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Physiological and biomechanical determinants of swimming performance: Volume II

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Physiological and biomechanical determinants of swimming performance: Volume II

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Editorial: Physiological and biomechanical determinants of swimming performance—volume 2

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Editorial on the Research Topic
Physiological and biomechanical determinants of swimming performance—volume 2

The objective of this Research Topic was to develop and strengthen evidence of training and swimming performance to increase scientific knowledge in the area, considering that understanding the biomechanical, physiological, and neuromuscular determinants of swimming performance is still challenging. This way, 13 manuscripts have been reviewed and approved for this research topic (volume II). We can categorize the 13 manuscripts into three major areas of swimming research: physiology and prescription; biomechanics; performance assessment and prediction. Furthermore, we highlight that 10 of the manuscripts were carried out with the participation of at least two research institutions, often from different countries, which may demonstrate the need for international interchange and exchange of ideas and methodologies across researchers and laboratories.

Concerning physiological aspects of swimming training and performance, studies focused on oxygen uptake kinetics, back-extrapolation reliability, and critical speed. Almeida et al. (*Time Limit and VO_2 Kinetics at Maximal Aerobic Velocity: Continuous vs. Intermittent Swimming Trials*) assessed 22 male swimmers in an incremental protocol to estimate, among others, the maximal aerobic velocity, then applied intermittent and continuous swimming protocols, both at maximal aerobic velocity. They noted that: (i) intermittent trials training is preferable rather than continuous training for aerobic capacity; and (ii) $\dot{V}O_2$ kinetics do not appear to influence time spent at severe intensity domain in both intermittent and continuous swimming training. However, the $\dot{V}O_2$ and its kinetic measurements in swimming still generate debate about their methods. Thus Massini et al. (*The reliability of back-extrapolation in estimating $\dot{V}O_2$peak in different swimming performances at severe intensity domain*) estimated $\dot{V}O_2$ by back-extrapolation for 20 swimmers after (i) an incremental intermittent step protocol and (ii) a 200 m single-trial. Among the results, they found that the initial phase of the $\dot{V}O_2$ recovery profile provided different (although reliable) conditions to the estimate of $\dot{V}O_2$peak with back-extrapolation procedures, which accounted for the effect of anaerobic release on $\dot{V}O_2$ off-kinetics, but compromised, exceptionally, the $\dot{V}O_2$peak estimate in 200 m single-trial. Focusing on training prescription with critical speed, Raimundo et al.

(*Modeling the Expenditure and Reconstitution of Distance Above Critical Speed During Two Swimming Interval Training Sessions*) suggest that the time constant of the reconstitution of the maximum distance that can be performed above critical speed is not constant during two high-intensity interval sessions with the same recovery intensity.

The studies that focused on the biomechanics of swimming, in this special volume, can be grouped into three main topics: (i) inertial and pressure systems; (ii) tumble turn; breaststroke pullout; and undulatory underwater speed; and (iii) active drag, propulsion and kinematics. Rad et al. (*Monitoring weekly progress of front crawl swimmers using IMU-based performance evaluation goal metrics*) investigated inertial measurement unit (IMU) with a single IMU on the 16 swimmers' sacrum during training sessions, specifically along ten weeks in 25-m all-out front crawl. Five goal metrics from the IMU signals representing the swimmer's performance in the swimming phases (wall push-off, glide, stroke preparation, free-swimming) and in the entire lap were estimated. The results showed that the goal metrics for the free-swimming phase and the entire lap predicted the swimmer's progress well. Regarding pressor sensors, Santos et al. (*Reliability of using a pressure sensor system to measure in-water force in young competitive swimmers*) analyzed the front crawl over 25-m all-out of 15 age-group swimmers with the pressure sensor system (Aquanex System). They concluded that the system seems to be a reliable device for measuring the hand resultant force during front crawl in young swimmers and can be used to monitor the changes over time.

Concerning the tumble turn performance, Koster et al. *(Implications of the choice of distance-based measures in assessing and investigating tumble turn performance*) intended to understand better the implications of choosing a particular distance-based performance measure for assessing and investigating tumble turn performance in freestyle swimming. In this way, 2,813 turns performed by 160 swimmers were analyzed. The results revealed that performance measures with short(er) distances are more sensitive to changes in the adaptation time and reflect the wall contact time better than performance measures with long(er) distances, which in contrast, are more useful if the focus is on the approach speed prior to the turn. David et al. (*Improving tumble turn performance in swimming—the impact of wall contact time and tuck index*) examined the effect of wall contact time and tuck Index on tumble turn performance and their interrelations by experimentally manipulating both variables. The results underscored the importance of wall contact time and tuck Index of the tumble turn performance, as well as their interrelations with other performance determining variables in this regard, with the importance of individual tuning. Regarding the breaststroke pull-out, McCabe et al. (*The Characteristics of the Breaststroke Pullout in Elite Swimming)* characterized the underwater breaststroke pullout technique trends and assessed the effectiveness of each technique as utilized by elite male and female swimmers. The study found no difference in performance outcome for each pullout technique, indicating that one's individual preference should guide technique selection. Concerning the undulatory underwater movement, Kuhn and Legerlotz (*Ankle joint flexibility affects undulatory underwater swimming speed*) investigated the impact of ankle joint flexibility on swimming velocity and kick efficiency during undulatory underwater by comparing kinematics of swimming trials with reduced, normal, and enhanced maximum angles of plantar flexion. Swimming velocity and kick efficiency did not differ between normal and increased plantar flexion. The results suggest that undulatory underwater velocity is affected by impaired plantar flexion.

Concerning active drag, Lopes et al. (*Numerical and experimental methods used to evaluate active drag in swimming: A systematic narrative review*) performed a systematic review to update the body of knowledge on active drag in swimming through numerical and experimental methods. Seventy-five studies on active drag in swimming and the methodologies applied to study them were analyzed and kept for synthesis. There were significantly fewer numerical studies than experimental ones. Based on the complexity of active drag, studying this phenomenon must continue to improve swimming performance. About the propulsion, Morais et al. (*Understanding the role of propulsion in the prediction of front-crawl swimming velocity and in the relationship between stroke frequency and stroke length*) aimed to: (i) determine swimming velocity based on a set of anthropometric, kinematic, and kinetic variables, and; (ii) understand the stroke frequency–stroke length combinations associated with swimming velocity and propulsion in young sprint swimmers. Swimming velocity was predicted by an interaction of anthropometrics, kinematics, and kinetics. Faster velocities in young sprinters of both sexes were achieved by an optimal combination of stroke frequency–stroke length. The propulsion data showed the same trend. The highest propulsion was not necessarily associated with higher velocity achievement.

Regarding the performance assessment and prediction, considering the 400-m front crawl test as a useful tool to assess aerobic power and capacity, Correia et al. (*Kinematic, arm-stroke efficiency, coordination, and energetic parameters of the 400-m front-crawl test: a meta-analysis*) provided a meta-analysis assessing representative variables for the kinematic, arm-stroke efficiency, coordination, and energetic parameters of the 400-m front crawl test. High heterogeneity (>75%) was found among the outcome parameters in the studies on the meta-analysis. The average speeds seem to be the most responsible and influential in the arm-stroke efficiency, coordination, and energetic parameters for improved 400-m front-crawl performance. Finally, Born et al. (*Performance development of European swimmers across the Olympic cycle*) quantified the performance development of race time and key performance indicators of European swimmers across the last Olympic cycle (from 2016 to 2021) and provided reference values for long-course swimming pool events for both sexes from 50 m to 1,500 m including butterfly, backstroke, breaststroke, freestyle, and individual medley. Individual events from the 2016 and 2021 European swimming championships were included in the analysis. Among the results, clean swimming velocities were faster in 12 (males) and 5 (females) events. For alternating swimming strokes, i.e., backstroke and freestyle, effect sizes indicated improved swimming efficiency with an inverse relationship between reduced stroke rate and increased distance per stroke.

In summary, this issue advances the knowledge in topics of practical importance related to swimming performance. It highlights the contribution of several research areas, including physiology, biomechanics, new technologies and race analysis and, performance progression. In terms of physiology, training planning of continuous or intermittent sessions, oxygen kinetics, and critical speed remain hot topics in swimming research. In biomechanics, analyzing specific parts and components of a race remains critical and will help a substantial performance improvement. New technologies using reliable devices will help improve training quality, and we expect further improvement soon.

Author contributions

FSC, PF, AT, TB, and CM wrote and proofread this editorial. All authors contributed to the article and approved the submitted version.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Understanding the Role of Propulsion in the Prediction of Front-Crawl Swimming Velocity and in the Relationship Between Stroke Frequency and Stroke Length

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Introduction: This study aimed to: 1) determine swimming velocity based on a set of anthropometric, kinematic, and kinetic variables, and; 2) understand the stroke frequency (SF)–stroke length (SL) combinations associated with swimming velocity and propulsion in young sprint swimmers.

Methods: 38 swimmers (22 males: 15.92 ± 0.75 years; 16 females: 14.99 ± 1.06 years) participated and underwent anthropometric, kinematic, and kinetic variables assessment. Exploratory associations between SL and SF on swimming velocity were explored using two two-way ANOVA (independent for males and females). Swimming velocity was determined using multilevel modeling.

Results: The prediction of swimming velocity revealed a significant sex effect. Height, underwater stroke time, and mean propulsion of the dominant limb were predictors of swimming velocity. For both sexes, swimming velocity suggested that SL presented a significant variation (males: $F = 8.20$, $p < 0.001$, $\eta^2 = 0.40$; females: $F = 18.23$, $p < 0.001$, $\eta^2 = 0.39$), as well as SF (males: $F = 38.20$, $p < 0.001$, $\eta^2 = 0.47$; females: $F = 83.04$, $p < 0.001$, $\eta^2 = 0.51$). The interaction between SL and SF was significant for females ($F = 8.00$, $p = 0.001$, $\eta^2 = 0.05$), but not for males ($F = 1.60$, $p = 0.172$, $\eta^2 = 0.04$). The optimal SF–SL combination suggested a SF of 0.80 Hz and a SL of 2.20 m (swimming velocity: 1.75 m s^{-1}), and a SF of 0.80 Hz and a SL of 1.90 m (swimming velocity: 1.56 m s^{-1}) for males and females, respectively. The propulsion in both sexes showed the same trend in SL, but not in SF (i.e., non-significant variation). Also, a non-significant interaction between SL and SF was observed (males: $F = 0.77$, $p = 0.601$, $\eta^2 = 0.05$; females: $F = 1.48$, $p = 0.242$, $\eta^2 = 0.05$).

Conclusion: Swimming velocity was predicted by an interaction of anthropometrics, kinematics, and kinetics. Faster velocities in young sprinters of both sexes were achieved by an optimal combination of SF–SL. The same trend was shown by the propulsion data. The highest propulsion was not necessarily associated with higher velocity achievement.

Keywords: youth, swimming, technique, performance, stroke parameters

INTRODUCTION

Competitive swimming is a time-based sport where the athlete must travel a given distance at maximum velocity (Seifert et al., 2007). Power input and transport energy cost are the two main underlying factors that allow faster velocities to be achieved:

$$v = \frac{\dot{E}_{tot}}{C} \tag{1}$$

in which v is the swimming velocity (in $m{\cdot}s^{-1}$), $\dot{E}_{tot}$ is the energy expenditure (in $ml{\cdot}kg^{-1}{\cdot}m^{-1}$; also known as total power input–W), and C is the energy cost of swimming (in $J{\cdot}kg^{-1}{\cdot}m^{-1}$) (Barbosa et al., 2010). Thus, swimming performance has a strong relationship with the mean swimming velocity across a given stroke event (Craig et al., 1985).

Predicting swimming velocity is the main goal of researchers and coaches (Morais et al., 2012; Abbes et al., 2018). Swimming velocity is highly dependent from anthropometric variables (Nevill et al., 2020; Oliveira et al., 2021), kinematics and motor control (Morais et al., 2012; Figueiredo et al., 2016; Silva et al., 2019), energetics/efficiency (Figueiredo et al., 2016; Barbosa et al., 2019), and dry-land strength and power (Girold et al., 2012; Strzala et al., 2019). However, most recent research trends highlighted swimming performance as a holistic phenomenon that is strongly dependent from the interaction between several variables of different scientific fields (Figueiredo et al., 2016; Morais et al., 2021). The potential interaction between swimming performance determinants (i.e., scientific fields, domains, and variables that may determine or predict swimming performance) provides the platform for different and multiple patterns of behavior to emerge on an individual basis. There is an interplay among several variables that ultimately will affect the swimming velocity (Morais et al., 2012; Figueiredo et al., 2016). Therefore, small gains by each variable can trigger a change in the interplay among the components of the system which will ultimately "affect" the variable being determine (in this case swimming velocity). It has been indicated, both experimentally (Tsunokawa et al., 2019; Morais et al., 2020a) and numerically (Bilinauskaite et al., 2013; Cohen et al., 2018), that a greater propulsion is related to faster swimming velocity. A study conducted by Santos et al. (2021) reviewed the state of the art about human propulsion in competitive swimming. Propulsion in swimming refers to the force generated by the swimmer through the actions of upper and lower limbs to promote forward motion (Barbosa et al., 2020). However, there is little awareness of the role that propulsion can play when it interacts with other variables. Thus, being propulsion a key-factor for the swimming velocity improvement, it seems of major importance understanding the magnitude of its influence when interacted with other key-factors.

As with any other cyclic phenomena, the mean swimming velocity depends on the frequency and length of the stroke:

$$\bar{v} = SF \cdot SL \tag{2}$$

In which $\bar{v}$ is the mean swimming velocity (in $m{\cdot}s^{-1}$), SF is the stroke frequency (in Hz), and SL is the stroke length (in m) (Craig and Pendergast, 1979). Therefore, the mean swimming velocity can be improved by increasing SF, SL, or both concurrently. In freestyle events (i.e., front-crawl), it is known that increasing swimming velocity, based on higher SF, leads to a higher energy cost of transportation (Wakayoshi et al., 1993; Komar et al., 2012). Conversely, increasing swimming velocity by increasing SL is associated with a small increment in energy cost (Barbosa et al., 2008). Thus, understanding the relationship between SF and SL is of paramount importance to reach a certain mean swimming velocity (Craig and Pendergast, 1979; Dormehl and Osborough, 2015).

Overall, in all swimming events (i.e., strokes and distances), swimmers can use two main pacing strategies: 1) higher SF and shorter SL, or 2) lower SF and longer SL (Maglischo, 2003; Hellard et al., 2008). Swimmers can even trade-off SF and SL during an event. Whenever an increase in SF is observed, there is often a consequential tendency for SL to decrease (Seifert et al., 2010). Contrastingly, if SF decreases, SL tends to increase (Psycharakis et al., 2008). This happens because swimmers take more time to complete the full stroke cycle (Alberty et al., 2011). In the specific case of freestyle sprinters racing the 50 m event, it was shown that elite swimmers (participating in major competitions such as European and World championships) present an all-out strategy (Simbaña-Escobar et al., 2018; Morais et al., 2022). That is, swimmers exhibit a positive pacing–swimming velocity decrease over time, with a SF decrease and a SL increase over time (Morais et al., 2022). Nonetheless, it was suggested that swimmers may needed to change the SF–SL combination to maintain a given pace (Dekerle et al., 2005). Moreover, whenever swimmers fail to maintain SF, they are often advised to maintain SL to minimize the decrease in swim velocity (Seifert et al., 2005).

Besides the spatial-temporal factors mentioned above, one can argue that other factors can account for dynamics in the SF–SL relationship. For instance, upper limb propulsion may also play an influential role. Overall, it was experimentally shown that propulsion presents a significant and positive relationship with swim velocity (Morais et al., 2020a; Koga et al., 2020). That is, higher propulsion by the upper limbs leads to faster swim velocities. Notwithstanding, it must be pointed out that propulsion generated by the upper limbs account for 90% of the swim velocity (lower limbs actions are responsible for remaining 10%) (Deschodt et al., 1999). Regarding the influence that propulsion may have on SF and SL, it was suggested that the capability to keep a given propulsion intensity throughout the in-water phase of the stroke cycle (i.e., pull and push motion–propulsion) can explain reductions in SF, subsequently leading to a longer SL. Alternatively, a shorter SL can be associated with a lower capability to generate sufficient propulsion necessary to overcome drag (Craig et al., 1985). Others verified that after 4 years of high-velocity training, the participants of their study were able to swim at a given submaximal velocity with a slower SF (i.e., with a longer SL) (Termin and Pendergast, 2000). One can speculate that at least one key-factor for this was the increase of propulsion generated by the swimmers that allowed to swim at faster velocities with slower SF. However, beside such assumptions, one cannot find in the literature evidence about the role that propulsion plays in this SF–SL relationship. As a result, it is logical that understanding the role that propulsion may have on the SF–SL relationship is of paramount importance for swimmers and coaches to support practitioners in designing and developing training programs. This will allow to identify SF–SL combinations that might elicit better performances.

The purposes of the present study were to (1): predict swimming velocity based on a set of anthropometric, kinematic, and kinetic variables, and; 2) understand the SF–SL combinations associated with swimming velocity and propulsion in young sprint swimmers. It was hypothesized that: 1) kinetic variables would be retained as swimming velocity predictors, interacted with anthropometrics and kinematics (all of them with a positive and significant effect), and; 2) the fastest swims are characterized by the highest SF but not the lowest SL, and propulsion plays a determinant and positive role in the SF–SL ratio and swimming velocity.

METHODS

Participants

The participants were 38 swimmers (22 males: 15.92 ± 0.75 years-old, FINA points: 566.77 ± 56.82 in the 100 m freestyle event–short course meter swimming pool; 16 females: 14.99 ± 1.06 years-old, FINA points: 602.25 ± 77.35 in the 100 m freestyle event–short course meter swimming pool). Swimmers were recruited from a national squad that competed at international championships and contained age-group national champions and record holders, i.e., Tier 3 (McKay et al., 2022). The inclusion criteria for the participants were: 1) being male and female sprint specialists in their age-group in freestyle sprinting events, and; 2) having participated in daily training sessions from the beginning of the season and without injuries. Participants had more than 5 years of competitive experience; trained six to seven swimming sessions per week; and, had at least one dry-land strength and conditioning session per week. Swimmers were informed about the study procedures as well as the possible risks that could arise from the study. Parents or guardians as well as the swimmers themselves provided informed consent. All procedures were in accordance with the Declaration of Helsinki regarding human research, and the University Ethics Board approved the research design.

Experimental Design

This was a cross-sectional study. After a standardized 1,000 m warm-up, swimmers completed three all-out trials of 25 m freestyle with a push-off start, the fastest trial being used for analysis. Swimmers were instructed to hold their breath during such intermediate distance to avoid modifications in coordination due to breathing. Rest time between trials was 30 min. In-water warm-up and trial performance took place in a 25 m indoor swimming pool (water temperature: 27.5°C; air temperature: 26.0°C; relative humidity: 67% prior to the swimming performance assessment). As part of the trial performance, kinematic and kinetic variables were measured.

Anthropometric Assessment

Participants initially underwent an anthropometric assessment. At this time, the swimmers' hand dominancy was assessed by self-report as suggested elsewhere (Morais et al., 2020b). Height (H, in cm) was measured as the distance between the vertex to the floor (with the swimmers in the orthostatic position) using a digital stadiometer (SECA, 242, Hamburg, Germany). Body mass (BM, in kg) was measured on a digital scale (TANITA, BC-730, Amsterdam, Netherlands). The swimmer's arm span (AS, in cm) was measured using digital photogrammetry. Swimmers were placed in an orthostatic position, with both arms in lateral abduction at a 90° angle with the trunk. Both arms and fingers were fully extended. The distance between the tip of each third finger was measured with a dedicated software (Udruler, AVPSoft, United States) (Morais et al., 2020b). For hand surface area (HSA, in cm^2), swimmers placed their hands onto a copy machine for surface area scanning. Each HSA was determined using the digital scan by a dedicated software (Udruler, AVPSoft, United States) (Morais et al., 2012).

Stroke Kinematic Assessment

To determine maximum velocity, a speedometer apparatus (Swim speedo-meter, Swimsportec, Hildesheim, Germany) was attached to the swimmers' hip (Barbosa et al., 2019). In-house built software (LabVIEW®, v. 2010), previously acquired (f = 50 Hz), displayed velocity-time data across each swimmer's trial (Barbosa et al., 2011). Data was exported to an interface by a 12-bit resolution acquisition card (USB-6008, National Instruments, Austin, Texas, United States). Afterwards, data was imported into signal processing software (AcqKnowledge v. 3.9.0, Biopac Systems, Santa Barbara, United States). Signals were handled using a Butterworth fourth order low-pass filter (cut-off: 5Hz, based on the analysis of the residual error vs cut-off frequency output) (Barbosa et al., 2019). A video camera (Sony FDR-X3,000, Japan) was also attached to a rail at the edge of the swimming pool and recorded swimmers in the sagittal plane. The camera was synchronized with the velocity-time software by a light signal. When the speedo-meter starts acquiring data, a light is enhanced in the software. The camera filmed this moment so that afterwards the velocity-time curve can be synchronized with the video.

The following stroke kinematic variables were determined via assessment of three consecutive stroke cycles during the intermediate 15 m of the swimming pool. The in-water phase of the stroke cycle was considered to start at the hand's entry and finishes at the hand's exit. Swimming velocity (v, in $m \cdot s^{-1}$) was retrieved from the velocity-time curve. Based on video recording assessment, stroke frequency (SF, in Hz) was calculated by the number of cycles per unit of time, specifically the time required to complete a full cycle ($f = 1/P$; where P is the period), later converted to Hz. The stroke length (SL, in m) was calculated as SL = v/SF (Craig and Pendergast, 1979). The intra-cyclic variation of the horizontal swimming velocity (dv, in %) was computed as the coefficient of variation (CV): CV = one standard deviation/mean * 100 (Barbosa et al., 2010). The underwater stroke time of each upper limb ($UST_{dominant}$ and $UST_{non\text{-}dominant}$, in s) was computed as the time spent between the entry of the hand in the water and its exit. Then, the mean of both upper limbs was calculated ($UST_{stroke\ cycle}$, in s).

