRV measurements and performance assessments at the beginning and at the end of overload periods can provide useful insights into swimmer's individual training limits. Future studies should investigate the individual effects of consecutive cycles (along a season) of overload periods followed by tapering and a competition on daily HRV and swimming performance to confirm these contentions also including effects on swimming biomechanical parameters (Figueiredo et al., 2012; Lee et al., 2017).

Conclusion

A mean overload of 27% in training loads within a two-week period did not impair dry-land strength and swimming performances in elite swimmers nor their mood state profile. Vagally-mediated biomarkers appears to be highly sensitive to changes in training loads and capable of interpreting variations in daily training loads (regardless of the assessment method) imposed on swimmers. Elite swimmers appear to have different fatigue thresholds, so overload periods should be individualized and observed increases in mean HR and decreases in LnRMSSD after an overload period should not be considered as an overtraining symptom, but rather a normal response to a short-term increase in training load (confirmed by the lack of modification on HRV data between cycles 2 and 3 with similar training loads). A combination of HRV, psychological and performance monitoring should be implemented to evaluate the effects of short-term overloading training periods on competitive swimmers.

Chapter 8

General discussion

Swimming training has a long tradition rooted in an intuitively driven approach and the concept of a coach as an artist capable of uniquely understanding the underlying processes of competitive success still has many followers (Vilas-boas et al., 2020). However, it is simultaneously an activity that has long been the subject of scientific scrutiny, on which scientific research has continuously provided knowledge and methodological tools of extreme relevance over time (Anderson et al., 2008; Costa et al., 2012; Fernandes et al., 2018; Monteiro et al., 2020; Clemente-Suárez et al., 2021). These have decisively contributed to the extraordinary progress made in the performance capacity of swimmers. In today's context, diminishing the available tools for determining the needs and priorities of the process at a given moment by primarily recognizing successful coaching as an art, intuition is dangerous (Vilas-boas et al., 2020).

The training evaluation and control became particularly critical in the context of elite swimmers, especially those integrated into high-performance training centres and national teams, with aspirations to participate in prestigious competitions such as European championships, World championships and the Olympic Games (Costa et al., 2010; Mujika et al., 2018; Pyne et al., 2004). Moreover, it plays a vital role in fostering a healthier swimming career, avoiding the continuously rising of dropouts when the academic path starts to be more exigent (Emmonds et al., 2023). Through precise, well-developed and continually planned training, informed by comprehensive testing data, we have the potential to shift the paradigm away from imposing high volume and endless hours of swimming on the young swimmers, colloquially referred to as "counting tiles" (Clemente-Suárez et al., 2017; Nugent et al., 2017; Zacca et al., 2020).

The primary challenge that must be addressed for effective planning is comprehending the genetic requirements of swimmers and the intricate interplay between anthropometric traits and swimming performance. Factors such as age,

sex, competitive level, and swimming specialization, encompassing both technique and distance, significantly influence this relationship. By investigating into these aspects, coaches can gain valuable insights into talent identification and trainability in swimming. The systematic review with the meta-analysis presented in **Chapter 2** showed 138 anthropometrical variables assessed along the years when exploring their relationships with swimming performance (spanning from the earliest study in 1978 to the most recent in 2023). This ongoing research topic reveals that the alleged common understanding of how anthropometry influences performance, particularly in elite swimming, is not yet fully elucidated (Mallett et al., 2020; Peulic et al., 2023).

Swimming speed can be calculated by multiplying stroke frequency (the rate of upper limb cycles per time unit) with stroke length (the distance covered during a full cycle of upper limb movements, measured by the ratio of speed to stroke frequency) (Craig & Pendergast, 1979; Ribeiro et al., 2017; Silveira et al., 2017). Changes in swimming velocity are the result of either an increase or decrease in stroke frequency and stroke length (Carvalho et al., 2020; Toussaint et al., 2006). This relationship can be affected by various factors, including anthropometric characteristics. Somatic attributes, which are largely inherited, play a significant role in shaping swimming technique (Barbosa et al., 2019; Ferreira et al., 2021; Issurin, 2017; Lätt et al., 2009b) and optimal performance in swimming is traditionally associated with advanced technical skills and advantageous anthropometric dimensions (Lätt et al., 2009a; Morais et al., 2021).

Within this limited set of anthropometric variables explored in the meta-analysis, a combination of more genetically determined (height and arm span) but also trainable traits (body fat and lean mass) were included. This suggests that while a substantial genetic influence exists for enhanced swimming performance, certain traits are malleable and can be manipulated to accentuate or compensate for inherent genetic predispositions (Issurin, 2017). However, it is crucial to note that our findings are associated with a low and very low level of certainty of evidence due to an analysis with moderate risk of bias in trials, low number of

participants included in the analyses and/or the confidence interval crossed the small effect size in main analyses.

It was possible to identify positive effects of anthropometric traits in front crawl swimming, specifically in distances up to 100 m, for trained and national level swimmers corresponding to Tiers 2 and 3. However, there is a notable lack of sufficient information to describe how anthropometry impacts elite and world-class swimming performance corresponding to Tiers 4 and 5. Additionally, it was emphasized the need for more studies using tests specifically tailored to the swimmers specific technique and distance, since mechanical advantages derived from certain anthropometric traits require a minimum level of technical proficiency to be effectively achieved (Carvalho et al., 2023). Despite being known the potential gains on having bigger levers allowing to produce higher moments of force, it lacks proof that it is achieved by the swimmers. In fact, there are swimmers that defy the conventional norms regarding height and yet achieve international success (Mallett et al., 2020).

Even in the Portuguese context, there is an example of a female Portuguese swimmer that achieved 5th place in world championships and 11th position in the Olympic games whose height is 163 cm, clearly below the mean of international female swimmers (Mallett et al., 2020). A more recent example of the impact of diverse anatomies on swimming performance is evident in the results from Fukuoka, with Thomas Ceccon, the current world record holder in the 100 m backstroke, exhibiting an anatomy typically associated with optimal results in that specific technique (tall stature and long upper limb lengths). Interestingly, he also secured victory in the 50 m butterfly, despite possessing a completely different anatomy compared to Diogo Ribeiro (the smallest among the three) with less ~10 cm and Maxime Grousset (the most muscular) that finished in second and third places (respectively). Remarkably, the performance gap between those three swimmers in the final was merely 0.1 s, and in the semifinal, Maxime Grousset even achieved a better time that would have secured him the second place if repeated. There exist many other examples like the latter, particularly when

looking to the world records and international results of the 50 and 100 m front crawl events. This scenario underscores the complexity of factors influencing swimming outcomes, highlighting that diverse anatomical profiles can yield competitive success across different events. Indeed, this perspective shifts the focus from the natural selection of elite swimmers based on their inherent anthropometric traits to understanding how training and swimming techniques can be tailored to compensate for less advantageous physical characteristics.

However, for young and adolescent swimmers (based on ages of peaking performances), the impact of growth and development on their anthropometric characteristics can greatly influence technical indexes and, as a result, their overall performance (Barzdukas et al., 1992; Ferraz et al., 2020). It is widely acknowledged that swimmers sharing the same chronological age may exhibit notable differences in biological maturation, training experience and overall development (Abbott et al., 2021). While chronological age itself may not independently forecast swimming performance, it is intricately connected to critical determinants (Lobato et al., 2023). For instance, swimmers with a longer chronological age are more likely to have completed adolescence, achieved peak bone mass and possessed advantageous anthropometric and physical attributes (Dos Santos et al., 2021; Lobato et al., 2023). Additionally, older swimmers tend to showcase advanced cognitive development, including decision-making skills, as well as heightened mental and emotional factors like motivation, self-efficacy and self-esteem. The likelihood of having undergone more specialized training and competition in a specific sport also increases with higher chronological age. Thus, although chronological age is not a singular predictor, its association with performance determinants is evident.

Therefore, it is understandable that there may be challenges in interpreting the relationships between anthropometry and swimming performance, particularly when the assessments are predominantly conducted in young swimmers within low competitive tiers. Another discussion that may arise from our review is the need for standardization of the units of measures used when assessing

relationships between anthropometry and performance (e.g. body fat mass, lean mass or muscle mass presented as % of body mass or in kg). The common practice of using diverse swimming performance metrics, including velocity, time, or FINA/World Aquatics points, also diminishes the comprehensive analysis that can be performed in meta-analyses. Therefore, there is a clear call for ongoing research in the domain of swimmers' anthropometry and its relationship with performance. The imperative to refine methodologies and ensure consistency in measurements will contribute to a more robust and nuanced understanding of the intricate interplay between physical attributes and swimming outcomes, particularly in elite and world class levels.

Transitioning throughout the swimming performance deterministic model (Barbosa et al., 2013), the competitive swimming races, spanning from ~20 s to 15 min (e.g. the 50 and 1500 m events), necessitate well-developed aerobic and anaerobic energy pathways to support swimmers' exertions (Massini et al., 2023; Zamparo et al., 2011; Peyrebrune et al., 2014). The prescription of training sets is a primary concern for coaches and researchers have consistently sought to characterize various efforts in swimming (Fernandes et al., 2024; Olbrecht, 2000; Pyne et al., 2001; Toubekis & Tokmakidis, 2013; Vilas-Boas et al., 2014). To address the need for a less disruptive and time-consuming protocol, the 200 m intermittent incremental variant was chosen. The 5 x 200 m protocol (Fernandes et al., 2010) was then employed to validate its use for characterizing the anaerobic threshold across all four swimming techniques.

The results from **Chapter 3** demonstrated that the use of an intermittent incremental protocol of 5 x 200 m (30 s interval) is valid for specifically and accurately determining the $[La^-]_{AnT}$ in the four conventional swimming techniques from a biophysical perspective. Moreover, due to its shorter duration compared to other incremental protocols it may be more frequently integrated into swimming training cycles, especially at the elite level. It was observed that only in the front crawl technique were the $[La^-]_{AnT}$ lower than $4 \text{ mmol}\cdot\text{L}^{-1}$, in line with literature (Stegmann & Kindermann, 1982; Fernandes et al., 2011; Figueiredo, Morais, et

al., 2013; Pelarigo et al., 2017) that disagrees with the use of the average value of 4 mmol·L⁻¹ proposed by Mader (1978).

The mean [La⁻]_{AnT} values indeed exhibited variations among swimming techniques, ranging from < 2 to > 5 mmol·L⁻¹, indicating significant inter-variability. This divergence may be attributed to specialized anaerobic training regimen of elite swimmers, especially for those specializing in non-front crawl techniques, where competitive events typically span from 50 to 200 meters (Nugent et al., 2019; Pyne et al., 2014). It can also be consequence of the non-specialized and high-volume training commonly observed in earlier stages of their careers (Nugent et al., 2017). Emphasizing the significance of determining individual AnT, the observed wide ranges highlight the limitations of using averaged values such as 4 or 3.5 mmol·L⁻¹, which fail to account for inter-individual variability and the specificity of swimming techniques and events (Faude et al., 2009; Fernandes et al., 2010; Stegmann & Kindermann, 1982).

The differences between swimming techniques in [La⁻]_{AnT} highlight the need to determine it in the technique in which the swimmer specializes, rather than assessing it solely in the front crawl technique. This emphasizes the importance of tailoring physiological assessments to the specific demands of each swimming technique. The above-referenced comparisons between swimming techniques were made possible since v_{AnT} occurred at ~92% of the velocity of the last protocol step in all four of the swimming techniques, a similar value to that found in the literature (Fernandes et al., 2008; Zacca et al., 2016) and that can be assumed as the velocity that elicits maximal $\dot{V}O_2$ based on the secondary criteria of [La⁻] ≥ 8 mmol·l⁻¹ (Howley et al., 1995; Monteiro et al., 2022).

In **Chapter 3** it was also demonstrated an increase in SR and a decrease in SL throughout the incremental protocol across all swimming techniques. These findings align with previous research (Psycharakis et al., 2008; Figueiredo, Morais, et al., 2013). The observed changes were not linear, and from the AnT onward, they exhibited an exponential pattern. This allowed the identification of

inflection points for SR and deflection points for SL revealing that the anaerobic threshold signifies not only a physiological transition but also a biomechanical one for all four conventional swimming techniques (Fernandes et al., 2024). These results are consistent with findings by for the crawl technique in samples of ≤ 15 swimmers (Figueiredo, Morais, et al., 2013; Jesus et al. 2015; Pelarigo et al., 2016). The study presented in **Chapter 3** underscores this methodology potential to objectively quantify training intensities based on both physiological and biomechanical variables in the four conventional swimming techniques, enhancing its applicability in a training context.

It is important to recognize that all swimming events involve a combination of the different energy systems (Gastin, 2001). Despite not typically being associated with the distances and durations of competitive swimming events (ranging from 50 to 1500 meters), AnT is a crucial parameter for all swimmers (Fernandes et al., 2024). Their training often involves sessions of 2 hours or more, with most swimmers training twice a day and covering distances from 5 to 10 km per session. This underlines the utility of the AnT in enabling swimmers to perform and recover from the substantial training loads imposed on them (Fernandes et al., 2011; Skorski et al., 2012). From a general perspective, the higher the velocity at the AnT, the lower the decrease in velocities during swimming efforts and higher their capacity for recovery (Poole et al., 2021). Also, Elite swimmers have demonstrated their velocities at $\dot{V}O_2\text{max}$ and AnT to be very close to each other, likely reflecting the impact of the extensive training volumes they undergo during their development (Nugent et al., 2017).

Complementary, the comprehensive analysis of the $[La^-]$ vs. speed curve aimed to determine the $[La^-]_{\text{rate}}$ and BLIS across the four swimming techniques. The primary goal of these variables is to characterize the anaerobic contribution to efforts at intensities above AnT, specifically in the high and severe intensity domains (cf. Fernandes et al., 2011; de Jesus et al., 2015; Almeida-Coelho et al., 2016). Results revealed considerable variability among swimmers that may be attributed to the diverse sample specializations (sprint, middle-distance and long

distance), the predominantly aerobic nature of their training due to high practiced volumes (Salo, 1993; Costill, 1999) and the influence of SR and SL on those behaviours (Almeida-Coelho et al., 2016). The findings suggest that the $[La^-]_{rate}$ and BLIS can serve as a valuable metrics for analysing the impact of training on individual swimmers' anaerobic capacity. Nevertheless, it is important to note that the reproducibility of this measure should be tested in future studies.

The results presented in **Appendices I and II** indicate the feasibility of assessing AnT using a 5 x 200 m incremental medley protocol, as well as the AnT for each swimming techniques segments (using the velocities of each 50 m partial and the $[La^-]$ obtained at the end of each step of the referred step protocol). This approach enables a tactical and more objective prescription for submaximal training sets tailored to medley events. Elite swimmers demonstrated an ability to enhance their 200m velocity across all swimming techniques, underscoring the method's applicability primarily to high-skilled athletes rather than those at lower proficiency levels.

These preliminary studies also enabled the determination of $\dot{V}O_{2max}$ (and respective velocity), providing a prescription for training tailored to medley swimming throughout a large range of intensities. Notably, the $\dot{V}O_{2max}$ values obtained align with those reported for the front crawl technique among elite swimmers, but the relationship between velocities at $\dot{V}O_{2max}$ and AnT is higher compared to the front crawl swimmers (94 vs. 92%; Zacca et al., 2019), possibly due to the variable swimming velocity inherent in medley events (González-Ravé et al., 2023). Our results can be used as reference values for medley swimmers as well using that approach to plan complete training sets without needing to swim only in medley or using the front crawl technique to perform physiological enhancement training. Determination of biomechanical AnT (with SR and SL) for each technique based on the 5 x 200 m is also possible using the same method but it needs to be further explored.

Although we demonstrated that biomechanical parameters can be used to define physiological boundaries and to prescribe training sets, it is important to note that the biomechanical field offers a choice of additional information (Barbosa et al., 2010; Figueiredo, Pendergast, et al., 2013). Biomechanical evaluation plays a crucial role in improving swimmers' performance and preventing injuries caused by repetitive cyclic movements (Batalha et al., 2013; Batalha et al., 2015; Figueiredo et al., 2016; Serra et al., 2017). However, it remains uncertain how the competitive level of a swimmer influences the relationships between anthropometry, strength and power with sprint swimming performance (Amaro et al., 2019; Tan et al., 2021). The results of **Chapter 4** showed that arm span was the strongest anthropometric predictor of butterfly, backstroke and front crawl sprint performances (although few anthropometric traits were assessed). However, the breaststroke sprint model detailed here did not involve an anthropometric measure given the likelihood of the swimmers weaker technique level (evidenced by the lowest stroke index values). Those results highlight the need of a minimum level of technical quality to effectively utilize mechanical advantages (Toussaint & Truijens, 2006).

Furthermore, independently of the swimming techniques, we showed that upper limbs strength and power testing can be used to allocate swimmers in different performance groups, in accordance with a previous study (Wiażewicz & Eider, 2021). However, within the same performance level, our data was not consistent, with unclear relationships between sprint swimming performance and upper limbs strength and power. The relationships between sprint performance and the lower limbs strength and power were evident for the four techniques in the elite group and for front crawl and backstroke in the non-elite group. This outcome for the lower limbs is contrary to what was observed in the associations with the upper limbs strength variables. The importance of the lower limb strength and power assessment for the understanding of sprint performance is corroborated by direct relationships between countermovement jump work and both tethered swimming force exertion (Morouço, Neiva, et al., 2011) and sprint performance (Keiner et al., 2021). In addition, lower limbs strength and power assessment can be used

to understand the positive plyometric training effects on swimming performance (Potdevin et al., 2011).

The isokinetic dynamometer is the laboratorial gold standard to evaluate muscle strength, asymmetries and imbalances in force production, permitting analysis of specific muscle groups and movements (Batalha et al., 2015; Rupp et al., 1995; Secchi et al., 2011). Our elite group swimmers presented the higher shoulder torque and power at 300°/s, while the non-elite swimmers produced the higher torque at 90°/s and higher power at 300°/s. These results indicate that elite swimmers have greater ability to produce force under conditions closer to the real practice. An unexpected outcome of the study was the elite swimmers exhibiting lower range of motion compared to the non-elite counterparts. This result likely reflects that the most advanced swimmers selected an optimal amplitude to replicate the upper limbs actions during the in-water horizontal phases (without trunk rotation).

In **Appendix III** we have showed that only in the shoulder extension at 90°/s condition was observed that the preferred member can produce higher mean power values than the contralateral one. This could be justified by the fact that competitive swimming movements are performed at angular velocities greater than 90°/s, since there were no differences at the 300°/s condition. Considering the longer events (800 and 1500 m) with an average SR value of ~30 cycles/min (0.50 Hz) and in the fastest events (50 and 100 m) an average value of 50 cycles/min (0.83 Hz), the corresponding angular velocities will be 180 e 300°/s, respectively (Zamparo et al., 2005; Martin et al., 1981). Since swimmers are well trained at competitive angular velocities, they can suppress eventual symmetrical problems found in lower angular velocities.

The elite swimmers shoulder external and internal rotation ratios revealed lower ratios than the normative values typically observed in young swimmers and the general population (Ellenbecker & Davies, 2000; Ellenbecker & Roetert, 2003; Batalha et al., 2012). Ratios below 66% are often associated with significant

imbalances and joint instability (Ellenbecker & Davies, 2000; Ellenbecker & Roetert, 2003) and this discrepancy can be attributed to the high training volumes typical in swimming, which predominantly engage the internal rotators, potentially leading to underdevelopment of the shoulder's external rotators (Batalha et al., 2021; Bak, 2010). Therefore, is evident that elite swimmers have a necessity for regular and systematic compensatory training focused on developing the shoulder external rotation muscles, aiming for balanced muscular development (McLeod, 2010; Batalha et al., 2013).

In addition, as start time in competitive swimming might represent up to ~26% of the total race time depending on the event (Cossor & Mason, 2001) and is fundamental for the final outcome, we explored the relationships between isokinetic power produced during shoulder and knee extensions and swimming track start performance. The large and very large relationships observed between mean power and block time during the track starts demonstrated that swimmers that can produce higher power values, resulting in a high push-off velocity and long flight distance (Benjanuvatra et al., 2007; Vantorre et al., 2014), also spent more time in the block phase. However, the absence of relations between mean power production and 15 m time evidenced that, even with more time spent in the block, swimmers do not present worst 15 m performances. That observation opens a door of exploring strength training without fear of deleterious effects of start performances and the swimmers with higher shoulder and knee power need should improve the training of starting technique to be able to spend less time in block phase. However, longitudinal studies should be performed to understand how these relationships are sustain during periods of power training.

The methodology employed in this thesis allowed for the establishment of muscular strength profiles for upper and lower limbs, as well as ratios between external and internal shoulder rotation for elite swimmers. In the field of symmetry, it is important to explore the notion that symmetries in swimmers may result more from technical proficiency than from muscular or joint imbalances in a specific task. This highlights the idea that changes in laterality, or the intensity

of asymmetries, may depend on what athletes are executing (Bishop et al., 2021; Bishop et al., 2017; Morouço et al., 2015). This can vary based on factors such as different velocities, types of movements, or even in contexts where efforts are sustained for extended periods. Therefore, the need to assess and compare the asymmetries in-water and dry-land contexts in elite swimmers were of much importance. The results found in the **Chapter 5** regarding isokinetic evaluation symmetry and tethered swimming showed that the symmetry is consequence of the tasks constrains and affected by the expertise of the swimmer in realizing the task.

Additionally, it was observed that swimmers have identical contralateral force symmetry indices in and out of water, though without any relation between them, probably justified by the direction of the asymmetries. During front crawl and backstroke, the preferred upper limb seems to act as a control for local asymmetries, ensuring globally balanced swimming. In contrast, the non-preferred upper limb appears to dominate in propulsive force production (Seifert et al., 2005; Morouço et al., 2015). Thus, isokinetic evaluation proved to be a valuable tool for analysing muscular imbalances, highlighting how these can affect force production in tethered swimming.

Tethered swimming was effective in identifying asymmetries in force production related to swimming technique, particularly in front crawl and backstroke, which were not dependent on muscular imbalances. However, the symmetry topic is not yet fully consensual around scientific community due to numerous numbers of formulas to define asymmetries (Bishop et al., 2016) and requires further research and conceptualization depending on the tasks and context that they are applied. For instance, in an isokinetic test where the movement is fully controlled and defined by the machine, the objective is to evaluate muscular force production with minimal technical impact. In other hand, swimming is a task highly influenced by technical constraints and efficiency and also by the constant adaptation to the water movements and changes in support. With that, the differences in direction of symmetry even not expected was not surprising. The

novelty was the sustainability of similar contralateral asymmetries regardless being performed in dry-land or in water.

The validity and reliability of isokinetic assessments (Baltzopoulos & Brodie, 1989; Maffiuletti, et al., 2007; Bassan, et al., 2015) and tethered swimming evaluations (Dopsaj et al., 2004; Kjendlie & Thorsvald, 2006; Toubekis et al., 2010) enhance the potential of these methodologies for the evaluation and training control of swimmers. They could be valuable tools for monitoring the training process of swimmers from the beginning to the end of the sports seasons regarding the development of balanced muscular strength, as well as changes in the technical pattern of front crawl and backstroke swimming, particularly in terms of the symmetry of propulsive force application.

The tethered swimming evaluations not only allows to understand the symmetry but also the variations in force production during swimming. Swimming techniques that show greater intracycle velocity variations also exhibit larger intracycle variations in force production (Morouço, Keskinen, et al., 2011; Vilas-Boas et al., 2011) and are associated with higher energy expenditure (Fernandes et al., 2014). However, the latter associations had not yet been demonstrated, particularly in high-level competitive swimmers. The results of **Appendix IV** showed very large positive correlation between energy cost and fatigue index in a 30 s tethered swimming but lacked to show relationships between energy cost and coefficient of variation of force production.

Given the multifactorial nature of swimming performance, and that a predicting model should be as practical as possible (Silva et al., 2007), the input data selection should be derived from the literature (biomechanical, physiological, psychological, genetical and contextual variables; Barbosa et al, 2010; Figueiredo, Pendergast, et al., 2013), and integrate data easy to collect and apply in the training context (Post et al. 2022). **Chapter 6** showed that a group of simple practical tests can be used to monitoring swimming training when interpreted based on an artificial neural network model combined with Shapley additive

explanations values. It was showed that training background and duration, anthropometry, impulse and stroke rate are fundamental variables that explain competitive performance in junior swimmers. Dry-land training appeared as predominant for achieving higher FINA/World Aquatics points in the elite group. The lower limb power (expressed by lower-body countermovement jump impulse) is highly important irrespective of the level of the swimmer. A test battery of countermovement jumping, and anthropometric measures is simple to be used in the field, increasing the practical relevance of our study protocol.

An important controversial result was found in this study where height presented negative effects on swimming performance. In swimming, the taller and longer arm span swimmers typically have biomechanical advantages (Lätt et al., 2010; Strzała et al., 2020). Even if in early ages an anthropometric advantage is related with early maturational development (Lätt et al., 2009a), in adult swimmers the main anthropometric variables (such as height, weight and body mass index) are less likely to distinguish the higher performance level swimmers (Lätt et al., 2010; Dopsaj et al., 2020). Nevertheless, the outcome that arm span presented positive effects on swimming performance conforms with existing data (Strzała et al., 2020), and is more important in terms of biomechanical advantage than height. It is important to understand that anthropometry is only one of the determinants that influence swimming performance (Barbosa et al., 2010; Costa et al., 2012), and being tall alone is not sufficient to swim at a high standard.

From the consistent results of **Chapters 3 and 6** showing a good capability of lower limb strength and power to predict front crawl sprint performance or performance in general (respectively), it reopens an old discussion on the role and importance of lower limbs to the overall swimming velocity (potentially suggesting more than the 10% previously identified and accepted; Deschodt et al., 1999; Silveira et al., 2017). Our results are in line with other data indicating the importance of lower limb strength and power in dry-land capability to apply force in-water (Morouço et al., 2015; Carvalho et al., 2019). Moreover, the lower limb actions contribution to the force production in front crawl (~31%; Morouço et

al., 2015) and velocities performed only using the lower limbs actions (from 57-86% of full technique; Bartolomeu et al., 2018), justifies further explorations using new mathematical approaches (Bartolomeu et al., 2024).

The **Appendix 5** using an innovative approach applied to the velocity vs. time curve analysis (wavelet transform) showed that the lower limbs frequencies presented higher contribution (< 50%) to the total energy of the variations in the velocity signal. Therefore, we believe that the upper limbs propulsive actions, when combined with an optimal coordination of lower limbs, can help to achieve a higher mean velocity and technical stability (Fernandes et al., 2022; Silva et al., 2022). Also, the lower limbs actions remain essential to the body streamline by diminishing the trunk inclination (Andersen et al., 2023; Gourgoulis et al., 2014). It is suggested that lower limbs actions should not be considered as perturbations of the upper limbs movements (Bartolomeu et al., 2024; Gourgoulis et al., 2014) or as contributors to increased energy cost for the same relative velocities (Ribeiro et al., 2015; Silveira et al., 2017). However, further analysis is needed to better understand the frequencies contributions based on the groups division, particularly to identify if the upper limbs actions propulsive phases produce frequencies that are also related to the lower limbs actions (Barbosa et al., 2023; Bartolomeu et al., 2024).

The culmination of assessing various deterministic models related to swimming performance lies in their integration into the training periodization. This involves understanding how to incorporate their information effectively to monitor and interpret changes during different training periods (Fernandes et al., 2024; Hellard et al., 2013). Firstly, it is important to explore how the most used training load assessment methods in swimming training (one based on physiological demands and the other on psychological factors) respond and compare to each other during an overload period. In the longitudinal study, presented in **Chapter 7** results showed that total load (physiological) and RPE load (psychophysiological) methods behaved similarly for most of the monitoring period, differing only during competitive moments or Saturday training sessions.

It appears that elite swimmers typically perceive accurately the loads imposed on them in daily training but indicating that physiological and psychological loads have different influences and should be considered in parallel when characterizing external loads. The autonomic nervous system response, defined mainly as changes in the HRV behaviour (Buchheit, 2014), could reproduce the external load (independently of the assessment method) that the elite swimmer was subjected to. A mean overload of 27% in training loads (physiological) within a two-week period did not impair dry-land strength and swimming performances in elite swimmers nor their profile of mood state.

Several studies have employed training load prescription based HRV measurements (Garet et al., 2004; Javaloyes et al., 2020; Nakamura et al., 2015; Vesterinen et al., 2016). However, a notable lack of consistency in the methods used to assess its sensitivity is apparent (Manresa-Rocamora et al., 2021). The sensitivity of HRV should be defined by its capability to predict changes observed in training loads, as alterations in performance are intricately tied to cardiac autonomic activity and other physiological factors (Halsen & Jeukendrup, 2004; Mujika et al., 2018). Establishing a standardized and reliable approach to assess HRV sensitivity is crucial for its effective utilization in training load prescription and monitoring. If HRV fails to consistently mirror daily shifts in training loads, it casts doubt on their value as reliable markers for monitoring training.

Our results demonstrated that vagally mediated biomarkers appears to be highly sensitive to changes in training loads and capable of predicting the daily training loads imposed to swimmers. Since elite swimmers appear to have different fatigue thresholds, overload periods should be individualized and the observed increases in mean HR and decreases LnRMSSD after an overload period should not be considered as an overtraining symptom. Instead, these changes should be interpreted as a normal response to a short-term increase in training load (confirmed by the lack modification on HRV between cycles 2 and 3 with similar training loads). A combination of HRV, psychological and performance monitoring

can be implemented to evaluate the effects of short-term overloading training periods imposed in competitive swimmers.

For the analysis of the results of the **Chapter 7**, we decided to use the Bonferroni correction to be as conservative as possible, avoiding mislead by the increase of type 1 error. At first glance it is important to explore the elite data as a group to have a stronger generalizing power and defining patterns in this specific group. That approach helped us to define new concepts and compare with the “normal” population of swimmers. However, in elite swimming, success is based on the smallest margins (every World championship or Olympic Games final proves it; Santos et al., 2023) often pushing up against their genetic ceiling (Pyne et al., 2004). As such, it is more important to reduce false negatives (Turner et al., 2021) and respective potential opportunities that may stimulate positive adaptations.

Other frequently used correction approaches, such as the Holm-Bonferroni (step-down), the Hochberg-Bonferroni (step-up) and false discovery rates could be used (Menyhart et al., 2021). From these, the former correction can be a more viable approach to our sample and study design (repeated measures and lower number of subjects and comparisons). Since the initial statistical analysis (with Bonferroni corrections) presented several almost significant changes, we believed that highlighting that new results could bring relevant discussion. Using that approach new modifications on HRV were observed decrease in supine RMSSD and an increase in peak HR. That chapter allowed to demonstrate also how analysis using elite swimmers or other athletes should be explored from different ways.

An important discussion that emerged from this last research is the training load assessment. Since the calculation of any load needs to present a measure of volume (e.g., time, distance, repetitions) and intensity (e.g. kg, velocity, HR or lactate zones). The latter one can be absolute or normalized/relative to the swimmer (Impellizzeri et al., 2023), and for calculations of normalized intensity in an early phase it is needed internal data collection that could be from a

physiological test or even using the RPE. Some misconceptions in our point of view are presented regarding the RPE when assuming that it is an internal load representative, when it should be rather a normalizer of intensity to use for training/exercise load calculations.

Throughout this academic work, we can understand that the efficiency of the training process is profoundly determined by the ability to gather objective data about the capacities and needs of each swimmer. Thus, the effectiveness of the training process can only be improved if accompanied by an enhancement of the methodologies used to assess in a multidisciplinary way several determinants of swimming performance. However, this thesis serves as a checkpoint of more objective evaluation and control of training as also highlighted elsewhere (Fernandes et al., 2024). It is worthwhile to continue evolving in research, initially attempting to address some of the limitations presented in the current studies. The preparation of an elite swimmer is not a fortuitous process it is an extremely complex and time-consuming process that involves numerous variables of diverse nature. We were able to present research embracing the principal determinants groups that are involved in swimming performance (see Figure 1 of **Chapter 1**), and how to combine them in testing and monitoring protocols to understand the training effects and fatigue thresholds from elite swimmers.

Other important factor that emerged from the studies present in this thesis is how to describe, present and analyse elite swimmers' data to provide proper information for their training. Lastly but not least, the goal of this thesis was, in addition to produce knowledge, to give support to all swimmers and coaches in their daily training process. From all the tests presented along this work, reports were produced for the swimmers and coaches together with an explanation about how they could interpret and use the information for training. The incremental protocol was the most applied given its relevance to define training zones (see Fernandes et al., 2024) based both on physiological and biomechanical variables.

Chapter 9

Conclusions

In this section, we consolidate the insights and implications derived from our extensive research focused on evaluation and training control in swimming. This thesis has navigated through intricate experimental investigations and a rigorous review of specialized literature, culminating in a set of conclusions that advance our comprehension of effective evaluation methods and training strategies for competitive swimming. The conclusions presented here are the result of an in-depth analysis of empirical data, alignment with current scientific understanding, and practical applicability in training contexts. They aim to provide valuable perspectives on optimizing swimmer performance, enhancing training methodologies, and refining evaluation techniques. The following are the key conclusions drawn from our research, offering a synthesis of our findings and their significance in the field of swimming evaluation and training control:

- (i) With low and very low certainty of evidence, body lean mass, height and arm span seems to favour better performances in front crawl up to 100 m in male but only arm span in females for the regional and national levels. The knowledge of influence of anthropometrics on performance in international and world class level swimmers remains limited;
- (ii) The commonly employed 5 x 200 m intermittent incremental protocol proved effective in accurately assessing the AnT in all four conventional swimming techniques and in medley.
- (iii) The individual anaerobic threshold in the four conventional swimming techniques seems to be a biophysical boundary that can be determined by assessing $[La^-]$ behaviour and general biomechanical parameters (especially SR and SL);
- (iv) The $[La^-]$ at AnT varies with each of the four conventional swimming techniques, emphasizing the importance of determining AnT in each

swimmer's specialty, beyond the commonly used front crawl for aerobic capacity development;

- (v) The $[La^-]_{rate}$ and BLIS are useful tools for quantifying anaerobic system energy beyond the AnT boundary and for monitoring the training effect on swimmers' anaerobic capacity;
- (vi) AnT in medley swimming represent higher percentage of the $\dot{V}O_{2max}$ compared to the other conventional swimming techniques;
- (vii) Elite swimmers demonstrated higher strength and power levels in both upper and lower limbs compared to non-elite counterparts. These attributes showed moderate to large positive correlations with sprint swimming performance;
- (viii) Variables related to upper and lower limbs strength effectively differentiated top and low-tier sprint performances, regardless of the employed swimming technique;
- (ix) Only countermovement jumps related variables sustain its capability of distinguish better sprint performance in elite swimmers and, therefore, should be used for controlling sprint performance training;
- (x) Evaluating muscle imbalances should closely replicate the swimmers' training movements, as they demonstrated the capacity to decrease muscle asymmetry when the assessment aligns with their training practices, particularly the angular velocities of the limbs action;
- (xi) Swimmers showed significant imbalance in shoulder rotation strength with external to internal rotation ratios falling below normative values, suggesting a risk for severe imbalances and joint instability;
- (xii) It is crucial to integrate compensatory training that targets and strengthens the shoulder external rotators, ensuring balanced muscle development and reducing potential for injury;
- (xiii) Swimmers with greater average power in shoulder and knee extensions have longer block times during starts with no negative impact on 15 m performance;
- (xiv) While swimmers exhibit comparable symmetry indices in aquatic and dry-land settings, these indices are not related. Asymmetries observed during

swimming are likely due to technical adjustments made by swimmers to the aquatic environment constraints, whereas asymmetries measured in dry-land isokinetic contexts are attributed to muscular imbalances. This distinction underlines the complexity of interpreting symmetry in different conditions;

- (xv) The swimmers preferred upper limb seems to be used for technique control and to balance asymmetries during swimming, while their non-preferred arm contributes more to propulsive force;
- (xvi) Isokinetic tests and tethered swimming effectively detect force production asymmetries, but they serve different purposes, particularly for identifying muscular imbalances and assessing swimming technique (respectively);
- (xvii) Swimmers that better sustain higher propulsive forces over 30 s tethered test showed with lower energy costs at 200 m front crawl;
- (xviii) Tethered swimming test seems an effective tool for real-time technical efficiency assessment, where swimmers should aim to minimize inter-cycle force variations;
- (xix) It is possible to predict swimming performance (FINA/World Aquatics points) based on simple tests applied in daily training when using an artificial neural network model combined with Shapley additive explanations values;
- (xx) Training background and duration, anthropometry, impulse and stroke rate are fundamental variables that explain competitive performance in junior swimmers;
- (xxi) Dry-land training emerged as a predominant factor for achieving higher FINA/World Aquatics points in the elite swimmers;
- (xxii) It was demonstrated that the lower limb power (expressed by lower-body countermovement jump impulse) is highly important irrespective of the level of the swimmer;
- (xxiii) Frequency analysis using wavelet transform of the velocity-time curve is effective for examining contributions of various frequency groups to the overall signal, demonstrating high accuracy with minimal error between original and reconstructed data;

- (xxiv) It was found that frequencies normally assumed for lower limbs alone accounted for about $50.0 \pm 4.6\%$ of the signal energy, highlighting their significant contribution to swimming performance, reigniting the debate on the overall role of lower limbs in swimming;
- (xxv) A mean overload of $\sim 27\%$ in training loads within a two-week period did not impair dry-land strength and swimming performances in elite swimmers nor their mood state profile;
- (xxvi) Vagally-mediated biomarkers proved to be highly sensitive to changes in training loads and capable of interpreting variations in daily training loads imposed on swimmers (regardless of the assessment method);
- (xxvii) Since elite swimmers demonstrated different fatigue thresholds, overload periods should be individualized. The observed increases in mean HR and decreases in LnRMSSD after an overload period should not be considered as an overtraining symptom, but rather a normal response to a short-term increase in training load;
- (xxviii) In an individualized analysis it was showed that only when impairments in swimming or strength performance post-overload periods are coupled with adverse HRV and mean heart rate responses, it may indicate the onset of an overtraining syndrome that is challenging to reverse within the typical two-week tapering period;
- (xxix) A combination of vagally-mediated biomarkers, psychological and performance monitoring tools should be used to define and evaluate training loads in competitive swimmers.

Chapter 10

Recommendations for future research

The primary objective of this dissertation was to showcase the potential of training evaluation and control, aiming to facilitate its integration into the swimmers training process. Considering our findings, we believe it is crucial to continue researching this topic, with a specific focus on:

- (i) Exploring the relationships between anthropometric characteristics and performance in elite swimmers using swimming performance tests in their specialty regarding swimming technique and distance, controlling the sex and age effects.
- (ii) Exploring the effect of changes in the $[La^-]$ vs swimming velocity relationship along the training seasons and improvements in swimming performance along all distances and techniques;
- (iii) Exploring the use of AnT for medley swimming using biomechanical parameters, particularly SR and SL;
- (iv) Analyse a wider range of swimmers divided by swimming technique specialty and level to clarify the effect of upper and lower limbs strength and power on sprint performance;
- (v) Analyse the symmetry in the production of force in swimmers of different performance levels, in aquatic and dry-land settings, to understand the influence of the performance level on eventual symmetries;
- (vi) Assessing the variability of the symmetry index throughout the tethered swimming test, specifically examining how fatigue can influence technical efficiency and symmetry;
- (vii) Exploring the use of different methods of calculation of contralateral asymmetries in a longitudinal approach comparing the responses in different competitive levels and sex;
- (viii) Exploring the capability of countermovement jump training on improving swimming performances, particularly in sprint events.

- (ix) Exploring the use of artificial neural network model with Shapley additive explanations values combining the results in simple tests and combining with information of training loads to predict performance enhancements along the training season;
- (x) Determine if there is, indeed, a cause-and-effect relationship between isokinetic power and higher time spent in the start block phase;
- (xi) Additional analysis is required to gain a more comprehensive understanding of frequency contributions within the velocity signal, especially concerning the division of upper and lower limb frequency groups. It is essential to investigate the interplay of frequencies between upper and lower limb actions;
- (xii) Develop new methods to assess the training loads in swimming and combining it with daily HRV measurements and performance assessment in the beginning and end of overload training periods to provide useful insights of swimmers individual limits of training loads;
- (xiii) Investigate the individual effects of consecutive cycles (along a training season) of overload periods followed by tapering and a competition on daily HRV and swimming performance to confirm these contentions also including effects on swimming biomechanical variables.

Chapter 11

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Chapter 1

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Chapter 2

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Appendix I

Assessment of the individual anaerobic threshold in medley swimmers

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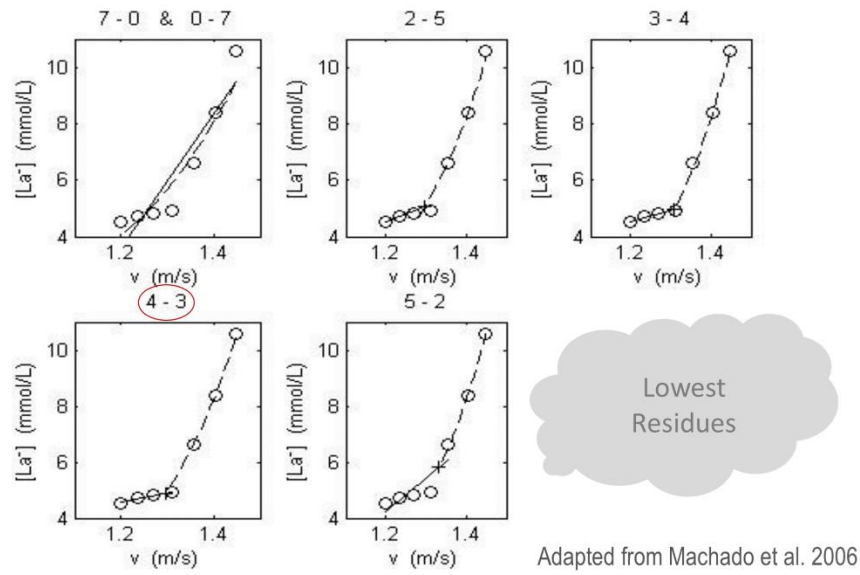
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Program and Abstracts of the XIIIth International Symposium on Biomechanics and Medicine in Swimming

Abstract

The anaerobic threshold (AnT) is the preferential indicator of aerobic capacity and, although different methodologies are used to assess it, individualized approaches are the most adequate (in opposition to the widely spread standard mean 4.0 mmol/l value). This has been almost exclusively done using the front crawl technique, with few studies conducted in backstroke, breaststroke and butterfly and none carried out in medley. Since aerobic capacity is also frequently developed using medley training sets, we aimed to assess the AnT in medley through the blood lactate concentrations $[La^-]$ and velocity curve, following two approaches (see Figure 1): (i) using an individual medley (50 m per swimming technique - 200 m medley) step protocol and (ii) using the velocities of each 50 m partial and the $[La^-]$ obtained at the end of each step of the referred step protocol. Eleven elite swimmers (nine male and two females of 19.6 ± 2.1 and 21.5 ± 0.7 years of age) performed a 5 x 200 m medley intermittent protocol (increments of 0.05 m/s between steps and 30 s intervals), with blood samples being collected from the fingertip at rest, during the intervals and at the end of the protocol. The AnT was assessed by the combination of linear and exponential regressions using the (La^- vs velocity curve modelling method (cf. Fernandes et al, 2011). Paired t-test was performed to compare data. $[La^-]$ at AnT was 3.94 ± 0.97 mmol/l (ranging from 1.7 to 5.1 mmol/l), demonstrating its high variability between subjects, although v_{AnT} and $v_{4 \text{ mmol/L}}$ were similar 1.38 ± 0.04 and 1.37 ± 0.05 m/s). Using the second approach, the interpolated v_{AnT} for each swimming technique were 1.58 ± 0.05 , 1.37 ± 0.07 , 1.20 ± 0.07 and 1.41 ± 0.06 m/s respectively for butterfly, backstroke, breaststroke and front crawl, with the v_{AnT} being 1.39 ± 0.04 m/s (similar to the v_{AnT} assessed considering the final 200 m performances; $p > 0.05$). Data suggest that it is possible to assess AnT in a 5 x 200 m incremental medley protocol, as well as a medley segmented AnT, allowing a tactical and more objective submaximal training set prescription for medley events.

Approach 1



Adapted from Machado et al. 2006

Approach 2

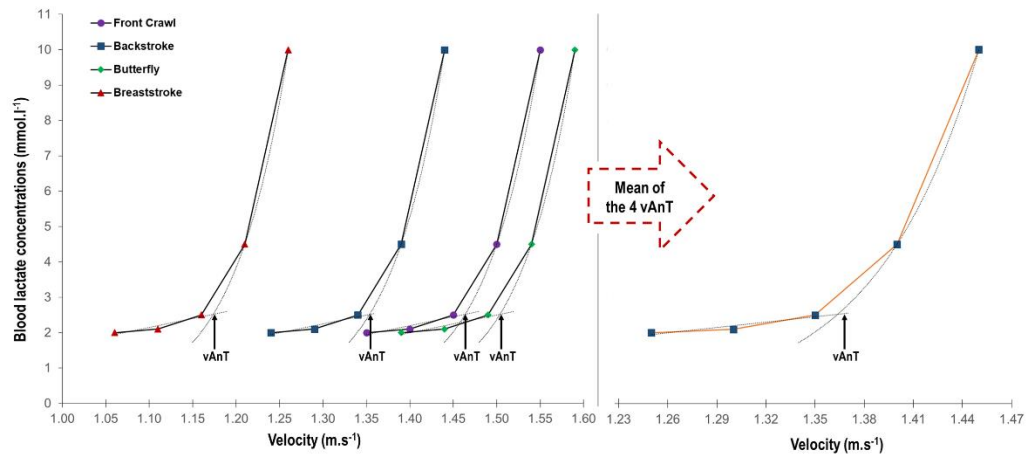


Figure 1: Example of the two approaches used to determination of medley v_{AnT} .

Appendix II

Avaliação do limiar anaeróbio e consumo máximo de oxigénio em nadadores de estilos

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Motricidade, 15, 30-31 (Distinguished with the 1st Prize at the 42nd Technical-Scientific Congress of the Portuguese Swimming Association)

Introdução

O limiar anaeróbio (LAn) e o consumo máximo de oxigénio ($\dot{V}O_{2\text{máx}}$) são indicadores preferenciais de avaliação da capacidade e potência aeróbias de nadadores. A sua determinação é frequente para especialistas numa determinada técnica de nado (sobretudo em crol), desconhecendo-se valores de referência para estilos (ainda que a capacidade e a potência aeróbias sejam frequentemente treinadas utilizando séries onde se combinam as quatro técnicas convencionais). Neste estudo determinaram-se as concentrações de lactato sanguíneo ($[La^-]$) e o $\dot{V}O_2$ correspondentes aos LAn e $\dot{V}O_{2\text{máx}}$, e respetivas velocidades (v_{LAn} e $v\dot{V}O_{2\text{máx}}$) em estilitas.

Métodos

Sete nadadores e quatro nadadoras de elite (19.0 ± 3.2 vs. 17.5 ± 2.4 anos de idade e 790 ± 87 vs. 762 ± 60 pontos FINA aos 200 m estilos), realizaram um protocolo incremental intermitente de 5 x 200 m estilos (incrementos de $0.05\text{m}\cdot\text{s}^{-1}$ entre patamares e 30s de intervalos). As $[La^-]$ (Lactate Pro 2, Arkay, Japão) e o $\dot{V}O_2$ (K4b², Cosmed, Itália) foram avaliados após cada patamar. A partir da curva velocidade vs. $[La^-]$, o LAn foi assumido como o ponto de interceção da combinação de uma regressão linear e uma exponencial (Fernandes et al., 2011), utilizando-se duas abordagens: (i) as velocidades e $[La^-]$ finais de cada 200 m e (ii) as velocidades de cada parcial de 50m e as $[La^-]$ do patamar correspondente. O $\dot{V}O_2$ foi determinado através de uma regressão linear dos valores dos primeiros 20 s de recuperação. A correlação de Pearson, a correlação intraclasse e o teste t de medidas repetidas foram utilizados para calcular o grau de associação e a fiabilidade, e para comparar as v_{LAn} ($p < 0.05$). A v_{LAn} de estilos foi expressa em % da $v\dot{V}O_{2\text{máx}}$ de estilos. A v_{LAn} de cada técnica foi expressa em % da performance de cada técnica nos 200 m estilos competitivos à data da avaliação.

Resultados

Os valores das $[La^-]$ ao LAn e o $\dot{V}O_{2m\acute{a}x}$ foram de $4.5 \pm 0.9 \text{ mmol}\cdot\text{L}^{-1}$ e $68.0 \pm 7.8 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$. As v_{LAn} obtidas com as duas abordagens foram semelhantes (1.359 ± 0.067 vs. $1.366 \pm 0.065 \text{ m}\cdot\text{s}^{-1}$; $r = 0.98$; $CCI = 0.991$; $IC95\% = [0.966-0.998]$), correspondendo a $94.2 \pm 0.2\%$ da $v\dot{V}O_{2m\acute{a}x}$. Para cada técnica de nado, as v_{LAn} obtidas foram 1.54 ± 0.09 , 1.37 ± 0.07 , 1.20 ± 0.07 e $1.41 \pm 0.06 \text{ m}\cdot\text{s}^{-1}$ (mariposa, costas, bruços e crol, respetivamente), correspondendo a 85.9 ± 4.1 , 86.2 ± 3.9 , 89.2 ± 3.3 e $84.4 \pm 4.9\%$ das velocidades na prova de 200 m estilos de cada nadador.

Discussão

A proximidade entre as $[La^-]$ ao LAn e o valor fixo de $4 \text{ mmol}\cdot\text{L}^{-1}$ deve ser vista com cautela uma vez que a variabilidade existente entre nadadores ($3-6.4 \text{ mmol}\cdot\text{L}^{-1}$) demonstra a necessidade de uma avaliação individualizada. Os valores de $\dot{V}O_{2m\acute{a}x}$ encontrados são semelhantes aos reportados na técnica de crol em nadadores de elite. No entanto, a relação entre a v_{LAn} e a $v\dot{V}O_{2m\acute{a}x}$ é superior à descrita para crolistas (94 vs. 92% cf. Zacca et al., 2019) possivelmente pelo facto da v_{LAn} não ser constante durante uma prova de estilos. O presente estudo possibilitou determinar o LAn e $\dot{V}O_{2m\acute{a}x}$ específicos de estilos (e respetivas velocidades), permitindo uma prescrição de treino submáximo tático e mais objetivo para eventos de estilos.

Appendix III

Isokinetic evaluation of elite swimmers: does it well relate with starting performance?

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Abstract

The aim of the current work was to isokinetic evaluate, in a contralateral way, two of the most characteristic movements of swimmers training process (shoulder and knee extensions) and the muscles related to one of the most swimming characteristic injuries (shoulder internal and external rotators). In addition, it was aimed to determine the existence of direct relationship between isokinetic force and track start related variables. Thirteen elite swimmers performed five isokinetic evaluations (shoulder and knee extension at 90 and 300°/s, and shoulder internal and external rotation at 180°/s) and three 15 m starts (using track start technique) on an instrumented starting block. It were registered the mean power for all isokinetic evaluations and the torque for shoulder rotation, as well as the block, movement and 15 m times. Repeated measures t-test was used for individual comparisons between contralateral upper and lower limbs isokinetic force variables and Pearson correlation coefficients (controlling gender effect) were calculated between isokinetic force variables and start performance. Results suggest that when simulated movements assume characteristics close to the actual practice, swimmers are appreciably symmetrical regarding upper limbs actions (90°/s = 107.0 ± 36.4 vs 95.9 ± 34.7 with $p < 0.05$, and 300°/s = 202.0 ± 87.2 vs 191.1 ± 84.0 with $p > 0.05$). However, due to the high training volumes with internal rotators prevalence, the low ratios between shoulder internal and external rotation found (61.4 ± 10.4 and $53.8 \pm 7.0\%$ for preferred and non-preferred upper limb, respectively) shows that the importance that is normally recommended for the balanced muscle development should be reinforced. In addition, swimmers with higher values of power in shoulder and knee extension spend more time spend in block during starts, but without being prejudicial to 15 m performances.

Keywords: swimming, biomechanics, isokinetic, start, performance

Introduction

Biomechanical evaluation is fundamental to enhance performance in competitive swimming, since it depends on both physical condition and technique (Fernandes & Vilas-Boas, 2006; Zamparo et al., 2014). In addition, competitive swimming involves systematic training (typically twice per day), repeating the same movements thousand times per training unit, leading to the development of overload injuries (Becker, 2011; Serra et al., 2017). Complementarily, it is expected that, for hydrodynamic and inertial reasons, swimming technique should be symmetrical, i.e., the contralateral movements performed by the upper and lower limbs follow the same motor path and the force and resultant power applied by each body side are similar.

In this sense, the extension of the shoulder and knee (two of the most characteristic swimming movements) and the muscles most related to the internal and external rotation of the shoulder (in which occurs the shoulder pain, one of the most characteristic swimmers injuries; Van Dorssen et al., 2015) need deeper analyses regarding contralateral force production. Our aims were to evaluate the above referred movements regarding power production, analyzing eventual differences between contralateral limbs and defining the ratio between shoulder internal and external rotation torque forces. In addition, as start time in competitive swimming might represent up to ~25% of the total race time (depending on the event), and is fundamental for the final outcome, a complementary aim was to determine if isokinetic power produced during shoulder and knee extensions is directly related with swimming track start performance.