Propulsion Assessment

Kinetic data were acquired simultaneously with kinematic data. Thus, the same three consecutive stroke cycles were analyzed. Pressure sensors (Swimming Technology Research, United States; https://swimmingtechnology.com/aquanexanalysis/) were used to measure propulsion (f = 100 Hz) (Havriluk, 2013). This system is based on sensors that estimate in-water pressure (Havriluk, 1988; Barbosa et al., 2020). The sensors were placed between the third and fourth metacarpals to measure the pressure differential between the palmar and dorsal surfaces. This location is assumed as being a good proxy for the application point of propulsion vector on the hand (Gourgoulis et al., 2013). The application of additional sensors on each hand was avoided as it can affect technique, due to cabling surrounding the upper limb. Additional sensors may change the geometry and volume of the hand, impacting the ecological validity of the propulsion data. At the beginning of each performance trial, swimmers were asked to keep their hands immersed at a depth of 0.50 m for 10 s to calibrate the system. The pressure sensor data were transferred to the Aquanex software (Aquanex v. 4.2 C1211, Richmond, United States) by an A/D converter (Morais et al., 2020b). Afterwards, time-force series were imported into a signal processing software (AcqKnowledge v. 3.9.0, Biopac Systems, Santa Barbara, United States). Signals were again handled using a Butterworth fourth order low-pass filter (cut-off: 5 Hz). For each dominant and non-dominant in-water phase of the stroke cycle, the mean propulsion ($F_{mean\_dominant}$ and $F_{mean\_non\text{-}dominant}$, in N) and peak force ($F_{peak\_dominant}$ and $F_{peak\_non\text{-}dominant}$, in N) were determined. Afterwards, the $F_{mean\_stroke\ cycle}$ (the mean force produced in one full stroke cycle, in N) was calculated. The intra-cyclic variation of the propulsion of each upper limb ($dF_{dominant}$ and $dF_{non\text{-}dominant}$, in %) was computed based on equation 3. Then, the mean across both upper limbs was calculated ($dF_{mean\_stroke\ cycle}$, in %).

Statistical Analysis

Initially, the Kolmogorov-Smirnov and the Levene tests were used to assess normality and homoscedasticity, respectively. Descriptive statistics means and one standard deviation (±1SD) were calculated. Exploratory associations between SL and SF on swimming velocity were explored using the two-way ANOVA (independent for males and females) ($p < 0.05$). Swimming velocity was entered as the dependent variable with both SL and SF categorized (rounded) as independent variables (males: 13 categories for SL and 4 for SF; females: 8 categories for SL and 3 for SF). "Rounding" consists of converting continuous variables (in this case SF and SL) into categories. Later, a similar analysis was performed on the propulsion to verify which values corresponded to a given swimming velocity rounded by SL and SF. For both swimming velocity and propulsion non-estimable means were not considered. Thus, only the combinations observed for both males and females were analyzed. Eta square (η^2) was used as an effect size index and interpreted as: 1) without effect if $0 < \eta^2 \leq 0.04$; 2) minimum if $0.04 < \eta^2 \leq 0.25$; 3) moderate if $0.25 < \eta^2 \leq 0.64$ and; 4) strong if $\eta^2 > 0.64$ (Ferguson, 2009).

To calculate the swimming velocity, multilevel modeling was used. Swimming velocity was defined as the dependent variable. The remaining anthropometric, kinematic (except SF and SL), and kinetic variables were defined as independent or predictor variables ($p < 0.05$). The analysis was performed using the MLwiN multilevel modeling software (Bristol, United Kingdom). Multilevel modeling is an extension of ordinary multiple regression in which data have a hierarchical or clustered structure. The hierarchy consists of units or measurements grouped at different levels. In the current study, it is assumed that the swimmers are a random sample, representing the level 2 units, and the swimmers' repeated measurements (three consecutive stroke cycles), the level 1 units (Morais et al., 2020a). The 95% confidence intervals (95CI) were computed. A multicollinearity phenomenon was not detected since the independent variables were all computed independently from the dependent one. Differential calculus was used to estimate the point at which the dependent variables peaked when a significant quadratic association was identified (i.e., H and $F_{mean\_dominant}$) (Alcock, 2016).

RESULTS

Table 1 presents the descriptive statistics (mean ± 1SD) for all measured variables. Males presented higher anthropometrics and larger kinematics and kinetics than their female counterparts (**Table 1**).

The results of the multilevel regression analysis that predict swimming velocity are reported in **Table 2**. A significant sex effect was verified (estimate = 0.2003, 95CI: 0.1309 to 0.2697, $p < 0.001$) (**Table 2**). The $UST_{dominant}$ was the independent variable that presented the highest effect (estimate = -0.1787, 95CI: 0.3504 to -0.0070, $p = 0.0207$). Differential calculus showed that the optimal value for the $F_{mean\_dominant}$ was 34.75 N and for the H was 174.67 cm. From those values onwards the swimming velocity decreased.

Table 3 shows the swimming velocity and propulsion categorization by SL round, SF round, and its interaction. Regarding swimming velocity for both sexes, SL (males: F = 8.20, $p < 0.001$, $\eta^2 = 0.40$; females: F = 18.23, $p < 0.001$, $\eta^2 = 0.39$)

TABLE 1 | Descriptive data for all the variables assessed by sex. In-water variables include the data from the three stroke cycles measured.

	Males			Females		
Anthropometrics	**Mean±1SD**			**Mean±1SD**		
BM [kg]	68.93 ± 6.99			56.66 ± 5.94		
H [cm]	176.91 ± 5.57			162.63 ± 6.80		
AS [cm]	182.81 ± 8.24			167.56 ± 6.96		
$HSA_{dominant}$ [cm^2]	139.04 ± 10.07			114.52 ± 11.84		
$HSA_{non\text{-}dominant}$ [cm^2]	140.57 ± 11.72			114.05 ± 11.94		
	Mean±1SD			**Mean±1SD**		
Kinematics	**1st stroke cycle**	**2nd stroke cycle**	**3rd stroke cycle**	**1st stroke cycle**	**2nd stroke cycle**	**3rd stroke cycle**
v [$m\cdot s^{-1}$]	1.63 ± 0.07	1.63 ± 0.10	1.62 ± 0.08	1.43 ± 0.08	1.43 ± 0.08	1.41 ± 0.08
dv [%]	10.26 ± 4.59	10.06 ± 4.71	9.73 ± 4.35	7.99 ± 1.92	8.10 ± 2.27	8.72 ± 1.80
SF [Hz]	0.86 ± 0.06	0.86 ± 0.08	0.86 ± 0.08	0.81 ± 0.05	0.81 ± 0.05	0.82 ± 0.04
SL [m]	1.91 ± 0.14	1.91 ± 0.13	1.89 ± 0.16	1.76 ± 0.10	1.77 ± 0.09	1.73 ± 0.09
$UST_{dominant}$ [s]	0.84 ± 0.11	0.85 ± 0.10	0.86 ± 0.10	0.77 ± 0.11	0.77 ± 0.11	0.79 ± 0.10
$UST_{non\text{-}dominant}$ [s]	0.80 ± 0.08	0.81 ± 0.09	0.82 ± 0.07	0.74 ± 0.08	0.75 ± 0.09	0.75 ± 0.11
$UST_{stroke\ cycle}$ [s]	0.82 ± 0.09	0.83 ± 0.09	0.84 ± 0.08	0.76 ± 0.09	0.76 ± 0.10	0.77 ± 0.10
	Mean±1SD			**Mean±1SD**		
Propulsion	**1st stroke cycle**	**2nd stroke cycle**	**3rd stroke cycle**	**1st stroke cycle**	**2nd stroke cycle**	**3rd stroke cycle**
$F_{mean\_dominant}$ [N]	40.26 ± 6.34	38.88 ± 6.34	39.22 ± 7.57	33.64 ± 4.31	32.70 ± 4.45	32.86 ± 4.36
$F_{peak\_dominant}$ [N]	65.77 ± 10.69	62.73 ± 9.87	63.89 ± 11.21	57.13 ± 8.37	54.16 ± 8.14	54.09 ± 8.25
$dF_{dominant}$ [%]	43.69 ± 10.76	44.18 ± 9.19	45.53 ± 10.77	43.94 ± 8.23	43.98 ± 9.05	43.18 ± 8.60
$F_{mean\_non\text{-}dominant}$ [N]	37.35 ± 6.42	37.45 ± 5.57	37.04 ± 6.02	32.67 ± 5.05	33.59 ± 5.24	31.93 ± 4.41
$F_{peak\_non\text{-}dominant}$ [N]	65.60 ± 11.67	64.27 ± 8.90	63.07 ± 9.29	55.42 ± 10.37	54.68 ± 10.78	53.62 ± 9.79
$dF_{non\text{-}dominant}$ [%]	53.62 ± 11.80	49.18 ± 8.30	50.08 ± 9.20	46.91 ± 11.27	43.48 ± 10.31	45.57 ± 9.46
$F_{mean\_stroke\ cycle}$ [N]	38.80 ± 5.50	38.16 ± 4.85	38.23 ± 5.70	33.16 ± 3.98	33.15 ± 4.20	32.09 ± 2.97
$dF_{mean\_stroke\ cycle}$ [%]	48.65 ± 9.86	46.68 ± 6.88	47.68 ± 6.48	45.42 ± 8.59	43.73 ± 8.22	44.37 ± 7.99

BM–body mass; H–height; AS–arm span; $HSA_{dominant}$–hand surface area of the dominant limb; $HSA_{non\text{-}dominant}$–hand surface area of the non-dominant limb; v–swim velocity; dv–intra-cyclic variation of the swim velocity; SF–stroke frequency; SL–stroke length; $UST_{dominant}$–underwater stroke time of the dominant limb; $UST_{non\text{-}dominant}$–underwater stroke time of the non-dominant limb; $UST_{stroke\ cycle}$–mean underwater stroke time of the stroke cycle; $F_{mean\_dominant}$–mean propulsion of the dominant upper-limb; $F_{peak\_dominant}$–peak propulsion of the dominant upper-limb; $dF_{dominant}$–intra-cyclic variation of the dominant upper-limb force; $F_{mean\_non\text{-}dominant}$–mean propulsion of the non-dominant upper-limb; $F_{peak\_non\text{-}dominant}$–peak propulsion of the non-dominant upper-limb; $dF_{non\text{-}dominant}$–intra-cyclic variation of the non-dominant upper-limb force; $F_{mean\_stroke\ cycle}$–mean propulsion of the full stroke cycle; $dF_{mean\_stroke\ cycle}$–mean intra-cyclic variation of the full stroke cycle force.

TABLE 2 | Fixed effects of the final swimming velocity model computed with standard errors (SE), 95% confidence intervals (95CI), test-score (z-score), and significance value (p).

	Estimate	SE	z-score	P	95CI
Sex	0.2003	0.0354	5.7	<0.001	0.1309 to 0.2697
H	0.1048	0.0357	2.9	<0.001	0.0348 to 0.1747
H^2	-0.0003	0.0001	-3.0	0.0017	-0.0005 to -0.0001
$UST_{dominant}$	-0.1787	0.0876	-2.0	0.0207	-0.3504 to -0.0070
$F_{mean\_dominant}$	0.0139	0.0064	2.2	0.0149	0.0014 to 0.0264
$F_{mean\_dominant}^2$	-0.0002	0.0001	-2.0	0.0228	-0.0004 to -0.000004

H–height; $UST_{dominant}$–underwater stroke time (dominant upper-limb); $F_{mean\_dominant}$–mean propulsion produced by the dominant upper-limb.

and SF (males: F = 38.20, $p < 0.001$, $\eta^2 = 0.47$; females: F = 83.04, $p < 0.001$, $\eta^2 = 0.51$) presented significant effects. The interaction between SL and SF was significant for females (F = 8.00, $p = 0.001$, $\eta^2 = 0.05$), but not for males (F = 1.60, $p = 0.172$, $\eta^2 = 0.04$). Regarding the propulsion for both sexes, the same trend was verified in SL (males: F = 2.54, $p = 0.013$, $\eta^2 = 0.32$; females: F = 3.07, $p < 0.012$, $\eta^2 = 0.34$), but not in SF (males: F = 1.91, $p = 0.144$, $\eta^2 = 0.06$; females: F = 0.78, $p = 0.466$, $\eta^2 = 0.02$). The interaction between SL and SF was non-significant for both sexes (males: F = 0.77, $p = 0.601$, $\eta^2 = 0.05$; females: F = 1.48, $p = 0.242$, $\eta^2 = 0.05$) (**Table 3**).

Figure 1 depicts the swimming velocity categorized by SL and SF (Panel A–males; Panel B–females). In males (**Figure 1**–panel A) the SF–SL combination corresponding to the fastest swimming velocity suggested a SF of 0.80 Hz and a SL of 2.20 m (swimming velocity: 1.75 m s^{-1}). For females (**Figure 1**–panel B), the SF–SL combination indicated a SF of 0.80 Hz and a SL of 1.90 m (swimming velocity: 1.56 m s^{-1}). **Figure 1** also depicts the propulsion categorized by SL and SF (Panel C–males; Panel D–females). The highest propulsion in males (44.28 N) was observed with a combination of 0.90 Hz (SF) and 1.75 m (SL), and in females (42.94 N) by combining a SF of

TABLE 3 | Male and female two-way ANOVAs considering swimming velocity and propulsion by SL round, SF round, and their interaction (see **Figure 1**).

	Males			Females		
Swim velocity	**F-ratio**	**p**	**η^2**	**F-ratio**	**p**	**η^2**
SL round	8.20	<0.001	0.40	18.23	<0.001	0.39
SF round	38.20	<0.001	0.47	83.04	<0.001	0.51
SL * SF round	1.60	0.172	0.04	8.40	0.001	0.05
R^2	0.831			0.889		
Mean square error	0.002			0.001		
Propulsion						
SL round	2.54	0.013	0.32	3.07	0.012	0.34
SF round	1.91	0.144	0.06	0.78	0.466	0.02
SL * SF round	0.77	0.601	0.05	1.48	0.242	0.05
R^2	0.576			0.427		
Mean square error	18.733			10.327		

Propulsion–correspond to the $F_{mean\_stroke\ cycle}$ (mean propulsion of the full stroke cycle); SL, stroke length; SF, stroke frequency; η^2–eta square (effect size index).

0.80 Hz with a SL of 1.95 m. Considering the swimming velocity against SL, and taking into account the propulsion delivered at each SF (Panel E–males; Panel F–females), it is possible to observe that the SF–SL combination to achieve the fastest velocity was not the one providing the highest propulsion (**Figure 1**).

DISCUSSION

The aim of this study was to predict swimming velocity based on a set of anthropometric, kinematic, and kinetic variables, and understand the SF–SL combinations associated with swimming velocity and propulsion in young sprint swimmers. The main findings are that swimming velocity model produced a significant sex effect (being males fastest than females) and retained as predictors the anthropometrics (H), kinematics ($UST_{dominant}$), and kinetics ($F_{mean\_dominant}$). The fastest swimming velocity for both sexes was not achieved either at the highest SF or SL. Moreover, the highest propulsion was not responsible for delivering the fastest swimming velocity.

Swimming velocity retained as significant predictors sex, H, H^2, $UST_{dominant}$, $F_{mean\_dominant}$, and $F_{mean\_dominant}^2$. Since the sample included post-pubertal swimmers (males: 15.92 ± 0.75 years-old; females: 14.99 ± 1.06 years-old) a sex effect was expected. Thus, unsurprisingly, males were faster than females. Height was the best predictor retained by the model. The literature demonstrates that the fastest swimmers are taller and have a wider arm span and larger body dimensions in relation to the upper body (Nevill et al., 2015; Figueiredo et al., 2016). The $UST_{dominant}$ and the $F_{mean\_dominant}$ (kinematics and kinetics, respectively) were also retained. The $UST_{dominant}$ had a negative relationship with swimming velocity (i.e., less time performing the in-water phase of the stroke cycle led to a faster velocity), whereas a larger $F_{mean\_dominant}$ led to a faster velocity. Imbalances in the swimming velocity achieved by each upper limb were observed at these ages and competitive levels (Morais et al., 2020a). The motion performed by the dominant limb allowed the swimmers to reach faster velocities, taking less time to perform the in-water phase of the stroke cycle (UST) and producing more propulsion (Morais et al., 2020a). Moreover, it has been shown that when under task constraint, as the SF increases, the UST becomes shorter, leading to the production of more propulsion and thus speeding up (Cohen et al., 2018). It was shown that even during all-out bouts (i.e., maximum velocity), both upper limbs have different partial contributions to swimming velocity (Morais et al., 2020a). That said, the dominant upper limb plays a key role in the swimming velocity achieved.

Besides H and $F_{mean\_dominant}$, H^2 and $F_{mean\_dominant}^2$ were also retained by the model. This showed that swimming velocity increased with H and $F_{mean\_dominant}$, but only up to a given extend. In this particular set of participants, the maximum velocity was achieved if H = 174.67 cm and if $F_{mean\_dominant}$ = 34.75 N. Literature clearly acknowledges the positive relationship between height and the upper limbs length for general population (Fairbanks and Fairbanks, 2005), and swimmers in particular (Kjendlie and Stallman, 2011). A study that focused on the importance of anthropometry in swimming velocity observed that the advantage of longer upper limbs could potentially be mechanically disadvantageous in some respects, as it requires muscles to apply greater force (Nevill et al., 2015). Having longer upper limbs can only be seen as an advantage if a concomitant increase in strength in the upper limbs happens. The $F_{mean\_dominant}$ peaked at 34.75 N. From this force magnitude onwards, swimming velocity decreased. Swimming velocity is characterized by a periodically accelerated motion based on the net balance between thrust (i.e., propulsion) and drag forces acting on the swimmer's body (Barbosa et al., 2010). That is, during swimming, accelerations and deaccelerations of the swimmer's body occur, leading to changes in velocity (known as intra-cyclic variation of the swim velocity) (Barbosa et al., 2010). Thus, swimmers can achieve faster swimming velocities when they are able to generate propulsion while reducing drag force (resistance to forward motion) (Toussaint and Beek, 1992). However, to generate higher propulsion, swimmers may suffer misalignments along their longitudinal axis which can lead to a larger frontal surface area and consequently to a higher drag (Morais et al., 2020c). Thus, despite generating higher propulsion they can be under a higher drag immediately after which will promote a decrease in their swimming velocity. Moreover, the amount of fluid that is accelerated during propulsion depends on the shape of the body and the pattern of the water flow around the body. Therefore, a heavier swimmer needs to apply a higher propulsion just to overcome inertia and dislocate added mass (Caspersen et al., 2010). This enhances the meaningful relationship between propulsion and the swimmers' anthropometric features. Another reason can be related to the pitching and sweepback angles of the hand. Numerical studies reported that such angles have a meaningful effect on the propulsion generated by the swimmer's hands (Bilinauskaite et al., 2013; Cohen et al., 2020). There may be specific moments of the in-water phase of the stroke cycle in which the propulsion vector is not oriented in the opposite direction of the displacement, as noted previously. In our study, swimmers were asked to perform all-out trials at maximum velocity without any constraint in their stroke mechanics. Therefore, it can be

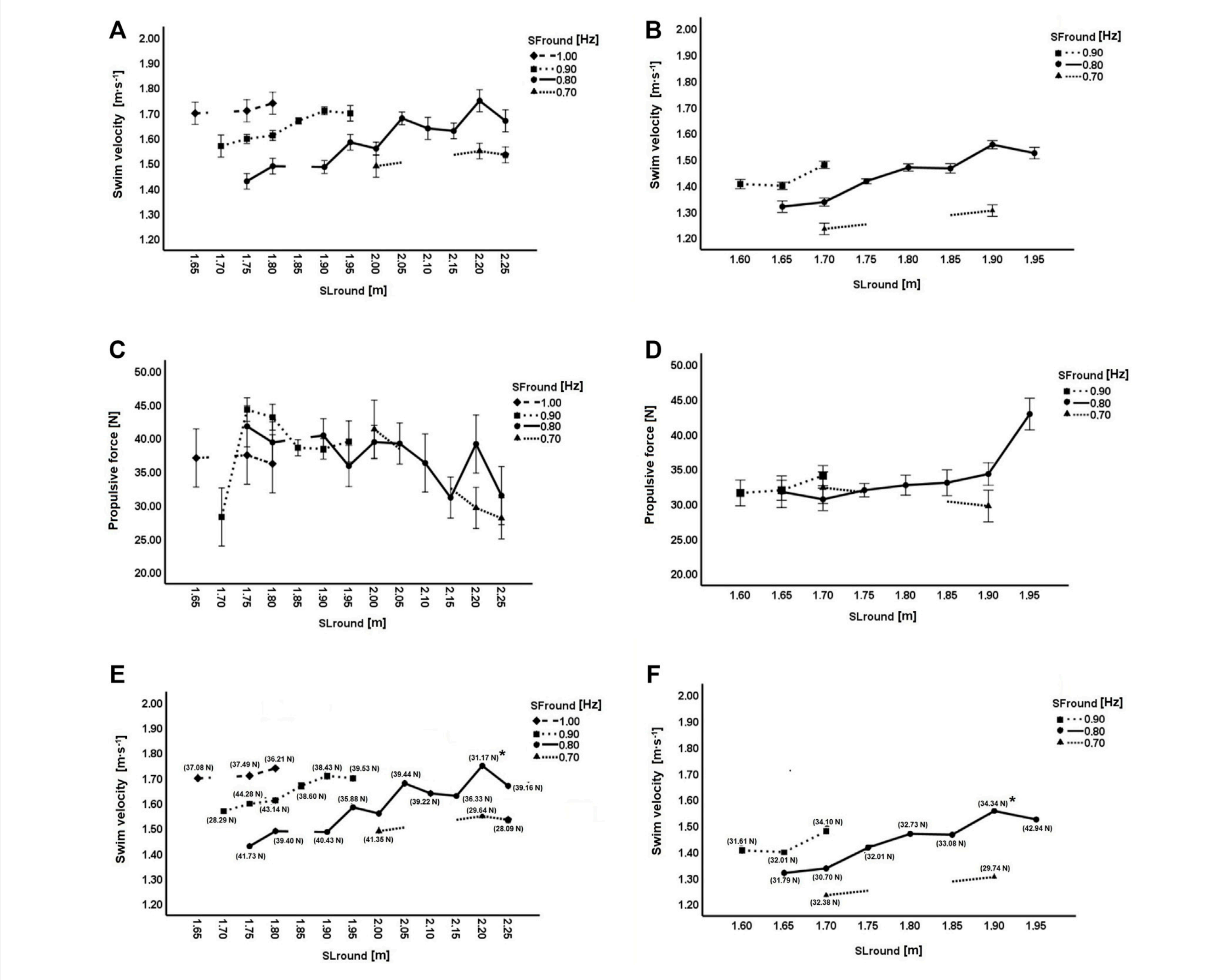

FIGURE 1 | Swimming velocity rounded by SF and SL: Panel **(A)** males; Panel **(B)** females. Propulsion rounded by SF and SL: Panel **(C)** males; Panel **(D)** females. Swim velocity rounded by SF and SL, with correspondent propulsion ($F_{mean\_stroke\ cycle}$) in each SL–SF combination: Panel **(E)** males; Panel **(F)** females. * - Panel **(E)**: highest swimming velocity achieved by male swimmers (1.75 m s^{-1}); Panel **(F)**: highest swimming velocity achieved by female swimmers (1.56 m s^{-1}). Error bars represent one standard deviation.

argued that greater propulsion does not always lead to faster swimming performances. This is depicted in **Figure 1** (Panel E–males; Panel F–females) in which swimming velocity was analyzed against SL and considered the propulsion delivered at each SF. As such, coaches must be advised to this phenomenon to better understand that it is not "enough" to increase propulsion if swimmers do not adopt an ideal hydrodynamic profile and consequently decrease drag.

In adult/elite (Seifert et al., 2007), and youth swimming (Silva et al., 2019) it has been shown that the fastest swimmers (males and females) were characterized by a faster velocity, higher SF and longer SL compared to their slower counterparts. Moreover, the literature reports considerable insights on the practice of monitoring SF, noting the potential to determine submaximal swimming velocities above which SL will begin to drop (Barden and Kell, 2009; Koga et al., 2020). However, scarce information can be found on the combinations between the two main variables of stroke mechanics (i.e., SF and SL) that are responsible for swimming velocity in both adult/elite and young swimmers. A study by Craig and Pendergast (1979) observed an "optimal" SF–SL combination in adult/elite sprint swimmers, suggesting this to be adopted in competition. For young swimmers, our data revealed a significant effect of SL and SF for both sexes when adopting velocity as the dependent variable (SL and SF were rounded as the independent or predictor variables). Studies have reported that increases in swimming velocity in both sexes are associated with faster SF (Seifert et al., 2007; Morris et al., 2016). The improvement of SF can happen in a relatively short period of time within a training program (Girold et al., 2006). Bio-feedback training programs have been reported to be conducive to such improvements (Hermann et al., 2012). On the other hand, increasing swimming velocity based on a longer SL requires a higher training period, despite promoting energy savings (Wakayoshi et al., 1993; Barbosa et al., 2008).

Overall, there are interactions between SF–SL and swimming velocity. **Figure 1** suggests that swimming velocity tends to increase with greater SL and SF, even though more evidently in females. It should be noted that the fastest swimming velocity was not achieved at the fastest SF nor at the longest SL. The fastest velocity was achieved at an "optimal" SF–SL combination. Indeed, previous research has suggested that attempts should be made to determine at what velocity and to what extend SL and SF change (Dekerle, 2006). A study by Koga et al. (2020) reported the effect of exceeding the SF at maximum swimming velocity. Swimmers were instructed to perform a SF faster than the one delivered at maximum velocity. The authors observed that swimming velocity did not significantly increase when the SF exceeded the SF at maximum velocity. However, a significant decrease in SL was noted whenever a faster SF was performed (Koga et al., 2020). Notwithstanding, our data based on a categorized SL and SF as the independent or predictor variables revealed that this relationship is not always negative (i.e., whenever SF increases, the SL decreases, and vice-versa). Rather than a clear inverse relationship, a sinusoidal profile was observed between SF and SL. That is, several SF–SL combinations can be observed. It was argued that maximum swimming velocity could not be achieved during long stroke cycles (i.e., slower SF), and that each swimmer should choose the "optimal" SF to increase his/her swimming velocity (Nakashima and Ono, 2014). The same authors reported that maximum joint torque by the upper limbs was responsible for a longer SL at the same SF. This suggests that kinetics (i.e., propulsion) might play a key role in the SF–SL relationship.

In adult/elite swimmers (Tsunokawa et al., 2019) and young swimmers (Morais et al., 2020a) it has been observed a positive association between propulsion and swimming velocity. The increase in propulsion led to an increase in swimming velocity. However, when rounding SL and SF by propulsion, a significant effect was noted in both sexes for SL. It was demonstrated that specific technique instructions allowed an increase in swimming velocity and SL with an increase in propulsion (Havriluk, 2009). However, a non-significant effect was verified on SF and on the SL-SF interaction. Indeed, the fastest swimming velocity was not achieved by the highest propulsion when rounding by SL–SF. The literature about propulsion in swimming reports that the in-water force produced by the swimmer is not always in the direction of the body's center of mass displacement (Bilinauskaite et al., 2013; Soh and Sanders, 2021). In this case, the increase in the magnitude of the propulsion does not produce an increase in swimming velocity (Havriluk, 2009). On the other hand, it has been shown that faster SF promoted increases in propulsion and, consequently, in swimming velocity (Cohen et al., 2018). The latter study conducted a numerical simulation based on a scan of a female swimmer. The upper limbs' motion was the same in all strokes and optimized conditions (e.g., hands' orientation). Even though numerical simulations provide insightful information, they do not allow us to understand how different constraints can impose significant variability in motor behavior. The SF exceeding the SF at maximum velocity was shown to reduce the propulsion of the hand during the push phase, caused by the decrease in the angle of attack (Koga et al., 2020). If sprinters are instructed to perform at a very fast SF, this can result in rushing the catch phase and producing less force or a poorly space-oriented vector force. Moreover, faster SF's are promoted by an increase in hand velocity, which could be related to more propulsion by the hand but also a reduction in the propulsion duration (i.e., impulse). It is also influenced by the ability of the swimmer to generate propulsion. If the swimmer is not "strong" enough, he/she can change the movement pattern to find less resistance in the hand, and consequently reducing the propulsion. Thus, the effective propulsion (force in the direction of the displacement) is diminished.

Overall, swimming velocity prediction retained a significant sex effect, and was determined by anthropometric, kinematic, and kinetic variables. Even though, H and $F_{mean\_dominant}$ presented a positive and significant effect, it was shown that swimming velocity started to decrease after reaching a given H and $F_{mean\_dominant}$. Coaches should be aware that longer leverages can only be an advantage if swimmers are able to produce an amount of strength that can be transferred to water (i.e., propulsion). Moreover, generating higher propulsion may not present the desired effect (i.e., fastest swimming velocity). If swimmers do not maintain a streamlined position by avoiding longitudinal misalignments, this may increase their frontal surface area and consequently drag. It was shown that maximum swimming velocity was not achieved at the highest SF or longest SL. Rather, it was achieved by an "optimal" SF–SL combination. The fastest velocity was not achieved at the highest propulsion. This may be related to the pitching and sweepback angles of the hand, which during the entire in-water phase of the stroke cycle may not be properly oriented in the opposite direction of the swimmer's displacement. Thus, despite exerting higher amount of propulsion, it may not be mechanically advantageous if not well oriented. One must be aware that an increase in propulsion by itself may not directly lead to an increase in swimming velocity. As such, age-group coaches, and swimmers, rather than focusing exclusively on increasing SF, should find the "optimal" SF–SL combination. They must also pay attention to the swimmer's hand orientation.

As main limitations, it can be considered that: 1) the SF–SL combinations reported in this study are only representative of the stroke mechanics of age-group sprinters without breathing actions; 2) the restrictive number of swimmers and stroke cycles included in the study, that may affect the results in an objective of generalization to a race or training performed in a 50 m swimming pool; 3) only the propulsion of the upper limbs was measured (nonetheless it accounts 90% of the total swimming velocity), and; 4) other variables than force may testify from the kinetics of the swimming motion, for instance impulse. One can suggest that future studies: 1) assess the role of propulsion in the SF–SL combination in different age-groups; 2) assess the role of propulsion in the SF–SL combination at different race paces or incremental tests, and; 3) include the kinematics of the hand to have insight on the amount of propulsion oriented in the direction of the displacement. Hand kinematics will allow us to obtain information about the amount of effective propulsion and swimming efficiency.

CONCLUSION

It can be concluded that swimming velocity was predicted by an interplay of variables related to anthropometry, kinematics, and kinetics. Swimming velocity increases up to a given H and $F_{mean\_dominant}$. Upon that, anthropometric features can only play a positive and significant role on swimming velocity if swimmer's also increase in muscle strength. Higher propulsion also plays a key-role on swimming velocity but if well orientated. Moreover, in age-group sprinters of both sexes, the fastest swimming velocity was not achieved with the fastest SF nor with the shortest SL. The fastest velocity was achieved by an "optimal" SF–SL combination. Likewise, the fastest velocity was not reached while delivering the highest propulsion. Thus, coaches must be aware that an increase by the SF may not promote a velocity increase. Same rational for the propulsion. A substantial focus must be put in the SF–SL combinations, to understand which one delivers better performance in an individual way.

DATA AVAILABILITY STATEMENT

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

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by University of Beira Interior Review Board. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

AUTHOR CONTRIBUTIONS

JM, TB, and DM conceived and designed the study. JM and AN performed the data analysis. JM, TB, SC and DM carried out the drafting of the manuscript. All authors reviewed the manuscript and approved the submitted version.

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Performance Development of European Swimmers Across the Olympic Cycle

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The aims of the study were to (1) quantify the performance development of race times and key performance indicators of European swimmers across the last Olympic cycle (from 2016 to 2021) and (2) provide reference values for long-course swimming pool events for both sexes from 50 m to 1,500 m including butterfly, backstroke, breaststroke, freestyle, and individual medley. Individual events from the 2016 and 2021 European swimming championships were included. Specifically, 246 men (age: 24.2 ± 3.4 years, FINA points: 890 ± 40) and 256 women races (age: 24.2 ± 4, FINA points: 879 ± 38) of the finalists were recorded and key performance indicators and split times analyzed. Performance differences in finalists of the 2016 and 2021 European championships were determined by an independent *t*-test and Cohen's *d* effect size. Reference values were retrieved from 2021 European championship finalists and are provided for all key performance indicators. Race times improved significantly ($P < 0.05$) or showed moderate ($d = 0.5$–1) to large effect sizes ($d > 1$) in 14 (men) and 6 (women) out of 16 events. Improvements were primarily evident in 100 m and 200 m events for males, as well as BR and sprint events for female swimmers. While start times improved in 15 (men) and 14 (women) events, turn times remained inconclusive in both sexes. Generally, breakout distances increased. Clean swimming velocities were faster in 12 (men) and 5 (women) events. In particular, for alternating swimming strokes, i.e., backstroke and freestyle, effect sizes indicated improved swimming efficiency with an inverse relationship between reduced stroke rate and increased distance per stroke. Coaches and performance analysts may use the present reference values as comparative data for race analyses and to specifically prepare swimmers for the various race sections. Data on the performance development should be used to analyze swimmers' potential and set goals for the various events and the next Olympic cycle.

Keywords: reference values, competition, development, athletes, sports

INTRODUCTION

From a historical perspective, swimming performance has substantially improved since 1960 (Nevill et al., 2007), with women showing an even steeper performance incline than men (Stanula et al., 2012; Sandbakk et al., 2018). After world records plateaued leading up to the 1990s (Nevill et al., 2007), swimming performance has improved slowly but steadily throughout the last decades, in particular in sprint and long-distance events (Konig et al., 2014). The gender-gap in swimming performance has settled at 10% (Nevill et al., 2007; Sandbakk et al., 2018), but decreases the longer the race distance (Wolfrum et al., 2013; Sandbakk et al., 2018). With the continuous development, up-to-date analyses are required to quantify recent performance progression during the Olympic cycle. Detailed race analyses discover potentials and exhibit perspectives for future performance developments specific to sex, race distance, and swimming stroke (Polach et al., 2021; Polach and Born, 2022). In particular, the recent Olympic cycle requires scientific attention. Due to the COVID-19 pandemic, the Olympic Games were postponed, and the Olympic cycle was extended from 4 to 5-years (IOC, 2021). While the longer timeframe increased the window for performance development, COVID-19 lockdowns compromised race times of the top-50 swimmers by 1–2% in the 2019–2020 season (Costa et al., 2021).

However, race section times and key performance indicators may not develop equally to race times. As start performance correlated with the swimmers' strength abilities (West et al., 2011), on-land training routines and strength and conditioning programs are specifically designed to improve the acyclic phases, i.e., start and turn performances (Bishop et al., 2013), which became increasingly important indicators for modern swim races (Morais et al., 2019; Born et al., 2021; Polach et al., 2021). Indeed, the new world record in the men's 1,500 m short-course freestyle (FR) event was broken by improved turns rather than clean swimming performance (Polach et al., 2021; Polach and Born, 2022). Therefore, in addition to total race time, performance development must be assessed for each race section and key performance indicator separately.

At major international competitions, swim analysts closely monitor and analyze races to provide quantitative feedback to their swimmers and coaches (Barbosa et al., 2021). Reference values established by world-class swimmers and championship finalists provide guidelines and benchmarks for individualized case reports (Barbosa et al., 2021). Previous research in the field of race analysis mainly focused on a particular swimming stroke (Gonjo and Olstad, 2020b; Olstad et al., 2020) or race distance (Morais et al., 2019, 2020; Polach et al., 2021) with an underrepresentation of female swimmers (Gonjo and Olstad, 2020a). Therefore, a comprehensive data set with up-to-date reference values for both sexes and long-course pool events from 50 m to 1,500 m including butterfly (BU), backstroke (BA), breaststroke (BR), FR, and individual medley (IM) is warranted.

The aims of the study were to (1) quantify the performance development of race times and key performance indicators in European swimmers across the last Olympic cycle (from 2016 to 2021) and (2) provide reference values for long-course pool events of top elite swimmers for both sexes from 50 m to 1,500 m including BU, BA, BR, FR, and IM.

MATERIALS AND METHODS

Participants

To determine whether key performance indicators and race section times at the European championships provide internationally representative reference values for performance development across the Olympic cycle, race times were extracted from the publicly available database www.swimrankings.net and compared between 2016 and 2021 Olympic games and European championships. To investigate key performance indicators and race section times, individual events from the 2016 and 2021 European long-course swimming championships were included. Specifically, 246 men [mean (minimum–maximum) age: 24.2 ± 3.4 years (17–36), FINA points: 890 ± 40 (771–1,025)] and 256 women in finals [age: 24.2 ± 4 (15–39), FINA points: 879 ± 38 (765–1,005)] were recorded and analyzed for the present study. All participants at the LEN (Ligue Européenne de Natation). European swimming championships agreed to be recorded for television broadcasting and race analysis. The study was approved by the institutional review board of the Swiss Federal Institute of Sport Magglingen (Reg.-Nr. 140_LSP_072021) and is in accordance with the ethical principles for medical research involving human subjects of the World Medical Association (Declaration of Helsinki).

Data Analysis

Eight stationary cameras recorded the swimmers in each lane individually at a frame rate of 50 Hz and with a panning view. They were placed halfway along the length of the pool, i.e., around the 25 m mark, 20 m away from the pool, and 5 m above the water surface. Video footage of the 2016 European championships was collected using V59 PTZ cameras (Axis Communications AB, Lund, Sweden). High-definition video cameras (2x XAVC S, Sony Group Corporation, Minato, Japan, 5x HC-X1000 and 1x HC-X1500, Panasonic Corporation, Kadoma, Japan) were used for the 2021 European championships. Race times were electronically measured and provided by the official timekeeper, along with the date of birth, which was used to calculate the swimmers' age (Microplus Informatica, Marene CN, Italy).

Race analyses were conducted as described previously (Gonjo and Olstad, 2020a; Barbosa et al., 2021) and video footages were manually analyzed using motion analysis software (Kinovea 0.9.1; Joan Charmant & Contrib., kinovea.org). Video footages were synchronized to the visible light flash of the starting signal and markings at the lane ropes were used to identify the 5, 15, 25, 35, and 45 m marks of each lap. Start times were measured from the starting signal until the top of the head reached the 15 m mark. Turn times were defined as the time from the top of the head reaching the 5 m mark before, to the 15 m mark after the pool wall. As movement velocity progressively reduces during the underwater phase (Gonjo and Olstad, 2020b), breakout distances rather than velocities were measured for a global description of the underwater performance. Breakout distances were measured from the pool wall until the head broke through the water surface. The number of floats on the lane ropes was used to calculate breakout distance to a 10th of a meter. To account for the intra-and inter-lap variability (Simbana-Escobar et al., 2018), stroke rate and distance per stroke were measured twice during each lap. Firstly, at the 15 m mark, but with at least one arm stroke completed after the breakout to limit the interference of transition from the underwater to clean swimming phase (Trinidad et al., 2020), and secondly at the 35 m mark. Stroke rate was determined as 60 divided by stroke time, while distance per stroke was defined as stroke time × section velocity. To compare the results of the present study to previously reported short-course (25 m pool length) data (Olstad et al., 2020), clean swimming velocities rather than times were measured. Clean swimming velocities were determined between the 15 and 45 m mark of each lap. The mean stroke rate, distance per stroke, and clean swimming velocity of each race were used for the statistical analysis. Timestamps tagged in the motion analysis software were imported to a specific spreadsheet to calculate split times for the corresponding key performance indicators (Excel 365, Microsoft Corporation, Redmond, USA).

Missing values due to blocked vision, e.g., by a referee or reflections on the water surface, were replaced by the mean value of that particular final. From a total of 19,254 data points, 12 (0.06%) missing values were treated accordingly. Due to an error in the video recordings of the men's 1,500 m FR final in 2016, only the races of the 3 podium swimmers were available completely, and thus, compared only to the 3 podium swimmers in the 2021 European championships. To ensure inter-rater reliability, 5% of all races were analyzed in duplicate by a second race analyst. Intra-class correlation coefficients with 95% CI showed high reliability for all key performance indicators, i.e., start time 0.995 (0.989–0.998), breakout distance 0.981 (0.957–0.991), turn time 0.998 (0.995–0.999), clean swimming velocity 1 (0.999–1), stroke rate 0.99 (0.978–0.996), and distance per stroke 0.997 (0.992–0.998).

Statistical Analysis

The statistical analyses were conducted using the statistical software package JASP version.14 (JASP-Team, University of Amsterdam, Amsterdam, The Netherlands). Descriptive data are presented as mean ± *SD*. Development of race times at the Olympic games and European championships across the 5-year Olympic cycle was determined with a 2-way ANOVA: competition (Olympic games vs. European championships) × year (2016 vs. 2021). After confirmation of normality, Tukey's *post-hoc* test was applied, or Bonferroni's test was used if the Levene test showed unequal variances (Field, 2013). Reference values were established based on the mean values of the eight finalists of the particular event at the 2021 European championships. Performance development was assessed and differences between the performance of finalists of the 2016 and 2021 European championships were determined with a Student *t*-test for independent samples with a two-sided alternative hypothesis. If Levene's test showed unequal variances, Welch's *t*-test was used. If the Shapiro-Wilk showed non-normal distributed data, a Mann-Whitney test was conducted. Statistical significance was accepted with an alpha-level ≤ 0.05. To assess results for practical relevance, Cohen's *d* effect sizes (ES) were calculated for the Student and Welch *t*-test (Cohen, 1969; Fröhlich et al., 2009). Effect sizes for the Mann-Whitney test were based on the rank biserial correlation. According to the research population of elite athletes, effect sizes were classified as trivial (<0.25), small (0.25–0.5), moderate (0.5–1), and large (>1), as recommended previously (Fröhlich et al., 2009).

TABLE 1 | Age (mean ± standard deviation) of the 2021 European championship finalists, with a significant difference (*) to the 2016 finalists.

Event	Age (years)	
	Males	Females
Butterfly		
100 m	21.8 ± 2.7 $_{-1.63}$ *	25.0 ± 3.8 $_{0.44}$
200 m	23.1 ± 2.7 $_{-0.04}$	24.4 ± 4.0 $_{-0.03}$
Backstroke		
100 m	22.6 ± 2.1 $_{-0.08}$	25.1 ± 3.1 $_{0.75}$
200 m	24.0 ± 3.0 $_{0.36}$	22.3 ± 3.8 $_{-0.11}$
Breaststroke		
100 m	24.9 ± 2.4 $_{0.27}$	23.8 ± 4.4 $_{0.74}$
200 m	25.8 ± 2.7 $_{0.56}$	25.3 ± 4.8 $_{0.42}$
Freestyle		
50 m	27.5 ± 3.6 $_{0.50}$	27.1 ± 4.4 $_{0.09}$
100 m	20.8 ± 1.9 $_{-2.70}$ *	25.6 ± 5.0 $_{0.19}$
200 m	22.6 ± 3.1 $_{-0.25}$	23.9 ± 4.9 $_{-0.20}$
400 m	23.4 ± 2.8 $_{0.74}$	22.1 ± 4.5 $_{-0.48}$
1,500/800 m	26.0 ± 1.0 $_{1.00}$	24.0 ± 3.4 $_{0.87}$
Individual medley		
200 m	25.3 ± 5.3 $_{0.06}$	24.1 ± 5.1 $_{-0.03}$
400 m	24.8 ± 4.7 $_{0.03}$	23.4 ± 4.9 $_{-0.38}$

Positive and negative effect sizes in $_{subscript\ font}$ indicate increased or decreased age from 2016 to 2021, respectively.

RESULTS

The number of individuals that qualified for the final of the same event in both the 2016 and 2021 European championships varied from 0 to 4 and was on average 23.44%. Regarding age, the finalists in 2021 were significantly younger in the 100 m BU and FR events compared to 2016. Moderate to large ES indicated older age for 200 m BR, 50 m FR, 400 m FR, and 1,500 m FR. Female finalists were older with moderate ES for 50 m BA, 100 m BA, 100 m BR, and 800 m FR. Descriptive age data for all events are provided in **Table 1**.

Race times significantly improved from 2016 to 2021 European championships in 6 events for males, i.e., 100 m BA, 100 and 200 m BR, 100 and 200 m FR, and 200 m IM (**Table 2**), but only 2 events for female swimmers, i.e., 100 m BR and 50 m FR (**Table 3**). In particular, the race times of male European swimmers approximated the Olympic level. While 10 male events in 2016 were significantly faster at the Olympic games than the

TABLE 2 | Development of race times in male finalists at the Olympic Games (OG) and European championships (EC) across the 5-year Olympic cycle.