Methods

Thirteen swimmers from the Olympic and Pre-Olympic Portuguese swimming team (10 with right and three with left lateral preference), eight males and five females, voluntarily participated in the current study. Their main physical

characteristics were: 21.6 ± 4.1 vs 19.8 ± 2.5 years old, 76.1 ± 9.5 vs 60.7 ± 4.7 kg of body mass, 1.80 ± 0.50 vs 1.68 ± 0.55 m of height, 23.4 ± 2.1 vs 21.5 ± 1.7 of BMI and 834.6 ± 28.6 vs 827.4 ± 28.9 FINA points of best competitive performance, for male and female swimmers (respectively). It was observed that males are taller and heavier than females, but without any other difference even regarding their best competitive performance (evidencing a similar expertise level). Swimmers and coaches were informed about the purpose of the evaluations and any known risks, providing individual consent for participation in the experiments.

Three tests were performed on an isokinetic dynamometer (Biodex System 4 - Biodex Medical Systems, Inc., USA): shoulder internal and external rotation, and extension and flexion, as well as knee extension and flexion. Shoulder and knee extension tests were performed at two distinct velocities (90 and 300°/s), while shoulder internal and external rotation were performed only at 180 degrees/s. It was considered the mean power values in all the tests, as well as the mean torque in shoulder rotation, for constructing a ratio between shoulder internal and external rotation. The above-referred velocities were chosen to obtain a low angular velocity normally used for clinical proposes (ratio analyses) and a high angular velocity similar with velocities obtained when swimming.

Swimmers were instructed to perform maximal one-way force during the shoulder and knee extension phase, looking for a more realistic approach to the swimming motions. Swimmers were installed in the dynamometer chair according to the manufacturer's instructions, being the handgrip on shoulder extension the only modification (Figure 1). After a warm-up period on free dynamometer (without constrain of velocity), each swimmer performed five sub-maximal repetitions at each pre-defined angular velocity for adaptation. The tests consisted in performing 10 maximal repetitions, with at least 90 s of rest between repetitions, with strong verbal encouragement from the evaluators.



Figure 1. Conditioning in Biodex for upper limb simulated action (left: initial position; right: final position). The identified circles represent the hand positioning.

In addition, three maximal 15 m trials were performed, six swimmers in front crawl and seven in butterfly (with 5 min minimum rest in-between). For collecting starting time data (the best trial was chosen for subsequent analysis) it was used the track start technique and an instrumented starting block (cf. Mourão et al., 2015). It were analysed the duration of the block time (between starting signal and the block loss contact - referred as "reaction time" by the timing systems), the movement time (since the first visible change of the block reaction forces and the loss of contact - block time subtracted to reaction time) and the 15 m time (time until the head crosses the 15 m mark). At the beginning of the testing session, subjects completed a brief questionnaire providing their training background and to determine whether they had left or the right body side preferences for starting and swimming.

An independent samples t-test was implemented for comparing gender characteristics and a repeated measures t-test was used for individual comparisons between contralateral upper and lower limbs isokinetic force variables. Pearson correlation coefficients (controlling gender effect) were calculated between isokinetic force variables and start performances, with the force values of preferred and nonpreferred limbs being combined in one to represent upper and lower limb force. The threshold used to qualitatively assess the correlations used the following criteria: < 0.1 (trivial), 0.1-0.3 (small), 0.3-0.5 (moderate), 0.5-0.7 (large), 0.7-0.9 (very large) and > 0.9 (nearly perfect), for a p

< 0.05 level (Hopkins, 2002). All statistical procedures were conducted on SPSS 25.0 statistical software (IBM, USA).

Results

Results concerning the comparison of the preferred and non-preferred upper and lower limbs regarding power production are presented in Table 1. In the shoulder extension at 90°/s, the preferred member produced higher mean power values than the non-preferred upper limb ($p < 0.05$). In all other force variables, there is a similar power production between contralateral body sides.

Table 1. Mean $\pm$ SD power values of the preferred and non-preferred limbs during shoulder and knee extension, and shoulder internal and external rotation.

Variable	Preferred side	Non-Preferred side
Shoulder extension power at 90°/s (W)	107.0 $\pm$ 36.4	95.9 $\pm$ 34.7*
Shoulder extension power at 300°/s (W)	202.0 $\pm$ 87.2	191.1 $\pm$ 84.0
Knee extension power at 90°/s (W)	173.0 $\pm$ 49.8	176.3 $\pm$ 51.8
Knee extension power at 300°/s (W)	308.0 $\pm$ 109.0	298.0 $\pm$ 84.6
Internal rotation power at 180 °/s (W)	79.8 $\pm$ 41.4	76.7 $\pm$ 36.4
External rotation power at 180 °/s (W)	51.7 $\pm$ 26.2	47.3 $\pm$ 20.6

*Significant differences ($p \leq 0.05$)

Table 2 presents the mean $\pm$ SD torque values of shoulder internal and external rotation and the ratio between them. It is possible to understand that, even presenting similar contralateral torque values for shoulder internal and external rotation ($p > 0.05$), the ratio of shoulder rotators tends to be higher for the preferred upper limb than for the non-preferred ($p < 0.10$). It is also possible to observe that the ratios of shoulder rotators in our swimmers are lower than the normative values presented for normal persons or for above head sports (66-75%, respectively).

Table 2. Torque values of shoulder internal and external rotation and corresponding rotators torque ratio.

Variable	Shoulder internal rotation (N·m ⁻¹)	Shoulder external rotation (N·m ⁻¹)	Ratio (%)
Preferred upper limb	55.0 ± 21.9	32.9 ± 12.8	61.4 ± 10.4
Non-Preferred upper limb	55.8 ± 20.9	29.8 ± 9.5	53.8 ± 7.0

In addition, Table 3 presents the correlation coefficients (and *p* values) between starting and isokinetic power related variables. There are direct relationships between shoulder extension power at 90 and 300°/s and block and movement times, as well between knee extension power at 90°/s and movement time (*p* < 0.05).

Table 3. Pearson correlation coefficients (and *p* values) between starting performances and isokinetic power variables.

	Block time	Movement time	15 m time
Shoulder extension power at 90°/s	.66 (.03)	.83 (.00)	-.14 (.68)
Shoulder extension power at 300°/s	.71 (.02)	.74 (.01)	.01 (.98)
Knee extension power at 90°/s	.51 (.11)	.78 (.00)	-.29 (.40)
Knee extension power at 300°/s	.39 (.23)	.58 (.06)	.30 (.38)

Discussion

Only in the shoulder extension at 90°/s condition was observed that the preferred member can produce higher mean power values than the contralateral one. This could be justified by the fact that competitive swimming movements are performed at angular velocities greater than 90°/s, since there were no differences at the 300°/s condition. Considering the longer events (800 and 1500 m) with an average SR value around 30 cycles/min (0.50 Hz) and in the fastest events (50 and 100 m) an average value of 50 cycles/min (0.83 Hz), the corresponding angular velocities will be respectively, 180 e 300°/s. Therefore,

once swimmers are well trained at competitive angular velocities, they are able to suppress eventual symmetrical problems found in lower angular velocities. The upper limbs angular velocity during swimming can be calculated with the formula: angular velocity (in rad/s) = $2\pi \times \text{stroke rate (SR)}$ being necessary to convert afterwards to °/s (Zamparo et al., 2005; Martin et al., 1981).

The comparisons between shoulder external and internal rotation of our swimmers presented lower ratios than normative values for young swimmers and common people (values < 66% are usually related to severe imbalances and joint instability; Ellenbecker & Davies, 2000; Ellenbecker & Roetert, 2003; Batalha et al., 2012). This can be explained by the swimming typically high training volumes with prevalence of internal rotators, which will lead to a lower development of the shoulder external rotators (Bak, 2010). This finding reinforces the need to regularly and systematically promote a compensatory training centred on the development of the shoulder external rotation muscles, seeking a balanced muscular development (McLeod, 2010; Batalha et al., 2013).

The large and very large relationships observed between mean power and block time during the track starts ($r = [.66 \text{ to } .83]$ with $p < 0.05$) demonstrate that swimmers that are able to produce higher power values, resulting in a high push-off velocity and long flight distance (Benjanuvatra et al., 2007; Vantorre et al., 2014), also spend more time in the block phase to make that possible. However, the absence of relations between mean power production and 15 m time evidence that, even with more time spent in the block, swimmers will not present worst 15 m performances. This finding suggests that coaches and swimmers should improve the training of starting technique to be able to spend less time in block phase combined with power training. Further research is needed to determine if there is, indeed, a cause-and-effect relationship between power acquisition and higher time spent in start block phase.

Conclusion

When laboratorial simulated movements assume characteristics closer to those of actually swimming, swimmers are more symmetrical regarding upper limbs. The importance given to the muscular development of shoulder external rotators should be reinforced in order to obtain better force ratios between shoulder rotators. In addition, swimmers with higher mean power, at shoulder and knee extension, spend more time in block during starts, without being prejudicial to 15 m performances.

Appendix IV

Energy cost and propulsive force variability in elite front crawl swimmers

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Abstract

Metabolic conditioning and propulsive force development are fundamental to achieve higher swimming performances, justifying its systematic evaluation. We aimed to assess the energy cost and propulsive force variables during front crawl maximal efforts, confirming their eventual direct relationship. Eight elite swimmers, four male and four female (20.5 ± 1.3 vs 18.5 ± 2.4 years old and 829 ± 23 vs 845 ± 26 FINA points of best competitive performance) performed 200m bout and 30 s stationary tethered maximal front crawl tests.

Blood lactate concentrations ($[La^-]$) and oxygen uptake ($\dot{V}O_2$, assessed by backward extrapolation) were obtained during the 200m test recovery period, allowing computing energy expenditure (E) and energy cost (C; Figueiredo et al., 2011). In addition to general propulsive force variables (minimum, maximum and mean force values), the fatigue index (Findex, the ratio between the difference of the first and last 5s mean force, and the mean force of first 5 s), propulsive force decay (Fdecay, the slope of the propulsive force regression line) and respective coefficient of variation (CV, ratio between the standard deviation and the average of the mean force), were determined for the 30 s tethered exertion.

During the 200 m swim a velocity of $1.61 \pm 0.07 \text{ m} \cdot \text{s}^{-1}$, $11.0 \pm 0.4 \text{ mmol} \cdot \text{L}^{-1}$ of $[La^-]$, $71.3 \pm 8.2 \text{ mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ of $\dot{V}O_2$, $263.6 \pm 44.0 \text{ kJ}$ of E and $1.32 \pm 0.22 \text{ kJ} \cdot \text{m}^{-1}$ of C were observed, with aerobic, anaerobic lactic and anaerobic alactic pathways accounting for 75.1 ± 1.6 , 13.8 ± 2.3 and $11.0 \pm 1.1\%$ of E. In tethered swimming, it were obtained 16.27 ± 2.02 , 282.7 ± 19.1 and $117.2 \pm 7.8 \text{ N}$ of minimum, maximum and mean force, $17.4 \pm 11.7\%$ of Findex, $0.98 \pm 0.8 \text{ N} \cdot \text{s}^{-1}$ of Fdecay and $51.8 \pm 5.9\%$ of CVforce. Very large correlation values were observed between C and Findex ($r = 0.80$, $p = 0.018$), and Fdecay ($r = -0.80$, $p = 0.019$). No relationships were found between C and CVforce, and between Findex, Fdecay and CVforce ($p > 0.05$).

Data suggest that coaches and swimmers should focus on the ability to resist to fatigue through the achievement of a higher swimming economy (lower C) when performing the front crawl technique. In addition, the lack of relationships between C and CVforce is probably explained by the different tests duration that, although being performed at maximal effort, represent different metabolic intensities.

Appendix V

Upper and lower limbs contribution during maximal front crawl swimming: a frequency approach

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Abstract

We seek to separate and analyse each limb frequencies energy relative to the velocity signal total energy throughout wavelet transform. Eight elite swimmers (two males and six females) completed a 25 m front crawl maximal effort. A mechanical speedometer attached to a belt around the swimmers hip acquired the instantaneous velocity. The velocity vs. time curve (without the gliding and finishing sections) was analysed by continuous wavelet transform using the Analytic Morlet wavelet family. Frequency groups were formed for the upper and lower limbs (0.6 to 2.5 and 2.5 to 7.5 Hz) based on the stroke frequency associated to sprint swimming and the ratio of 1:3 for upper to lower limbs. The energy of each group of frequencies oscillates during the maximal front crawl bout ranging from 23.7 ± 2.8 to 47.2 ± 5.0 and from 36.2 ± 8.3 to $62.4 \pm 4.8\%$ of upper and lower limbs frequencies (respectively). The energy frequencies of the upper and lower limbs explained 72-93% of the total energy of the velocity variations signal, and in $50.0 \pm 4.6\%$ by the lower limbs corresponding frequencies. These surprisingly results suggest that the contribution of the lower limbs in maintaining or rising sprint swimming velocity may be much greater than previously thought.

Keywords: sprint swimming, wavelets transform, front-crawl

Introduction

Swimming is a demanding form of locomotion that requires coordination of the upper and lower limbs to efficiently propel the body in a highly resistant environment (Guignard et al., 2019). Traditionally, the coordination between upper and lower limbs is assessed using frequency ratios, such as 1:1, 1:2 and 1:3, with the numerator and the denominator representing the number of upper and lower limbs actions (Guignard et al., 2019; Millet et al., 2002). The 1:3 frequency ratio is normally associated with sprinting and high swimming velocities (Mezêncio et al., 2020; Guignard et al., 2019; Silveira et al., 2017). Besides the widespread assumption of the optimal 1:3 frequency ratio demonstrating that synchronised and coordinated actions can produce a smooth force to time profile resulting in a reduced intra-cycle velocity variation (Mezêncio et al., 2020), the lower limbs propulsion contribution in front crawl swimming remains ambiguous (Bartolomeu et al., 2018).

Within front crawl swimming, limbs contribution seems to differ, with the lower limbs actions being commonly considered a factor of secondary importance for front crawl propulsion (10-15%), while the upper limbs showed a predominant propulsive role, accounting for ~85-90% of the total propulsion (Andersen & Sanders, 2018; Gourgoulis et al., 2014; Deschodt et al., 1999). However, the previous referred studies use the upper limbs swimming as a reference to compare to the full body swimming (Gourgoulis et al., 2014; Deschodt et al., 1999). Contrasting findings have emerged, indicating that swimmers can attain roughly 57-86% of the velocity achieved during full-body swimming when relying solely on the lower limbs (Bucher, 1975; Bartolomeu et al., 2018). Other approaches, like tethered front crawl swimming (Morouço et al., 2015) and simulating front crawl swimming in a dry-land machine (Swaine et al., 2010), found lower limbs actions contribution (~31% and $37.3 \pm 4.1\%$, respectively).

These controversial results with higher percentages of lower limbs contribution undoubtedly put in question the believe that swimming propulsion is almost

entirely due to upper limbs and trunk (Toussaint & Beek, 1992), at least over short duration and very high intensity bouts. Therefore, the role of the lower limbs action during swimming needs to be further explored using a novel approach. The wavelet transform can simultaneously elucidate local spectral and temporal information within a signal, and capture changes in frequency content over time, making it suitable for analysing signals with transient events or varying frequencies (Zheng & Yuan, 2022). Since the contribution of the lower limbs to the overall swimming velocity remains unclear and is an important research topic, the aim of the current work was to use wavelet transform on velocity vs. time curve to separate and analyse the energy of the frequencies assigned to upper and lower limbs to the total energy of the transformed velocity signal.

Methods

Eight elite junior swimmers (two male and six female) of [17, 18] vs. 15.4 ± 1.2 years of age, [176, 181] vs. 169.0 ± 4.1 cm of height and [63.3, 73.8] vs. 58.4 ± 4.5 kg of body mass, with [705, 775] vs. 704 ± 64 World Aquatics (FINA) points of best competitive front crawl performance (respectively) voluntarily participated in the current study. Swimmers were classified as level 3 (Ruiz-Navarro et al., 2023) and five were sprinters. All participants were healthy (with no serious injury or illness in the last six months) and provided individual consent for participation after explanation of the purpose, procedures, benefits and risks of the study. The project was conducted in accordance with the local research ethics committee (CEFADE 28 2019) and the Declaration of Helsinki.

In a 1.90 m deep 25 m indoor swimming pool with 27° C water temperature and after a 1000 m low to moderate swimming warm-up (Neiva et al., 2014), swimmers performed 25 m front crawl at a maximal intensity starting in water and without a standardised breathing pattern. A mechanical speedometer attached to the swimmers hip at the central point of the lumbar region measured the instantaneous velocity during the trial with a sample rate of 50 Hz. Swimmers performances were recorded by an underwater and an aerial camera (Go Pro 7,

California, USA), operating at 120 Hz sampling frequency, with 1920×1080 pixel resolution in wide mode, fixed to a camera set-up that was pushed alongside the pool (Fernandes et al., 2022). Video and speedometer were synchronized by visual and auditive signals.

The velocity vs. time curve assessed through the speedometer (without the gliding and finishing sections) was analysed by continuous wavelet transform using the Analytic Morlet wavelet family on MATLAB (MATLAB R, 2023a, The MathWorks Inc., Natick, MA, USA). Previously, the data was clustered by energy magnitude via K-means analysis, forming three groups (the first group with energy $< 1\%$ of the signal total energy was eliminated). Frequency groups were then created for the upper (0.6 to 2.5 Hz) and lower limbs (> 2.5 to 7.5 Hz) based on the assumption that the velocity curve is composed by the frequencies of the contralateral upper and lower limbs, up to twice the frequencies assumed for a complete cycle (Guignard et al., 2019; Arellano et al., 2022; Morais et al., 2022). Velocity vs. time curves were reconstructed with the frequencies associated with upper and lower limbs and the contribution curves for each frequency group was computed.

Biomechanical analysis was performed through videos with Kinovea software (Charmant & contributors, 2021) to allow assessment of the upper and lower limbs cycle rates (between 7.5 and 20 m sprint section) by the time taken to complete three consecutive upper or lower limbs cycles. The video was used also to confirm the time analysis limitations imposed to the velocity vs. time curve and to interpret the wavelet transforms based on swimming limbs actions. Since the literature assumes the upper limbs as main responsible for propulsive forces during front crawl swimming (Andersen & Sanders, 2018; Gourgoulis et al., 2014), the frequency cut-off of 2.5 Hz was chosen to minimize the upper limbs frequencies that could be found on lower limbs group. Descriptive analyses were obtained for all variables and data were checked for distribution normality with the Shapiro-Wilk test.

Results

Front crawl sprint performance, upper and lower limbs rates and energy transformations are presented in Table 1, with a minimum of 1:3 upper to lower limbs frequency ratio being found for all swimmers. The individual limbs rates assessed through video analysis reached up to 2.2 and 7 Hz for one upper and lower limbs action (respectively). The total energy of velocity vs. time signal was explained between 72 and 93% and the velocity vs. time curve was reconstructed with a mean error between the original and reconstructed curves integrals of [0.0007 to 0.011%] using the trapezoidal rule. The lower limbs frequencies contribution presented an average of 50% of the total energy of the velocity variations signal.

Table 1. Biomechanical variables extracted from video recording and upper and lower limbs frequencies energy during the 25 m front crawl sprint.

Variables	Mean $\pm$ SD	Min energy (mean $\pm$ SD)	Max energy (mean $\pm$ SD)
25 m time (s)	13.67 $\pm$ 0.71	-	-
25 m velocity (m·s ⁻¹)	1.83 $\pm$ 0.10	-	-
Stroke rate (cycles·min ⁻¹)	52.7 $\pm$ 3.7	-	-
Lower limbs cycle rate (cycles·min ⁻¹)	160.0 $\pm$ 13.4	-	-
Stroke rate (Hz)	0.88 $\pm$ 0.06	-	-
Lower limbs cycle rate (Hz)	2.67 $\pm$ 0.22	-	-
Upper limb action rate (Hz)	1.76 $\pm$ 0.12	-	-
Lower limb action rate (Hz)	5.33 $\pm$ 0.45	-	-
Upper limbs (% of total energy of the signal)	35.1 $\pm$ 3.5	23.7 $\pm$ 2.8	47.2 $\pm$ 5.0
Lower limbs (% of total energy of the signal)	50.0 $\pm$ 4.6	36.2 $\pm$ 8.3	62.4 $\pm$ 4.8
Upper + lower limbs (% of total energy of the signal)	85.2 $\pm$ 2.3	71.7 $\pm$ 4.0	93.0 $\pm$ 2.1

The mean with standard deviation contribution curves of upper and lower limbs frequency groups during the 25 m front crawl swimming of the eight swimmers can be observed in the Figure 1. The higher frequencies presented a consistent higher contribution for the total energy of the velocity variations signal.

Complementary, an example of the frequency energy contribution analysis and reconstruction of the velocity vs. time curve for a female and a male sprint swimmer is showed in the Figure 2 (panels A and B, respectively). Both male and female presented similar combined frequencies contribution but with different behaviours, particularly the female upper and lower limbs that alternated their contribution numerous times (Figure 2 - panel A).

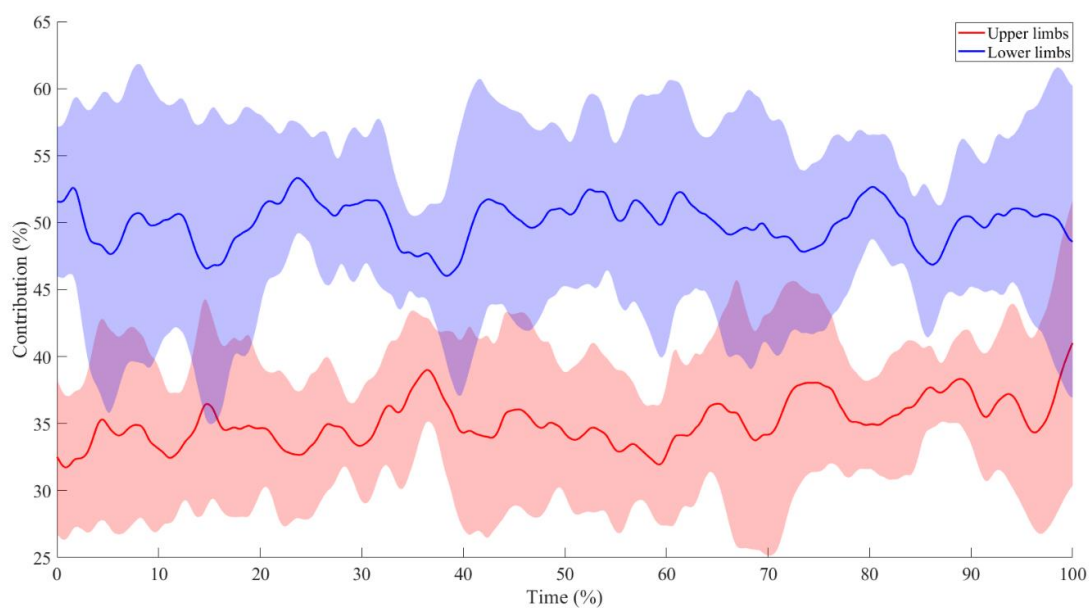


Figure 1. Mean with standard deviation contribution curves of upper and lower limbs frequency groups during the 25 m front crawl swimming (red and blue curves, respectively).

Discussion

The current results showed that all swimmers adopted the 1:3 frequency ratio when sprinting at front crawl, corroborating the existing literature (Guignard et al., 2019; Mezêncio et al., 2020). The assessed swimming velocities and stroke rates are similar to sprint events (Arellano et al., 2022) and to high velocities associated with the 1:3 frequency ratio (Mezêncio et al., 2020). During sprint events (i.e., in Olympic and World Championships) swimmers reach stroke rates up to 70 cycles·min⁻¹ in the first 25 m of the competition, corresponding to 1.17 and 2.34 Hz for upper limbs cycle and action (respectively; Arellano et al., 2022; Morais et al., 2022). The observed maximum values of 2.2 and 7 Hz for upper and lower

limbs actions (respectively) are in line with literature, corroborating our 2.5 Hz cut-off as conservative and proper frequency groups division.

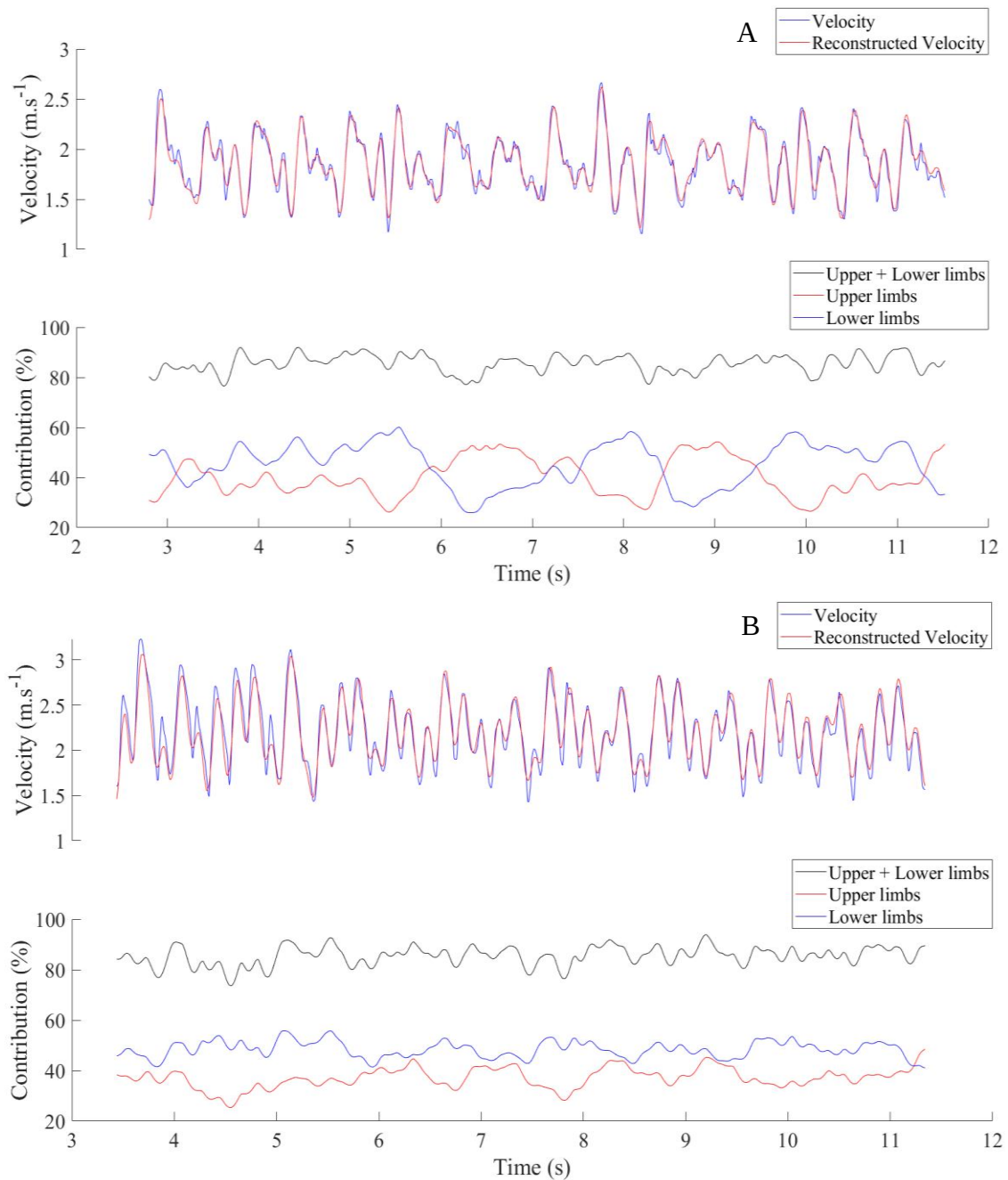


Figure 2. Example of one female (panel A) and male (panel B) sprint swimmers velocity vs. time curves (original and reconstructed with the frequencies from upper and lower limbs groups) and contribution curves of upper + lower, upper and lower limbs frequency groups during the 25 m front crawl swimming (black, red and blue curves, respectively).