		Year					
		2016	**2021**		***F***	***P***	$_{p}\eta^{2}$
Butterfly							
100 m	OG	00:51.28 ± 00.46	00:50.65 ± 00.71	(a)	$F_{(1\|28)} = 10$	<0.01	0.26
	EC	00:51.85 ± 00.64	00:51.17 ± 00.50	(b)	$F_{(1\|28)} = 7$	0.01	0.20
				(c)	$F_{(1\|28)} = 0$	0.90	0.00
200 m	OG	01:54.77 ± 01.40	01:54.43 ± 01.44	(a)	$F_{(1\|28)} = 2$	0.19	0.06
	EC	01:55.85 ± 01.34	01:54.78 ± 01.73	(b)	$F_{(1\|28)} = 2$	0.19	0.06
				(c)	$F_{(1\|28)} = 0$	0.50	0.02
Backstroke							
100 m	OG	00:52.68 ± 00.54	00:52.44 ± 00.38	(a)	$F_{(1\|28)} = 28$	<0.01	0.50
	EC	00:54.20 ± 00.25 #	00:53.07 ± 00.23 *#	(b)	$F_{(1\|28)} = 69$	<0.01	0.71
				(c)	$F_{(1\|28)} = 12$	<0.01	0.29
200 m	OG	01:55.09 ± 01.10	01:55.82 ± 01.84	(a)	$F_{(1\|28)} = 1$	0.29	0.04
	EC	01:58.56 ± 01.87 #	01:56.59 ± 01.55	(b)	$F_{(1\|28)} = 14$	<0.01	0.33
				(c)	$F_{(1\|28)} = 6$	0.03	0.17
Breaststroke							
100 m	OG	00:58.99 ± 00.84	00:58.60 ± 00.66	(a)	$F_{(1\|28)} = 12$	<0.01	0.30
	EC	01:00.33 ± 00.97 #	00:58.80 ± 00.67 *	(b)	$F_{(1\|28)} = 7$	0.01	0.21
				(c)	$F_{(1\|28)} = 4$	0.05	0.13
200 m	OG	02:07.81 ± 00.28	02:07.65 ± 00.84	(a)	$F_{(1\|28)} = 8$	0.01	0.22
	EC	02:10.33 ± 01.29 #	02:08.54 ± 01.18 *	(b)	$F_{(1\|28)} = 24$	<0.01	0.46
				(c)	$F_{(1\|28)} = 5$	0.03	0.16
Freestyle							
50 m	OG	00:21.67 ± 00.23	00:21.60 ± 00.23	(a)	$F_{(1\|28)} = 2$	0.19	0.06
	EC	00:21.99 ± 00.25 #	00:21.85 ± 00.19	(b)	$F_{(1\|28)} = 12$	<0.01	0.31
				(c)	$F_{(1\|28)} = 0$	0.66	0.01
100 m	OG	00:47.96 ± 00.25	00:47.63 ± 00.41	(a)	$F_{(1\|28)} = 18$	<0.01	0.39
	EC	00:48.55 ± 00.22 #	00:47.89 ± 00.38 *	(b)	$F_{(1\|28)} = 14$	<0.01	0.33
				(c)	$F_{(1\|28)} = 2$	0.16	0.07
200 m	OG	01:45.47 ± 00.44	01:44.87 ± 00.53	(a)	$F_{(1\|28)} = 10$	<0.01	0.27
	EC	01:47.01 ± 00.74 #	01:45.98 ± 01.02 * #	(b)	$F_{(1\|28)} = 27$	<0.01	0.49
				(c)	$F_{(1\|28)} = 1$	0.41	0.02
400 m	OG	03:44.24 ± 02.36	03:44.30 ± 00.76	(a)	$F_{(1\|28)} = 1$	0.36	0.03
	EC	03:47.19 ± 01.72 #	03:46.05 ± 01.32	(b)	$F_{(1\|28)} = 16$	<0.01	0.37
				(c)	$F_{(1\|28)} = 1$	0.31	0.04
1,500 m	OG	14:46.81 ± 08.81	14:50.66 ± 10.33	(a)	$F_{(1\|28)} = 1$	0.44	0.02
	EC	14:54.78 ± 10.23	14:56.52 ± 10.72	(b)	$F_{(1\|28)} = 4$	0.06	0.12
				(c)	$F_{(1\|28)} = 0$	0.77	0.00
Individual medley							
200 m	OG	01:57.13 ± 01.16	01:56.61 ± 01.09	(a)	$F_{(1\|28)} = 17$	<0.01	0.37
	EC	02:00.05 ± 00.87 #	01:57.77 ± 00.68 *	(b)	$F_{(1\|28)} = 36$	<0.01	0.56
				(c)	$F_{(1\|28)} = 7$	0.02	0.19
400 m	OG	04:11.22 ± 03.72	04:10.62 ± 00.63	(a)	$F_{(1\|28)} = 4$	0.07	0.11
	EC	04:16.05 ± 02.36 #	04:13.23 ± 02.59	(b)	$F_{(1\|28)} = 17$	<0.01	0.37
				(c)	$F_{(1\|28)} = 2$	0.23	0.05

(a) Main effect: year (2016 vs. 2021).
(b) Main effect: competition (OG vs. EC).
(c) Interaction effect: year × competition.
**Significant difference compared to 2021.*
 # Significant difference compared to OG.
Race times were compared with a 2-way ANOVA: competition (Olympic games vs. European championships) × year (2016 vs. 2021).

TABLE 3 | Development of race times in female finalists at the Olympic Games (OG) and European championships (EC) across the 5-year Olympic cycle.

		Year					
		2016	**2021**		***F***	***P***	$_p\eta^2$
Butterfly							
100 m	OG	00:56.63 ± 00.56	00:56.14 ± 00.58	(a)	$F_{(1\|27)} = 1$	0.31	0.04
	EC	00:57.90 ± 01.15 #	00:57.84 ± 00.40 #	(b)	$F_{(1\|27)} = 31$	<0.01	0.54
				(c)	$F_{(1\|27)} = 1$	0.43	0.02
200 m	OG	02:06.40 ± 01.32	02:06.78 ± 01.80	(a)	$F_{(1\|28)} = 1$	0.48	0.02
	EC	02:08.49 ± 01.27 #	02:08.82 ± 01.17 #	(b)	$F_{(1\|28)} = 17$	<0.01	0.38
				(c)	$F_{(1\|28)} = 0$	0.96	0.00
Backstroke							
100 m	OG	00:58.86 ± 00.26	00:58.43 ± 00.69	(a)	$F_{(1\|28)} = 3$	0.08	0.10
	EC	01:00.05 ± 00.92 #	00:59.59 ± 00.72 #	(b)	$F_{(1\|28)} = 23$	<0.01	0.45
				(c)	$F_{(1\|28)} = 0$	0.96	0.00
200 m	OG	02:07.84 ± 01.29	02:06.75 ± 01.42	(a)	$F_{(1\|28)} = 3$	0.11	0.09
	EC	02:10.11 ± 02.17	02:09.10 ± 02.11	(b)	$F_{(1\|28)} = 13$	<0.01	0.32
				(c)	$F_{(1\|28)} = 0$	0.95	0.00
Breaststroke							
100 m	OG	01:06.47 ± 01.06	01:05.85 ± 00.62	(a)	$F_{(1\|28)} = 11$	<0.01	0.29
	EC	01:07.43 ± 00.71	01:06.32 ± 00.33 *	(b)	$F_{(1\|28)} = 8$	0.01	0.21
				(c)	$F_{(1\|28)} = 1$	0.34	0.03
200 m	OG	02:22.37 ± 01.01	02:21.70 ± 01.91	(a)	$F_{(1\|28)} = 1$	0.25	0.05
	EC	02:24.16 ± 02.47	02:23.29 ± 01.76	(b)	$F_{(1\|28)} = 7$	0.02	0.19
				(c)	$F_{(1\|28)} = 0$	0.89	0.00
Freestyle							
50 m	OG	00:24.23 ± 00.22	00:24.23 ± 00.20	(a)	$F_{(1\|28)} = 5$	0.03	0.16
	EC	00:24.79 ± 00.39 #	00:24.34 ± 00.25 *	(b)	$F_{(1\|28)} = 12$	<0.01	0.31
				(c)	$F_{(1\|28)} = 5$	0.03	0.16
100 m	OG	00:53.05 ± 00.25	00:52.61 ± 00.38	(a)	$F_{(1\|28)} = 8$	0.01	0.22
	EC	00:54.41 ± 01.20 #	00:53.55 ± 00.33 #	(b)	$F_{(1\|28)} = 24$	<0.01	0.46
				(c)	$F_{(1\|28)} = 1$	0.38	0.03
200 m	OG	01:55.12 ± 00.91	01:55.01 ± 00.96	(a)	$F_{(1\|28)} = 0$	0.98	0.00
	EC	01:57.48 ± 01.14 #	01:57.61 ± 01.34 #	(b)	$F_{(1\|28)} = 41$	<0.01	0.59
				(c)	$F_{(1\|28)} = 0$	0.76	0.00
400 m	OG	04:03.08 ± 03.35	04:02.68 ± 04.13	(a)	$F_{(1\|28)} = 0$	0.99	0.00
	EC	04:07.63 ± 02.35 #	04:07.99 ± 02.33 #	(b)	$F_{(1\|28)} = 20$	<0.01	0.41
				(c)	$F_{(1\|28)} = 0$	0.73	0.00
800 m	OG	08:18.68 ± 06.85	08:19.90 ± 04.86	(a)	$F_{(1\|28)} = 0$	0.82	0.00
	EC	08:28.48 ± 04.91 #	08:28.12 ± 05.10 #	(b)	$F_{(1\|28)} = 22$	<0.01	0.43
				(c)	$F_{(1\|28)} = 0$	0.69	0.01
Individual medley							
200 m	OG	02:09.93 ± 02.50	02:10.03 ± 01.68	(a)	$F_{(1\|28)} = 0$	0.74	0.00
	EC	02:11.69 ± 02.28	02:11.11 ± 01.21	(b)	$F_{(1\|28)} = 4$	0.05	0.13
				(c)	$F_{(1\|28)} = 0$	0.63	0.01
400 m	OG	04:33.15 ± 03.47	04:35.94 ± 02.87	(a)	$F_{(1\|28)} = 2$	0.18	0.06
	EC	04:39.12 ± 04.22 #	04:39.96 ± 04.15	(b)	$F_{(1\|28)} = 14$	<0.01	0.34
				(c)	$F_{(1\|28)} = 1$	0.46	0.02

(a) Main effect: year (2016 vs. 2021).
(b) Main effect: competition (OG vs. EC).
(c) Interaction effect: year × competition.
**Significant difference compared to 2021.*
 # Significant difference compared to OG.
Race times were compared with a 2-way ANOVA: competition (Olympic games vs. European championships) × year (2016 vs. 2021).

European championships, this was only the case for 2 events in 2021. In comparison, race times for 9 and 7 female events at the European championships were slower than at the Olympic games in 2016 and 2021, respectively.

Reference values for race times and key performance indicators were retrieved from the 2021 European championship finalists and are presented with the performance development across the Olympic cycle in **Table 4** (men) and **Table 5** (women). Descriptive data (mean ± standard deviation) for both European championships, including effect sizes with 95% CIs, *P*-values, and %-differences for performance development from 2016 to 2021 are provided in **Supplementary Tables 1–8**.

Regarding performance development across the 5-year timespan, start times improved (in 15 events for men and 14 events for women), while turn-times remained inconclusive for both sexes. Generally, breakout distances increased. Clean swimming velocities became faster (in 12 events for men and 5 events for women). ES indicated an inverse relationship between reduced stroke rate and increased distance per stroke, in particular for alternating swimming strokes, i.e., BA and FR.

DISCUSSION

The present study provides reference values for long-course swimming pool events for both sexes from 50 to 1,500 m including BU, BA, BR, FR, and IM. Descriptive data (mean ± *SD*) and %-differences between both the 2016 and 2021 European championships are provided in **Supplementary Material** and may be used for practical assessment of performance development. In particular, male European swimmers approximated the performance level of the Olympic games and significantly improved race times across the 5-year timespan in 100 m BA, 100 m and 200 m BR, 100 m and 200 m FR, and 200 m IM. Performance development was less pronounced in female swimmers, where race times only improved significantly for 100 m BR and 50 m FR. A comparison of key performance indicators showed significantly improved start times with medium to large ES for longer breakout distances. Furthermore, clean swimming velocities improved, while changes in turn performances remained inconclusive. Effect sizes indicated an inverse relationship between reduced stroke rate and increased distance per stroke in particular for alternating swimming strokes, i.e., BA and FR.

Due to limited accreditations for race analysts and scientists at the Olympic games, the present study determined benchmarks for key performance indicators from races at the European swimming championships. To relate performance data of European swimmers to the Olympic level, the development of race times across the 5-year timeframe was compared between the European championships and Olympic games. The results show that male European swimmers caught up with the world-class swimmers across the recent Olympic cycle, as only 2 events in 2021, compared to 10 in 2016, were significantly slower than in the Olympic finals. Therefore, key performance indicators and race section times can be used as benchmarks for a broad range of international male swimmers. In contrast, in 2021 female European swimmers still showed significantly slower race times in 7 events, thus, the actual race time needs to be considered when using the reference values for international female swimmers.

In the present study, start times improved across the 5-year Olympic cycle. The start involves the on-block, flight, underwater, and transition to clean swimming phases (Tor et al., 2015b). In particular, during phases above water, i.e., block and flight phases, previous studies found that start performance was related to the horizontal take-off velocity (Tor et al., 2015b) and swimmers' maximal strength abilities (West et al., 2011). Multiple studies have shown that particularly the acyclic phases, i.e., start performance, profit from various strength training methods (Bishop et al., 2013; Thng et al., 2019). However, on-block force production could not be investigated with the video-based race analyses, and altered strength abilities and conditioning regimes that may have improved start performance across the recent years are a matter of future studies. Yet, the present study showed medium to large ES for improved breakout distances in addition to the improved start performances across the Olympic cycle. While the present study is the first to report competition-based breakout distances for IM to the best of our knowledge, the underwater phase is a critical race section, as the momentum gained from the push-off transitions to the clean swimming phase (Veiga and Roig, 2017; Olstad et al., 2020). As drag forces are lower underwater than at the surface (Tor et al., 2015a), swimmers aim to extend the underwater phase to the regulatory limits of 15 m (FINA, 2022). Previously reported underwater distances were shorter (13.1 ± 1 m) (Olstad et al., 2020) compared to the present study (14 ± 0.7 m). However, the performance level of the swimmers in previous studies was lower (688 ± 87 FINA points) compared to the present European championship finalists (890 ± 40 FINA points). Therefore, higher-ranked swimmers achieved faster underwater velocities and underwater distances were related to swimming performance (Pla et al., 2021). However, lack of oxygen due to restricted breathing results in apnea-induced discomfort (Veiga et al., 2022). In order to not interfere with transition and clean swimming phases, the length of the underwater phase should match an individual's optimum rather than maximum (Veiga et al., 2022). Specific breathing maneuvers and apnea training regimes may help to achieve longer underwater phases (Woorons et al., 2016; Robertson et al., 2020).

Improved race times were accompanied by faster clean swimming velocities, rather than turn performances, this was particularly noteworthy for middle-distance events. In practice, turns are performed repeatedly between every lap. However, with most training sessions performed at low intensities (Pollock et al., 2019), most turns are performed with slower velocities than during competition. In contrast, speed training referred to as alactic sprints by practitioners, is typically performed from 15 to 25 m after pushing off the pool wall or from the starting block (Pollock et al., 2019). However, turns require a complex set of specific technical skills, i.e., the timing of wall approach, rotation, push-off, gliding, underwater kicking, and transition to full-stroke swimming (Olstad et al., 2020; Nicol et al., 2021). The complexity of these performance indicators contributing to total turn time underlines the importance of race pace-specific

TABLE 4 | Reference values (mean ± standard deviation) for key performance indicators retrieved from male 2021 European championship finalists with significant difference (*) to the 2016 finalists.

Event	Start time (s)	Breakout distance after start (m)	Turn time (s)	Breakout distance after turn (m)	Clean swimming velocity (m/s)	Stroke rate (bpm)	Distance per stroke (m)
Butterfly							
100 m	$5.53 \pm 0.19_{1.54}^{*}$	$13.4 \pm 0.4_{0.28}$	$10.39 \pm 0.13_{0.06}$	$11.7 \pm 1.5_{0.38}$	$1.84 \pm 0.02_{0.95}$	$56.1 \pm 2.6_{0.86}$	$1.98 \pm 0.11_{-0.38}$
200 m	$5.91 \pm 0.08_{2.07}^{*}$	$13.5 \pm 0.3_{0.78}$	$11.55 \pm 0.18_{-0.39}$	$9.8 \pm 1.3_{0.62}$	$1.68 \pm 0.03_{0.53}$	$49.8 \pm 1.8_{0.26}$	$2.03 \pm 0.10_{-0.05}$
Backstroke							
100 m	$6.20 \pm 0.17_{1.33}^{*}$	$13.3 \pm 0.7_{-0.79}$	$10.15 \pm 0.16_{1.07}^{*}$	$11.5 \pm 1.1_{0.30}$	$1.77 \pm 0.02_{1.92}^{*}$	$49.7 \pm 3.4_{-0.22}$	$2.15 \pm 0.14_{0.60}$
200 m	$6.46 \pm 0.23_{0.73}$	$13.6 \pm 0.6_{0.14}$	$10.99 \pm 0.33_{0.68}$	$11.4 \pm 2.2_{0.92}$	$1.62 \pm 0.03_{1.00}$	$41.4 \pm 2.5_{-0.50}$	$2.35 \pm 0.12_{0.82}$
Breaststroke							
100 m	$6.43 \pm 0.25_{1.50}^{*}$	$14.0 \pm 0.7_{0.50}$	$11.77 \pm 0.11_{1.22}^{*}$	$10.5 \pm 0.9_{0.97}$	$1.60 \pm 0.02_{1.38}^{*}$	$55.2 \pm 3.7_{0.68}$	$1.75 \pm 0.11_{-0.45}$
200 m	$6.47 \pm 0.36_{0.81}$	$15.5 \pm 1.7_{0.42}$	$12.55 \pm 0.20_{-0.25}$	$10.8 \pm 1.0_{0.42}$	$1.48 \pm 0.02_{1.55}^{*}$	$35.7 \pm 3.1_{-0.39}$	$2.51 \pm 0.21_{0.76}$
Freestyle							
50 m	$5.31 \pm 0.11_{1.33}^{*}$	$10.4 \pm 1.7_{0.35}$			$2.12 \pm 0.02_{-0.39}$	$61.9 \pm 1.8_{-0.45}$	$2.05 \pm 0.06_{0.41}$
100 m	$5.55 \pm 0.14_{2.02}^{*}$	$11.9 \pm 0.7_{0.55}$	$9.51 \pm 0.19_{-0.60}$	$8.1 \pm 1.7_{0.53}$	$1.98 \pm 0.02_{1.55}^{*}$	$50.9 \pm 2.4_{-0.99}$	$2.34 \pm 0.10_{1.43}^{*}$
200 m	$5.84 \pm 0.16_{0.92}$	$12.3 \pm 0.6_{0.76}$	$10.39 \pm 0.18_{-0.33}$	$7.4 \pm 1.3_{1.47}^{*}$	$1.81 \pm 0.02_{0.66}^{*}$	$43.4 \pm 2.0_{-0.31}$	$2.51 \pm 0.12_{0.64}$
400 m	$6.07 \pm 0.16_{1.31}^{*}$	$11.3 \pm 2.0_{0.22}$	$10.87 \pm 0.13_{-0.59}$	$6.8 \pm 0.5_{1.53}^{*}$	$1.70 \pm 0.01_{1.05}^{*}$	$39.5 \pm 2.8_{-1.26}^{*}$	$2.60 \pm 0.17_{1.47}^{*}$
1,500 m	$6.67 \pm 0.06_{0.17}$	$10.6 \pm 1.1_{0.05}$	$11.37 \pm 0.11_{-0.81}$	$5.1 \pm 1.1_{-0.33}$	$1.65 \pm 0.01_{0.00}$	$37.8 \pm 5.1_{-0.34}$	$2.64 \pm 0.36_{0.37}$
Individual medley							
200 m	$5.84 \pm 0.15_{1.23}^{*}$	$12.7 \pm 0.5_{-1.02}$	$11.80 \pm 0.22_{-0.24}$	$9.6 \pm 0.9_{0.05}$	$1.63 \pm 0.02_{2.85}^{*}$	$44.3 \pm 1.7_{0.22}$	$2.22 \pm 0.10_{0.48}$
400 m	$6.26 \pm 0.19_{1.01}$	$12.7 \pm 0.9_{0.28}$	$12.43 \pm 0.18_{-0.07}$	$8.2 \pm 0.9_{0.03}$	$1.53 \pm 0.02_{1.28}^{*}$	$40.5 \pm 1.5_{-0.28}$	$2.27 \pm 0.09_{0.60}$

Positive and negative effect sizes in $_{\mathit{subscript\ font}}$ *indicate improved or decreased performance, respectively.*

TABLE 5 | Reference values (mean ± standard deviation) for key performance indicators retrieved from female 2021 European championship finalists with significant difference (*) to the 2016 finalists.