The energy of each frequency group oscillated during the 25 m front crawl, with the lower limbs frequencies presenting higher contribution ($< 50\%$) to the total energy of the velocity variations signal. These results evidence the possible impact of lower limbs actions in the overall full body swimming propulsion, conserving kinetic energy, allowing a reduced intra-cycle velocity variation profile, by helping to overcome the inertia caused by the upper limbs coordination (Chollet et al., 2000; Mezêncio et al., 2020). Therefore, we believe that the upper limbs propulsive actions, when combined with an optimal coordination of lower limbs, can help to achieve a higher mean velocity and technical stability (Fernandes et al., 2022). Also, the lower limbs actions remain essential to the body streamline by diminishing the trunk inclination, suggesting that lower limbs actions should not be considered as perturbations of the upper limbs movements (Gourgoulis et al., 2014).

Our results evidenced that the reconstruction of the swimming velocity vs. time curve through the inverse continuous 1-D wavelet transform is a good approach, confirmed by the almost inexistant percentual error between the original and reconstructed curves integrals using the trapezoidal rule. This demonstrates that the energy contributions can explain the swimming instantaneous velocity variations during a 25 m front crawl sprint. The curious results observed on the female regarding the shifts of upper and lower limbs actions contribution to the overall signal energy where then associated with a synchronized video analysis. It was observed that the highest peaks in the lower limbs actions contribution coincided with a more prominent downward movement (the most propulsive phase, characterized by a higher knee flexion; Wei et al., 2014) on their dominant side during the entry phase of the dominant upper limb, by probably adding thrust in the beginning of the propulsive phase (Mezêncio et al., 2020). However, that effect was not observed in consecutive upper limbs cycles, explaining the shifts of upper limbs contribution and lack of technique consistency.

The video analysis also allowed to observe that the male swimmer had a more regular lower limbs actions that can indicate a more stable swimming technique

and coordination between upper and lower limbs actions. This seems to justify the ability of maintaining the lower limbs actions contribution consistently above the upper ones, similar to the mean behaviour found in Figure 1. The surprising results of the current study open an old discussion about lower limbs overall contribution in maintaining or rising velocity during full body swimming, suggesting that their importance may be much greater than previously thought. However, further analysis is needed to better understand the frequencies contributions based on the groups division, particularly to identify if the upper limbs actions propulsive phases produce frequencies that are also related to the lower limbs actions.

Supplementary material I

Table S1. Full search strategies for PubMed, Scopus, Web of Science databases, and Biomechanics and Medicine in Swimming Symposia.

Database	Observations	Adapted Query and Database Filters
Scopus	The search for title and abstract also includes keywords	(TITLE-ABS-KEY (swim*) AND TITLE-ABS-KEY (perform* OR test* OR velocity* OR speed* OR distance* OR "FINA point*" OR "World Aquatic" OR time OR bout*) AND TITLE-ABS-KEY (anthropometr* OR somat* OR "body composition" OR bioimpedance OR morpholo* OR skinfold* OR "skin fold*"))
PubMed	Nothing to report	"swim*"[Title/Abstract] AND ("perform*"[Title/Abstract] OR "test*"[Title/Abstract] OR "velocity*"[Title/Abstract] OR "speed*"[Title/Abstract] OR "distance*"[Title/Abstract] OR "fina point*"[Title/Abstract] OR "world aquatic*"[Title/Abstract] OR "time"[Title/Abstract] OR "bout*"[Title/Abstract]) AND ("anthropometr*"[Title/Abstract] OR "somat*"[Title/Abstract] OR "body composition"[Title/Abstract] OR "bioimpedance"[Title/Abstract] OR "morpholo*"[Title/Abstract] OR "skinfold*"[Title/Abstract] OR "skin fold*"[Title/Abstract])
Web of Science	Title/abstract is not available in this database. The option "Topic" includes title, abstract and keywords, and is used instead	swim* (Topic) AND Perform* OR test* OR velocity* OR speed* OR Distance* OR "FINA point*" OR "World Aquatic" OR time OR Bout* (Topic) AND Anthropometr* OR somat* OR "body composition" OR Bioimpedance OR morpholo* OR skinfold* OR "skin fold*" (Topic)
Biomechanics and Medicine in Swimming Symposia	Title/abstract is not available in this database. The option "All Fields" is used instead	(All Fields: swim*) AND (All Fields: Perform* OR test* OR velocity* OR speed* OR Distance* OR "FINA point*" OR "World Aquatic point*" OR time OR Bout*) AND (All Fields: Anthropometr* OR somat* OR "body composition" OR Bioimpedance OR morpholo* OR skinfold* OR "skin fold*")

Supplementary material II

Table S2. Studies characteristics and correlations.

Authors (year)	Total sample - Females (%) / Males (%) G1 - n Males / n Females G2 - n Males / n Females (...)	Tier Age (mean $\pm$ SD)	Correlational domain Variable performance – Variable anthropometry: $r=*$ (*significant correlation)
Abbes et al., (2023)	16 - Males (100%)	Tier 2 13.13 $\pm$ 2.06 years	200m front crawl v (m.s ⁻¹) - height (cm): $r = 0.490^*$ 200m front crawl v (m.s ⁻¹) - body mass (kg): $r = 0.465^*$
Akşit et al., (2017)	50 - Males (50%) / Females (50%) 25 Males / 25 Females	Tier 3 Males / Females 12.4 $\pm$ 1.2/ 12.0 $\pm$ 0.9 years	Males / Females critical velocity (m.s ⁻¹) - triceps skinfold (mm): $r = -0.10 / r = 0.10$ critical velocity (m.s ⁻¹) - subscapular skinfold (mm): $r = 0.13 / r = 0.25$ critical velocity (m.s ⁻¹) - midaxillary skinfold (mm): $r = 0.22 / r = 0.32$ critical velocity (m.s ⁻¹) - chest skinfold (mm): $r = -0.08 / r = 0.31 / r = 0$ critical velocity (m.s ⁻¹) - biceps skinfold (mm): $r = -0.02 / r = 0.34^*$ critical velocity (m.s ⁻¹) - suprailiac skinfold (mm): $r = 0.49^* / r = 0.19$ critical velocity (m.s ⁻¹) - abdominal skinfold (mm): $r = 0.22 / r = 0.03$ critical velocity (m.s ⁻¹) - thigh skinfold (mm): $r = -0.02 / r = 0.21$ critical velocity (m.s ⁻¹) - calf skinfold (mm): $r = 0.16 / r = 0.42^*$ critical velocity (m.s ⁻¹) - sitting height (cm): $r = 0.68^* / r = 0.54^*$ critical velocity (m.s ⁻¹) - arm span (cm): $r = 0.75^* / r = 0.40^*$ critical velocity (m.s ⁻¹) - forearm (cm): $r = 0.37^* / r = 0.29$ critical velocity (m.s ⁻¹) - thigh (cm): $r = 0.57^* / r = 0.02$ critical velocity (m.s ⁻¹) - lower leg (cm): $r = 0.75^* / r = 0.47^*$ critical velocity (m.s ⁻¹) - total leg (cm): $r = 0.73^* / r = 0.23$ critical velocity (m.s ⁻¹) - foot (cm): $r = 0.78^* / r = 0.44^*$ critical velocity (m.s ⁻¹) - biacromial diameter (cm): $r = 0.72^* / r = 0.17$ critical velocity (m.s ⁻¹) - transverse chest breadth (cm): $r = 0.81^* / r = 0.55^*$ critical velocity (m.s ⁻¹) - bideltoid breadth (cm): $r = 0.80^* / r = 0.57^*$ critical velocity (m.s ⁻¹) - bitrochanteric breadth (cm): $r = 0.71^* / r = 0.57^*$ critical velocity (m.s ⁻¹) - biepicondylar humerus breadth (cm): $r = 0.73^* / r = 0.37^*$ critical velocity (m.s ⁻¹) - styloid breadth (cm): $r = 0.47^* / r = -0.17$ critical velocity (m.s ⁻¹) - hand width (cm): $r = 0.69^* / r = 0.03$ critical velocity (m.s ⁻¹) - biepicondylar femur breadth (cm): $r = 0.73^* / r = 0.03$ critical velocity (m.s ⁻¹) - foot width (cm): $r = 0.79^* / r = 0.19$ critical velocity (m.s ⁻¹) - shoulder girth (cm): $r = 0.77^* / r = 0.64^*$ critical velocity (m.s ⁻¹) - thoracic girth (cm): $r = 0.64^* / r = 0.60^*$ critical velocity (m.s ⁻¹) - relaxed arm girth (cm): $r = 0.63^* / r = 0.52^*$ critical velocity (m.s ⁻¹) - biceps flexed circumference (cm): $r = 0.65^* / r = 0.61^*$ critical velocity (m.s ⁻¹) - forearm girth (cm): $r = 0.70^* / r = 0.49^*$ critical velocity (m.s ⁻¹) - wrist girth (cm): $r = 0.69^* / r = 0.27$ critical velocity (m.s ⁻¹) - hip girth (cm): $r = 0.72^* / r = 0.66^*$ critical velocity (m.s ⁻¹) - thigh circumference (cm): $r = 0.61^* / r = 0.61^*$ critical velocity (m.s ⁻¹) - calf circumference (cm): $r = 0.69^* / r = 0.50^*$ critical velocity (m.s ⁻¹) - ankle girth (cm): $r = 0.70^* / r = 0.45^*$ critical velocity (m.s ⁻¹) - endomorphy: $r = 0.14 / r = 0.17$ critical velocity (m.s ⁻¹) - mesomorphy: $r = 0.18 / r = -0.24$ critical velocity (m.s ⁻¹) - ectomorphy: $r = -0.16 / r = -0.55^*$

Table S2. (continued)

Authors (year)	Total sample - Females (%) / Males (%) G1 - n Males / n Females G2 - n Males / n Females (...)	Tier Age (mean $\pm$ SD)	Correlational domain Variable performance – Variable anthropometry: $r=*$ (*significant correlation)
Araújo et al., (1979)	16 - Males (69%) / Females (31%) 11 Males / 5 Females	Tier 3 Males / Females 15.4 $\pm$ 0.4 / 15.2 $\pm$ 0.6 years	males / females 12.5 m front crawl time (s) - endomorphy: $r = 0.22$ / $r = 0.30$ 12.5 m front crawl time (s) - mesomorphy: $r = -0.08$ / $r = 0.16$ 12.5 m front crawl time (s) - ectomorphy: $r = 0.22$ / $r = -0.56$
Banerjee, (2019)	25 - Males (100%)	Tier 3 16.5 $\pm$ 0.5 years	50 m front crawl time (s) - foot width (cm): $r = 0.16$ 50 m front crawl time (s) - foot length (cm): $r = 0.22$ 50 m front crawl time (s) - calf circumference (cm): $r = -0.47^*$ 50 m front crawl time (s) - thigh circumference (cm): $r = -0.48^*$
Barbosa et al., (2019)	1 - Males (100%)	Tier 5 25 years	50 m front crawl time (s) - lean body mass (kg): $r = -0.55^*$
Barzdukas et al., (1992)	101 - Females (100%) G1: 49 Females G2: 28 Females G3: 24 Females	Tier 3 G1: 168.48 $\pm$ 11.45 months G2: 184.36 $\pm$ 3.96 months G3: 196.43 $\pm$ 3.95 months	200 m front crawl time (s) - BMI (kg/m ²): $r = 0.86^*$
Bielec & Jurak, (2019)	41 - Males (63%) / Females (37%) 26 Males / 15 Females	Tier 2 Males / Females 12.1 $\pm$ 0.5 / 12.2 $\pm$ 0.5 years	Males / Females 50 m front crawl (FINA points) - body height (cm): $r = 0.67^*$ / $r = 0.60^*$ 50 m front crawl (FINA points) - hand width (cm): $r = 0.39^*$ / $r = 0.39$ 50 m front crawl (FINA points) - hand length (cm): $r = 0.51^*$ / $r = 0.52^*$ 50 m front crawl (FINA points) - arm span (cm): $r = 0.60^*$ / $r = 0.57^*$ 50 m front crawl (FINA points) - body mass (kg): $r = 0.16$ / $r = 0.47$ 50 m front crawl (FINA points) - BMI (kg/m ²): (kg/m ²): $r = -0.33$ / $r = 0.14$ 50 m front crawl (FINA points) - body fat (%) $r = -0.58^*$ / $r = 0.15$ 200 m medley (FINA points) - body height (cm): $r = 0.57^*$ / $r = 0.44$ 200 m medley (FINA points) - hand width (cm): $r = 0.35$ / $r = 0.21$ 200 m medley (FINA points) - hand length (cm): $r = 0.44^*$ / $r = 0.50$ 200 m medley (FINA points) - arm span (cm): $r = 0.49^*$ / $r = 0.43$ 200 m medley (FINA points) - body mass (kg): $r = 0.09$ / $r = 0.36$ 200 m medley (FINA points) - BMI (kg/m ²): (kg/m ²): $r = -0.33$ / $r = 0.06$ 200 m medley (FINA points) - body fat (%) $r = -0.56^*$ / $r = -0.00$
Bond et al., (2015)	50 - Males (42%) / Females (58%) 21 Males / 29 Females	Tier 3 Males / Females 13.6 $\pm$ 1.7 / 13.4 $\pm$ 1.3 years	100 m front crawl time (s) - height (m): $r = -0.654^*$ 100 m front crawl time (s) - body mass (kg): $r = -0.543^*$ 100 m front crawl time (s) - arm length (cm): $r = -0.561^*$ 100 m front crawl time (s) - lower arm length (cm): $r = -0.483^*$ 100 m front crawl time (s) - hand length (cm): $r = -0.626^*$ 100 m front crawl time (s) - upper leg length (cm): $r = -0.350^*$ 100 m front crawl time (s) - foot length (cm): $r = -0.494^*$ 100 m front crawl time (s) - sum of skinfolds (mm): $r = 0.410^*$

Table S2. (continued)

Authors (year)	Total sample - Females (%) / Males (%) G1 - n Males / n Females G2 - n Males / n Females (...)	Tier Age (mean $\pm$ SD)	Correlational domain Variable performance – Variable anthropometry: $r=*$ (*significant correlation)
Carvalho et al., (2023)	30 - Males (50%) / Females (50%) G1 Elite: 9 Males / 7 Females G2 Non-elite: 6 Males / 8 Females	Tier 3 and Tier 4 Males / Females G1: 20.7 $\pm$ 3.3 / 20.7 $\pm$ 3.3 years G2: 15.9 $\pm$ 1.7 / 15.9 $\pm$ 1.7 years	Males / Females G1: 25 m butterfly time (s) - arm span (cm): $r = -0.37$ / $r = -0.56$ 25 m backstroke time (s) - arm span (cm): $r = -0.06$ / $r = -0.69$ 25 m front crawl time (s) - arm span (cm): $r = -0.39$ / $r = -0.76$ G2: 25 m butterfly time (s) - arm span (cm): $r = -0.51$ / $r = -0.04$ 25 m backstroke time (s) - arm span (cm): $r = -0.36$ / $r = -0.12$ 25 m front crawl time (s) - arm span (cm): $r = -0.70$ / $r = -0.50$ All 25 m butterfly time (s) - arm span (cm): $r = -0.34^*$ 25 m backstroke time (s) - arm span (cm): $r = -0.39^*$ 25 m front crawl time (s) - body mass (kg): $r = -0.46^*$ 25 m front crawl time (s) - arm span (cm): $r = -0.69^*$ 25 m front crawl time (s) - height (cm): $r = -0.56$
Chatard et al., (1990)	84 - Males (57%) / Females (43%) 48 Males / 36 Females	Tier 3 Males / Females 16.1 $\pm$ 3.5 / 14.8 $\pm$ 2.0 years	Males / Females 400 m front crawl v (m.s ⁻¹) - height (cm): $r = 0.64$ / $r = 0.66$ 400 m front crawl v (m.s ⁻¹) - body mass (kg): $r = 0.61$ / $r = 0.70$ 400 m front crawl v (m.s ⁻¹) - body surface area (m ²): $r = 0.64$ / $r = 0.70$ 400 m front crawl v (m.s ⁻¹) - height (cm): $r = 0.71$ / $r = 0.49$ 400 m front crawl v (m.s ⁻¹) - body mass (kg): $r = 0.72$ / $r = 0.61$ 400 m front crawl v (m.s ⁻¹) - body surface area (m ²): $r = 0.73$ / $r = 0.58$
Costa et al., (2020)	12 - Males (100%)	Tier 4 and Tier 5 20.0 $\pm$ 3.54 years	200 m front crawl time (s) - height (m): $r = -0.47^*$ 200 m front crawl time (s) - body mass (kg): $r = -0.45^*$ 200 m front crawl time (s) - arm span (m): $r = -0.51^*$
Daly et al., (1988)	247 - Males (49%) / Females (51%) 121 Males / 126 Females	Tier 4 Males / Females 15.5 (range from 10.8 to 22.7) / 14.5 (range from 10.0 to 18.0) years	Males / Females 100 m breaststroke time (s) - height (cm): $r = 0.52^*$ / $r = 0.37^*$ 100 m breaststroke time (s) - height ² /body mass: $r = -0.50^*$ / $r = -0.21^*$ 100 m breaststroke time (s) - shoulder width/hip width (cm): $r = 0.23^*$ / $r = 0.09$ 100 m breaststroke time (s) - hand surface/drag surface (cm ²): $r = -0.36^*$ / $r = -0.34^*$ 100 m breaststroke time (s) - foot surface/drag surface (cm ²): $r = -0.49^*$ / $r = -0.25$
Demirkan et al., (2019)	22 - Males (45%) / Females (55%) 10 Males / 12 Females	Tier 3 Males / Females 11.9 $\pm$ 0.7 / 12.1 $\pm$ 0.9 years	50 m butterfly time (s) - height (cm): $r = -0.460^*$ 50 m breaststroke time (s) - height (cm): $r = -0.484^*$ 50 m butterfly time (s) - upper limb length (cm): $r = -0.449^*$ 50 m breaststroke time (s) - upper limb length (cm): $r = -0.536^*$ 50 m breaststroke time (s) - biceps circumference (cm): $r = -0.430^*$ 50 m breaststroke time (s) - hand length (cm): $r = -0.491^*$ 50 m breaststroke time (s) - upper body length (cm): $r = -0.501^*$

Table S2. (continued)

Authors (year)	Total sample - Females (%) / Males (%) G1 - n Males / n Females G2 - n Males / n Females (...)	Tier Age (mean $\pm$ SD)	Correlational domain Variable performance – Variable anthropometry: $r=*$ (*significant correlation)
Demirkan et al., (2023)	40 - Males (100%) G1: 20 Males G2: 20 Males	Tier 3 G1: 12.50 $\pm$ 0.51 years G2: 14.35 $\pm$ 0.48 years	G1 50 m front crawl time (s) - arm span (cm): $r = -0.81^*$ 50 m front crawl time (s) - chest circumference (cm): $r = -0.73^*$ 50 m front crawl time (s) - lean body mass(kg): $r = -0.72^*$ 50 m front crawl time (s) - height (cm): $r = -0.75^*$ G2: 50 m front crawl time (s) - forearm circumference (cm): $r = -0.73^*$ 50 m butterfly time (s) - height (cm): $r = -0.74^*$ 50 m butterfly time (s) - arm span (cm): $r = -0.75$ 50 m butterfly time (s) - forearm circumference (cm): $r = -0.84^*$ 50 m butterfly time (s) - wrist diameter (cm): $r = -0.74^*$ 50 m backstroke time (s) - foot length (cm): $r = -0.72^*$ 50 m backstroke time (s) - forearm circumference (cm): $r = -0.71^*$
do Bonfim et al., (2021)	25 - Females (100%) G1 pre-menarche: 16 Females G2 post-menarche: 9 Females	Tier 2 Total: 13.92 $\pm$ 2.05 years G1: 11.7 $\pm$ 0.63 years G2: 15.17 $\pm$ 1.36 years	G1 / G2 100 m front crawl time (s) - skinfold thickness triceps + abdomen + thigh (tenth of a mm): $r^2 = 0.039$; $r = -0.20$ / $r^2 = 0.015$; $r = -0.12$ 100 m front crawl time (s) - body mass (kg): $r^2 = 0.199$; $r = -0.45$ / $r^2 = 0.295$; $r = -0.54^*$ 100 m front crawl time (s) - height (cm): $r^2 = 0.000$; $r = 0.0$ / $r^2 = 0.326$; $r = 0.57^*$ 100 m front crawl time (s) - BMI (kg/m^2): $r^2 = 0.010$; $r = 0.1$ / $r^2 = 0.048$; $r = 0.22$
Dopsaj et al., (2020)	82 - Males (56%) / Females (44%) 46 Males / 36 Females	Tier 4 Males / Females 22.9 $\pm$ 4.2 / 21.0 $\pm$ 4.7 years	Males / Females FINA points - height (cm): $r = 0.187$ / 0.535^* FINA points - body mass (kg): $r = 0.215$ / 0.396^* FINA points - BMI (kg/m^2): (kg/m^2): $r = 0.087$ / -0.085 FINA points - body fat (kg): $r = -0.148$ / -0.566^* FINA points - skeletal lean body mass (kg): $r = 0.350^*$ / 0.730^* FINA points - lean body mass (kg): $r = 0.294^*$ / 0.702^* FINA points - body fat (%): $r = -0.224$ / -0.695^* FINA points - skeletal lean body mass (%): $r = 0.353^*$ / 0.732^* FINA points - lean body mass (%): $r = 0.223$ / 0.697^* FINA points - body fat index (kg/m^2): $r = -0.170$ / -0.642^* FINA points - skeletal lean BMI (kg/m^2): (kg/m^2): $r = 0.323^*$ / 0.684^* FINA points - lean BMI (kg/m^2): (kg/m^2): $r = 0.228$ / 0.621^* FINA points - protein fat index (kg): $r = 0.392^*$ / 0.655^*
Douda et al., (2010)	72 G1 pre-pubertal: 30 G2 pubertal: 42	Tier 2 G1: 10.5 $\pm$ 0.5 years G2: 13.7 $\pm$ 1.5 years	G1 / G2 / All 50 m front crawl time (s) - height (cm): $r = -0.44^*$ / $r = -0.64^*$ / $r = -0.73^*$ 50 m front crawl time (s) - body mass (kg): $r = 0.07$ / $r = -0.56^*$ / $r = -0.618^*$ 50 m front crawl time (s) - arm span (cm): $r = -0.40^*$ / $r = -0.65^*$ / $r = -0.72^*$ 50 m front crawl time (s) - sitting/standing height ratio: $r = -0.01$ / $r = -0.04$ / $r = -0.02$ 50 m front crawl time (s) - biacromial diameter (mm): $r = -0.30$ / $r = -0.57^*$ / $r = -0.65^*$ 50 m front crawl time (s) - chest breadth (mm): $r = -0.27$ / $r = -0.46^*$ / $r = -0.59^*$ 50 m front crawl time (s) - shoulder circumference (cm): $r = -0.46^*$ / $r = -0.52^*$ / $r = -0.68^*$ 50 m front crawl time (s) - chest circumference (cm): $r = -0.33$ / $r = -0.51^*$ / $r = -0.65^*$ 50 m front crawl time (s) - arm circumference (cm): $r = -0.15$ / $r = -0.35^*$ / $r = -0.52^*$ 50 m front crawl time (s) - midthigh circumference (cm): $r = -0.28$ / $r = -0.42^*$ / $r = -0.56^*$ 50 m front crawl time (s) - calf circumference (cm): $r = 0.27$ / $r = -0.25$ / $r = -0.39^*$ 50 m front crawl time (s) - BMI (kg/m^2): $r = 0.23$ / $r = -0.16$ / $r = -0.13$ 50 m front crawl time (s) - body fat (%): $r = 0.36$ / $r = 0.45^*$ / $r = 0.22$ 50 m front crawl time (s) - lean body mass (kg): $r = -0.29$ / $r = -0.64^*$ / $r = -0.68^*$

Table S2. (continued)

Authors (year)	Total sample - Females (%) / Males (%) G1 - n Males / n Females G2 - n Males / n Females (...)	Tier Age (mean $\pm$ SD)	Correlational domain Variable performance – Variable anthropometry: r=* (*significant correlation)
Duché et al., (1993)	25 - Males (100%)	Tier 2 11.3 $\pm$ 1.0 years	Not referred direction of correlations rather than height 50 m front crawl time (s) - height (cm): r = -0.60* 50 m front crawl time (s) - sitting height (cm): r = 0.43 50 m front crawl time (s) - body mass (kg): r = 0.38 50 m front crawl time (s) - body fat (%): r = 0.08 50 m front crawl time (s) - biacromial diameter (cm): r = 0.40 50 m front crawl time (s) - biiliac diameter(cm): r = 0.48* 50 m front crawl time (s) - thoracic section area (m ²): r = 0.19 50 m front crawl time (s) - body area (m ²): r = 0.47 50 m front crawl time (s) - length upper limb (cm): r = 0.55* 50 m front crawl time (s) - length arm (cm): r = 0.32 50 m front crawl time (s) - length forearm (cm): r = 0.40 400 m front crawl time (s) - height (cm): r = -0.43* 400 m front crawl time (s) - sitting height (cm): r = 0.38 400 m front crawl time (s) - body mass (kg): r = 0.18 400 m front crawl time (s) - body fat (%): r = 0.27 400 m front crawl time (s) - biacromial diameter (cm): r = 0.25 400 m front crawl time (s) - biiliac diameter(cm): r = 0.36 400 m front crawl time (s) - thoracic section area (m ²): r = 0.23 400 m front crawl time (s) - body area (m ²): r = 0.28 400 m front crawl time (s) - length upper limb (cm): r = 0.43* 400 m front crawl time (s) - length arm (cm): r = 0.19 400 m front crawl time (s) - length forearm (cm): r = 0.50
Espada et al., (2023)	16 - Males (69%) / Females (31%) 11 Males / 5 Females	Tier 3 Males / Females 18.0 $\pm$ 4.0 / 16.8 $\pm$ 3.6 years	200 m front crawl v (m.s ⁻¹) - trunk lean mass + bone mass content: r = 0.74* 200 m front crawl v (m.s ⁻¹) - upper limb lean mass + bone mass content: r = 0.72* 200 m front crawl v (m.s ⁻¹) -total lean mass + bone mass content: r = 0.71* 200 m front crawl v (m.s ⁻¹) - lower limb lean mass + bone mass content: r = 0.64* 200 m front crawl v (m.s ⁻¹) - total fat mass: r = -0.56* 200 m front crawl v (m.s ⁻¹) -upper limb fat mass: r = -0.55* 200 m front crawl v (m.s ⁻¹) - trunk fat mass: r = -0.54* 200 m front crawl v (m.s ⁻¹) - lower limb fat mass: r = -0.54*
Ferraz et al., (2020)	98 - Males (51%) / Females (49%) G1 u-13: 26 Males / 25 Females G2 u-12: 24 Males / 23 Females	Tier 3 Males / Females G1: 13.62 $\pm$ 0.25 / 12.48 $\pm$ 0.30 years G2: 12.69 $\pm$ 0.26 / 11.63 $\pm$ 0.28 years	50 m front crawl time (s) - height (m): r = -0.553* 50 m front crawl time (s)- body mass (kg): r = -0.450* 50 m front crawl time (s) - arm span (m): r = -0.477* 400 m front crawl time (s) - height (m): r = -0.577* 400 m front crawl time (s) - body mass (kg): r = -0.434* 400 m front crawl time (s) - arm span (m): r = -0.500*
Geladas et al., (2005)	263 - Males (68%) / Females (32%) 178 Males / 85 Females	Tier 3 Males / Females 12.78 $\pm$ 0.047 / 12.68 $\pm$ 0.063 years	Males / Females 100 m front crawl time (s) - height (cm): r = -0.61* / r = -0.31* 100 m front crawl time (s) - body mass (kg): r = -0.65* / r = -0.12 100 m front crawl time (s) - body fat (%): r = -0.11 / r = -0.10 100 m front crawl time (s) - upper extremity length (cm): r = -0.64* / r = -0.23* 100 m front crawl time (s) - hand length (cm): r = -0.57* / r = -0.30* 100 m front crawl time (s) - foot length (cm): r = -0.49* / r = -0.16 100 m front crawl time (s) - chest circumference (cm): r = -0.64* / r = -0.09 100 m front crawl time (s) - biacromial diameter (cm): r = -0.61* / r = -0.16 100 m front crawl time (s) - biiliac diameter (cm): r = -0.46* / r = -0.09

Table S2. (continued)

Authors (year)	Total sample - Females (%) / Males (%) G1 - n Males / n Females G2 - n Males / n Females (...)	Tier Age (mean $\pm$ SD)	Correlational domain
			Variable performance – Variable anthropometry: $r=*$ (*significant correlation)
Ghouroghchi & Pahlevani, (2021a) / Ghouroghchi & Pahlevani, (2021b)	122 - Males (100%) G1 50 m breaststroke: 31 Males G2 100 m breaststroke: 29 Males G3 200 m breaststroke: 23 Males G4 50 m butterfly: 33 Males G5 100 m butterfly: 24 Males	Tier 3 G1: 12.35 $\pm$ 0.49 years G2: 12.31 $\pm$ 0.47 years G3: 12.26 $\pm$ 0.45 years G4: 12.30 $\pm$ 0.47 years G5: 12.38 $\pm$ 0.50 years	50 m breaststroke time (s) - sitting height (cm): $r = 0.0001$ 50 m breaststroke time (s) - arm span (cm): $r = -0.329$ 50 m breaststroke time (s) - head circumference (cm): $r = -0.106$ 50 m breaststroke time (s) - trunk circumference at nipple height (cm): $r = -0.168$ 50 m breaststroke time (s) - trunk circumference at hip (cm): $r = -0.023$ 50 m breaststroke time (s) - forearm length (cm): $r = -0.117$ 50 m breaststroke time (s) - hand length (cm): $r = -0.322$ 50 m breaststroke time (s) - thigh length (cm): $r = -0.338$ 50 m breaststroke time (s) - tibia length (cm): $r = -0.315$ 50 m breaststroke time (s) - foot length (cm): $r = -0.291$ 50 m breaststroke time (s) - triceps skinfold (mm): $r = 0.215$ 50 m breaststroke time (s) - subscapularis skinfold (mm): $r = 0.338$ 50 m breaststroke time (s) - supraspinatus skinfold (mm): $r = -0.461^*$ 100 m breaststroke time (s) - sitting height (cm): $r = 0.167$ 100 m breaststroke time (s) - arm span (cm): $r = -0.188$ 100 m breaststroke time (s) - head circumference (cm): $r = -0.242$ 100 m breaststroke time (s) - trunk circumference at nipple height (cm): $r = -0.108$ 100 m breaststroke time (s) - trunk circumference at hip (cm): $r = 0.055$ 100 m breaststroke time (s) - forearm length (cm): $r = -0.194$ 100 m breaststroke time (s) - hand length (cm): $r = -0.205$ 100 m breaststroke time (s) - thigh length (cm): $r = -0.157$ 100 m breaststroke time (s) - tibia length (cm): $r = -0.253$ 100 m breaststroke time (s) - foot length (cm): $r = -0.182$ 100 m breaststroke time (s) - triceps skinfold (mm): $r = 0.364$ 100 m breaststroke time (s) - subscapularis skinfold (mm): $r = 0.186$ 100 m breaststroke time (s) - supraspinatus skinfold (mm): $r = 0.307$ 200 m breaststroke time (s) - sitting height (cm): $r = -0.203$ 200 m breaststroke time (s) - arm span (cm): $r = -0.472^*$ 200 m breaststroke time (s) - head circumference (cm): $r = -0.070$ 200 m breaststroke time (s) - trunk circumference at nipple height (cm): $r = -0.242$ 200 m breaststroke time (s) - trunk circumference at hip (cm): $r = -0.006$ 200 m breaststroke time (s) - forearm length (cm): $r = -0.402$ 200 m breaststroke time (s) - hand length (cm): $r = 0.082$ 200 m breaststroke time (s) - thigh length (cm): $r = -0.131$ 200 m breaststroke time (s) - tibia length (cm): $r = -0.392$ 200 m breaststroke time (s) - foot length (cm): $r = -0.158$ 200 m breaststroke time (s) - triceps skinfold (mm): $r = 0.236$ 200 m breaststroke time (s) - subscapularis skinfold (mm): $r = 0.271$ 200 m breaststroke time (s) - supraspinatus skinfold (mm): $r = 0.167$ 50 m butterfly time (s) - sitting height (cm): $r = -0.116$ 50 m butterfly time (s) - arm span (cm): $r = -0.082$ 50 m butterfly time (s) - head circumference (cm): $r = 0.136$ 50 m butterfly time (s) - trunk circumference at nipple height (cm): $r = 0.042$ 50 m butterfly time (s) - trunk circumference at hip (cm): $r = 0.050$ 50 m butterfly time (s) - forearm length (cm): $r = -0.099$ 50 m butterfly time (s) - hand length (cm): $r = -0.233$

Table S2. (continued)

Authors (year)	Total sample - Females (%) / Males (%) G1 - n Males / n Females G2 - n Males / n Females (...)	Tier Age (mean $\pm$ SD)	Correlational domain Variable performance – Variable anthropometry: $r=*$ (*significant correlation)
(cont.)	122 - Males (100%)	Tier 3	50 m butterfly time (s) - thigh length (cm): $r = -0.122$ 50 m butterfly time (s) - tibia length (cm): $r = 0.060$ 50 m butterfly time (s) - foot length (cm): $r = 0.152$ 50 m butterfly time (s) - triceps fat (mm): $r = 0.289$ 50 m butterfly time (s) - subscapularis fat (mm): $r = -0.434*$ 50 m butterfly time (s) - supraspinatus fat (mm): $r = 0.322$ 100 m butterfly time (s) - sitting height (cm): $r = 0.013$ 100 m butterfly time (s) - arm span (cm): $r = 0.154$ 100 m butterfly time (s) - head circumference (cm): $r = -0.371$ 100 m butterfly time (s) - trunk circumference at nipple height (cm): $r = -0.206$ 100 m butterfly time (s) - trunk circumference at hip (cm): $r = 0.098$ 100 m butterfly time (s) - forearm length (cm): $r = -0.114$ 100 m butterfly time (s) - hand length (cm): $r = -0.166$ 100 m butterfly time (s) - thigh length (cm): $r = -0.196$ 100 m butterfly time (s) - tibia length (cm): $r = 0.179$ 100 m butterfly time (s) - foot length (cm): $r = 0.014$ 100 m butterfly time (s) - triceps fat (mm): $r = 0.489*$ 100 m butterfly time (s) - subscapularis fat (mm): $r = 0.561*$ 100 m butterfly time (s) - supraspinatus fat (mm): $r = 0.377$
Ghouroghchi & Pahlevani, (2021a) / Ghouroghchi & Pahlevani, (2021b)	G1 50 m breaststroke: 31 Males G2 100 m breaststroke: 29 Males G3 200 m breaststroke: 23 Males G4 50 m butterfly: 33 Males G5 100 m butterfly: 24 Males	G1: 12.35 ± 0.49 years G2: 12.31 ± 0.47 years G3: 12.26 ± 0.45 years G4: 12.30 ± 0.47 years G5: 12.38 ± 0.50 years	
	122 - Males (100%)	Tier 3	50 m front crawl time (s) - sitting height (cm): $r = 0.0001$ 50 m front crawl time (s) - arm span (cm): $r = -0.060$ 50 m front crawl time (s) - head circumference (cm): $r = -0.037$ 50 m front crawl time (s) - trunk circumference at nipple height (cm): $r = -0.073$ 50 m front crawl time (s) - trunk circumference at hip (cm): $r = 0.027$ 50 m front crawl time (s) - forearm length (cm): $r = 0.068$ 50 m front crawl time (s) - hand length (cm): $r = 0.306$ 50 m front crawl time (s) - thigh length (cm): $r = 0.208$ 50 m front crawl time (s) - tibia length (cm): $r = -0.089$ 50 m front crawl time (s) - foot length (cm): $r = 0.120$ 50 m front crawl time (s) - triceps fat (mm): $r = 0.044$ 50 m front crawl time (s) - subscapularis fat (mm): $r = 0.073$ 50 m front crawl time (s) - supraspinatus fat (mm): $r = -0.084$ 100 m front crawl time (s) - sitting height (cm): $r = -0.120$ 100 m front crawl time (s) - arm span (cm): $r = -0.169$ 100 m front crawl time (s) - head circumference (cm): $r = -0.236$ 100 m front crawl time (s) - trunk circumference at nipple height (cm): $r = -0.188$ 100 m front crawl time (s) - trunk circumference at hip (cm): $r = -0.207$ 100 m front crawl time (s) - forearm length (cm): $r = -0.172$ 100 m front crawl time (s) - hand length (cm): $r = -0.174$ 100 m front crawl time (s) - thigh length (cm): $r = -0.039$ 100 m front crawl time (s) - tibia length (cm): $r = -0.129$ 100 m front crawl time (s) - foot length (cm): $r = -0.400*$ 100 m front crawl time (s) - triceps fat (mm): $r = 0.106$ 100 m front crawl time (s) - subscapularis fat (mm): $r = 0.313$ 100 m front crawl time (s) - supraspinatus fat (mm): $r = 0.230$ 200 m front crawl time (s) - sitting height (cm): $r = 0.023$ 200 m front crawl time (s) - arm span (cm): $r = -0.090$ 200 m front crawl time (s) - head circumference (cm): $r = -0.243$
	G1 50 m front crawl: 39 Males G2 100 m front crawl: 30 Males G3 200 m front crawl: 30 Males G4 400 m front crawl: 21 Males G5 50 m backstroke: 29 Males G6 100 m backstroke: 30 Males G7 200 m backstroke: 27 Males	G1: 12.49 ± 0.51 years G2: 12.47 ± 0.51 years G3: 12.50 ± 0.51 years G4: 12.48 ± 0.51 years G5: 12.41 ± 0.50 years G6: 12.50 ± 0.93 years G7: 12.57 ± 0.51 years	

Table S2. (continued)

Authors (year)	Total sample - Females (%) / Males (%) G1 - n Males / n Females G2 - n Males / n Females (...)	Tier Age (mean $\pm$ SD)	Correlational domain Variable performance – Variable anthropometry: r=* (*significant correlation)
(cont.)	122 - Males (100%)	Tier 3	200 m front crawl time (s) - trunk circumference at nipple height (cm): r = -0.101
Ghouroghchi & Pahlevani, (2021a) / Ghouroghchi & Pahlevani, (2021b)	G1 50 m front crawl: 39 Males G2 100 m front crawl: 30 Males G3 200 m front crawl: 30 Males G4 400 m front crawl: 21 Males G5 50 m backstroke: 29 Males G6 100 m backstroke: 30 Males G7 200 m backstroke: 27 Males	G1: 12.49 $\pm$ 0.51 years G2: 12.47 $\pm$ 0.51 years G3: 12.50 $\pm$ 0.51 years G4: 12.48 $\pm$ 0.51 years G5: 12.41 $\pm$ 0.50 years G6: 12.50 $\pm$ 0.93 years G7: 12.57 $\pm$ 0.51 years	200 m front crawl time (s) - trunk circumference at hip (cm): r = -0.075 200 m front crawl time (s) - forearm length (cm): r = -0.064 200 m front crawl time (s) - hand length (cm): r = 0.056 200 m front crawl time (s) - thigh length (cm): r = 0.090 200 m front crawl time (s) - tibia length (cm): r = -0.059 200 m front crawl time (s) - foot length (cm): r = -0.130 200 m front crawl time (s) - triceps skinfold (mm): r = 0.112 200 m front crawl time (s) - subscapularis skinfold (mm): r = -0.030 200 m front crawl time (s) - supraspinatus skinfold (mm): r = -0.145 400 m front crawl time (s) - sitting height (cm): r = 0.129 400 m front crawl time (s) - arm span (cm): r = 0.132 400 m front crawl time (s) - head circumference (cm): r = -0.507* 400 m front crawl time (s) - trunk circumference at nipple height (cm): r = -0.213 400 m front crawl time (s) - trunk circumference at hip (cm): r = -0.082 400 m front crawl time (s) - forearm length (cm): r = 0.122 400 m front crawl time (s) - hand length (cm): r = 0.186 400 m front crawl time (s) - thigh length (cm): r = 0.230 400 m front crawl time (s) - tibia length (cm): r = 0.132 400 m front crawl time (s) - foot length (cm): r = -0.110 400 m front crawl time (s) - triceps skinfold (mm): r = 0.147 400 m front crawl time (s) - subscapularis skinfold (mm): r = 0.228 400 m front crawl time (s) - supraspinatus skinfold (mm): r = 0.205 50 m backstroke time (s) - sitting height (cm): r = -0.050 50 m backstroke time (s) - arm span (cm): r = -0.112 50 m backstroke time (s) - head circumference (cm): r = -0.056 50 m backstroke time (s) - trunk circumference at nipple height (cm): r = -0.174 50 m backstroke time (s) - trunk circumference at hip (cm): r = -0.286 50 m backstroke time (s) - forearm length (cm): r = -0.010 50 m backstroke time (s) - hand length (cm): r = -0.276 50 m backstroke time (s) - thigh length (cm): r = -0.142 50 m backstroke time (s) - tibia length (cm): r = -0.075 50 m backstroke time (s) - foot length (cm): r = -0.065 50 m backstroke time (s) - triceps skinfold (mm): r = -0.038 50 m backstroke time (s) - subscapularis skinfold (mm): r = -0.197 50 m backstroke time (s) - supraspinatus skinfold (mm): r = -0.146 100 m backstroke time (s) - sitting height (cm): r = -0.342 100 m backstroke time (s) - arm span (cm): r = -0.307 100 m backstroke time (s) - head circumference (cm): r = -0.160 100 m backstroke time (s) - trunk circumference at nipple height (cm): r = -0.381* 100 m backstroke time (s) - trunk circumference at hip (cm): r = -0.523* 100 m backstroke time (s) - forearm length (cm): r = -0.412* 100 m backstroke time (s) - hand length (cm): r = -0.400* 100 m backstroke time (s) - thigh length (cm): r = -0.461 100 m backstroke time (s) - tibia length (cm): r = 0.120 100 m backstroke time (s) - foot length (cm): r = -0.235 100 m backstroke time (s) - triceps skinfold (mm): r = -0.174 100 m backstroke time (s) - subscapularis skinfold (mm): r = -0.155

Table S2. (continued)

Authors (year)	Total sample - Females (%) / Males (%) G1 - n Males / n Females G2 - n Males / n Females (...)	Tier Age (mean $\pm$ SD)	Correlational domain Variable performance – Variable anthropometry: r=* (*significant correlation)
(cont.) Ghouroghchi & Pahlevani, (2021a) / Ghouroghchi & Pahlevani, (2021b)	122 - Males (100%) G1 50 m front crawl: 39 Males G2 100 m front crawl: 30 Males G3 200 m front crawl: 30 Males G4 400 m front crawl: 21 Males G5 50 m backstroke: 29 Males G6 100 m backstroke: 30 Males G7 200 m backstroke: 27 Males	Tier 3 G1: 12.49 $\pm$ 0.51 years G2: 12.47 $\pm$ 0.51 years G3: 12.50 $\pm$ 0.51 years G4: 12.48 $\pm$ 0.51 years G5: 12.41 $\pm$ 0.50 years G6: 12.50 $\pm$ 0.93 years G7: 12.57 $\pm$ 0.51 years	100 m backstroke time (s) - supraspinatus skinfold (mm): r = -0.048 200 m backstroke time (s) - sitting height (cm): r = -0.399* 200 m backstroke time (s) - arm span (cm): r = -0.355 200 m backstroke time (s) - head circumference (cm): r = -0.097 200 m backstroke time (s) - trunk circumference at nipple height (cm): r = -0.336 200 m backstroke time (s) - trunk circumference at hip (cm): r = 0.600* 200 m backstroke time (s) - forearm length (cm): r = -0.117 200 m backstroke time (s) - hand length (cm): r = -0.400* 200 m backstroke time (s) - thigh length (cm): r = -0.228 200 m backstroke time (s) - tibia length (cm): r = -0.415* 200 m backstroke time (s) - foot length (cm): r = -0.268 200 m backstroke time (s) - triceps skinfold (mm): r = -0.051 200 m backstroke time (s) - subscapularis skinfold (mm): r = -0.137 200 m backstroke time (s) - supraspinatus skinfold (mm): r = -0.205
Gomez-Bruton et al., (2015)	98 - Males (53%) / Females (47%) 52 Males / 46 Females	Tier 3 Males / Females 15.1 $\pm$ 2.0 / 13.37 $\pm$ 2.0 years	All / Males / Females 50 m front crawl time (s) - body mass (kg): r = -0.440* / r = -0.461* / r = -0.214 50 m front crawl time (s) - BMI (kg/m ²): r = -0.089 / r = -0.114 / r = -0.036 50 m front crawl time (s) - height (cm): r = -0.602* / r = -0.687* / - 50 m front crawl time (s) - lean body mass (kg): r = -0.516* / r = -0.561* / r = -0.271 50 m front crawl time (s) - body fat (%): r = 0.316* / r = 0.219 / r = 0.186
Keskinen et al., (1989)	33 - Males (100%)	Tier 3 17.89 $\pm$ 3.69 years	10 m front crawl max v (m.s ⁻¹) - height (cm ²): r = 0.72* 10 m front crawl max v (m.s ⁻¹) - arm span (cm ²): r = 0.72* 10 m front crawl max v (m.s ⁻¹) - total length (arm up) (cm ²): r = 0.70* 10 m front crawl max v (m.s ⁻¹) - body mass (kg): r = 0.73* 10 m front crawl max v (m.s ⁻¹) - arm span / height: r = 0.349
Lätt et al., (2009b) / Lätt et al., (2009a)	26 - Females (100%)	Tier 3 12.7 $\pm$ 2.2 years	Partial correlations 400 m front crawl time (s) - lean body mass (kg): r > 0.564* (2 moments)
	29 - Males (100%)	Tier 3 13.0 $\pm$ 1.8 years	Partial correlations 400 m front crawl time (s) - height (cm): r = -0.47* 400 m front crawl time (s) - arm span (cm): r = -0.40* 400 m front crawl v (m.s ⁻¹) - height (cm): r = 0.40* 400 m front crawl v (m.s ⁻¹) - arm span (cm): r = 0.39* 400 m front crawl v (m.s ⁻¹) - body mass (kg): r = 0.45*
Lätt et al., (2010)	25 - Males (100%)	Tier 2 15.2 $\pm$ 1.9 years	Partial correlations: 100 m front crawl time (s) - height (cm): r = -0.536* 100 m front crawl time (s) - body mass (kg): r = -0.48 100 m front crawl time (s) - BMI (kg/m ²): r = -0.27 100 m front crawl time (s) - body fat (%): r = 0.061 100 m front crawl time (s) - body fat (kg): r = -0.174 100 m front crawl time (s) - lean body mass: r = -0.506 100 m front crawl time (s) - bone mass: r = -0.543* 100 m front crawl time (s) - tot bone mineral density (g.cm ⁻²): r = -0.462 100 m front crawl time (s) - spine bone mineral density (g.cm ⁻²): r = -0.516* 100 m front crawl time (s) - arm span (cm): r = -0.557*

Table S2. (continued)

Authors (year)	Total sample - Females (%) / Males (%) G1 - n Males / n Females G2 - n Males / n Females (...)	Tier Age (mean ± SD)	Correlational domain Variable performance – Variable anthropometry: r=* (*significant correlation)
Makar et al., (2022)	5 - Males (40%) / Females (60%) 2 Males / 3 Females	Tier 3 14.6 ± 0.89 years	200 m front crawl v (m.s ⁻¹) - body fat (%): r = -0.497 200 m front crawl v (m.s ⁻¹) - body fat (kg): r = -0.350 200 m front crawl v (m.s ⁻¹) - lean body mass (kg): r = 0.629 200 m front crawl v (m.s ⁻¹) - total body water: r = 0.630 200 m front crawl v (m.s ⁻¹) - mass: r = 0.103 200 m front crawl v (m.s ⁻¹) - BMI (kg/m ²): r = -0.032
Marinho et al., (2021a) / Marinho et al., (2021b)	92 - Females (100%) G1 U-16: 46 Females G2 U-15: 46 Females	Tier 3 14.1 ± 0.6 years	50 m front crawl time (s) - height (m): r = -0.23* 50 m front crawl time (s) - body mass (kg): r = -0.33* 50 m front crawl time (s) - arm span (m): r = -0.27*
	184 - Males (50%) / Females (50%) G1 > 500 FINA points: 28 Males / 54 Females G2 < 500 FINA points: 64 Males / 38 Females	Tier 3 Males / Females 14.6 ± 0.8 / 14.1 ± 0.6 years	50 m front crawl time (s) - height (m): r = -0.64* 400 m front crawl time (s) - height (m): r = -0.60* 50 m front crawl time (s) - body mass (kg): r = -0.67* 400 m front crawl time (s) - body mass (kg): r = -0.60* 50 m front crawl time (s) - arm span (m): r = -0.66* 400 m front crawl time (s) - arm span (m): r = -0.58*
Morais et al., (2012)	114 - Males (64%) / Females (36%) 73 Males / 41 Females	Tier 3 Males / Females 12.72 ± 1.03 / 11.47 ± 0.66 years	All / Males / Females 100 m front crawl time (s) - arm span (cm): r = - 0.35* / r = - 0.73* / r = - 0.16 100 m front crawl time (s) - hand surface area (cm ²): r = - 0.27/ r = - 0.17 / r = - 0.10
Morais et al., (2016)	100 - Males (49%) / Females (51%) 49 Males / 51 Females	Tier 3 All / Males / Females 12.3 ± 0.74 / 12.5 ± 0.76 / 12.2 ± 0.71 years	100 m front crawl time (s) - arm span (m): r = 0.59*
Morales & Arellano, (2006)	21 - Males (43%) / Females (57%) 9 Males / 12 Females	Tier 3 Males / Females 12 / 19 years	50 m front crawl time (s) - arm span (cm): r = -0.62*
Moreira et al., (2014)	25 - Males (48%) / Females (52%) 12 Males / 13 Females	Tier 3 Males / Females 12.8 ± 0.9 / 12.0 ± 0.9 years	Pre / Post 25 m front crawl v (m.s ⁻¹) - height (cm): r = 0.28 / r = 0.72* 25 m front crawl v (m.s ⁻¹) - arm span (cm): r = 0.27 / r = 0.69 * 25 m front crawl v (m.s ⁻¹) - hand surface area (cm ²): r = 0.31 / r = 0.72 * 25 m front crawl v (m.s ⁻¹) - foot surface area (cm ²): r = 0.15 / r = 0.59 *
Nasirzade, Ehsanbakhsh, Argavani, et al., (2014) / Nasirzade, Ehsanbakhsh, Ilbeygi, et al., (2014)	23 - Males (100%)	Tier 2 13.86 ± 0.86 years	50 m front crawl time (s) - vastus lateralis fascicle length (cm): r = -0.42* 50 m front crawl time (s) - gastrocnemius medialis fascicle length (cm): r = -0.33 50 m front crawl time (s) - gastrocnemius lateralis fascicle length (cm): r = -0.48* 50 m front crawl time (s) - triceps brachii fascicle length (cm): r = -0.33 50 m front crawl time (s) - body height (cm): r = -0.43* 50 m front crawl time (s) - body mass (kg): r = 0.14 50 m front crawl time (s) - BMI (kg/m ²): (kg·m ⁻²): r = -0.36 50 m front crawl time (s) - arm span (cm): r = -0.50* 50 m front crawl time (s) - shoulders width (cm): r = -0.38 50 m front crawl time (s) - arm length (cm): r = -0.13 50 m front crawl time (s) - thigh length (cm): r = -0.27 50 m front crawl time (s) - leg length (cm): r = -0.24
	23 - Males (100%) G1: 11 Males G2: 12 Males	Tier 2 G1: 13.86 ± 0.86 years G2: 13.86 ± 0.86 years	25 m front crawl time (s) - vastus lateralis fascicle length (cm): r = -0.43* 25 m front crawl time (s) - gastrocnemius medialis fascicle length (cm): r = -0.13 25 m front crawl time (s) - gastrocnemius lateralis fascicle length (cm): r = -0.42* 25 m front crawl time (s) - triceps brachii fascicle length (cm): r = -0.18