Event	Start time (s)	Breakout distance (m) after start	Turn time (s)	Breakout distance (m) after turn	Clean swimming velocity (m/s)	Stroke rate (bpm)	Distance per stroke (m)
Butterfly							
100 m	$6.33 \pm 0.18_{2.02}^{*}$	$13.2 \pm 1.0_{0.94}$	$11.63 \pm 0.25_{-0.08}$	$9.7 \pm 2.2_{0.83}$	$1.63 \pm 0.02_{-0.48}$	$56.4 \pm 3.0_{0.23}$	$1.74 \pm 0.10_{-0.37}$
200 m	$6.96 \pm 0.19_{0.54}$	$12.0 \pm 1.1_{0.06}$	$12.88 \pm 0.16_{-0.95}$	$8.0 \pm 1.5_{0.25}$	$1.50 \pm 0.02_{0.07}$	$51.6 \pm 2.5_{0.07}$	$1.75 \pm 0.09_{-0.07}$
Backstroke							
100 m	$7.09 \pm 0.20_{0.69}^{*}$	$13.4 \pm 0.5_{0.41}$	$11.48 \pm 0.29_{-0.36}$	$10.0 \pm 2.1_{-0.34}$	$1.58 \pm 0.04_{0.07}$	$48.1 \pm 3.4_{-0.65}$	$1.97 \pm 0.15_{0.65}$
200 m	$7.61 \pm 0.24_{0.00}$	$13.0 \pm 0.7_{0.16}$	$12.43 \pm 0.22_{-0.30}$	$8.5 \pm 1.6_{0.52}$	$1.48 \pm 0.03_{0.90}$	$41.1 \pm 4.0_{-0.87}$	$2.18 \pm 0.20_{1.18}^{*}$
Breaststroke							
100 m	$7.55 \pm 0.25_{0.69}^{*}$	$12.5 \pm 0.5_{1.10}^{*}$	$13.37 \pm 0.16_{-0.12}$	$8.7 \pm 0.5_{0.90}$	$1.43 \pm 0.01_{0.88}^{*}$	$48.6 \pm 6.1_{0.31}$	$1.79 \pm 0.22_{-0.07}$
200 m	$7.83 \pm 0.15_{1.27}^{*}$	$13.1 \pm 0.8_{0.84}^{*}$	$14.05 \pm 0.24_{-0.28}$	$9.2 \pm 0.6_{2.04}^{*}$	$1.34 \pm 0.02_{0.28}$	$35.8 \pm 3.8_{-0.21}$	$2.27 \pm 0.24_{0.32}$
Freestyle							
50 m	$6.01 \pm 0.17_{1.58}^{*}$	$11.8 \pm 0.9_{0.81}$			$1.91 \pm 0.02_{0.66}$	$60.2 \pm 2.9_{-0.18}$	$1.91 \pm 0.08_{0.40}$
100 m	$6.25 \pm 0.20_{1.61}^{*}$	$11.8 \pm 1.1_{0.89}$	$10.62 \pm 0.15_{0.19}$	$7.2 \pm 1.3_{0.87}$	$1.77 \pm 0.02_{0.71}$	$49.1 \pm 2.8_{-0.42}$	$2.17 \pm 0.13_{0.57}$
200 m	$6.65 \pm 0.17_{1.82}^{*}$	$10.5 \pm 0.7_{0.99}$	$11.51 \pm 0.16_{-0.40}$	$5.4 \pm 0.8_{1.03}$	$1.64 \pm 0.02_{-0.20}$	$43.7 \pm 2.8_{-0.41}$	$2.25 \pm 0.14_{0.36}$
400 m	$7.15 \pm 0.23_{0.67}$	$9.94 \pm 1.1_{0.04}$	$12.11 \pm 0.14_{-1.21}^{*}$	$3.9 \pm 0.7_{-0.63}$	$1.57 \pm 0.02_{0.42}$	$45.2 \pm 4.8_{0.32}$	$2.10 \pm 0.22_{-0.19}$
800 m	$7.23 \pm 0.22_{1.76}^{*}$	$9.73 \pm 0.9_{0.46}$	$12.21 \pm 0.16_{-0.12}$	$4.0 \pm 0.5_{-0.76}$	$1.53 \pm 0.02_{0.08}$	$44.8 \pm 3.8_{0.36}$	$2.06 \pm 0.16_{-0.33}$
Individual medley							
200 m	$6.74 \pm 0.24_{0.66}$	$12.3 \pm 1.1_{0.75}$	$13.17 \pm 0.23_{0.03}$	$7.2 \pm 1.1_{0.41}$	$1.47 \pm 0.01_{0.38}$	$45.2 \pm 2.4_{-0.02}$	$1.96 \pm 0.11_{0.10}$
400 m	$7.08 \pm 0.28_{0.45}$	$12.0 \pm 1.1_{0.54}$	$13.76 \pm 0.26_{-0.47}$	$6.2 \pm 0.4_{-0.33}$	$1.39 \pm 0.02_{0.23}$	$42.0 \pm 2.3_{-0.10}$	$1.99 \pm 0.09_{0.15}$

Positive and negative effect sizes in $_{\mathit{subscript\ font}}$ *indicate improved or decreased performance, respectively.*

turn drills implemented in speed training sessions. More research focusing on turn performance may enhance awareness and focus in practices on this particular part of the swim race. Thus, turn performance may allow for future performance developments, such as in the men's 1,500 m FR short-course event in which turn performance was the distinguishing factor for World championship finalists and a new World record (Polach et al., 2021; Polach and Born, 2022). Additionally, recent developments of new competition formats, i.e., the International Swimming League (ISL), which emphasizes short-course and sprint races, may further contribute to the development of the acyclic phases (ISL, 2022).

Generally, clean swimming velocity results from the product of stroke rate and stroke length. Across the Olympic cycle, effect sizes showed an improved swimming efficiency with decreased stroke rate and increased distance per stroke, in particular for the alternating swimming strokes, i.e., BA and FR. Previous studies showed the importance of on-land conditioning regimes to develop the required maximal strength for improvements in stroke length (Crowley et al., 2017). Traditional training methods, such as swimming with hand paddles and resisted in-water drills, have a larger effect on stroke rate and help to transfer strength gains to the sport-specific movement (Girold et al., 2006; Crowley et al., 2017). Therefore, current development toward higher awareness and implementation of on-land strength and conditioning and weight-lifting routines in elite swimmers (Crowley et al., 2018; Nugent et al., 2018; Pollock et al., 2019) may explain the increased distance per stroke across the Olympic cycle found in the present study.

In the present study, the age of European championship finalists was 20.8–27.5 years for males and 22.1–27.1 years for female swimmers. This is in line with previous findings showing that the age of peak performance varies between 21.4 and 26.1 years depending on the event (Allen et al., 2014). Based on race results, previous studies used longitudinal tracking to establish individual trajectories for performance development (Pyne et al., 2004; Post et al., 2020). By accounting for drop-out, the value of longitudinal tracking is clear (Born et al., 2022). However, the present study aimed to investigate the development of key performance indicators and race section times with video-based race analyses across an Olympic cycle. The number of individuals qualifying for the final of the same event in both the 2016 and 2021 European championships varied from 0 to 4 and was on average as low as 23.44%. This limited the longitudinal comparison of individual performance trajectories across the 5-year timeframe. To avoid the number of subjects randomly confounding findings due to lower statistical power in events with low sample size, all finalists of each event were therefore included in the cross-sectional analysis. Future studies should investigate individual pathways of the development of key performance indicators and race section times across a longer timeframe, i.e., from junior to elite age or even across the entire swimming career. With continuous data collection of video footage at future swimming competitions, i.e., European championships, such longitudinal studies will be possible by the end of the current Olympic cycle (2024). Additionally, multiple milestones, i.e., European championships in Glasgow 2018 and Rome 2022, could be added for a more detailed investigation of performance progression.

CONCLUSION

For the present study, up-to-date reference values of key performance indicators for long-course pool swimming events were retrieved from finalists at the 2021 European championship. In particular, male European swimmers approximated performance levels at the Olympic games and showed significantly improved races times in 100 m BA, 100 m and 200 m BR, 100 m and 200 m FR, and 200 m IM from 2016 to 2021. In 2021, only 2 European finals, compared to 10 in 2016, were significantly slower than the Olympic finals. Female European swimmers significantly improved in only 2 events across the 5-year timespan and remained slower in 7 events compared to Olympic finalists. Analysis of key performance indicators showed improved start performances, longer breakout distances, and improved clean swimming velocities. Effect sizes indicated reduced stroke rate in alternating swimming strokes, i.e., BA and FR, with an increase in distance per stroke. Coaches and performance analysts may use the present reference values as comparative data for race analyses and to specifically prepare for the various race sections. Data on the performance development should be used to analyze swimmers' potential and set goals for the various events and the next Olympic cycle.

DATA AVAILABILITY STATEMENT

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

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Swiss Federal Institute of Sport Magglingen. Written informed consent for participation was not required for this study in accordance with the national legislation and the institutional requirements.

AUTHOR CONTRIBUTIONS

The conception of the experimental design: D-PB and MR. Data collection and data analysis: D-PB, MS, OL, and MR. Data interpretation: D-PB, OL, BO, and MR. Preparing the manuscript: D-PB. Critically revising the manuscript: MS, OL, BO, and MR. Reading and approving final version of the manuscript: D-PB, MS, OL, BO, and MR. All authors contributed to the article and approved the submitted version.

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Improving tumble turn performance in swimming—the impact of wall contact time and tuck index

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Race time can be shortened by improving turn performance in competitive swimming, but this requires insight into the optimal turn technique. The aim of the present study was to examine the effect of Wall Contact Time (WCT) and Tuck Index on tumble turn performance and their interrelations by experimentally manipulating both variables, which has not been done in previous research. Eighteen Dutch national level swimmers (FINA points 552 ± 122) performed tumble turns with three different WCTs (shorter, preferred, longer) and three different Tuck Indices (higher, preferred, lower), which were recorded by four underwater cameras and a wall-mounted force plate. Linear kinematic and kinetic variables, including the approach velocity (V_{in}), wall adaptation time (T_{adapt}), percentage of active WCT (aWCT), peak push-off force (F_{Peak}) and exit velocity (V_{exit}), were extracted from the recordings and analyzed statistically, using the 5 m round trip time (5mRTT) as performance measure. The results indicated that the WCT should be sufficiently long to generate a high push-off force at the end of wall contact when the body is in a streamlined position. This led to a significantly shorter 5mRTT than a shorter or longer WCT. A linear mixed effect model yielded negative significant effects of WCT (−4.22, $p < 0.001$), F_{Peak} (−2.18, $p = 0.04$), V_{in} (−4.83, $p = 0.02$), T_{adapt} (−2.68, $p = 0.002$), and V_{exit} (−9.52, $p < 0.001$) on the 5mRTT. The best overall turning performance was achieved with a Tuck Index of 0.7, which suggests that some of the participating swimmers could benefit from adapting their distance to the wall while turning, as was exemplified by calculating the optimal Tuck Index for individual swimmers. These results underscore the importance of WCT and Tuck Index vis-à-vis tumble turn performance, as well as their interrelations with other performance determining variables in this regard.

KEYWORDS
free style, front crawl, optimization, prediction, flip turn

Introduction

The margin between winning a gold or silver medal on the 100 m freestyle during the Tokyo Olympic Games 2021 was 0.06 s. With such small differences, every opportunity for improvement should be exploited to optimize the chances of winning (Arellano et al., 1994; Morais et al., 2019). In general, performance improvement can be achieved in any of the four components of a swimming race, i.e. starting, free swimming, turning and finishing. Born et al. (2021) reported that the total turn time, defined from 5 to 10 m out of the wall, increases with the race distance, as does its contribution to the total swim time (Morais et al., 2019). Accumulated over entire race events, the time spent turning represents about 20 % of the total race time in the 100 m freestyle for elite male sprinters on the long course (i.e., 50 m pool) (Morais et al., 2019), and more than 40 % on the short course (i.e., 25 m pool). Arellano et al. reported a positive relationship between race time and total turn time with correlation coefficients ranging between 0.8 and 0.9 for various race distances (Arellano et al., 1994). One reason for such a high contribution to swimming performance is the high velocity that is achieved after a forceful push-off from the wall, which is significantly higher than the average swimming velocity (Shimadzu et al., 2008; Veiga and Roig, 2017). This implies that improving turning performance will not only result in a reduction of the overall race time but also in a better preparation for the next lane lap. Turning can therefore be considered a major determinant of swimming performance (Born et al., 2021) with substantial potential for improving the overall race result.

The overall turn performance is usually expressed as the cumulative duration of the approach, rotation, wall contact, glide, underwater propulsion, and stroke resumption (Puel et al., 2010). However, to identify those parts of the turn that are (most) amenable for improvement, it is necessary to split up the action sequence and examine the effects of specific performance determining variables. A major division can be made between the approach to and exit from the wall (Veiga et al., 2014). The approach to the wall depends on the swimmer's velocity (V_{in}) and the time needed to rotate around the transverse axis and place their feet on the wall, the so-called adaptation time (T_{adapt}). An effective push-off force, an appropriate amount of time spent on the wall and a properly streamlined position during the push-off and the subsequent glide phase are essential to a wall action resulting in a high turn performance (Lyttle et al., 1998, 1999; Mason and Cossor, 2001).

The aforementioned performance-determining variables of the tumble turn have been amply studied in previous research. The peak push-off force (F_{Peak}) has been considered the variable with the highest influence on the tumble turn time (Blanksby et al., 1996; Araujo et al., 2010). However, the generation of a high F_{Peak} was reported to be closely linked to both the Wall Contact Time (WCT) and Tuck Index (Blanksby et al., 1996; Araujo et al., 2010; Cossor et al., 2014; Skyriene et al., 2017). The WCT is defined as the time between the first wall contact of the swimmers' feet and the end of wall contact. Several studies have shown that a shorter WCT is related to a higher F_{Peak}, resulting in faster turn times (Blanksby et al., 2004; Pereira et al., 2006; Araujo et al., 2010). However, a longer WCT allows the swimmer time to produce the F_{Peak} more toward the end of the push-off. This might be an advantage as the swimmer will be in a more streamlined position during this phase of the action such that the produced force will result in higher acceleration and exit velocity (V_{exit}) due to a lower peak drag force (Lyttle et al., 1999). Since the WCT is actively used to generate this push-off force, the amount of active WCT (aWCT) should be considered when increasing the overall WCT.

The WCT correlates negatively with the Tuck Index (Blanksby et al., 2004; Pereira et al., 2006), implying that a higher Tuck Index is associated with a shorter WCT (Blanksby et al., 2004; Pereira et al., 2006). The Tuck Index is defined as the minimal distance of the hip from the wall expressed as a percentage of the trochanter major height. A Tuck Index of for instance 0.60 implies that the closest distance from the trochanter major to the wall corresponds to 60 % of the swimmer's leg length. Having the lower limbs in a less bent position implies that it takes less time to extend them. This can save time and may thus result in faster swim times. A Tuck Index of 0.57 ± 0.17 was reported in age-group swimmers (i.e., of 11.8 ± 0.7 years old) (Blanksby et al., 1996). This finding was replicated in subsequent studies, in which Tuck Indices ranging from 0.56 to 0.71 were reported (Cossor et al., 1999; Blanksby et al., 2004; Patz, 2005; Prins and Patz, 2006; Skyriene et al., 2017; Smithdorf, 2018). However, the literature also contains some inconsistent findings. Two studies reported a negative relationship between Tuck Index and turn performance (Cossor et al., 1999; Blanksby et al., 2004), while others reported a positive relationship (Cossor et al., 2014; Skyriene et al., 2017). This contradiction can be due to the large range of knee joint angles (29–161°) that were reported (Araujo et al., 2010) during the tumble turn. Besides reducing the time to extend the lower limbs, a higher Tuck Index means that the swimmers turn further away from the wall and thus have to cover a shorter distance swimming. However, there is an upper limit of the Tuck Index because swimmers also have to be able to generate an effective push-off force to exit from the wall at high speed. This suggests that an optimal Tuck Index exists, which needs to be identified to improve turn performance (Nicol et al., 2019).

Although the tumble turn and its performance determining variables have been extensively investigated in previous studies, none of these studies involved experimental manipulations of those variables to assess their effects on tumble turn performance and interrelations with other performance-determining variables. Experimental manipulation of performance determining variables is required to gain further insight into the complexity of the tumble turn for at least two reasons. First of all, it provides a means to induce sufficient variation in relevant variables (both the explicitly manipulated and other relevant variables) to derive reliable and meaningful prediction models (Nicol et al., 2019), an option that is precluded when focusing solely on the preferred turn technique. In addition, it allows to examine the performance response of each individual swimmer to the manipulation, which can then be interpreted in relation to more general results, such as a prediction model, to identify aspects of the tumble turn that might be improved through technique refinements in dedicated training sessions.

Against this background, the present study aimed to examine the effect of the WCT and Tuck Index on tumble turn performance, defined as the 5 m round trip time (5mRTT). This definition was chosen because it limits the influence of free swimming while still allowing to determine the speed underwater (Blanksby et al., 1996; Pereira et al., 2015). For this reason, the 5mRTT is the most commonly used performance measure in pertinent literature and the one recommended by Silveira et al. (2011) to describe the turning performance in sub-elite swimmers. A longer WCT was hypothesized to result in a shorter 5mRTT due to the improved position of the body during the push-off from the wall. Furthermore, a longer aWCT was hypothesized to be beneficial in generating a high F_{Peak} at an appropriate time, resulting in a higher V_{exit}. By the same logic, a shorter WCT was hypothesized to result in a higher F_{Peak}, as found in previous studies, but not in a shorter 5mRTT. Based on previous results, it was further hypothesized that, within the reported Tuck Index range of 0.55 to 0.70, a negative relationship exists between the Tuck Index and WCT on the one hand and a positive relationship between the Tuck Index and F_{Peak} on the other hand. Finally, it was hypothesized that the relationship between the Tuck Index and turn performance can be explained by a quadratic estimation function, based on the assumption that an optimal Tuck Index exists for each swimmer. In the context of examining this last hypothesis, an attempt was made to identify the optimal Tuck Index for the participating swimmers.

Materials and methods

Eighteen Dutch national-level swimmers (eight male, ten female, see Table 1 for further details) participated in the experiment. The participants or their legal guardians in case they were 16 years of age or younger signed an informed consent form before participation. To assess the performance level of the swimmers, who were all freestyle competitors, their personal best times and corresponding FINA points for the 100 m freestyle were collected. The FINA points were calculated based on the swimmers' personal best times as of July 2021 and expressed relative to the world record for male and female swimmers separately, up to a maximum of 1,000 FINA points. Personal best and FINA points are reported in Table 1.

The experiment was conducted in the 50 m long training pool of swim center De Tongelreep at Eindhoven, also known as the Pieter van den Hoogeband swimming pool. After having arrived at the center and signed the informed consent form, the swimmers performed a standardized warm-up routine of ~10 min, including two practice turns at high speed. Subsequently, a marker was attached to the trochanter major of the right femur to record the position of the hip during the turn trials proper.

In total, four test days were held within 1 week to acquire the data for this study. All swimmers performed 29 turns in total during a single measurement session, including the turns with the manipulations of the WCT and Tuck Index, respectively. In performing those turns, the swimmers were instructed to start at about 15 m from the wall, reach 100 m race speed at about 5 m before the wall and continue swimming at 100 m race speed until 15 m out of the wall. The first 5 turns of the measurement session were executed in a preferred manner by the swimmer. These trials provided the preferred WCT and Tuck Index, respectively, which served as the reference for the manipulations that were to follow. In the next 12 trials, the swimmers were invited to perform 6 turns with a 25 % shorter (short) and 6 turns with a 25 % longer (long) WCT than in the reference trials (see Figure 1 for the experimental protocol). The order in which the short and long trials were performed was counterbalanced over the participants. Similarly, in the last 12 trials, the swimmers were invited to perform 6 turns each in which they initiated the turn at least 15 % closer (close) and at least 15 % further

TABLE 1 Mean ± standard deviation of the participant's age, mass, height, leg length, and performance level.

	Age (years)	Mass (kg)	Height (m)	Leg length (m)	Personal Best (s)	FINA
All ($N = 18$)	19.0 ± 4.4	68.6 ± 12.7	1.80 ± 0.07	0.93 ± 0.05	60.97 ± 4.6	552 ± 122
Male ($N = 8$)	18.3 ± 5.2	70.3 ± 14.8	1.85 ± 0.08	0.96 ± 0.05	60.31 ± 6.49	499 ± 153
Female ($N = 10$)	19.4 ± 4.0	67.3 ± 11.4	1.76 ± 0.04	0.91 ± 0.04	61.66 ± 2.51	595 ± 74

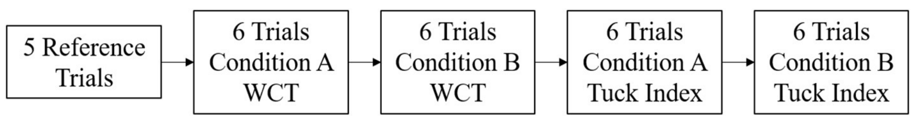

FIGURE 1
Schematic overview of the experimental protocol.

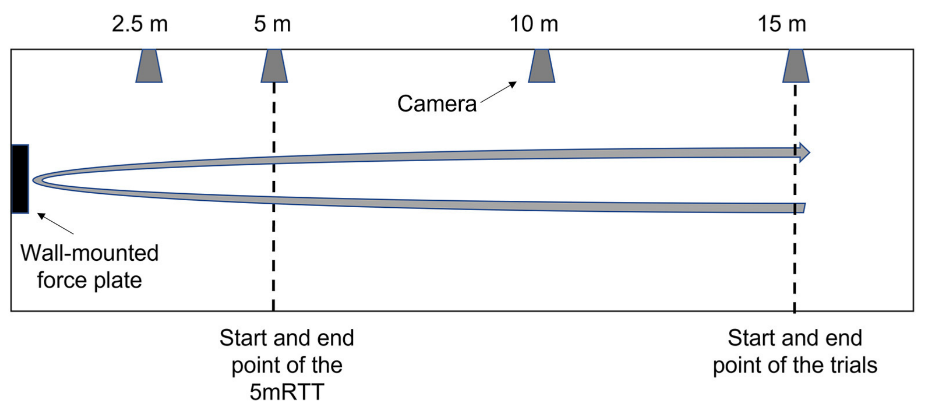

FIGURE 2
Experimental setup, displaying the location of the wall-mounted force plate (black rectangle) and the four cameras (gray trapezoids).

away (far) from the wall than in the reference trials. Analogous to the WCT manipulation, the order in which these trials were performed was counterbalanced over the participants. However, the trials with the WCT manipulation always preceded the trials with the Tuck Index manipulation (Figure 1). For the reference trials, the swimmers were instructed to perform the turns in their preferred manner. The short WCT trials were effectuated by asking them to turn with their feet leaving the wall as fast as possible, whereas for the long WCT turns they were asked to have their feet remaining on the wall as if to stick it. To execute the close turns, they were asked to turn closer to the wall in a way that their butt would almost touch the wall, whereas, for the far turns, they were asked to initiate the turn at a distance with having their legs almost extended when touching the wall.

To give direct feedback on the WCT, the force plate data was used. For the Tuck Index trials, the tumble turn initiation distance was used as a proxy, since the Tuck Index could only be assessed offline during the postprocessing procedure. Feedback was given after each trial about whether or not the experimental condition was met. Between trials, the swimmers could chose between an active or passive rest of 5 min to avoid fatigue. Trials were discarded as invalid if the swimmer did not hit the force plate, started the trial too early or too late, or did not meet the condition criteria.

A 900 × 600 × 40 mm Kistler force plate (1,000 Hz, 9691A, Switzerland) embedded in the wall of the pool where push-off forces are exerted and four digital video cameras (50 Hz, scA1400-30gc, Basler, Ahrensburg, Germany) were used to record each tumble turn. The cameras and the force plate were synchronized using the software package Streampix (Norpix, Streampix 7, 2016). All video recordings were analyzed using a custom-made software program called TurnAnalyzer (Escrito sport, Eindhoven, The Netherlands). The force data was filtered using a 5 Hz low-pass third-order Butterworth filter to exclude the influence of waves and other noise. The cameras were positioned on the lateral side of the pool, at the 2.5-, 5-, 10-, and 15-m marks, respectively (see Figure 2).

TABLE 2 Description of the variables of interest.

Tuck Index	Minimal distance of the hip from the wall expressed as a percentage of the trochanter major height
WCT (s)	Duration of the wall contact, defined by a force threshold of 20 N on the wall-mounted force plate
5mRTT (s)	Duration covering 5 m-in to 5 m-out of the wall
V_{in} (m/s)	Average approach speed between the 5 and 3 m mark before the turn.
T_{adapt} (s)	The time needed to bring the feet to the wall and measured from the time the head completely crossed the waterline until the first wall contact
F_{Peak} (N)	Maximum Force against the wall-mounted force plate
aWCT (%)	Active part of the WCT (see Figure 3)
5mOUT (s)	Duration from push-off from the wall until 5 m-out of the wall

From each video, the Tuck Index, 5mRTT, approach and exit velocity (V_{in}, V_{exit}) and the adaptation time (T_{adapt}), defined as the time spent by the swimmer to bring their feet to the wall, were determined (Table 2). WCT and peak Force (F_{Peak}) were derived from the force plate data using a threshold of 20 N to define the first and final point of contact (see Figure 3, Table 2).

The video recordings were also used to define the instant at which the WCT was partitioned into a passive and active part since this was not always visible in the force data. By combining the force plate and video data the percentage of active WCT (aWCT) was determined. The time frame of the first forward hip movement detectable on video was combined with the time frames of first wall contact and wall exit of the force plate. The instant of first wall contact until the first forward hip movement forms the passive part. Consequently, the aWCT was defined from the first forward hip movement until wall exit.

The 5mRTT was measured by the time between the swimmer's trochanter major crossing the 5 m mark on the way in and out of the wall. In addition, the 5mOUT was determined to examine the effect of the WCT and Tuck Index on the exit from the wall. The 5mOUT was defined as the time from first wall contact until the swimmer's trochanter major crossed the 5 m mark. The T_{adapt} was defined as the time required to bring the feet to the wall and starting from the time the swimmer's head completely crossed the waterline until the first wall contact (Figure 3). Various speed variables were also derived from the video recordings. The wall exit speed (V_{exit}) was calculated according to:

$$V_{exit} = \frac{(3 - d_{exit})}{(t_{3m} - t_{exit})}$$

where d_{exit} is the distance of the trochanter to the wall at last foot contact, t_{3m} is the instant the trochanter major passed the 3 m mark out of the wall and t_{exit} is the instant of last foot contact.

The data were analyzed using SPSS (IBM SPSS Statistics, Version, 27.0) and Matlab R2020b. To examine whether the swimmers achieved significantly different WCTs and Tuck Indices during the test conditions, 3 × 2 ANOVAs with repeated measures were performed with the experimental condition as the within-participant factor (3 levels) and sex as a between-subject factor (2 levels). Additionally, it was checked whether the manipulations resulted in differences for the 5mRTT and the F_{peak} using the same method. Bonferroni *post-hoc* tests were performed if significant main or interaction effects were found. Pearson correlation coefficients were calculated to see how the different variables were related to each other. In addition, a linear mixed effect model analysis was performed to examine the extent to which the WCT, F_{Peak}, T_{adapt}, V_{in}, and V_{exit} accounted for the 5mRTT. To estimate the optimal Tuck Index a quadratic estimation function was used on both the entire group and the individual swimmers. To gain further insight into the effect of the manipulations of WCT and Tuck Index, the Bland-Altman values and the degree of consistency among measurements by means of pairwise intra-class correlations were calculated using the equations described in Haghayegh et al. (2020).

Results

Manipulation of WCT

In total, 288 out of 306 tumble turn trials were included to examine the effect of WCT on turn performance. The statistical results are reported in Table 3. The WCTs were significantly different across the experimental conditions in the expected

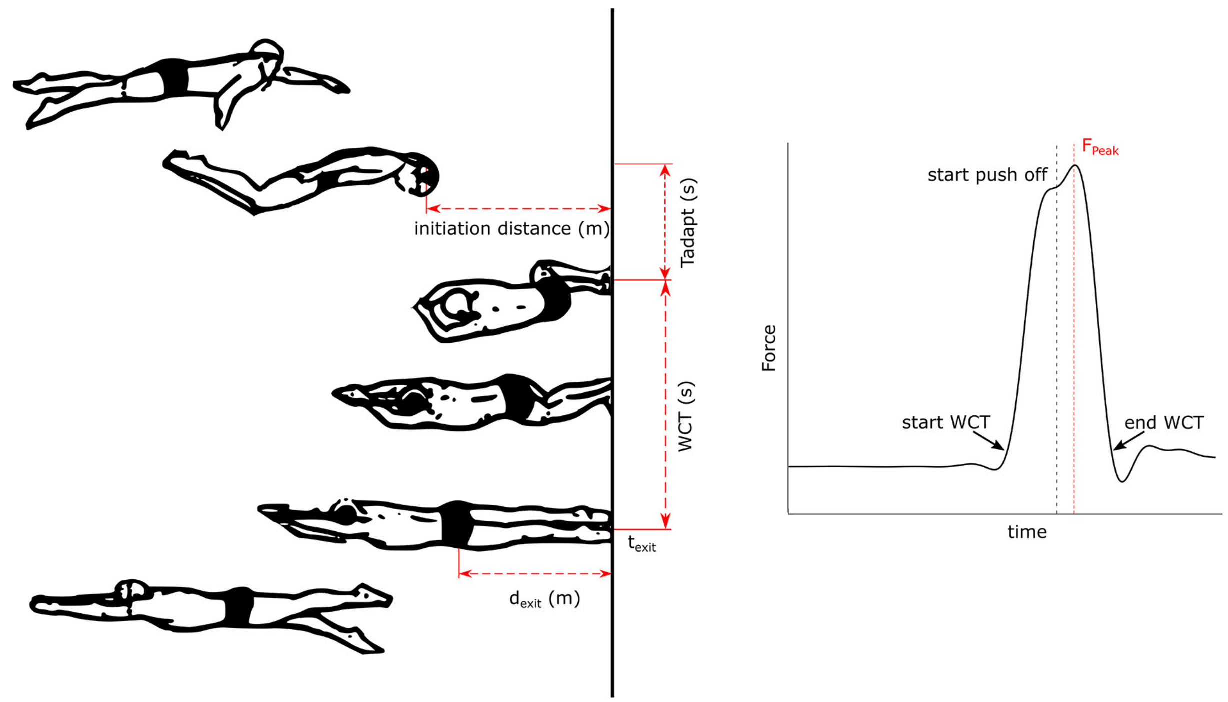

FIGURE 3
Left: Tumble turn technique [adapted from Puel et al. (2012)]: Illustrating the initiation distance, d_{exit}, WCT and T_{adapt}. Right: Typical force profile of a reference trial indicating the start and end of the WCT with a force > 20 N, F_{Peak} and the start of the push of phase.

TABLE 3 Descriptive (mean ± standard deviation) and statistical results of the 2 × 3 repeated measures ANOVA design with the manipulation condition as the within-subject factor (main effect) and sex as the between-subject factor (interaction effect).

Manipulating WCT	Sex	Short	Reference	Long	F-Statistics (condition)	F-Statistics (Sex)	p and d
WCT (s)	Male	0.3 ± 0.06	0.37 ± 0.04	0.47 ± 0.05	$F_{(1.47,23.51)} = 96.969$,	$F_{(1,16)} = 6.287$,	1 vs. 2: $p < 0.001$, $d = 1.77$,
	Female	0.25 ± 0.06	0.3 ± 0.05	0.4 ± 0.09	$p < 0.001$, $\eta_p{}^2 = 0.858$	$p = 0.023$, $\eta_p{}^2 = 0.282$	1 vs. 3: $p < 0.001$, $d = 2.09$,
							2 vs. 3: $p < 0.001$, $d = 2.67$
aWCT (%)	Male	70.3 ± 9.3	68.4 ± 6.6	61.6 ± 5.3	$F_{(2,32)} = 16.717$,	$F_{(1,16)} = 0.158$,	1 vs. 2: $p = 0.05$, $d = 1.08$,
	Female	73.4 ± 3.4	66.6 ± 3.9	62.8 ± 6.1	$p < 0.001$, $\eta_p{}^2 = 0.511$	$p = 0.697$, $\eta_p{}^2 = 0.010$	1 vs. 3: $p < 0.001$, $d = 1.22$,
							2 vs. 3: $p = 0.014$, $d = 2.62$
5mRTT (s)	Male	5.57 ± 0.63	5.38 ± 0.49	5.69 ± 0.51	$F_{(2,32)} = 12.658$,	$F_{(1,16)} = 4.653$,	1 vs. 2: $p = 0.127$, $d = 0.46$,
	Female	5.93 ± 0.23	5.87 ± 0.33	6.13 ± 0.36	$p < 0.001$, $\eta_p{}^2 = 0.442$	$p = 0.047$ $\eta_p{}^2 = 0.225$	1 vs. 3: $p < 0.001$, $d = 1.76$,
							2 vs. 3: $p = 0.087$, $d = 0.60$
5mOUT (s)	Male	2.65 ± 0.35	2.58 ± 0.29	2.73 ± 0.27	$F_{(1.27,20.32)} = 31.336$,	$F_{(1,16)} = 4.842$,	1 vs. 2: $p = 0.016$, $d = 0.72$,
	Female	2.88 ± 0.2	2.85 ± 0.21	3.02 ± 0.21	$p < 0.001$, $\eta_p{}^2 = 0.662$	$p = 0.043$, $\eta_p{}^2 = 0.232$	1 vs. 3: $p < 0.001$, $d = 2.40$,
							2 vs. 3: $p = 0.004$, $d = 0.95$
T_{adapt} (s)	Male	0.88 ± 0.06	0.89 ± 0.07	0.95 ± 0.04	$F_{(2,32)} = 15.135$,	$F_{(1,16)} = 0.435$,	1 vs. 2: $p = 0.387$, $d = 0.40$,
	Female	0.89 ± 0.07	0.92 ± 0.06	0.96 ± 0.08	$p < 0.001$, $\eta_p{}^2 = 0.486$	$p = 0.519$, $\eta_p{}^2 = 0.026$	1 vs. 3: $p = 0.004$, $d = 0.91$,
							2 vs. 3: $p < 0.001$, $d = 1.50$
F_{Peak} (N)	Male	1,195 ± 416	1,061 ± 359	1,073 ± 347	$F_{(2,32)} = 27{,}309$,	$F_{(1,16)} = 0.056$,	1 vs. 2: $p < 0.001$, $d = 1.27$,
	Female	1,245 ± 274	1,044 ± 224	952 ± 214	$p < 0.001$, $\eta_p^2 = 0.631$	$p = 0.816$, $\eta_p{}^2 = 0.003$	1 vs. 3: $p < 0.001$, $d = 0.46$,
							2 vs. 3: $p < 0.001$, $d = 1.36$
V_{in} (m/s)	Male	1.63 ± 0.16	1.7 ± 0.1	1.65 ± 0.13	$F_{(1.21,32)} = 5.811$,	$F_{(1,16)} = 10.953$,	1 vs. 2: $p = 0.049$, $d = 0.64$,
	Female	1.5 ± 0.07	1.54 ± 0.08	1.48 ± 0.08	$p = 0.021$, $\eta_p{}^2 = 0.266$	$p = 0.004$, $\eta_p{}^2 = 0.406$	1 vs. 3: $p < 0.001$, $d = 1.52$,
							2 vs. 3: $p = 1$, $d = 0.04$
V_{exit} (m/s)	Male	2.05 ± 0.34	2.19 ± 0.29	2.13 ± 0.31	$F_{(2,32)} = 14.321$,	$F_{(1,16)} = 9.934$,	1 vs. 2: $p < 0.001$, $d = 1.27$,
	Female	1.76 ± 0.15	1.83 ± 0.14	1.77 ± 0.11	$p < 0.001$, $\eta_p{}^2 = 0.472$	$p = 0.006$, $\eta_p{}^2 = 0.383$	1 vs. 3: $p = 0.149$, $d = 0.73$,
							2 vs. 3: $p = 0.027$, $d = 0.44$
Manipulating Tuck Index		**Close**	**Reference**	**Far**			
Tuck index	Male	0.44 ± 0.1	0.61 ± 0.06	0.78 ± 0.06	$F_{(2,22)} = 88.594$,	$F_{(1,16)} = 3.122$,	1 vs. 2: $p < 0.001$, d =1.39,
	Female	0.44 ± 0.09	0.68 ± 0.05	0.85 ± 0.07	$p < 0.001$, $\eta_p{}^2 = 0.89$	$p = 0.105$, $\eta_p{}^2 = 0.221$	1 vs. 3: $p < 0.001$, d =2.36,
							2 vs. 3: $p < 0.001$, $d = 3.55$
5mRTT (s)	Male	5.9 ± 0.64	5.39 ± 0.49	5.66 ± 0.55	$F_{(2,32)} = 77.757$,	$F_{(1,16)} = 8.309$,	1 vs. 2: $p < 0.001$, $d = 2.07$,
	Female	6.5 ± 0.31	5.89 ± 0.34	6.28 ± 0.25	$p < 0.001$, $\eta_p{}^2 = 0.829$	$p = 0.011$, $\eta_p{}^2 = 0.342$	1 vs. 3: $p = 0.001$, $d = 13.65$,
							2 vs. 3: $p < 0.001$, $d = 12.99$
WCT (s)	Male	0.54 ± 0.14	0.36 ± 0.04	0.25 ± 0.05	$F_{(1.13,18.02)} = 57.0$,	$F_{(1,16)} = 0.125$,	1 vs. 2: $p < 0.001$, $d = 1.38$,
	Female	0.61 ± 0.21	0.31 ± 0.05	0.2 ± 0.04	$p < 0.001$, $\eta_p{}^2 = 0.781$	$p = 0.728$, $\eta_p{}^2 = 0.008$	1 vs. 3: $p < 0.001$, $d = 2.05$,
							2 vs. 3: $p < 0.001$, $d = 1.96$
Initiation distance (m)	Male	0.87 ± 0.07	1.06 ± 0.09	1.32 ± 0.16	$F_{(1.41,22.73)} = 360.9$,	$F_{(1,16)} = 0.076$,	1 vs. 2: $p < 0.001$, $d = 3.45$,
	Female	0.8 ± 0.09	1.07 ± 0.07	1.35 ± 0.07	$p < 0.001$, $\eta_p{}^2 = 0.956$	$p = 0.786$, $\eta_p{}^2 = 0.005$	1 vs. 3: $p < 0.001$, $d = 3.75$,
							2 vs. 3: $p < 0.001$, $d = 4.59$
F_{Peak} (N)	Male	934 ± 328	1047 ± 352	1293 ± 521	$F_{(1.37,21.913)} = 56.926$,	$F_{(1,16)} = 13.346$,	1 vs. 2: $p < 0.001$, $d = 1.61$,
	Female	841 ± 195	1044 ± 224	1251 ± 257	$p < 0.001$, $\eta_p{}^2 = 0.781$	$p = 0.74$, $\eta_p{}^2 = 0.007$	1 vs. 3: $p < 0.001$, $d = 1.26$,
							2 vs. 3: $p < 0.001$, $d = 2.34$
V_{in} (m/s)	Male	1.63 ± 0.11	1.69 ± 0.11	1.62 ± 0.12	$F_{(1.381,22.095)} = 10.522$,	$F_{(1,16)} = 13.346$,	1 vs. 2: $p = 0.001$, $d = 1.09$,
	Female	1.48 ± 0.07	1.54 ± 0.09	1.46 ± 0.09	$p = 0.002$, $\eta_p{}^2 = 0.397$	$p = 0.002$, $\eta_p{}^2 = 0.455$	1 vs. 3: $p = 0.013$, $d = 0.82$,
							2 vs. 3: $p = 1.0$, $d = 0.22$
5mOUT (s)	Male	2.97 ± 0.32	2.68 ± 0.28	2.86 ± 034	$F_{(2,32)} = 25.935$,	$F_{(1,16)} = 0.599$,	1 vs. 2: $p < 0.001$, $d = 1.56$,
	Female	3.09 ± 0.35	2.8 ± 0.3	2.94 ± 0.27	$p < 0.001$, $\eta_p{}^2 = 0.618$	$p = 0.45$, $\eta_p{}^2 = 0.036$	1 vs. 3: $p = 0.003$, $d = 0.95$,
							2 vs. 3: $p = 0.006$, $d = 0.91$

The last column represents the results of the *post-hoc* testing (p-values and Cohen's d). η_p^2 = partial eta squared, 1 = Reference, 2 = Short / Close, 3 = Long/ Far. The data of the reference trials from the Manipulating WCT study vary slightly from those of the Manipulating Tuck Index study due to the different number of included trials.

directions, indicating that the manipulation was successful. The male swimmers showed significantly longer WCTs compared to the female swimmers. The aWCT decreased significantly from the shorter to the reference to the long WCTs, implying that the swimmers spent a longer time passively on the wall with increasing WCT. In this regard, no significant effects of sex were found. The highest F_{Peak} was generated during the short WCT trials and differed significantly from the reference trials and long contact trials.

There was a significant main effect of the WCT manipulation on the 5mRTT. *Post-hoc* testing revealed that the swimmers achieved shorter 5mRTT in the reference condition when compared to the long WCT condition, in the absence of any other significant differences. Overall, the 5mRTT was significantly shorter for the male swimmers than the female swimmers. However, there was no significant sex by condition interaction, implying that the differences in the 5mRTT between the conditions were not biased by the differences between sexes.

By splitting up the turn action into approach and exit components, the results revealed that T_{adapt} differed significantly between the conditions, with a longer T_{adapt} for the long WCT trials when compared to the reference and short contact trials. Furthermore, there was a significant effect of condition on V_{in}. During the short and long WCT conditions the V_{in} was significantly lower compared to V_{in} in the reference condition, while in all conditions the speed was significantly higher for the male swimmers than for the female swimmers. A similar effect of WCT was found in the 5mOUT, with the reference trials showing the lowest 5mOut time and all experimental conditions being significantly different from each other.

The best fitting linear mixed effect model (AIC: −150.99, LL: 110.5, Intercept: 3.12, $p < 0.001$) involved significant negative effects of WCT ($p < 0.001$), F_{Peak} ($p = 0.04$), V_{in} ($p = 0.02$), T_{adapt} ($p = 0.002$), and V_{exit} ($p < 0.001$) on the 5mRTT, resulting in the following model equation:

$5mRTT = 3.1231–4.2276 \times WCT−2.1799 \times F_{Peak}$-4.8258 $\times V_{in}$-2.677 $\times T_{adapt}$-9.5239 $\times V_{exit} + \varepsilon$

The ICC and Bland-Altman (BA) values were as follows [bias (95 % CI), LoAL = Lower level of agreement (95 % CI), LoAU: Upper level of agreement (95 % CI)]:

Reference vs. Short: ICC: $r = 0.96$, $p < 0.001$, BA: bias: −0.061 [−0.08; −0.04], LoAL: −0.128 [−0.16; −0.10], LoAU: 0.006 [−0.02; 0.04].

Reference vs. Long: ICC: $r = 0.85$, $p < 0.001$, BA: bias: −0.102 [−0.13; −0.08], LoAL: −0.198 [−0.24; −0.16], LoAU: −0.006 [−0.05; 0.04].

Long vs. Short: ICC: $r = 0.78$, $p = 0.002$, BA: bias: −0.163 [−0.19; −0.13], LoAL: −0.28 [−0.34; −0.23], LoAU: −0.043 [−0.10; 0.01].

These values correspond to good to excellent reliability concerning the consistency and a good agreement between conditions (Haghayegh et al., 2020).

Manipulation of tuck index

In total, 287 out of 306 tumble turn trials were included to examine the effect of the Tuck Index on turn performance. The detailed statistical results are reported in Table 3. The realized Tuck Indices were significantly different across the experimental conditions in the absence of a significant effect of sex. The *post-hoc* tests revealed that the Tuck Index in the reference condition was significantly lower compared to the far condition and significantly higher compared to the close condition, indicating that also this manipulation was successful.

There was a significant effect of condition on the 5mRTT. *Post-hoc* tests revealed that performance was significantly better in the reference condition than in the far and close condition, respectively. Male swimmers were significantly faster than female swimmers in the absence of a significant interaction involving sex. The experimental manipulation of the Tuck Index also affected the WCT. The *post-hoc* tests revealed that the WCT significantly decreased from the close to the reference to the far condition. During the far condition, the swimmers generated the highest F_{Peak} while it was lowest in the close condition.

The experimental manipulation affected both the approach and exit components of the turn. A significant effect was found for the turn initiation distance, because the initiation of the turn in the reference condition occurred significantly further from the wall compared to the close condition and significantly closer to the wall compared to the far condition. Moreover, turning during the far condition occurred significantly further from the wall compared to the close condition. Also, a significant main effect of the condition was found for V_{in}. *Post-hoc* testing revealed that V_{in} was significantly higher in the reference condition than in the close and far condition. There was no significant difference between the far and close condition. Male swimmers were significantly faster before the turn compared to female swimmers. This indicates that the differences in turn performance in the reference, far and close trials might have been attributable to a change in speed before the turn. The 5mOUT was used to examine whether the turn was different between the trials, independent of the swimming velocity before the turn. A significant main effect of the condition was found for the 5mOUT. *Post-hoc* testing showed that the 5mOUT was significantly shorter for the reference condition compared to both the far and close conditions, while the far condition resulted in significantly a shorter 5mOUT time when compared to the close condition. This indicates that the turn was indeed different between the experimental conditions, independent of the swimming speed before the turn.

A negative correlation between Tuck Index and WCT ($r = −0.830$, $p < 0.001$) and a positive correlation between Tuck Index and F_{Peak} were found ($r = 0.473$, $p < 0.001$), in the absence of a significant correlation between Tuck Index and 5mRTT ($r = −0.102$, $p = 0.100$).