Table S2. (continued)

Authors (year)	Total sample - Females (%) / Males (%) G1 - n Males / n Females G2 - n Males / n Females (...)	Tier Age (mean $\pm$ SD)	Correlational domain Variable performance – Variable anthropometry: $r=*$ (*significant correlation)
Nasirzade et al., (2015)	22 - Males (100%)	Tier 2 14.52 $\pm$ 0.77 years	200 m front crawl time (s) - body height (cm): $r = -0.71^*$ 200 m front crawl time (s) - arm span (cm): $r = -0.62^*$ 200 m front crawl time (s) - shoulders width (cm): $r = -0.48^*$ 200 m front crawl time (s) - arm length (cm): $r = -0.44^*$ 200 m front crawl time (s) - body mass (kg): $r = -0.37$ 200 m front crawl time (s) - BMI (kg/m^2): $r = -0.23$ 200 m front crawl time (s) - thigh length (cm): $r = -0.24$ 200 m front crawl time (s) - leg length (cm): $r = -0.17$ 200 m front crawl time (s) - vastus lateralis fascicle length (cm): $r = -0.45^*$ 200 m front crawl time (s) - gastrocnemius medialis fascicle length (cm): $r = -0.38$ 200 m front crawl time (s) - gastrocnemius lateralis fascicle length (cm): $r = -0.25$ 200 m front crawl time (s) - triceps brachii fascicle length (cm): $r = -0.64^*$
Noriega-Sánchez et al., (2015)	17 - Males (47%) / Females (53%) 8 Males / 9 Females	Tier 3 Males / Females 19.4 $\pm$ 0.7 / 16.9 $\pm$ 3.2 years	Males / Females 100 m front crawl time (s) - height (cm): $r = -0.28$ / $r = -0.39$ 100 m front crawl time (s) - BMI (kg/m^2): $r = -0.29$ / $r = 0.49$ 100 m front crawl time (s) - skinfold thickness sum (mm): $r = -0.44$ / $r = 0.50$
Ozkadi et al., (2022)	40 - Males (50%) / Females (50%) 20 Males / 20 Females	Tier 3 Male: 16.50 $\pm$ 0.51 years Female: 16.50 $\pm$ 0.51 years	Females 50 m front crawl time (s) - foot length (cm): $r^2 = 0.497$; $r = -0.705^*$ 50 m front crawl time (s) - forearm circumference (cm): $r^2 = 0.528$; $r = -0.727^*$ 50 m backstroke time (s) - height (cm): $r^2 = 0.616$; $r = -0.785^*$ 50 m backstroke time (s) - hand length (cm): $r^2 = 0.551$; $r = -0.742^*$ 50 m backstroke time (s) - foot length (cm): $r^2 = 0.652$; $r = -0.808^*$ 50 m backstroke time (s) - forearm circumference (cm): $r^2 = 0.596$; $r = -0.773^*$ 50 m backstroke time (s) - wrist diameter (cm): $r^2 = 0.505$; $r = -0.710^*$ 50 m backstroke time (s) - body fat (%): $r^2 = 0.653$; $r = 0.808^*$ 50 m breaststroke time (s) - height (cm): $r^2 = 0.518$; $r = -0.72^*$ 50 m breaststroke time (s) - hand length (cm): $r^2 = 0.669$; $r = -0.818^*$ 50 m breaststroke time (s) - foot length (cm): $r^2 = 0.634$; $r = -0.796^*$ 50 m breaststroke time (s) - biceps flexion circumference (cm): $r^2 = 0.543$; $r = -0.737^*$ 50 m breaststroke time (s) - forearm circumference (cm): $r^2 = 0.712$; $r = -0.843^*$ 50 m breaststroke time (s) - wrist diameter (cm): $r^2 = 0.536$; $r = -0.732^*$ 50m butterfly time (s) - height (cm): $r^2 = 0.521$; $r = -0.722^*$ 50 m butterfly time (s) - biceps flexion circumference (cm): $r^2 = 0.519$; $r = -0.721^*$
Pelayo et al., (1996)	173 - Males (51%) / Females (49%) G1: 21 Males / 20 Females G2: 20 Males / 21 Females G3: 23 Males / 22 Females G4: 24 Males / 22 Females	Tier 3, Tier 4 and Tier 5 Do not specify	Females 100 m front crawl v ($\text{m}\cdot\text{s}^{-1}$) - height (cm): $r = 0.72^*$ 400 m front crawl v ($\text{m}\cdot\text{s}^{-1}$) - body Mass (kg): $r = 0.44^*$
Perciavalle et al., (2014)	21 - Males (100%) G1 Front crawl: 12 Males G2 Backstroke: 4 Males G3 Medley: 3 Males G4.1 Breaststroke: 1 Male G4.2 Breaststroke: 1 Male	Tier 3 20.2 $\pm$ 2.3 years	All 100 m performance (% Italian record) - 2D:4D ratio: $r = 0.76^*$ 100 m performance (% Italian record) - ape index: $r = -0.12$ Separated 100 m front crawl time (s) - 2D:4D ratio: $r = 0.40$ 100 m front crawl time (s) - ape index: $r = -0.24$ 100 m backstroke time (s) - 2D:4D ratio: $r = 0.97$ 100 m backstroke time (s) - ape index: $r = 0.14$

Table S2. (continued)

Authors (year)	Total sample - Females (%) / Males (%) G1 - n Males / n Females G2 - n Males / n Females (...)	Tier Age (mean $\pm$ SD)	Correlational domain Variable performance – Variable anthropometry: r=* (*significant correlation)
Pereira et al., (2010)	27 - Males (31%) / Females (69%) 11 Males / 16 Females	Tier 4 15.33 $\pm$ 1.0 years	FINA points - body Mass (kg): r = 0.43* FINA points - height (cm): r = 0.60*
Pessoa et al., (2016)	11 - Males (100%)	Tier 3 18.0 $\pm$ 4.0 years	200 m front crawl v (m.s ⁻¹) - lean upper limb mass (kg): r = 0.76* 200 m front crawl v (m.s ⁻¹) - lean trunk mass (kg): r = 0.75* 200 m front crawl v (m.s ⁻¹) - lean lower limb mass (kg): r = 0.69* 200 m front crawl v (m.s ⁻¹) - lean body mass (kg): r = 0.74*
Rama et al., (2006)	494 - Males (64%) / Females (36%) G1: 97 Males / 125 Females G2: 219 Males / 53 Females	Tier 3 Males / Females G1: 13-14 / 12-13 years G2: 15-16 / 14 years	Males / Females G1: LEN points - body Mass (kg): r = 0.258* / - LEN points - height (cm): r = 0.320* / r = 0.218* LEN points - sitting height (cm): r = 0.330* / - LEN points - arm span (cm): r = 0.266* / r = 0.285* LEN points - hand length (cm): - / r = 0.317* LEN points - biacromial diameter (cm): - / r = 0.366* G2 Males: LEN points - body Mass (kg): r = 0.406* LEN points - height (cm): r = 0.332* LEN points - sitting height (cm): r = 0.310* LEN points - arm span: r = 0.345* LEN points - hand length (cm): r = 0.159* LEN points - foot length (cm): r = 0.154* LEN points - biacromial diameter (cm): r = 0.369* LEN points - biiliac diameter (cm): r = 0.155* LEN points - chest depth (cm): r = 0.245*
Reis et al., (2012)	26 - Males (100%) G1 100m: 12 Males G2 200m: 14 Males	Tier 3 G1: 18.6 $\pm$ 2.8 years G2: 17.1 $\pm$ 2.3 years	FINA points - body mass (kg): r = 0.78*; r ² = 0.60
Rozi et al., (2018)	25 - Males (100%)	Tier 3 15 $\pm$ 1.5 years	100 m front crawl time (s) - height (cm): r = 0.810* 100 m front crawl time (s) - body mass (kg): r = 0.720* 100 m front crawl time (s) - sitting height (cm): r = 0.762* 100 m front crawl time (s) - arm span (cm): r = 0.835* 100 m front crawl time (s) - shoulders opening (cm): r = 0.751* 100 m front crawl time (s) - pelvis opening (cm): r = 0.608* 100 m front crawl time (s) - chest depth (cm): r = 0.345* 100 m front crawl time (s) - chest circumference (cm): r = 0.720* 100 m front crawl time (s) - left arm length (cm): r = 0.784* 100 m front crawl time (s) - breast skinfold (mm): r = 0.431* 100 m front crawl time (s) - biceps skinfold (mm): r = 0.666* 100 m front crawl time (s) - triceps skinfold (mm): r = 0.631* 100 m front crawl time (s) - subscapular skinfold (mm): r = 0.405* 100 m front crawl time (s) - iliac skinfold (mm): r = 0.451* 100 m front crawl time (s) - gastrocnemius skinfold (mm): r = 0.542*

Table S2. (continued)

Authors (year)	Total sample - Females (%) / Males (%) G1 - n Males / n Females G2 - n Males / n Females (...)	Tier Age (mean $\pm$ SD)	Correlational domain
			Variable performance – Variable anthropometry: $r=*$ (*significant correlation)
Saavedra et al., (2010)	133 - Males (49%) / Females (51%) 66 Males / 67 Females	Tier 3 Males / Females 13.6 $\pm$ 0.6 / 11.5 $\pm$ 0.6 years	Males / Females FINA points - height (cm): $r = 0.634^*$ / $r = 0.504^*$ FINA points - sitting height (cm): $r = 0.579^*$ / $r = 0.398^*$ FINA points - arm span (cm): $r = 0.587^*$ / $r = 0.459^*$ FINA points - body mass (kg): $r = 0.500^*$ / $r = 0.414^*$ FINA points - hand length (cm): - / $r = 0.401^*$ FINA points - hand width (cm): - / $r = 0.256^*$ FINA points - foot length (cm): $r = 0.441^*$ / $r = 0.326^*$ FINA points - foot width (cm): $r = 0.375^*$ / - FINA points - biacromial diameter (cm): $r = 0.350^*$ / - FINA points - biiliac diameter (cm): $r = 0.309^*$ / - FINA points - bitrochanteric breadth (cm): $r = 0.392^*$ / - FINA points - knee breadth (cm): $r = 0.287^*$ / $r = 0.281^*$ FINA points - elbow breadth (cm): $r = 0.314^*$ / - FINA points - chest circumference(cm): $r = 0.380^*$ / $r = 0.527^*$ FINA points - biceps flexed circumference (cm): $r = 0.304^*$ / $r = 0.252^*$ FINA points - gluteal girth (cm): - / $r = 0.430^*$ FINA points - thigh circumference (cm): $r = 0.263^*$ / - FINA points - leg circumference (cm): - / $r = 0.310^*$ FINA points - biacromial diameter/height index: - / $r = -0.448^*$ FINA points - chest girth/height index: - / $r = 0.269^*$ FINA points - body fat (%): $r = 0.259^*$ / - FINA points - mesomorphy: $r = -0.244^*$ / $r = -0.242^*$
			G1: Males / Females 100 m front crawl time (s) - body mass (kg): $r = -0.58^*$ / 0.84^* 400 m front crawl time (s) - body mass (kg): $r = -0.44$ / 0.71 100 m front crawl time (s) - height (cm): $r = -0.51^*$ / 0.36 400 m front crawl time (s) - height (cm): $r = -0.38$ / 0.20 100 m front crawl time (s) - sitting height (cm): $r = -0.45$ / 0.36 400 m front crawl time (s) - sitting height (cm): $r = -0.26$ / 0.29 100 m front crawl time (s) - upper limbs length (cm): $r = -0.48$ / 0.64 400 m front crawl time (s) - upper limbs length (cm): $r = -0.33$ / 0.53 100 m front crawl time (s) - lower limbs length (cm): $r = -0.53^*$ / 0.28 400 m front crawl time (s) - lower limbs length (cm): $r = -0.46$ / 0.08 100 m front crawl time (s) - arm span (cm): $r = -0.54^*$ / 0.41 400 m front crawl time (s) - arm span (cm): $r = -0.39$ / 0.19 100 m front crawl time (s) - feet length (cm): $r = -0.41$ / 0.74 400 m front crawl time (s) - feet length (cm): $r = -0.38$ / 0.53 100 m front crawl time (s) - hands length (cm): $r = -0.45$ / -0.02 400 m front crawl time (s) - hands length (cm): $r = -0.27$ / -0.04 100 m front crawl time (s) - trunk width (cm): $r = -0.48$ / 0.69 400 m front crawl time (s) - trunk width (cm): $r = -0.33$ / 0.68 100 m front crawl time (s) - trunk circ. (cm): $r = -0.24$ / 0.88^* 400 m front crawl time (s) - trunk circ. (cm): $r = -0.02$ / 0.91^* 100 m front crawl time (s) - BF%: $r = -0.10$ / 0.84^* 400 m front crawl time (s) - BF%: $r = -0.06$ / 0.66 100 m front crawl time (s) - lean body mass (kg): $r = -0.60^*$ / 0.28 00 m front crawl time (s) - lean body mass (kg): $r = -0.47$ / 0.42
Seffrin et al., (2022)	60 - Males (73%) / Females (27%) G1: 16 Males / 6 Females G2: 17 Males / 6 Females G3: 11 Males / 4 Females	Tier 3 Males / Females G1: 11.50 $\pm$ 0.52 / 11.67 $\pm$ 0.52 years G2: 13.53 $\pm$ 0.62 / 13.33 $\pm$ 0.52 years G3: 18.09 $\pm$ 2.12/ 16.25 $\pm$ 0.96 years	

Table S2. (continued)

Authors (year)	Total sample - Females (%) / Males (%) G1 - n Males / n Females G2 - n Males / n Females (...)	Tier Age (mean $\pm$ SD)	Correlational domain Variable performance – Variable anthropometry: r=* (*significant correlation)
(cont.) Seffrin et al., (2022)	60 - Males (73%) / Females (27%) G1: 16 Males / 6 Females G2: 17 Males / 6 Females G3: 11 Males / 4 Females	Tier 3 Males / Females G1: 11.50 $\pm$ 0.52 / 11.67 $\pm$ 0.52 years G2: 13.53 $\pm$ 0.62 / 13.33 $\pm$ 0.52 years G3: 18.09 $\pm$ 2.12 / 16.25 $\pm$ 0.96 years	G2: Males / Females 100 m front crawl time (s) - Body mass (kg): r = -0.78* / 0.49 400 m front crawl time (s) - body mass (kg): r = -0.53* / 0.79 100 m front crawl time (s) - height (cm): r = -0.57* / -0.53 400 m front crawl time (s) - height (cm): r = -0.35 / -0.14 100 m front crawl time (s) - sitting height (cm): r = -0.62* / 0.09 400 m front crawl time (s) - sitting height (cm): r = -0.32 / 0.54 100 m front crawl time (s) - upper limbs length (cm): r = -0.74* / -0.68 400 m front crawl time (s) - upper limbs length (cm): r = -0.50* / -0.55 100 m front crawl time (s) - lower limbs length (cm): r = -0.28 / -0.76 400 m front crawl time (s) - lower limbs length (cm): r = -0.24 / -0.59 100 m front crawl time (s) - arm span (cm): r = -0.72* / -0.44 400 m front crawl time (s) - arm span (cm): r = -0.47 / -0.19 100 m front crawl time (s) - feet length (cm): r = -0.34 / -0.06 400 m front crawl time (s) - feet length (cm): r = -0.08 / 0.40 100 m front crawl time (s) - hands length (cm): r = -0.41 / -0.47 400 m front crawl time (s) - hands length (cm): r = -0.10 / -0.15 100 m front crawl time (s) - trunk width (cm): r = -0.69* / 0.39 400 m front crawl time (s) - trunk width (cm): r = -0.39 / 0.69 100 m front crawl time (s) - trunk circ. (cm): r = -0.33 / 0.20 400 m front crawl time (s) - trunk circ. (cm): r = -0.09 / 0.49 100 m front crawl time (s) - BF%: r = -0.14 / 0.85* 400 m front crawl time (s) - BF%: r = -0.19 / 0.97* 100 m front crawl time (s) - lean body mass (kg): r = -0.83* / -0.50 400 m front crawl time (s) - lean body mass (kg): r = -0.53* / -0.16 G3: Males / Females 100 m front crawl time (s) - body mass (kg): r = -0.15 / -0.69 400 m front crawl time (s) - body mass (kg): r = 0.22 / -0.41 100 m front crawl time (s) - height (cm): r = -0.08 / -0.63 400 m front crawl time (s) - height (cm): r = -0.41 / -0.64 100 m front crawl time (s) - sitting height (cm): r = -0.32 / -0.90 400 m front crawl time (s) - sitting height (cm): r = -0.13 / -0.58 100 m front crawl time (s) - upper limbs length (cm): r = 0.31 / -0.06 400 m front crawl time (s) - upper limbs length (cm): r = 0.10 / -0.47 100 m front crawl time (s) - lower limbs length (cm): r = 0.19 / 0.42 400 m front crawl time (s) - lower limbs length (cm): r = -0.26 / -0.16 100 m front crawl time (s) - arm span (cm): r = 0.30 / -0.18 400 m front crawl time (s) - arm span (cm): r = 0.10 / -0.36 100 m front crawl time (s) - feet length (cm): r = -0.25 / -0.74 400 m front crawl time (s) - feet length (cm): r = -0.25 / -0.18 100 m front crawl time (s) - hands length (cm): r = 0.13 / -0.71 400 m front crawl time (s) - hands length (cm): r = 0.06 / -0.82 100 m front crawl time (s) - trunk width (cm): r = -0.12 / -0.52 400 m front crawl time (s) - trunk width (cm): r = 0.17 / -0.41 100 m front crawl time (s) - trunk circ. (cm): r = -0.32 / -0.25 400 m front crawl time (s) - trunk circ. (cm): r = -0.09 / -0.09 100 m front crawl time (s) - BF%: r = 0.17 / -0.75 400 m front crawl time (s) - BF%: r = 0.58 / -0.17

Table S2. (continued)

Authors (year)	Total sample - Females (%) / Males (%) G1 - n Males / n Females G2 - n Males / n Females (...)	Tier Age (mean $\pm$ SD)	Correlational domain Variable performance – Variable anthropometry: r=* (*significant correlation)
(cont.) Seffrin et al., (2022)	60 - Males (73%) / Females (27%) G1: 16 Males / 6 Females G2: 17 Males / 6 Females G3: 11 Males / 4 Females	Tier 3 Males / Females G1: 11.50 $\pm$ 0.52 / 11.67 $\pm$ 0.52 years G2: 13.53 $\pm$ 0.62 / 13.33 $\pm$ 0.52 years G3: 18.09 $\pm$ 2.12 / 16.25 $\pm$ 0.96 years	100 m front crawl time (s) - lean body mass (kg): r = -0.27 / -0.49 400 m front crawl time (s) - lean body mass (kg): r = -0.01 / -0.56
Sekulić et al., (2007)	68 - Males (67%) / Females (33%) 40 Males / 28 Females	Tier 3 Males / Females 15.2 $\pm$ 3 / 15.2 $\pm$ 3 years	Males / Females 50 m front crawl time (s) - height (cm): r linear = -0.73*; r nonlinear = 0.73* / r linear = -0.58*; r nonlinear = 0.64* 400 m front crawl time (min:s) - height (cm): r linear = -0.56*; r nonlinear = 0.57* / r linear = -0.72*; r nonlinear = 0.72* 50 m front crawl time (s) - body mass (kg): r linear = -0.63*; r nonlinear = 0.70* / r linear = -0.58*; r nonlinear = 0.64* 400 m front crawl time (min:s) - body mass (kg): r linear = -0.44*; r nonlinear = 0.57* / r linear = -0.72*; r nonlinear = 0.76* 50 m front crawl time (s) - BMI (kg/m ²): r linear = -0.39*; r nonlinear = 0.56* / r linear = -0.51*; r nonlinear = 0.64* 400 m front crawl time (min:s) - BMI (kg/m ²): r linear = -0.23; r nonlinear = 0.52* / r linear = -0.60*; r nonlinear = 0.64*
Shephard et al., (2014)	26 - Males (35%) / Females (65%) 9 Males / 17 Females	Tier 5 Males / Females 22.7 $\pm$ 2.7 / 22.2 $\pm$ 2.8 years	Males / Females FINA points - body mass (kg): r = 0.58* / r = 0.10 FINA points - body fat (kg): r = 0.58* / r = -0.15 FINA Points - lean body mass (kg): r = 0.55* / r = 0.28 FINA points - height (m): r = 0.54* / r = 0.50* FINA points - BMI (kg/m ²): r = 0.50* / r = -0.24 FINA points - body fat (%): r = 0.41 FINA points - sum 7 skinfolds (mm): r = 0.19 / r = -0.16
Siders et al., (1993)	74 - Males (42%) / Females (58%) G1 butterfly: 5 Males / 7 Females G2 backstroke: 8 Males / 5 Females G3 breaststroke: 3 Males / 4 Females G4 front crawl: 15 Males / 27 Females	Tier 3 and Tier 4 Males / Females 20.5 $\pm$ 1.9 / 19.7 $\pm$ 1.4 years	Partial correlations (remove effects of season and events): Males / Females 100 yards time (s) - body mass (kg): r = -0.193 / r = -0.05 100 yards time (s) - height (cm): r = -0.009 / r = -0.466* 100 yards time (s) - body mass in water (kg): r = -0.227 / r = -0.528* 100 yards time (s) - body fat (%): r = 0.102 / r = 0.351* 100 yards time (s) - body fat (kg): r = -0.050 / r = -0.291 100 yards time (s) - lean body mass (kg): r = -0.239 / r = -0.332* 100 yards time (s) - endomorphy: r = -0.014 / r = -0.239 100 yards time (s) - mesomorphy: r = -0.073 / r = -0.404* 100 yards time (s) - ectomorphy: r = -0.130 / r = -0.398*
Smith et al., (1988)	16 - Males (100%)	Tier 3 16 years or older	400 m v max (m.s ⁻¹) - arm span: r = 0.62 400 m v max (m.s ⁻¹) - arm/hand length (cm): r = 0.49
Smith, (1978)	40 - Males (50%) / Females (50%) 20 Males / 20 Females	Tier 3 Males / Females 21 / 19 years	25 yards front crawl time (s) - height (cm): r = -0.04 25 yards front crawl time (s) - leg length (cm): r = 0.18 25 yards front crawl time (s) - upper limb length (cm): r = -0.01
Sokołowski et al., (2021)	19 - Females (100%)	Tier 3 13.4 $\pm$ 0.26 years	Authors reported that the correlations between body composition and 100 m front crawl velocity were non-significant without presenting the specific r values

Table S2. (continued)

Authors (year)	Total sample - Females (%) / Males (%) G1 - n Males / n Females G2 - n Males / n Females (...)	Tier Age (mean $\pm$ SD)	Correlational domain Variable performance – Variable anthropometry: $r=*$ (*significant correlation)
Strzala et al., (2005)	16 - Males (100%)	Tier 3 16.3 $\pm$ 0.73 years	100 m front crawl v (m.s ⁻¹) - height (cm): $r = 0.55^*$ 100 m front crawl v (m.s ⁻¹) - body mass (kg): $r = 0.38$ 100 m front crawl v (m.s ⁻¹) - lean body mass (kg): $r = .57^*$ 400 m front crawl v (m.s ⁻¹) - height (cm): $r = 0.27$ 400 m front crawl v (m.s ⁻¹) - body mass (kg): $r = -0.26$ 400 m front crawl v (m.s ⁻¹) - lean body mass (kg): $r = 0.16$
Strzala et al., (2015)	27 - Males (100%)	Tier 3 15.7 $\pm$ 1.98 years	Partial correlations (when controlled for age) with velocity (averages) 200 m breaststroke v (m.s ⁻¹) - lean body mass (kg): $r = 0.32$ 200 m breaststroke v surface (m.s ⁻¹) - lean body mass (kg): $r = 0.17$ 200 m breaststroke v turns (m.s ⁻¹) - lean body mass (kg): $r = 0.38^*$
Strzala et al., (2017)	34 - Males (100%)	Tier 3 and Tier 4 19.3 $\pm$ 1.83 years	Second 25 m (of the 50 m butterfly) v (m.s ⁻¹) - body height (cm): $r = 0.05$ Second 25 m (of the 50 m butterfly) v (m.s ⁻¹) - body mass (kg): $r = 0.46^*$ Second 25 m (of the 50 m butterfly) v (m.s ⁻¹) - lean body mass (kg): $r = 0.48^*$
Strzala et al., (2019)	35 - Males (100%) G1 youth: 20 Males G2 junior: 15 Males	Tier 3 and Tier 4 G1: 17.3 $\pm$ 0.59 years G2: 20.6 $\pm$ 1.05 years	G1 / G2 50 m front crawl v (m.s ⁻¹) - body mass (kg): $r = 0.04$ / $r = 0.63^*$ 50 m front crawl v (m.s ⁻¹) - lean body mass (kg): $r = 0.19$ / $r = 0.78^*$ 50 m front crawl v (m.s ⁻¹) - body height (m): $r = 0.02$ / $r = 0.55^*$ 50 m front crawl v (m.s ⁻¹) - total body length (cm): $r = 0.08$ / $r = 0.58^*$ 50 m front crawl v (m.s ⁻¹) - arm span (cm): $r = -0.04$ / $r = 0.52^*$
Strzala et al., (2020)	26 - Males (100%)	Tier 3 19.8 $\pm$ 2.48 years	100 m front crawl v surf (m.s ⁻¹) - lean body mass (kg): $r = 0.41^*$ 100 m front crawl v surf (m.s ⁻¹) - total body water (kg): $r = 0.42^*$ 100 m front crawl v (m.s ⁻¹) - lean body mass (kg): $r = 0.50^*$ 100 m front crawl v (m.s ⁻¹) - total body water (kg): $r = 0.50^*$
Strzala et al., (2022)	28 - Males (100%)	Tier 3 and Tier 4 19.6 $\pm$ 2.59 years	100 m front crawl v100 (m.s ⁻¹) - body mass (kg): $r = 0.39^*$ 100 m front crawl v100 (m.s ⁻¹) - total body length (cm): $r = 0.43^*$ 100 m front crawl v surface (m.s ⁻¹) - body mass (kg): $r = 0.28$ 100 m front crawl v surface (m.s ⁻¹) - total body length (cm): $r = 0.30$
Tijani et al., (2019)	40 - Males (55%) / Females (45%) 22 Males / 18 Females	Tier 3 12.2 $\pm$ 0.5 years	25 m front crawl v (m.s ⁻¹) - body mass (kg): $r = 0.46^*$ 25 m front crawl v (m.s ⁻¹) - height (cm): $r = 0.5^*$ 25 m front crawl v (m.s ⁻¹) - arm span (cm): $r = 0.66^*$ 25 m front crawl v (m.s ⁻¹) - arm span/height ratio: $r = 0.59^*$ 25 m front crawl v (m.s ⁻¹) - BMI (kg/m ²): $r = 0.25$
Veliz et al., (2020)	27 - Males (52%) / Females (48%) 14 Males / 13 Females	Tier 4 Males / Females 15.6 $\pm$ 2.06 / 15.4 $\pm$ 1.93	Males 100 m front crawl time (s) - lean body mass (kg): $r = -0.893^*$ 50 m backstroke time (s) - body fat (%): $r = 0.829^*$ 50 m backstroke time (s) - lean body mass (kg): $r = -0.829^*$ 100 m backstroke time (s) - body fat (%): $r = 0.857^*$ 100 m backstroke time (s) - lean body mass (%): $r = -0.893^*$ 100 m backstroke time (s) - lean body mass (kg): $r = -0.893^*$ 50 m breaststroke time (s) - body fat (%): $r = 0.857^*$ 200 m individual medley time (s) - body fat (%): $r = -0.621^*$ 200 m individual medley time (s) - lean body mass (%): $r = 0.779^*$ 200 m individual medley time (s) - lean body mass (kg): $r = 0.878^*$ 200 m individual medley time (s) - muscle-bone index: $r = 0.804^*$ 200 m individual medley time (s) - bone mass (%): $r = -0.564^*$