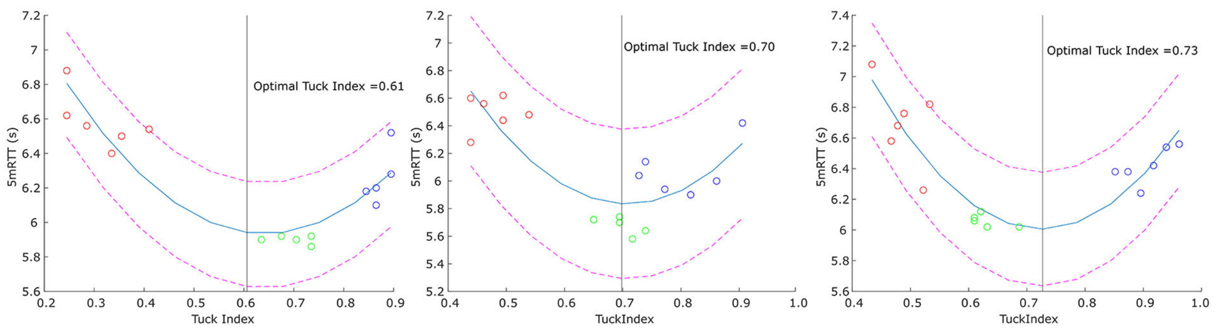

FIGURE 4
Prediction of the optimal Tuck Index for three selected swimmers. Red circles: Close condition trials, green circles: Reference condition trials, blue circles: Far condition trials. Pink dashed lines: 95 % prediction interval, black line: optimal Tuck Index.

For each participant, a prediction model was made for the optimal Tuck Index using a quadratic estimation function based on the 5mRTT (see Figure 4) and 5mOUT. These optimal Tuck Indices were compared with the participant's best trial to arrive at an individual advice as to how their turn performance might be improved. The intra-individual mean Tuck Index during the reference trials was 0.65 ± 0.06, while the predicted Tuck Index based on the 5mRTT and 5mOUT was estimated to be 0.70 ± 0.04 (range 0.64 and 0.77) and 0.69 ± 0.07 (range 0.58 and 0.83), respectively.

The ICC and Bland-Altman (BA) values were as follows [bias (95 % CI), LoAL = Lower level of agreement (95 % CI), LoAU: Upper level of agreement (95 % CI)]:

Reference vs. Close: ICC: $r = 0.41$, $p = 0.14$, BA: bias: −0.1661 [−0.23; −0.11], LoAL: −0.40 [−0.50; −0.30], LoAU: 0.068 [−0.04; 0.17].

Reference vs. Far: ICC: $r = 0.68$, $p = 0.01$, BA: bias: 0.207 [0.16; 0.25], LoAL: 0.035 [−0.04; 0.11], LoAU: 0.379 [0.30; 0.46].

Far vs. Close: ICC: $r = 0.36$, $p = 0.19$, BA: bias: 0.373 [0.32; 0.43], LoAL: 0.167 [0.08; 0.26], LoAU: 0.579 [0.49; 0.67].

These values correspond to a low to moderate reliability with regard to consistency and a moderate agreement between conditions (Haghayegh et al., 2020).

Discussion

In the present study, the effects of experimentally induced changes in the WCT and Tuck Index on the 5mRTT and other performance-related variables were examined. The results showed that the swimmers were able to change the two performance-related variables and that these changes affected their turn performance, as well as other performance-related variables, notably F_{max} and V_{exit}. Although on average the tumble turn performance was best in the reference trials compared to the manipulated trials, detailed statistical analyses of the experimentally induced variations in the performance-related variables of interest revealed that prolonging the WCT and adopting a Tuck Index of about 0.7 might help to improve the tumble turn performance.

Manipulation of WCT

The WCT and F_{Peak} results of the reference trials in this study were comparable to those of previous tumble turn studies (Lyttle et al., 1999; Puel et al., 2012; Cossor et al., 2014; Skyriene et al., 2017). The 5mRTT was shortest during the reference trials and longer for both the short and long WCT trials. This seems to contradict the results of the derived linear mixed model in which, as hypothesized, the WCT and the 5mRTT were negatively correlated. This apparent contradiction may be explained by other mediating variables of the turning performance. Nicol et al. included several performance-determining variables in their analysis and were unable to identify a single strong performance predictor. Based on this result, they concluded that it is necessary to adopt a holistic approach in which the turn technique is changed to examine the impact of these changes on performance (Nicol et al., 2019). By adopting such an approach in the present study we found that WCT, F_{Peak}, T_{adapt}, V_{in}, and V_{exit} all contribute significantly to the 5mRTT. Manipulating the WCT affected the F_{Peak} and V_{exit} with a shorter WCT resulting in a higher F_{Peak}, and a longer WCT accompanying a higher V_{exit}, which is consistent with previous findings (Lyttle et al., 1999; Klauck, 2005), as well as our hypotheses. The high F_{Peak} during a short WCT could have been caused by a high impact force, resulting in a less efficient push-off and finally a lower V_{exit} (Lyttle et al., 1998). The increased V_{exit} during the longer WCT is likely related to the later occurrence of F_{Peak} (Lyttle et al., 1999; Puel et al., 2012), which increases the acceleration during push-off due to the more streamlined position at the end of the WCT (Klauck, 2005; Puel et al., 2012). However, to have a beneficial effect on the tumble turn performance, the higher V_{exit} has to compensate for the time lost due to the longer WCT. Other relevant mediating variables are the glide depth, the initiation time of the dolphin kicks (Cossor et al., 2014) and the point of resurfacing (30), which were not taken into account in the present study. However, their impact on the tumble turn performance might nevertheless be limited according to Blanksby et al. (1996) and Nicol et al. (2019).

The swimmers in the present study further showed a decrease in the active WCT (aWCT) with increasing WCT, which might indicate that they had difficulty adapting to the task and could have made more efficient use of the time on the wall. The challenge of maintaining the same performance level while changing the WCT is also reflected in the adaptation time, which increased during the long WCT trials. To conclude, the results indicate that the WCT has to be sufficiently long to bring the body into a properly streamlined position in order to make optimal use of a powerful push-off force.

Manipulation of tuck index

Also, the Tuck Indices determined in this study are in line with those reported in previous studies, i.e., 0.61 ± 0.1 and 0.68 ± 0.05 for female and male swimmers in the present study vs. 0.56 ± 0.1 and 0.71 ± 0.09 in previous studies (Blanksby et al., 1996; Skyriene et al., 2017). On average, the 5mRTT was the fastest in the reference trials, compared to both the close and far conditions. The Tuck Index was negatively correlated with the WCT because it takes time to extend the legs. This finding is also in line with the results of previous studies (Cossor et al., 1999; Blanksby et al., 2004). In addition, the Tuck Index correlated positively with F_{Peak}, which is consistent with the results of Blanksby et al. (2004). This can be explained by the small knee flexion angle during close turns, which forces the extensor muscles to work at an inefficient length, thus producing less force compared to a larger knee flexion angle. Pereira et al. advised a knee angle between 110 and 120° for optimal turn performances (Pereira et al., 2006). Although it is strictly speaking inaccurate to directly translate knee angles into a Tuck Index, one may assume that the distance between the trochanter major and the wall is mainly influenced by the knee flexion angle, given that the sagittal plane is the main plane of movement. Based on this assumption, the estimated optimal Tuck Index of 0.70 would result in a knee flexion angle of 90°. This value is well below the range of knee joint angles suggested by Pereira et al. (2006). However, the methods used in the present study were quite different from the one used by Pereira et al. The optimal Tuck Index of 0.7, and hence the corresponding knee flexion angle of 90°, is the result of a quadratic model estimation and reflects the optimal value across all participants in this study. Pereira et al., in contrast, included only the preferred knee flexion angles that ranged between 29 and 161° and correlated them with the corresponding turn times. Hence, it might well be, that their participants did not make use of the optimal knee flexion angle to achieve the best turn performance. Also, they used a 7.5mRTT instead of the 5mRTT used in this study (Pereira et al., 2006). Interestingly, the knee joint angle of 90° that we arrived at is in line with the optimal angle for on-land squat jumps (Mitchell et al., 2017; Janicijevic et al., 2020). Even though the push-off from the wall is similar to vertical on-land squat jumps, little is known about the impact of body orientation (horizontal vs. vertical) and the drag force of the water (vs. the gravitational force on land) (Nicol et al., 2019). However, the push-off force and the force profile during wall push-off were found to be comparable to on-land squat jumps during maximum wall push-off and vertical on-land squat jumps (Guignard et al., 2017).

The optimal Tuck Index, as a result of the quadratic optimization function, was 0.70 ± 0.04. Prins and Patz also estimated the optimal Tuck Index and reported a value of 0.46 for achieving a maximum push-off velocity. However, as they acknowledged themselves, this might not result in an optimal round-trip time (Prins and Patz, 2006). Ultimately, the swimmer wants to swim as fast as possible; we therefore based the calculations on the 5mRTT. For some swimmers, this meant that their optimal Tuck Index fell within their reference values, while the prediction of the Tuck Index was higher than the reference values for some of the other swimmers (Figure 4), indicating that they might be able to turn faster when turning slightly further from the wall. This result illustrates the practical value of prediction models in seeking to optimize the performance of individual swimmers. Elite athletes are striving to optimize their performance in every possible way. Improving the turning technique holds great potential for improving swimming success due to the high contribution of the turn to the overall swim time. Also, elite swimmers have highly individual requirements and adjusting one of the determinants might result in an advantage for one swimmer and a disadvantage for another. By investigating the data on an individual level, such individual differences are taken into account. However, the predicted optimal Tuck Indices might be biased by the distance between the experimental conditions. Swimmers showing unequal differences between the three Tuck Index conditions will result in a shifted quadratic function compared to swimmers with balanced differences (Figure 4). As most swimmers showed greater differences between the close and the reference condition compared to the differences between the reference to the far condition, the optimal Tuck Index could therefore underestimate the true optimum.

In the current study, no significant relationship was found between the Tuck Index and 5mRTT, while in previous studies both positive (Cossor et al., 2014; Skyriene et al., 2017) and negative relationships (Blanksby et al., 2004) were reported. Our findings provide an explanation for these apparently contradictory results. Notably, the studies that found a positive relationship reported Tuck Indices slightly higher (Cossor et al., 2014; Skyriene et al., 2017) than the optimal Tuck Index of 0.7 derived in this study, whereas the studies that found a negative relationship reported Tuck Indices that were lower than 0.7. Including Tuck Indices that are both below and above the optimal value of 0.7 allowed us to identify the real relationship between the Tuck Index and the tumble turn performance, which is not linear, but quadratic.

The intra-class correlation between the different conditions revealed that the consistency of the Tuck Indices was only moderate. This could indicate that the swimmers had difficulty to consistently execute repeatable Tuck Indices within the manipulated conditions. This was not the case for the manipulation of the WCT. This result could have been anticipated considering that the adaptation of the Tuck Index represents a major invasion into the swimmer's preferred turn technique. However, this also implies that practicing the non-reference conditions for the Tuck Index could further increase the accuracy of the prediction model.

Limitations

The Tuck Index data of five swimmers were missing due to missing video recordings. The repeated measures ANOVA of the tuck index and the polyfit results were thus only performed with the data of 13 participants, that is, with a reduced sample size.

During the manipulation of the WCT and the Tuck Index, the swimmers were instructed to keep the approach of the wall and underwater phase as constant as possible. However, this was not the case for V_{in} and T_{adapt}. The slower V_{in} in the manipulated conditions might have been caused by the fact that the participating swimmers were less familiar with the experimental conditions than with the reference conditions. Additionally, the onset of fatigue might have played a role as well, even though the participants were allowed as much time as they liked to recover between trials. The swimmers indicated that they felt tired toward the end of the session, which might have affected the performance of the trials at the end of the day. This was reflected in a lower 5mRTT and V_{in} for the trials in question. Moreover, prior to the experiment, the swimming pool was closed due to COVID-19 regulations. It might have been the case that this interruption of the regular training schedule affected the overall performance when compared to regular training times. However, all included athletes were Dutch national-level swimmers, which might have mitigated the effect of the training situation on the reported outcomes.

The criteria for a valid trial were chosen in such a way that the manipulations resulted in distinct WCTs or Tuck Indices for each of the conditions. However, this resulted in a lack of information about the effect of those WCTs or Tuck Indices that range between the defined conditions, while it might be that the swimmer would swim their fastest turn performance in that range. Although it would have been beneficial to also cover these values, the number of trials was already high and a further increase would have most certainly led to fatigue.

Conclusion

To increase their tumble turn performance swimmers are recommended to focus on generating a high F_{Peak} at the end of the WCT when the body is in a properly streamlined position. To this end, a sufficiently long WCT is required. The present analyses further suggest that it is possible to recommend an optimal Tuck Index for individual swimmers, which might help to improve their tumble turn and thus their race performance. Further, the presented approach to estimate the optimal individual Tuck Index is readily applicable to a training session. Coaches and swimmers could therefore test whether an adaptation of the Tuck Index is indicated to improve the turn performance. Also, these two variables are readily adaptable by swimmers, whereas this might be more difficult for other variables. The present results need to be confirmed by an intervention study in which swimmers are trained to perform the tumble turn with the recommended WCTs and Tuck Indices.

Data availability statement

The datasets presented in this article are not readily available because they contain the data of elite athletes which might be identifyable if publishing the information. Requests to access the datasets should be directed to s.david@vu.nl.

Ethics statement

The studies involving human participants were reviewed and approved by the Scientific and Ethical Review Board (VCWE) of the Faculty of Behavioural and Movement Sciences of the Vrije Universiteit Amststerdam. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

Author contributions

PB, TG, and MD conceptualized and designed the study. SD, TG, and MD performed the literature search. TG, MD, and PK were involved in data collection and performed the data processing. SD and PB drafted the current manuscript. All authors substantially contributed to the interpretation of

the data, revised it critically, and approved the final version of the manuscript.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this study.

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Monitoring weekly progress of front crawl swimmers using IMU-based performance evaluation goal metrics

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Technical evaluation of swimming performance is an essential factor in preparing elite swimmers for their competitions. Inertial measurement units (IMUs) have attracted much attention recently because they can provide coaches with a detailed analysis of swimmers' performance during training. A coach can obtain a quantitative and objective evaluation from IMU. The purpose of this study was to validate the use of a new phase-based performance assessment with a single IMU worn on the sacrum during training sessions. Sixteen competitive swimmers performed five one-way front crawl trials at their maximum speed wearing an IMU on the sacrum. The coach recorded the lap time for each trial, as it remains the gold standard for swimmer's performance in competition. The measurement was carried out once a week for 10 consecutive weeks to monitor the improvement in the swimmers' performance. Meaningful progress was defined as a time decrease of at least 0.5 s over a 25 m lap. Using validated algorithms, we estimated five goal metrics from the IMU signals representing the swimmer's performance in the swimming phases (wall push-off, glide, stroke preparation, free-swimming) and in the entire lap. The results showed that the goal metrics for free-swimming phase and the entire lap predicted the swimmer's progress well (e.g., accuracy, precision, sensitivity, and specificity of 0.91, 0.89, 0.94, and 0.95 for the lap goal metric, respectively). As the goal metrics for initial phases (wall push-off, glide, stroke preparation) achieved high precision and specificity (≥0.79) in progress detection, the coach can use them for swimmers with satisfactory free-swimming phase performance and make further improvements in initial phases. Changes in the values of the goal metrics have been shown to be correlated with changes in lap time when there is meaningful progress. The results of this study show that goal metrics provided by the phase-based performance evaluation with a single IMU can help monitoring swimming progress. Average velocity of the lap can replace traditional lap time measurement, while phase-based goal metrics provide more information about the swimmer's performance in each phase. This evaluation can help the coach quantitatively monitor the swimmer's performance and train them more efficiently.

KEYWORDS

sports biomechanics, swimming, IMU sensor, swimming phase, phase-based evaluation, swimmer progress

Introduction

Swimming coaches aim to improve the performance of swimmers in intensive training sessions and prepare them for competition. Depending on the event, the swimmer completes multiple sets, each of which includes several swimming phases: a dive or wall push-off, a glide underwater, a stroke preparation, free-swimming to the end, and a turn to continue the next round with the same sequence of phases. Coaches should focus on each phase because a flawless performance by the swimmer in every phase is necessary to win (Mooney et al., 2016b). They mostly rely on observation and personal experience to monitor and evaluate a swimmer's performance. A coach expects swimmers to improve their performance by 1%–10% during a training season, depending on swimmer's level (Zacca et al., 2020; Ferreira et al., 2021), and usually tracks this progress by measuring lap time over different swimming distances (most commonly 400 m, as it is used to evaluate the swimmer's aerobic performance). However, lap time can only reflect the swimmer's overall progress and not their phase-based performance. The use of biomechanical parameters such as stroke rate, stroke length, and stroke index (product of average velocity and stroke length) (Morais et al., 2013) or body composition (Thng et al., 2022) are other methods proposed by researchers to track swimmer's progress.

The complexity of extracting performance-related parameters has led coaches to use technological tools to obtain an objective and quantitative analysis (Payton and Adrian Burden, 2017). Swimming coaches use a variety of analysis systems such as 2D and 3D cameras (Mooney et al., 2015), inertial measurement unit (IMUs) (Guignard et al., 2017), or physiological parameters such as heart rate (Crowcroft et al., 2017), or lactate monitors (Smith et al., 2002) to investigate the technical aspects of swimming. Although video-based systems are still the gold standard for swimming analysis, they generally suffer from several limitations in aquatic environments, such as cumbersome installation and calibration, water splashes and reflections, or limited recording volume (Callaway et al., 2010). As a result, there is still a need in the coaching community for supportive analysis systems (Mooney et al., 2016a). Improvements in the accuracy, scalability, and cost of Micro-electromechanical systems (MEMS) have led to IMUs becoming a credible option for swimmer motion tracking, as they can provide quick and easy-to-use feedback on detailed performance-related metrics (Ramos Félix et al., 2019).

Several studies have investigated the analysis of swimming with IMUs by extracting kinematic parameters in different phases and techniques such as stroke rate and stroke count (Davey and James, 2008), instantaneous velocity (Dadashi et al., 2012), tumble turn spatio-temporal parameters (Slawson et al., 2012) or wall push-off maximum velocity (Stamm, 2013). Although these studies have demonstrated the application of IMUs for swimming analysis, they have not related the obtained kinematic parameters to the swimmer's performance-related metrics. In our previous study, we used IMUs to automatically segment each swimming lap into wall push-off (*Push*), glide (*Glid*), stroke preparation (*StPr*), free-swimming (*Swim*), and turn phases (Hamidi Rad et al., 2021b). The algorithms developed in this study take a macro-micro approach by swimming bouts detection, lap separation, and swimming style identification at the macro level, and then divide each lap into phases by detecting spatio-temporal events on IMU acceleration and angular velocity data at the micro level. Subsequently, a variety of kinematic parameters were extracted from each phase and used to estimate phase-based goal metrics (*Push* maximum velocity, *Glid* end velocity, *StPr* average velocity, *Swim* average velocity and lap average velocity) for the swimmer's performance evaluation (Hamidi Rad et al., 2021a), indicating how well the swimmer performed the corresponding phase. However, to fully utilize the IMU sensor for training, assessing the sensitivity of IMU-based goal metrics to performance progress is of utmost importance.

Therefore, the main objective of this study was to validate the use of IMU-based goal metrics to monitor swimming performance during training sessions. Using the macro-micro approach to swimming analysis to separate the swimming phases (*Push*, *Glid*, *StPr*, and *Swim*) and the phase-based performance assessment on sacrum IMU, we estimated the goal metrics of each phase. We then analyzed the sensitivity of goal metrics in relation to the swimmer's progress across multiple training sessions. We assumed that 1) lap time is the most important representative of performance level and can be used to define meaningful progress, and 2) the goal metrics change in association with lap time when the swimmer makes meaningful progress.

Materials and methods

Measurement setup and protocol

Sixteen competitive swimmers from a swimming team participated in this study, and their characteristics are shown in Table 1. A waterproof band (Tegaderm, 3M Co., United States) was used to attach an IMU (Physilog® IV, GaitUp, CH.) to the swimmer's lower back on sacrum bone. The sensor recorded 3D angular velocity (±2000°/s) and 3D accelerometer (±16 g) at a sampling rate of 500 Hz. After installation of the sensor,

TABLE 1 Statistics of the swimmers. The values are presented as mean ± standard deviation.

Male	Female	Age (yrs)	Height (cm)	Weight (kg)	50 m Front crawl record (s)
9	7	14.6 ± 0.8	171.6 ± 6.9	55.9 ± 10.1	28.60 ± 2.04

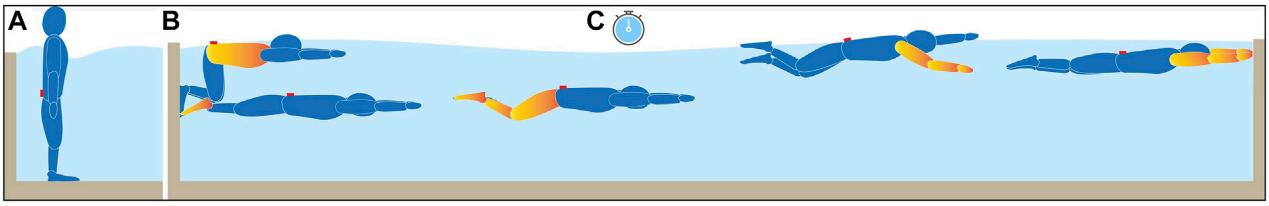

FIGURE 1
Measurement protocol with IMU (red box) attached to the sacrum. After functional calibration, the swimmer starts in the water with an upright posture **(A)** and performs all swimming phases at maximum speed while swimming to the other side in front crawl **(B)**. The coach records the lap time with a stopwatch during each lap **(C)**.

functional calibration was performed with simple out-of-water movements (upright standing and squatting) to make the data independent of the sensor exact position on swimmer's sacrum (Dadashi et al., 2013).

After a brief warm-up, swimmers were asked to swim five times one swimming pool length (one lap) in the same direction at maximum velocity, beginning with a 5-s upright stance before wall push-off in the water (Figures 1A). During a full lap, the swimmer went through all swimming phases so that we could analyze the goal metrics of each phase (Figures 1B). The coach recorded the lap time of all swimmers with a stopwatch during each attempt (Figures 1C). Each swimmer had 5 min rest between trials to avoid fatigue. To track the swimmers' progress, the same measurement was repeated once a week for ten sessions. Prior to participation, the measurement procedure was explained to each swimmer and they provided written informed consent. The measurement protocol of this study was approved by the EPFL Human Research Ethics Committee (HREC, No. 050/2018).