Table S2. (continued)

Authors (year)	Total sample - Females (%) / Males (%) G1 - n Males / n Females G2 - n Males / n Females (...)	Tier Age (mean $\pm$ SD)	Correlational domain
			Variable performance – Variable anthropometry: r=* (*significant correlation)
(cont.) Veliz et al., (2020)	27 - Males (52%) / Females (48%) 14 Males / 13 Females	Tier 4 Males / Females 15.6 $\pm$ 2.06 / 15.4 $\pm$ 1.93	Females: 50 m front crawl time (s) - body mass (kg): r = -0.790* 50 m front crawl time (s) - body fat (%): r = 0.755* 50 m front crawl time (s) - lean body mass (%): r = -0.762* 50 m front crawl time (s) - lean body mass (kg): r = -0.898* 50 m front crawl time (s) - bone mass (kg): r = -0.813*
Yarar et al., (2021)	15 - Males (100%)	Tier 2 21.06 $\pm$ 2.52 years	50 m front crawl time (s) - height (cm): r = -.606* 50 m front crawl time (s) - body mass (kg): r = -.229 50 m front crawl time (s) - body fat percentage (%): r = .075 50 m front crawl time (s) - midstylium-dactylium (cm): r = -.513 50 m front crawl time (s) - hand widths (cm): r = -.371 50 m front crawl time (s) - arm length (cm): r = -.606* 50 m front crawl time (s) - arm span (cm): r = -.562* 50 m front crawl time (s) - foot length (cm): r = .129 50 m front crawl time (s) - foot breadths (cm): r = -.425 50 m front crawl time (s) - leg length (cm): r = -.619* 50 m front crawl time (s) - sitting height (cm): r = -.400 50 m front crawl time (s) - biacromial diameters (cm): r = -.272 50 m front crawl time (s) - length of shank (cm): r = -.631* 100 m front crawl time (s) - height (cm): r = -.489 100 m front crawl time (s) - body mass (kg): r = -.011 100 m front crawl time (s) - body fat percentage (%): r = .252 100 m front crawl time (s) - midstylium-dactylium (cm): r = -.260 100 m front crawl time (s) - hand widths (cm): r = -.298 100 m front crawl time (s) - arm length (cm): r = -.521* 100 m front crawl time (s) - arm span (cm): r = -.433 100 m front crawl time (s) - foot length (cm): r = .246 100 m front crawl time (s) - foot width (cm): r = -.290 100 m front crawl time (s) - leg length (cm): r = -.384 100 m front crawl time (s) - sitting height (cm): r = -.275 100 m front crawl time (s) - biacromial diameters (cm): r = -.397 100 m front crawl time (s) - length of shank (cm): r = -.458

Supplementary material III

Table S3. Studies conflict of interest and funding.

Authors (year)	Conflict of interest / funding
Abbes et al., (2023)	No conflicts of interest. This work was supported by Qatar University – Internal grant (QUST-1-CAS-2018-32).
Akşit et al., (2017)	Not referred
Araújo et al., (1979)	Unreported
Banerjee, (2019)	Unreported
Barbosa et al., (2019)	The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article. The author(s) received no financial support for the research, authorship, and/or publication of this article.
Barzdukas et al., (1992)	Unreported
Bielec & Jurak, (2019)	Unreported
Bond et al., (2015)	The authors declare that there is no conflict of interests. Funding not referred.
Carvalho et al., (2023)	No conflicts of interest. This work is supported by national funding through the Portuguese Foundation for Science and Technology, I.P., under CIFI2D PhD individual grant: SFRH/BD/138876/2018
Chatard et al., (1990)	Unreported
Costa et al., (2020)	The authors declare no conflict of interest.
Daly et al., (1988)	This research was funded by the Portuguese Science and Technology Foundation, under the project UID04045/2020. Unreported
Demirkan et al., (2019)	The authors declare that there is no conflict of interests. Funding not referred.
Demirkan et al., (2023)	The authors declare no conflict of interest. This research received no external funding.
do Bonfim et al., (2021)	Unreported
Dopsaj et al., (2020)	The authors have no conflict of interest to declare. The results do not constitute endorsement of any product or device.no conflict of interest. This research received no external funding. The study was part of the Research Council of the Republic of Serbia (III47015).

Table S3. (continued)

Authors (year)	Conflict of interest / funding
Douda et al., (2010)	The authors declare that there is no conflict of interests. Funding not referred.
Duché et al., (1993)	Unreported
Espada et al., (2023)	No conflicts of interest. The Foundation for Science and Technology, I.P., Grant/Award Number UIDB/04748/2020 funded this research. M.C.E. and C.C.F. also acknowledge the financial support from Instituto Politécnico de Setúbal. This study has also been partially subsidized by the Aid for Research Groups (GR21149) from the Regional Government of Extremadura (Department of Economy, Science, and Digital Agenda), with a contribution from the European Union from the European Funds for Regional Development. Furthermore, the author J.M.G. is a beneficiary of a grant from the Spanish University System Upgrading Programme, Field of Knowledge: Biomedical (Grant Ref.: MS-18). The author D.M.P.F. would like to thank São Paulo Research Foundation—FAPESP (PROCESS 2016/04544-3 and 2018/16706-3) for the partial support and Coordenação de Aperfeiçoamento de Pessoal de Nível Superior—Brazil (CAPES—Finance Code 001) for the partial financial support to A.G.M. The collaboration of T.A.F.A. and E.A.C was possible thanks to the scholarships granted by CAPES, in the scope of the Program CAPES-Print, process number 88887.310463/2018-00, and International Cooperation Project numbers 88887.572557/2020-00 and 88887.310796/2018-00 (scholarships numbers: 88887.580265/2020-00 and 88887.572557/2020-00).
Ferraz et al., (2020)	The authors declare no conflict of interest. This work was supported by national funding through the Portuguese Foundation for Science and Technology, I.P., under project UID04045/2020.
Geladas et al., (2005)	The authors declare that there is no conflict of interests. Funding not referred.
Ghouroghchi & Pahlevani, (2021a)	None. Funding not referred.
Ghouroghchi & Pahlevani, (2021b)	None. Funding not referred.
Gomez-Bruton et al., (2015)	The authors declare that there is no conflict of interests. Funding not referred.
Keskinen et al., (1989)	Unreported The study was supported in part by grants from the Finish Central Sports Federation
Lätt et al., (2009)	The authors declare that there is no conflict of interests. Funding not referred.
Lätt et al., (2009)	The authors declare that there is no conflict of interests. Funding not referred.
Lätt et al., (2010)	The authors declare that there is no conflict of interests. Funding not referred.

Table S3. (continued)

Authors (year)	Conflict of interest / funding
Makar et al., (2022)	The authors declare that they have no competing interest. Funding not referred.
Marinho et al., (2021)	Unreported This work is supported by national funding through the Portuguese Foundation for Science and Technology, I.P., under project UID04045/2020.
Marinho et al., (2021)	No conflicts of interest. This work was supported by national funding through the Portuguese Foundation for Science and Technology, I.P., under project UID04045/2020.
Morais et al., (2012)	The authors declare that there is no conflict of interests. Funding not referred.
Morais et al., (2016)	No conflicts of interest. Jorge E. Morais gratefully acknowledges the Ph.D. scholarship granted by the Portuguese Science and Technology Foundation (FCT) (SFRH/BD/76287/2011).
Morales & Arellano, (2006)	The authors declare that there is no conflict of interests. Funding not referred.
Moreira et al., (2014)	The authors declare that there is no conflict of interests. Funding not referred.
Nasirzade, Ehsanbakhsh, Argavani, et al., (2014)	The authors declare that there is no conflict of interests. Funding not referred.
Nasirzade, Ehsanbakhsh, Ilbeygi, et al., (2014)	The authors declare that there is no conflict of interests. Funding not referred.
Nasirzade et al., (2015)	The authors declare that there is no conflict of interests. Funding not referred.
Noriega-Sánchez et al., (2015)	The authors declare that there is no conflict of interests. Funding not referred.
Ozkadi et al., (2022)	The authors declare that they have no competing interest. Funding not referred.
Pelayo et al., (1996)	Unreported
Perciavalle et al., (2014)	The authors declare that there is no conflict of interests. Funding not referred.
Pereira et al., (2010)	The authors declare that there is no conflict of interests. Funding not referred.
Pessoa et al., (2016)	The authors declare that there is no conflict of interests. Funding not referred.
Rama et al., (2006)	The authors declare that there is no conflict of interests. Funding not referred.
Reis et al., (2012)	The authors declare that there is no conflict of interests. Funding not referred.

Table S3. (continued)

Authors (year)	Conflict of interest / funding
Rozi et al., (2018)	Not referred
Saavedra et al., (2010)	The authors declare that there is no conflict of interests. Funding not referred.
Seffrin et al., (2022)	Aldo Seffrin received a research grand from the Coordenação de Aperfeiçoamento de Pessoal de Ensino Superior (CAPES - Coordination for the Improvement of Higher Education Personnel, Brazil).
Sekulić et al., (2007)	The authors declare that there is no conflict of interests. Funding not referred.
Shephard et al., (2014)	The authors declare that there is no conflict of interests. Funding not referred.
Siders et al., (1993)	Unreported
Smith et al., (1988)	Unreported
Smith, (1978)	Dr. R. R. Montpetit is supported by grants from FCAC Quebec (EQ-2335), and the Quebec Swimming Federation
	The authors declare that there is no conflict of interests. Funding not referred.
Sokołowski et al., (2021)	The authors declare no conflict of interest. This research received no external funding
Strzala et al., (2005)	Unreported
Strzala et al., (2015)	The authors declare that there is no conflict of interests. Funding not referred.
Strzala et al., (2017)	Not referred
Strzala et al., (2019)	The authors declare no conflict of interest. Funding not referred.
Strzala et al., (2020)	Unreported
Strzala et al., (2022)	The authors declare no conflict of interest. Financed by the University of Physical Education in Kraków and the Jerzy Kukuczka Academy of Physical Education in Katowice.
Tijani et al., (2019)	The authors declare no conflict of interest. Funding not referred.
Veliz et al., (2020)	Unreported
Yarar et al., (2021)	There are no conflicts of interest Funding not referred.
Dos Santos et al., (2021)	The authors declare that there is no conflict of interests. Funding not referred.

Table S3. (continued)

Authors (year)	Conflict of interest / funding
Nevill et al., (2020)	The authors declare that there is no conflict of interests. Funding not referred.
Rozi et al., (2019)	Not referred
Sammoud et al., (2019)	The authors declare that there is no conflict of interests. Funding not referred.
Sammoud et al., (2023)	Not referred
Thanopoulos et al., (2006)	Not referred
Thng et al., (2022)	The author(s) declare no potential conflict of interest with respect to the research, authorship, and/or publication of this article. This work was supported by the Queensland Academy of Sport's Sport Performance Innovation and Knowledge Excellence Unit in conjunction with Bond University Faculty of Health Sciences and Medicine

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Supplementary material IV

Table S4. Criteria for defining the risk of bias (low, unclear or high) based on the RoBANS tool.

Risk of bias	Selection of participants	Confounding variables	Measurement of exposure	Blinding of outcomes assessment	Incomplete outcome data	Selective outcome reporting
Low	Well-defined participants, all established in the same method (e.g. competitive swimmers)	Separate and correctly described information, reporting the results in a specific system	Presentation of the evaluations instruments reliability and complete description of the evaluations (e.g. definition of how many measures were taken in total)	Blinded mentioned or if the material is automatically described	The number of swimmers who made the evaluations is well described and the information presented in the methods is shown in the results	When the recorded protocol is consistent with the study
Unclear	Omitted information on the participants characterization (e.g. age or sex)	Omitted information (e.g. if separated but used sex together, the results may be confounded by the sex)	Omitted information about the reliability of the study and complete description of the evaluation (e.g. how many measures or bouts performed in total)	No blinded mentioned	Information restricted to the total number of swimmers and those who took the test, only presenting correlation values for significant ones	Unregistered protocol
High	Different type of swimmers (e.g. level or sex) and the study compare all together	The variables defined in the methods, however in the presentation of the results are not mentioned	There was poor reliability of the study or show little consistency in the evaluation description (e.g. they performed 3 performance trials and only evaluated one). The acceptable is the mean or only one if its performed individual as competition.	No blinded	Information described in the methods but not presented in the results or vice versa	When the recorded protocol is not consistent with the study

Supplementary material V

Secondary meta-analysis

Male swimmers, butterfly times (s) in distances up to 100 m and arm span (cm)

The meta-analysis presented in Figure 1 was performed between three trials (k = 3) totalizing 83 male swimmers (N = 83). Non-significant association was noted between outcomes (Fisher’s Z = -0.330, 95% CI -0.785 to 0.124, p = 0.155). Tests for the magnitude of the impact of heterogeneity were identified as significant (p = 0.009) and moderate ($I^2 = 70.6\%$). The arm span does not show a specific effect in butterfly distances up to 100 m for male swimmers.

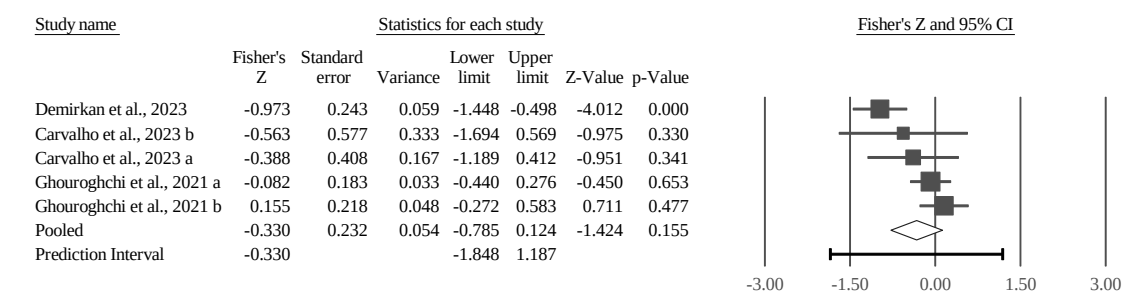


Figure 1. Forest plot outlining the association between **males butterfly times (s) in distances up to 100 m and arm span (cm)**. Plotted black squares denote studies effect sizes (Fisher’s Z), with 95% confidence intervals, and their area (size) represents studies relative weights. The white rhomboid represents the overall result. Studies with letter “a” and/or “b” denotes different groups in a single study.

Male swimmers, front crawl times (s) in distances of 200 and 400 m and arm span (cm)

The meta-analysis presented in Figure 2 was performed between four trials (k = 4) totalizing 114 male swimmers (N = 114). Non-significant association was noted between outcomes (Fisher’s Z = -0.316, 95% CI -0.618 to -0.013, p = 0.041). Tests for the magnitude of the impact of heterogeneity were identified as

significant ($p = 0.061$) and moderate ($I^2 = 55.6\%$). The arm span does not show a specific effect in front crawl distances of 200 and 400 m for male swimmers.

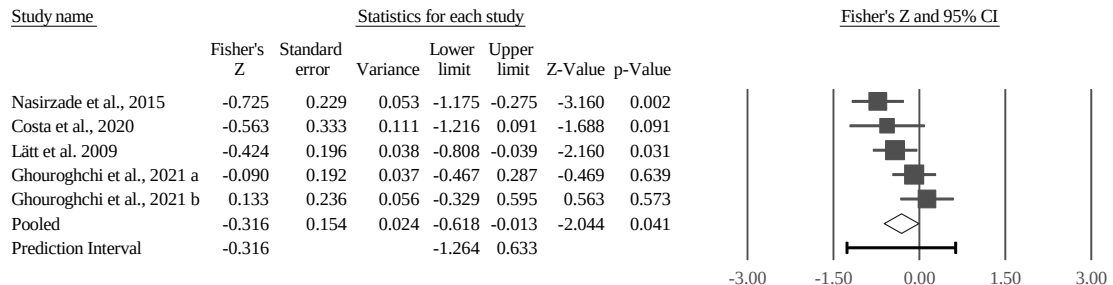


Figure 2. Forest plot outlining the association between **males front crawl times (s) in distances of 200 and 400 m and arm span (cm)**. Plotted black squares denote studies effect sizes (Fisher's Z), with 95% confidence intervals, and their area (size) represents studies relative weights. The white rhomboid represents the overall result. Studies with letter "a" and/or "b" denotes different groups in a single study.

Male swimmers, front crawl times (s) in distances of 200 and 400 m and height (cm)

The meta-analysis presented in Figure 3 was performed between six trials ($k = 6$) totalizing 163 male swimmers ($N = 163$). Significant association was noted between outcomes (Fisher's $Z = -0.560$, 95% CI -0.727 to -0.394, $p < 0.001$). Tests for the magnitude of the impact of heterogeneity were identified as non-significant ($p = 0.842$) and low ($I^2 = 0.0\%$). A sub-group analysis as per the year of articles publication indicated a significant correlation for articles published up to 2009 ($Z = -0.56$, $p < 0.001$) and after 2009 ($Z = -0.56$, $p < 0.001$), with no significant difference for the between sub-groups comparison ($p = 0.992$). The higher height favours better performances in front crawl distances of 200 and 400 m for male swimmers independently of the year of publication.

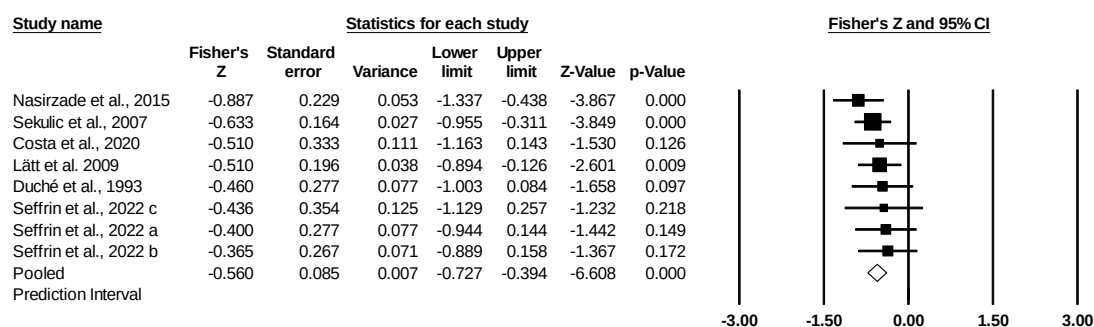


Figure 3. Forest plot outlining the association between **males front crawl times (s) in distances of 200 and 400 m and height (cm)**. Plotted black squares denote studies effect sizes (Fisher's Z), with 95% confidence intervals, and their area (size) represents studies relative weights. The white rhomboid represents the overall result. Studies with letter "a", "b" and/or "c" denotes different groups in a single study.

Male swimmers, front crawl times (s) in distances up to 100 m and body mass (kg)

The meta-analysis presented in Figure 4 was performed between seven trials ($k = 7$) totalizing 377 male swimmers ($N = 377$). Significant association was noted between outcomes (Fisher's $Z = -0.534$, 95% CI -0.748 to -0.319 , $p < 0.001$). Tests for the magnitude of the impact of heterogeneity were identified as significant ($p = 0.003$) and moderate ($I^2 = 65.6\%$). A sub-group analysis as per the athlete's tier level indicated a significant correlation for tier 3 ($Z = -0.69$, $p < 0.001$), although not for tier 2 ($Z = -0.21$, $p = 0.324$), with significant difference for the between sub-groups comparison ($p = 0.032$). The higher body mass favours better performances in front crawl distances up to 100 m for male swimmers independently of the tiers 2 and 3.

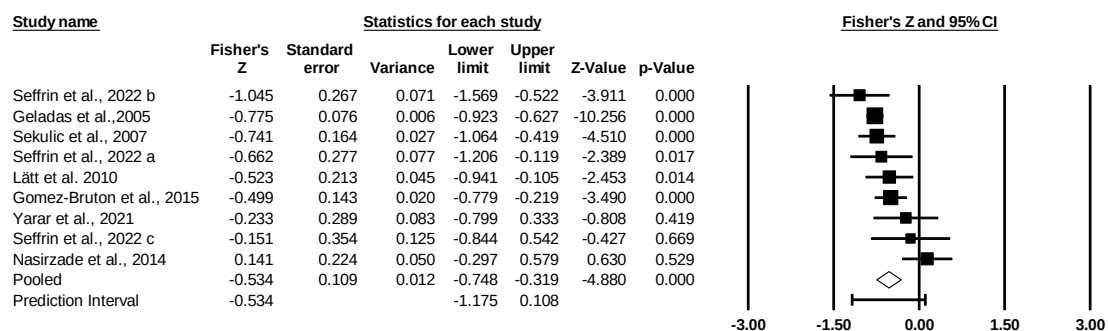


Figure 4. Forest plot outlining the association between **males front crawl times (s) in distances up to 100 m and body mass (kg)**. Plotted black squares denote studies effect sizes (Fisher's Z), with 95% confidence intervals, and their area (size) represents studies relative weights. The white rhomboid represents the overall result. Studies with letter "a" and/or "b" denotes different groups in a single study.

Male swimmers, front crawl times (s) in distances up to 100 m and foot length (cm)

The meta-analysis presented in Figure 5 was performed between four trials ($k = 4$) totalizing 287 male swimmers ($N = 287$). Non-significant association was noted between outcomes (Fisher's $Z = -0.106$, 95% CI -0.479 to 0.268 , $p = 0.579$). Tests for the magnitude of the impact of heterogeneity were identified as significant ($p < 0.001$) and high ($I^2 = 84.5\%$). The foot length does not show a specific effect in front crawl distances up to 100 m for male swimmers.

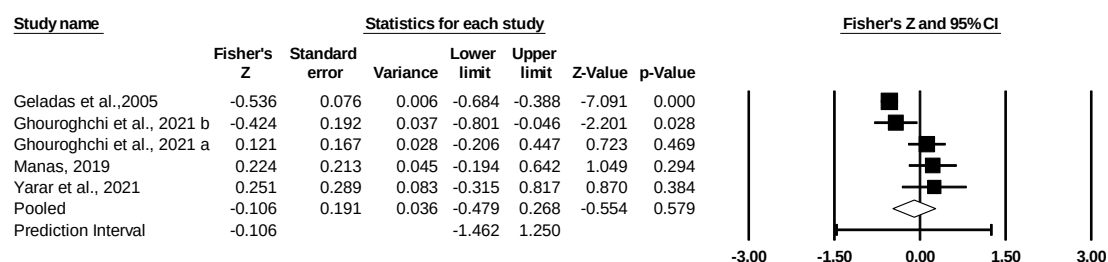


Figure 5. Forest plot outlining the association between **males front crawl times (s) in distances up to 100 m and foot length (cm)**. Plotted black squares denote studies effect sizes (Fisher's Z), with 95% confidence intervals, and their area (size) represents studies relative weights. The white rhomboid represents the overall result. Studies with letter "a" and/or "b" denotes different groups in a single study.

Male swimmers, front crawl times (s) in distances up to 100 m and body mass index (kg/m²)

The meta-analysis presented in Figure 6 was performed between five trials (k = 5) totalizing 148 male swimmers (N = 148). Significant association was noted between outcomes (Fisher's Z = -0.270, 95% CI -0.440 to -0.100, p = 0.002). Tests for the magnitude of the impact of heterogeneity were identified as non-significant (p = 0.706) and low (I^2 = 0.0%). The higher body mass index favours better performances in front crawl distances up to 100 m for male swimmers.

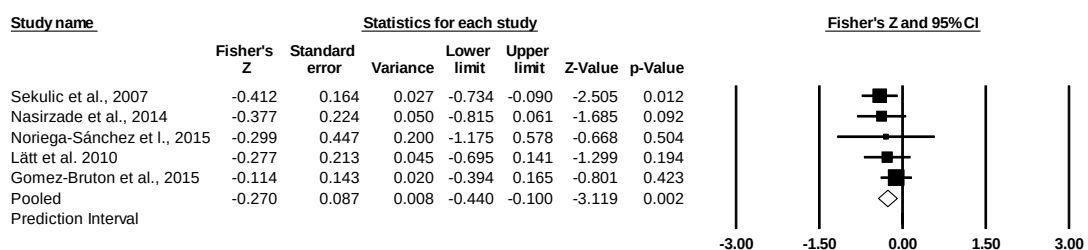


Figure 6. Forest plot outlining the association between **males front crawl times (s) in distances up to 100 m and body mass index (kg/m²)**. Plotted black squares denote studies effect sizes (Fisher's Z), with 95% confidence intervals, and their area (size) represents studies relative weights. The white rhomboid represents the overall result. Studies with letter "a" and/or "b" denotes different groups in a single study.

Female swimmers, front crawl times (s) in distances up to 100 m and body mass (kg)

The meta-analysis presented in Figure 7 was performed between seven trials (k = 7) totalizing 305 female swimmers (N = 305). Significant association was noted between outcomes (Fisher's Z = -0.342, 95% CI -0.578 to -0.107, p = 0.004). Tests for the magnitude of the impact of heterogeneity were identified as significant (p = 0.006) and moderate (I^2 = 61.0%). The body mass does not show a specific effect in front crawl distances up to 100 m for female swimmers. The only trial that reported positive effect of body mass in swimming performance was with young swimmers of 10-14 years old.

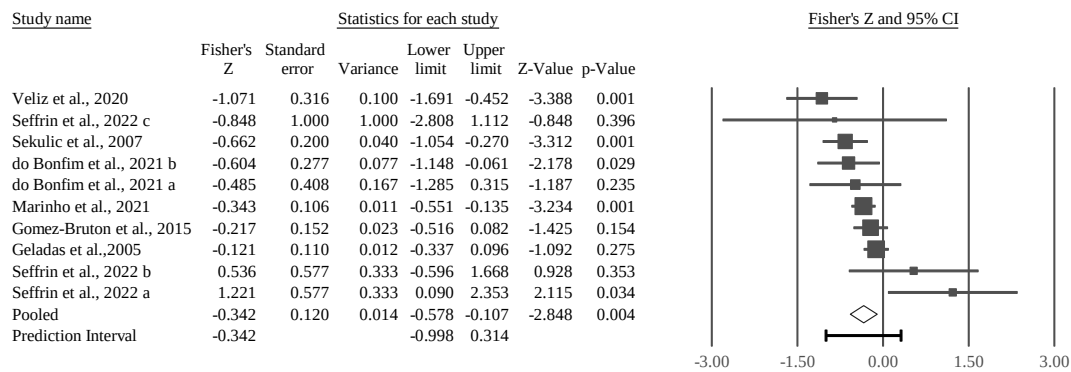


Figure 7. Forest plot outlining the association between **females front crawl times (s) in distances up to 100 m and body mass (kg)**. Plotted black squares denote studies effect sizes (Fisher's Z), with 95% confidence intervals, and their area (size) represents studies relative weights. The white rhomboid represents the overall result. Studies with letter "a", "b" and/or "c" denotes different groups in a single study.

Female swimmers, front crawl times (s) in distances up to 100 m and body mass index (kg/m²)

The meta-analysis presented in Figure 8 was performed between four trials (k = 4) totalizing 108 female swimmers (N = 108). Non-significant association was noted between outcomes (Fisher's Z = -0.029, 95% CI -0.381 to 0.324, p = 0.874). Tests for the magnitude of the impact of heterogeneity were identified as significant (p = 0.049) and moderate ($I^2 = 58.2\%$). The body mass index does not show a specific effect in front crawl distances up to 100 m for female swimmers.

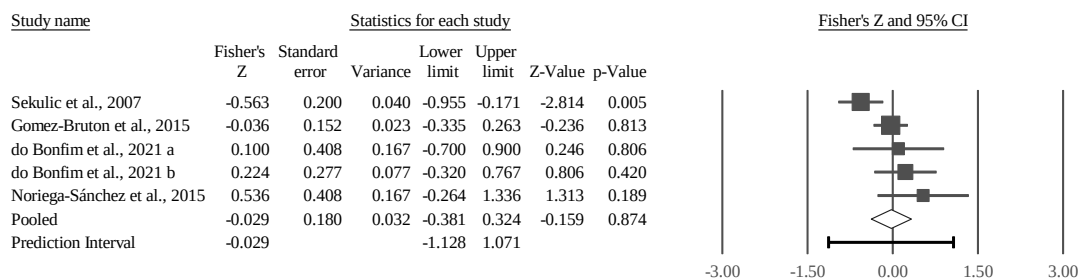


Figure 8. Forest plot outlining the association between **females front crawl times (s) in distances up to 100 m and body mass index (kg/m²)**. Plotted black squares denote studies effect sizes (Fisher's Z), with 95% confidence intervals, and their area (size) represents studies relative weights. The white rhomboid represents the overall result. Studies with letter "a" and/or "b" denotes different groups in a single study.

Male swimmers, front crawl velocity ($\text{m}\cdot\text{s}^{-1}$) in distances up to 100 m and total length (cm)

The meta-analysis presented in Figure 9 was performed between three trials ($k = 3$) totalizing 124 male swimmers ($N = 124$). Significant association was noted between outcomes (Fisher's $Z = 0.484$, 95% CI 0.209 to 0.760, $p = 0.001$). Tests for the magnitude of the impact of heterogeneity were identified as non-significant ($p = 0.081$) and moderate ($I^2 = 51.9\%$). The higher total length favours better performances (velocity) in front crawl distances up to 100 m for male swimmers.

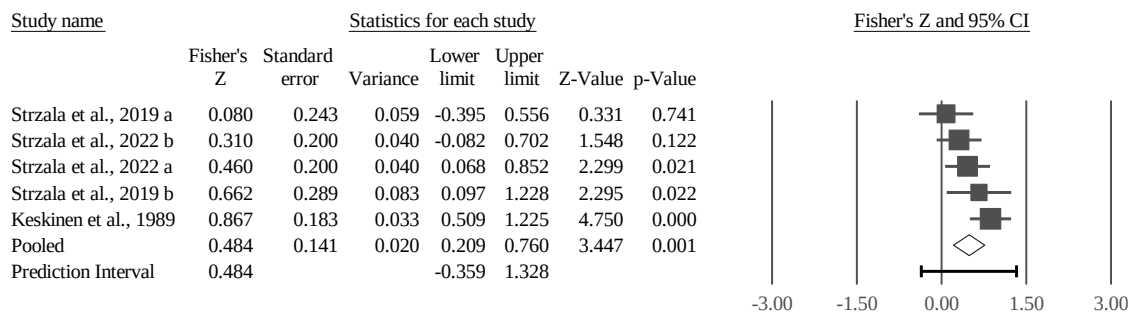


Figure 9. Forest plot outlining the association between **males front crawl velocity ($\text{m}\cdot\text{s}^{-1}$) in distances up to 100 m and total length (cm)**. Plotted black squares denote studies effect sizes (Fisher's Z), with 95% confidence intervals, and their area (size) represents studies relative weights. The white rhomboid represents the overall result. Studies with letter "a" and/or "b" denotes different groups in a single study.

Male swimmers, front crawl velocity ($\text{m}\cdot\text{s}^{-1}$) in distances up to 100 m and body mass (kg)

The meta-analysis presented in Figure 10 was performed between four trials ($k = 4$) totalizing 140 male swimmers ($N = 140$). Significant association was noted between outcomes (Fisher's $Z = 0.475$, 95% CI 0.203 to 0.747, $p = 0.001$). Tests for the magnitude of the impact of heterogeneity were identified as significant ($p = 0.047$) and moderate ($I^2 = 55.6\%$). The higher body mass favours better performances (velocity) in front crawl distances up to 100 m for male swimmers.

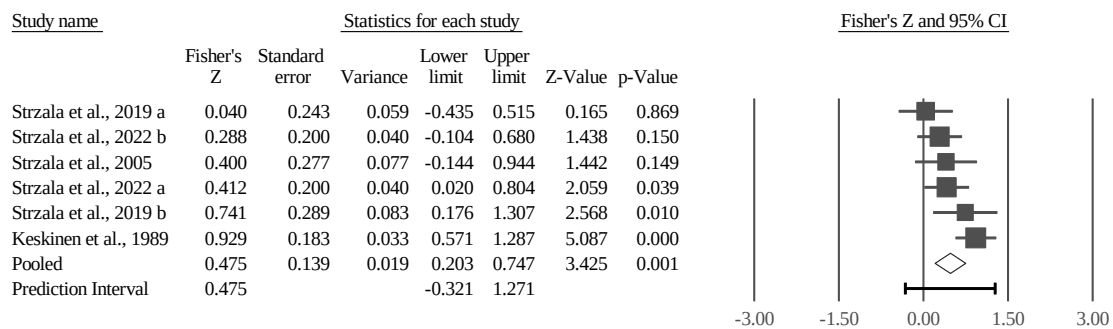


Figure 10. Forest plot outlining the association between **males front crawl velocity ($\text{m}\cdot\text{s}^{-1}$) in distances up to 100 m and body mass (kg)**. Plotted black squares denote studies effect sizes (Fisher's Z), with 95% confidence intervals, and their area (size) represents studies relative weights. The white rhomboid represents the overall result. Studies with letter "a" and/or "b" denotes different groups in a single study.

Male swimmers, front crawl velocity ($\text{m}\cdot\text{s}^{-1}$) in distances up to 100 m and body lean mass (kg)

The meta-analysis presented in Figure 11 was performed between three trials ($k = 3$) totalizing 77 male swimmers ($N = 77$). Significant association was noted between outcomes (Fisher's $Z = 0.583$, 95% CI 0.258 to 0.908, $p < 0.001$). Tests for the magnitude of the impact of heterogeneity were identified as non-significant ($p = 0.156$) and moderate ($I^2 = 42.6\%$). The higher body lean mass favours better performances (velocity) in front crawl distances up to 100 m for male swimmers.

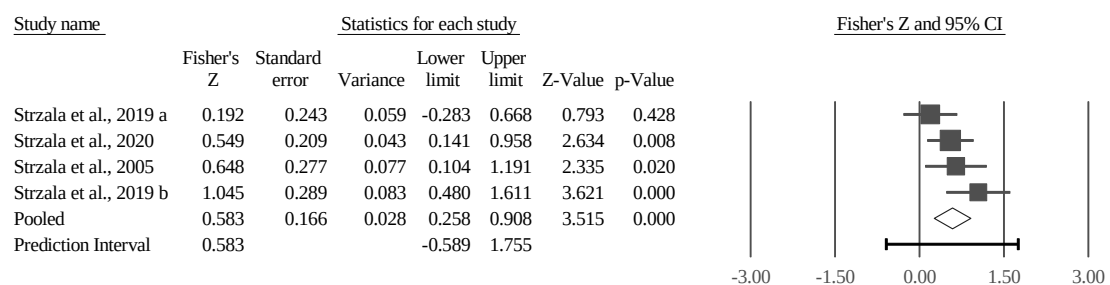


Figure 11. Forest plot outlining the association between **males front crawl velocity ($\text{m}\cdot\text{s}^{-1}$) in distances up to 100 m and body lean mass (kg)**. Plotted black squares denote studies effect sizes (Fisher's Z), with 95% confidence intervals, and their area (size) represents studies relative weights. The white rhomboid represents the overall result. Studies with letter "a" and/or "b" denotes different groups in a single study.

Male swimmers, front crawl velocity ($\text{m}\cdot\text{s}^{-1}$) in distances up to 100 m and height (cm)

The meta-analysis presented in Figure 12 was performed between three trials ($k = 3$) totalizing 84 male swimmers ($N = 84$). Significant association was noted between outcomes (Fisher's $Z = 0.553$, 95% CI 0.150 to 0.957, $p = 0.007$). Tests for the magnitude of the impact of heterogeneity were identified as significant ($p = 0.036$) and moderate ($I^2 = 65.0\%$). The higher height favours better performances (velocity) in front crawl distances up to 100 m for male swimmers.

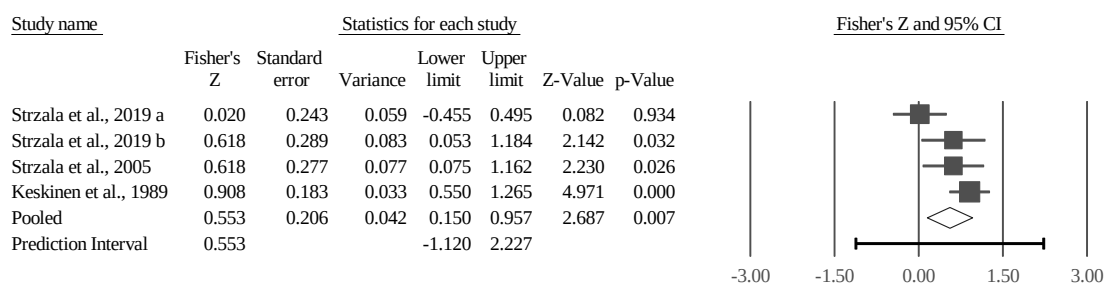


Figure 12. Forest plot outlining the association between **males front crawl velocity ($\text{m}\cdot\text{s}^{-1}$) in distances up to 100 m and height (cm)**. Plotted black squares denote studies effect sizes (Fisher's Z), with 95% confidence intervals, and their area (size) represents studies relative weights. The white rhomboid represents the overall result. Studies with letter "a" and/or "b" denotes different groups in a single study.

Male swimmers, front crawl velocity ($\text{m}\cdot\text{s}^{-1}$) in distances of 200 and 400 m and body mass (kg)

The meta-analysis presented in Figure 13 was performed between four trials ($k = 4$) totalizing 109 male swimmers ($N = 109$). Non-significant association was noted between outcomes (Fisher's $Z = 0.398$, 95% CI 0.019 to 0.778, $p = 0.040$). Tests for the magnitude of the impact of heterogeneity were identified as significant ($p = 0.022$) and moderate ($I^2 = 68.7\%$). The body mass does not show a specific effect in front crawl distances of 200 and 400 m for male swimmers.

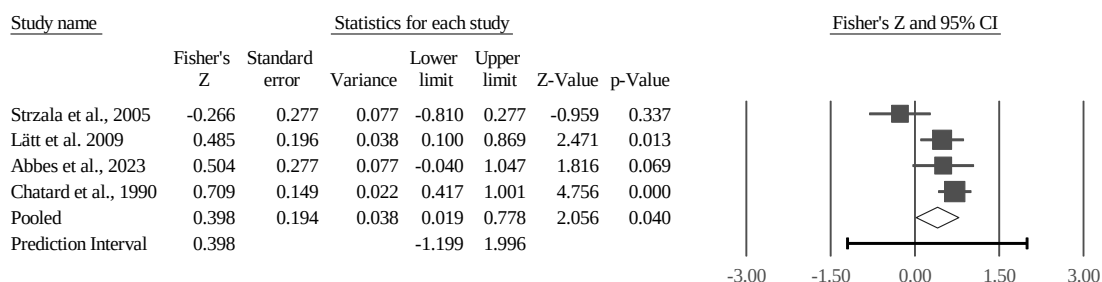


Figure 13. Forest plot outlining the association between **males front crawl velocity ($\text{m}\cdot\text{s}^{-1}$) in distances of 200 and 400 m and body mass (kg)**. Plotted black squares denote studies effect sizes (Fisher's Z), with 95% confidence intervals, and their area (size) represents studies relative weights. The white rhomboid represents the overall result. Studies with letter "a" and/or "b" denotes different groups in a single study.

Male swimmers, FINA / World Aquatics score points and body fat mass (kg)

The meta-analysis presented in Figure 14 was performed between three trials ($k = 3$) totalizing 138 male swimmers ($N = 138$). Non-significant association was noted between outcomes (Fisher's $Z = -0.411$, 95% CI -1.177 to 0.355 , $p = 0.293$). Tests for the magnitude of the impact of heterogeneity were identified as significant ($p < 0.001$) and high ($I^2 = 94.5\%$). The body fat mass does not show a specific effect in FINA / World Aquatics score points for male swimmers.

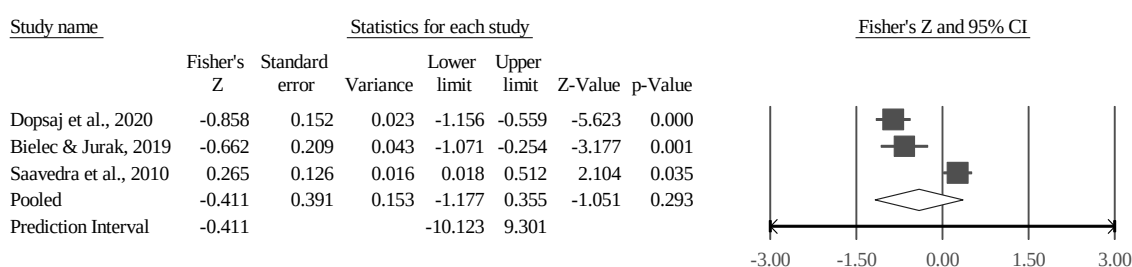


Figure 14. Forest plot outlining the association between **males score points and body fat mass (kg)**. Plotted black squares denote studies effect sizes (Fisher's Z), with 95% confidence intervals, and their area (size) represents studies relative weights. The white rhomboid represents the overall result. Studies with letter "a" and/or "b" denotes different groups in a single study.

Male swimmers, FINA / World Aquatics score points and body mass (kg)

The meta-analysis presented in Figure 15 was performed between four trials ($k = 4$) totalizing 150 male swimmers ($N = 150$). Significant association was noted between outcomes (Fisher's $Z = 0.480$, 95% CI 0.232 to 0.729, $p < 0.001$). Tests for the magnitude of the impact of heterogeneity were identified as non-significant ($p = 0.129$) and moderate ($I^2 = 47.1\%$). The higher body mass favours better performances (score points) for male swimmers.

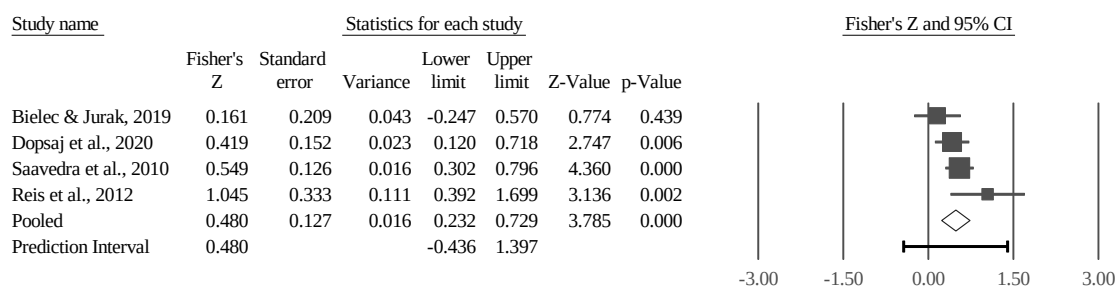


Figure 15. Forest plot outlining the association between **males score points and body mass (kg)**. Plotted black squares denote studies effect sizes (Fisher's Z), with 95% confidence intervals, and their area (size) represents studies relative weights. The white rhomboid represents the overall result. Studies with letter "a" and/or "b" denotes different groups in a single study.

Male swimmers, FINA / World Aquatics score points and body height (cm)

The meta-analysis presented in Figure 16 was performed between four trials ($k = 4$) totalizing 454 male swimmers ($N = 454$). Significant association was noted between outcomes (Fisher's $Z = 0.527$, 95% CI 0.336 to 0.718, $p < 0.001$). Tests for the magnitude of the impact of heterogeneity were identified as significant ($p = 0.010$) and moderate ($I^2 = 69.7\%$). The higher body height favours better performances (score points) for male swimmers.

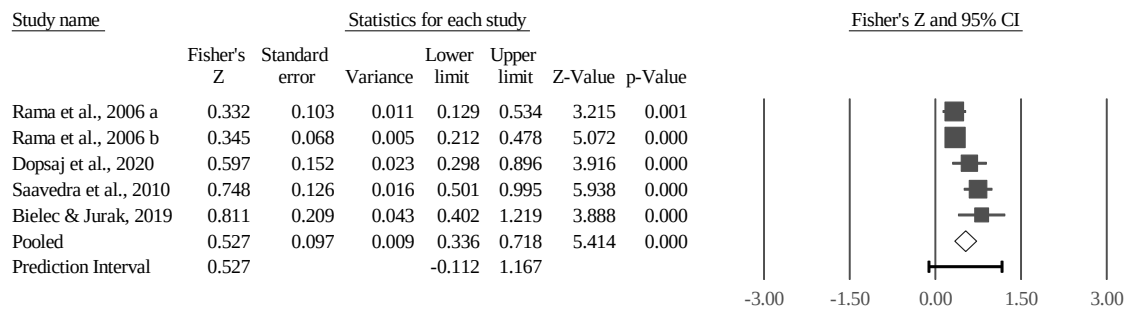


Figure 16. Forest plot outlining the association between **males score points in distances up to 100 m and body height (cm)**. Plotted black squares denote trials effect sizes (Fisher's Z), with 95% confidence intervals, and their area (size) represents trials relative weights. The white rhomboid represents the overall result. Trials with letter "a" and/or "b" "c" denotes different groups in a single study.

Male swimmers, FINA / World Aquatics score points and arm span (cm)

The meta-analysis presented in Figure 17 was performed between three trials ($k = 3$) totalizing 408 male swimmers ($N = 454$). Significant association was noted between outcomes (Fisher's $Z = 0.458$, 95% CI 0.269 to 0.646, $p < 0.001$). Tests for the magnitude of the impact of heterogeneity were identified as significant ($p = 0.036$) and moderate ($I^2 = 64.8\%$). The higher arm span favours better performances (score points) for male swimmers.

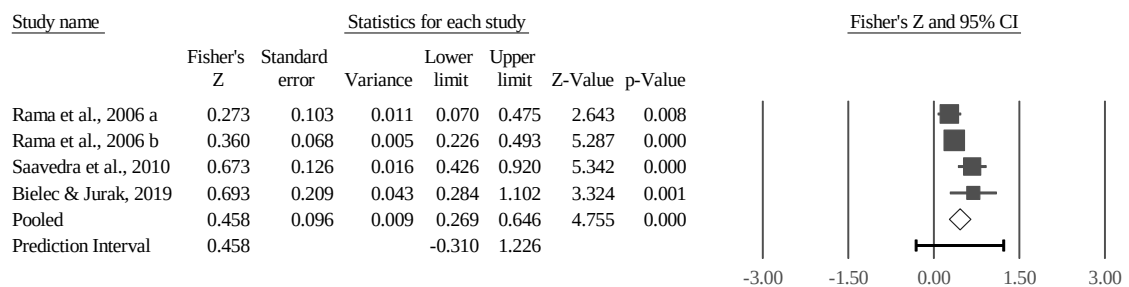


Figure 17. Forest plot outlining the association between **males score points and arm span (cm)**. Plotted black squares denote trials effect sizes (Fisher's Z), with 95% confidence intervals, and their area (size) represents trials relative weights. The white rhomboid represents the overall result. Trials with letter "a" and/or "b" denotes different groups in a single study.

Female swimmers, FINA / World Aquatics score points and body mass (kg)

The meta-analysis presented in Figure 18 was performed between three trials ($k = 3$) totalizing 118 female swimmers ($N = 118$). Significant association was noted between outcomes (Fisher's $Z = 0.381$, 95% CI 0.193 to 0.569, $p < 0.001$). Tests for the magnitude of the impact of heterogeneity were identified as non-significant ($p = 0.522$) and low ($I^2 = 0.0\%$). The higher body mass favours better performances (score points) for female swimmers.

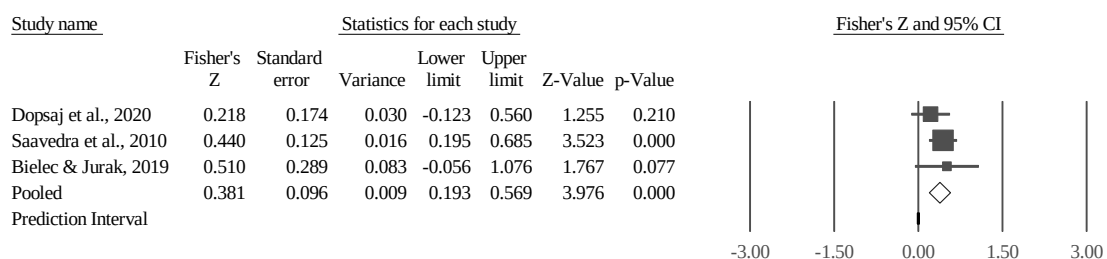


Figure 18. Forest plot outlining the association between **females score points and body mass (kg)**. Plotted black squares denote trials effect sizes (Fisher's Z), with 95% confidence intervals, and their area (size) represents trials relative weights. The white rhomboid represents the overall result.

Female swimmers, FINA / World Aquatics score points and body height (cm)

The meta-analysis presented in Figure 19 was performed between four trials ($k = 4$) totalizing 171 male swimmers ($N = 171$). Significant association was noted between outcomes (Fisher's $Z = 0.383$, 95% CI 0.159 to 0.607, $p = 0.001$). Tests for the magnitude of the impact of heterogeneity were identified as significant ($p = 0.134$) and moderate ($I^2 = 46.3\%$). The higher body height favours better performances (score points) for female swimmers.

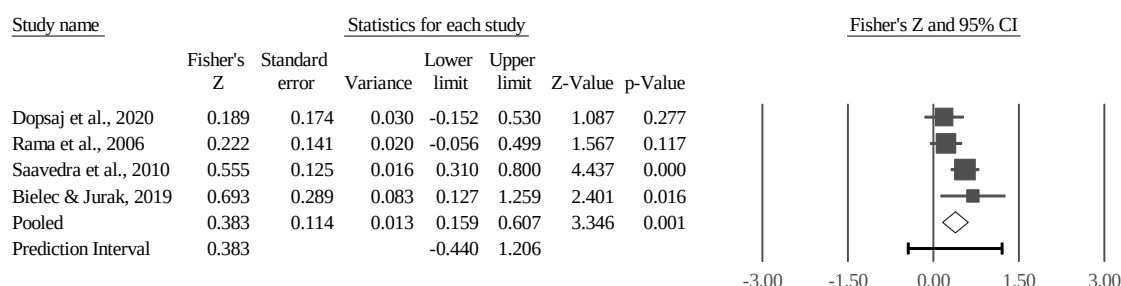


Figure 19. Forest plot outlining the association between **females score points and body height (cm)**. Plotted black squares denote trials effect sizes (Fisher's Z), with 95% confidence intervals, and their area (size) represents trials relative weights. The white rhomboid represents the overall result.

Female swimmers, FINA / World Aquatics score points and arm span (cm)

The meta-analysis presented in Figure 20 was performed between three trials ($k = 3$) totalizing 135 female swimmers ($N = 135$). Significant association was noted between outcomes (Fisher's $Z = 0.412$, 95% CI 0.237 to 0.587, $p < 0.001$). Tests for the magnitude of the impact of heterogeneity were identified as non-significant ($p = 0.553$) and low ($I^2 = 0.0\%$). The higher arm span favours better performances (score points) for female swimmers.

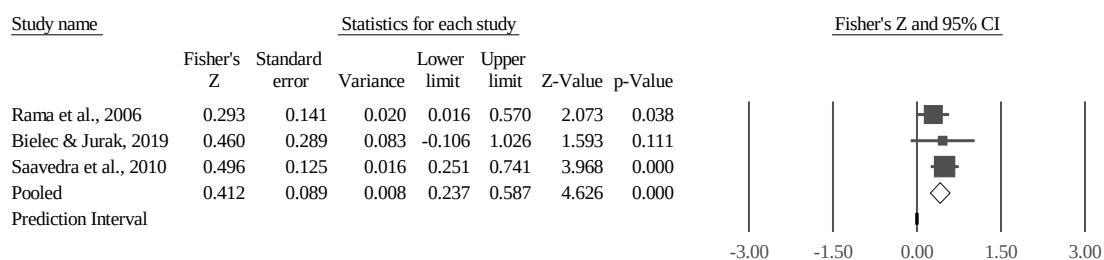


Figure 20. Forest plot outlining the association between **females score points and arm span (cm)**. Plotted black squares denote trials effect sizes (Fisher's Z), with 95% confidence intervals, and their area (size) represents trials relative weights. The white rhomboid represents the overall result.