Lap segmentation and phase-based performance evaluation

First, swimming bouts and laps were determined during each training session according to the validated algorithms of our macro-micro approach and then divided into four swimming phases of *Push*, *Glid*, *StPr* and *Swim* (Hamidi Rad et al., 2021b). *Push* phase begins with the forward movement of the swimmer's trunk and ends when the feet leave the wall. *Glid* phase lasts until the beginning of the dolphin kicks in front crawl style. *StPr* phase is the next phase that ends with the first arm stroke, which is the beginning of the *Swim* phase, and *Swim* phase ends when the swimmer's hand touches the wall. The method uses motion biomechanics to identify the events corresponding to the beginning and end of each phase for lap segmentation. Subsequently, based on our phase-based performance evaluation method (Hamidi Rad et al., 2021a), a set of spatio-temporal parameters reflecting various aspects of swimmer's performance were extracted from each phase. These parameters are categorized as propulsion, posture, efficiency and duration/rate to represent the most important aspects of performance. They were fed into *LASSO* (Least Absolute Shrinkage and Selection Operator) regression models to estimate five phase-based goal metrics that quantify the performance within each phase: *Push* maximum velocity, *Glid* end velocity, *StPr* average velocity, *Swim* average velocity, and lap average velocity respectively for phases of push, glide, stroke preparation, swim and the entire lap. These goal metrics were tracked during the measurements to assess their sensitivity to swimmer progress during weeks of training.

Sensitivity analysis

Sensitivity analysis was performed to assess how phase-based goal metrics react to swimmer's progress in two steps. In the first step, we considered all sessions of each swimmer with a significant change in lap time, as lap time is considered representative of swimming performance (Robertson et al., 2009). Using the data from the weekly measurements, we compared the swimmer's performance in each session to other sessions to find significant progress. According to the measurement protocol, five values (for each goal metric and for lap time) are obtained from each participant per session. Because the sample size for comparison between two sessions is small, we used Cliff's Delta (d) effect size analysis as a nonparametric method (Macbeth et al., 2011). This method allowed us to determine whether the achieved lap times and goal metrics differed significantly from one session to another. Each comparison set is assigned an effect size value to quantify the change (Eq. 1).

$$d = \frac{\#(x_i > x_j) - \#(x_i < x_j)}{n_1 n_2} \tag{1}$$

Where the cardinality symbol # indicates counting, x_i and x_j are the lap time or goal metric values of sessions i and j, respectively. n_1 and n_2 are the sizes of the two data sets, both equal to five in our study (i.e., the number of laps). The value of d estimates the probability that a value selected from the ith session is greater than a value selected from the jth session, minus the inverse probability. This can be referred to as a measure of dominance, indicating the degree of overlap between values from two test sessions. The d value is generally within the closed interval of [-1, +1] indicating the degree of overlap between the values from two sessions (effect size of +1.0 or −1.0 for no overlap and 0 for complete overlap). The effect size is considered significant if the confidence interval (CI) does not include zero. The upper and lower bounds of the asymmetric CI (range of δ_{lower} to δ_{higher}) for Cliff's d are constructed based on Eqs 2–4 as a more robust and conservative method (Feng and Cliff, 2004). $t_{\alpha/2}$ is the critical value of the t-distribution for the corresponding confidence level.

$$d_i = \frac{\#(x_i > x_j) - \#(x_i < x_j)}{n_1}, \quad d_j = \frac{\#(x_j > x_i) - \#(x_j < x_i)}{n_2} \tag{2}$$

$$s_d^2 = \frac{n_1^2 \sum_{i=1}^{n_1} (d_i - d)^2 + n_2^2 \sum_{j=1}^{n_2} (d_j - d)^2 + n_2^2 \sum_{i=1}^{n_1} \sum_{j=1}^{n_2} (d_{ij} - d)^2}{n_1 n_2 (n_1 - 1)(n_2 - 1)} \tag{3}$$

$$\delta_{lower}, \delta_{higher} = \frac{d - d^3 \pm t_{\alpha/2} s_d \left(1 - 2d^2 + d^4 + t_{\alpha/2}^2 s_d^2\right)^{1/2}}{1 - d^2 + t_{\alpha/2}^2 s_d^2} \tag{4}$$

Thus, the effect size values along with the CI ranges were calculated for comparing the five values of goal metrics or lap time between every two sessions using Eqs 1–4 and the significant pairs were separated. However, all significant changes in lap time should not be considered as meaningful progress. This is because the lap time value itself is subject to recording errors (using the stopwatch). Based on the training plan, the coach expected to see real progress in the swimmers after at least 3 weeks of training. Therefore, a meaningful lap time change ($MLTC$) was defined as the minimum threshold for meaningful progress. It is indeed similar to the concept of smallest worthwhile enhancement which is defined for competitions to estimate the minimum amount of improvement that is beneficial for athletes to win a race (Hopkins et al., 1999). However, we tend to compare swimmers only with themselves and not with others in training sessions. So we calculated the median lap time of comparisons that were 3 weeks apart (session 1 and session 4, session 2 and session 5, etc.). $MLTC$ is then calculated by taking the average of the differences of all these comparison pairs over all swimmers.

In the second step of the sensitivity analysis, among all significant differences identified in step one between test sessions, only those with a median change more than $MLTC$ were retained as meaningful progress. The entire process of the two steps for detecting significant pairs and then selecting the pairs with meaningful progress is explained by the following pseudocode, where m and n are two different session numbers that vary across all sessions with two loops and $LT_{i,j}$ is ith lap time of jth session.

```
START
  For m = 1:9
    For n = m+1:10
      Calculate d, δlower and δhigher for LT1:5,m and LT1:5,n with Equations 1-4
        If 0 ϵ [δlower,δhigher] THEN SignificantChange
          If Median(LT1:5,m) - Median(LT1:5,n) > MLTC  THEN MeaningfulProgress
          Else  SignificantChange but not MeaningfulProgress
          End
        Else InsignificantChange
        End
    End
  End
END
```

After obtaining all the pairs with meaningful progress, the relationship between changes of goal metrics and changes in lap time was examined for these pairs to analyze the sensitivity of goal metrics to progress by answering three questions:

(i) "Do the goal metrics predict meaningful progress, as does lap time?"
(ii) "How well do the goal metrics represent the swimmer's performance compared to the lap time?"
(iii) "What is the contribution share of each goal metric to swimming progress?"

To answer the first question, we analyzed the correspondence between progress detection by each goal metric and lap time. For each pair of sessions, we calculated whether the change (i.e., improvement) in the values of goal metrics was significant (i.e., true) or not significant (i.e., false) and then compared it to the meaningfulness of the change in lap time. The performance of goal metrics in predicting meaningful progress (i.e., a significant lap time more than $MLTC$) was assessed using the following association rules:

- True positive (TP): goal metric shows a significant change when there is a meaningful progress.

- True negative (*TN*): no significant change is observed with goal metric when there is no meaningful progress.
- False positive (*FP*): no meaningful progress, while the goal metric changes significantly.
- False negative (*FN*): meaningful progress, while the goal metric does not show significant change.

The values for accuracy, precision, specificity, and sensitivity to predict meaningful progress are calculated for each goal metric using Eqs 5–8.

$$Accuracy = \frac{TP + TN}{TP + TN + FP + FN} \tag{5}$$

$$Precision = \frac{TP}{TP + FP} \tag{6}$$

$$Sensitivity = \frac{TP}{TP + FN} \tag{7}$$

$$Specificity = \frac{TN}{TN + FP} \tag{8}$$

To answer the second question, how well the goal metrics represent swimming performance, effect size values were estimated for each significant change in the goal metric and compared to the effect size of lap time if there was a meaningful progress. The third question is about the relationship between the magnitude of change in each goal metric (i.e., change of *Push* maximum velocity ($\Delta Push$), *Glid* end velocity ($\Delta Glid$), *StPr* average velocity ($\Delta StPr$), *Swim* average velocity ($\Delta Swim$), and lap average velocity (ΔLap)) and the change in lap time ($\Delta LapTime$) when there is a meaningful progress. This analysis is performed by calculating the Pearson correlation (Benesty et al., 2009) between the changes in goal metrics and lap time values.

Results

A post-hoc sample size analysis was performed (Jones et al., 2003) considering the lowest acceptable sensitivity and specificity of 0.90 and 0.80, respectively, with a confidence interval of 90%, resulting in a sample size of 107 for this study. This means that at least this number of meaningful comparisons are needed to make a valid comparison between the change in goal metrics and the change in lap time. During the ten measurement sessions, there were seven absences due to swimmers being unavailable, and a total of 750 swimming laps were recorded. Each swimmer is compared to themselves during all measurement sessions, and 642 comparisons were made for all swimmers. 272 of the comparisons showed statistically significant progress (based on Cliff's delta analysis at a 95% confidence level). The accuracy, precision, sensitivity, and specificity of each of the goal metrics used to detect this significant change in lap time (i.e., the first step of the sensitivity analysis) can be found in the Supplementary Figure SA1. Next, comparison of sessions 3 weeks apart for the second step of the analysis yielded an *MLTC* value of 0.5 ± 0.2 *s*, resulting in 122 pairs of sessions with meaningful progress which is higher that the sample size. Each swimmer showed at least four comparison pairs with meaningful progress. The slower the swimmer was during the first test session (higher median of lap time), the higher the number of comparison pairs with meaningful progress (significant correlation coefficient of 0.70), because the swimmers who swim relatively slower have more room for performance improvement. The accuracy, precision, sensitivity, and specificity of each goal metric for detecting meaningful progress are shown in Figure 2.

Among the five metrics, lap and *Swim* average velocity achieved the highest values for accuracy, sensitivity, precision, and specificity (≥0.87). For the three metrics related to the initial phases of *Push*, *Glid* and *StPr*, precision and specificity were relatively high (≥0.79), whereas sensitivity was low (0.45–0.65). For the comparisons in which both meaningful progress in lap time was detected and the goal metric was significant, the effect size values and confidence interval were calculated (Table 2). Comparison of the effect size values for each goal metric and lap time shows lap average velocity and *Swim* average velocity are the best ones for progress detection (difference of 0.04 between effect size values). However, the other three goal metrics achieved lower effect size values than lap time.

The final set of results addresses the correlation analysis between the magnitude of changes in the goal metrics ($\Delta Push$, $\Delta Glid$, $\Delta StPr$, $\Delta Swim$, and ΔLap) and in lap time ($\Delta LapTime$) across all comparisons with meaningful progress. Histograms of the changes in the goal metrics are displayed in Figure 3. The root mean squared error (*RMSE*) for the estimation of each goal metric is extracted from our previous study (Hamidi Rad et al., 2021a) and shown specifically for each goal metric in vertical red lines in Figure 3. The delta values lying inside the range of *RMSE* (±*RMSE* range) are too small to be valid as they might happen due the model errors and should be removed. After removing the invalid delta values for each goal metric, we analyzed the contribution of each metric to the progress of swimming performance. Table 3 shows the average, standard deviation, and range for the changes in the goal metrics, as well as their correlation coefficient (*r*) with $\Delta LapTime$. Of the five goal metrics, $\Delta StPr$ shows the highest standard deviation (0.40 m/*s*). With the exception of $\Delta Push$, the change values of all goal metrics were significantly correlated with $\Delta LapTime$, however with weak correlation coefficients (Table 3).

Discussion

In this study, a single IMU, worn on sacrum, was used to identify the four major phases of a swimming lap and

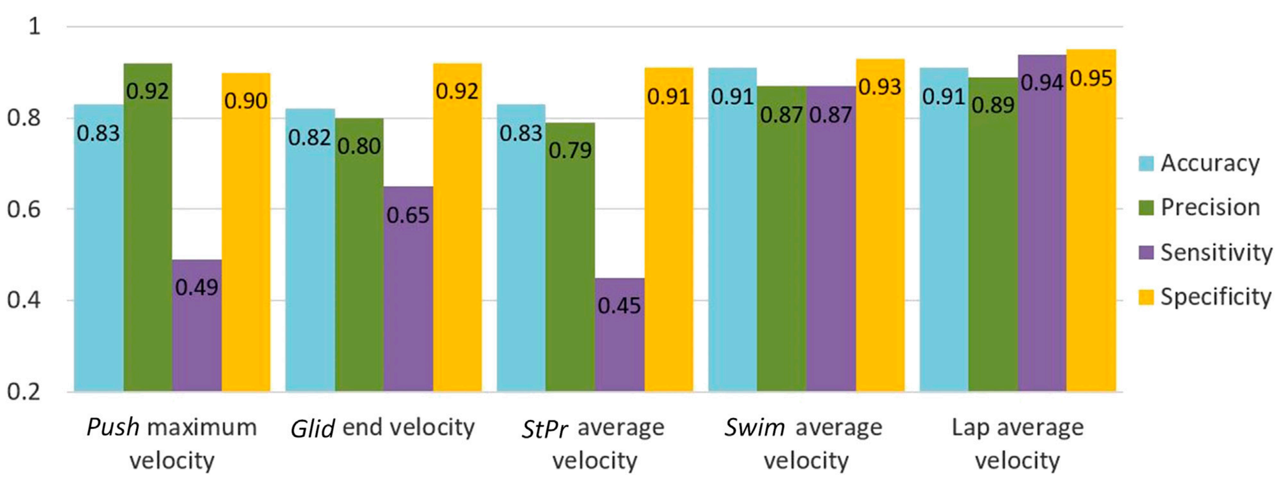

FIGURE 2
Accuracy, precision, sensitivity and specificity of goal metrics for detecting a meaningful progress (lap time change).

TABLE 2 Effect size and confidence interval of all goal metrics and lap time for the comparisons with both meaningful progress and significant goal metric change.

Goal metric		*Push* maximum velocity	*Glid* end velocity	*StPr* average velocity	*Swim* average velocity	*Lap* average velocity
Effect size [CI]	Goal metric	0.67 [0.26, 0.85]	0.78 [0.30, 0.90]	0.75 [0.26, 0.89]	0.92 [0.25, 0.96]	0.93 [0.27, 0.97]
	Lap time			0.96 [0.25, 0.98]		

calculate a performance-based goal metric for each of these phases and the entire lap. These goal metrics were then used to follow the swimmers' progress over ten training sessions. The results obtained confirmed our hypothesis of association between the phase-based goal metrics and swimmers' progress, but with varying sensitivity and degree of association in each phase.

As shown in Figure 2, lap average velocity and *Swim* average velocity achieved the highest accuracy, precision, sensitivity, and specificity (≥0.87) among all goal metrics to predict meaningful progress. Because lap time is used as a representative of performance, lap average velocity was expected to be highly associated with it. This goal metric could replace traditional lap time because it is not affected by human recording error. Furthermore, since the *Swim* phase is the longest phase of a lap, it should contribute more to lap time compared to other phases. Although the sensitivity of *Push* maximum velocity, *Glid* end velocity, and *StPr* average velocity are low, their specificity and precision are either at or above 0.80. Considering Eqs 6–8, the high specificity and precision is mainly due to a low number of false positives. It can be concluded that the three initial goal metrics are less good at detecting meaningful progress than the other two metrics. However, when they do detect progress, it is correct, indicating that they are relevant to progress assessment despite their low sensitivity.

Compared with similar results using goal metrics to detect significant (and not meaningful defined by *MLTC*) progress shown in Supplementary Figure SA1, using meaningful progress improved the results. The accuracy, precision, sensitivity, and specificity of all five goal metrics for detecting significant progress were lower because the procedure was affected by the lap time recording error. However, the sensitivity of the goal metrics for the initial phase remained low for the same reason. Overall, it appears that all phases are important for improving overall performance and progress is the result of mastering all phases of swimming. The coach can use the three metrics of the initial phases to provide an additional quantitative assessment. However, this argument does not apply in reverse, and a change in lap time is not essentially the result of better performance in the initial phases. It increases the number of false negatives and lowers the sensitivity of the initial phases goal metrics to overall progress.

In terms of effect sizes and confidence interval ranges, Table 2 shows that the effect size values of the goal metrics for lap average velocity and *Swim* average velocity are closest to the effect size of lap time, such that these two metrics are as strong as lap time in

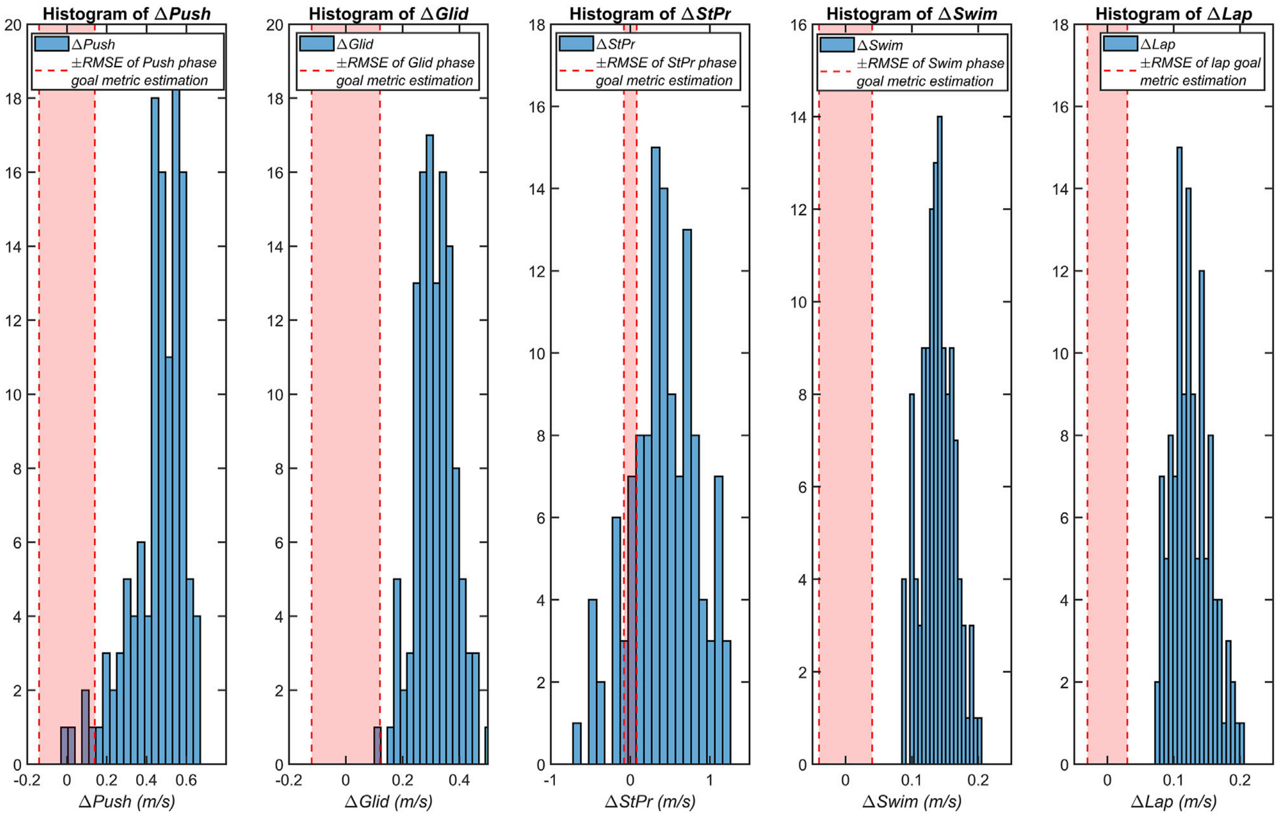

FIGURE 3
Histograms of changes in the five IMU goal metrics (Δ*Push*, Δ*Glid*, Δ*StPr*, Δ*Swim*, and Δ*Lap*) for the comparisons with meaningful progress. The estimation *RMSE* range of each goal metric is displayed with red dashed lines.

TABLE 3 Average, standard deviation, and range of each goal metric change and its correlation coefficient (*r*) with Δ*LapTime* for all meaningful progress comparisons. The change values that are below *RMSE* of each goal metric are removed.

Goal metric change	Δ*Push*	Δ*Glid*	Δ*StPr*	Δ*Swim*	Δ*Lap*
Average (*m/s*)	0.49	0.33	0.50	0.14	0.13
Standard deviation (*m/s*)	0.09	0.06	0.40	0.02	0.03
Range (*m/s*)	0.52	0.44	1.89	0.16	0.17
Correlation coefficient (*r*) with Δ*LapTime*	−0.04	−0.21**	−0.17**	−0.29***	−0.31***

*p-value < 0.05, ** p-value < 0.01, *** p-value < 0.001.

indicating progress. However, the effect size values of the goal metrics *Push* maximum velocity, *Glid* end velocity, and *StPr* average velocity are lower than lap time because they cannot represent the overall performance of the swimmers as well as lap time. It can be argued that if the swimmer is not making more progress in the *Swim* phase, there is still room for improvement in the initial phases and the coach should focus on these goal metrics to make further progress.

Figure 3 shows that among the five changes in the goal metric, only Δ*StPr* has worsened in some cases, while there is a meaningful progress on lap performance (negative values of the histogram). Due to the coaching strategy at this period of the season, the coach did not emphasize working on this phase for the swimmers with weak performances, and asked them to focus on other phases to compensate. Most of the change values of all goal metrics are outside the range of the

RMSE of the goal metric estimation. The correlation coefficients of the changes of all goal metrics with $\Delta LapTime$ are weak (<0.4) (Table 3). Since the change values of the goal metrics are reliable after removing the samples lying inside the $\pm RMSE$ range (Figure 3), the main reason for the weak correlation is the error in recording the lap time, since it is recorded by the coach with a handheld stopwatch, while this analysis requires a more precise method. However, since the correlations are significant, we can conclude that improving goal metrics contributes to swimmer's progress and the coach should use all of these metrics in the training sessions.

In order to obtain a larger, more varied data set, both male and female swimmers were used to generate our results, and comparison based on individual differences is beyond the scope of this study. For technical reasons, only front crawl technique is examined here. However, based on our previous research (Hamidi Rad et al., 2021a), similar goal metrics can be extracted from other main swimming techniques (backstroke, butterfly, and breaststroke) to perform the same study. The lap time was recorded using stopwatch which is prone to human error and using more precise measurement methods such as cameras can increase the quality of this analysis. Since we had only one-way laps in the measurements, the turn phase was not evaluated in this study. The number of lap repetitions per swimmer was limited to five to avoid a fatigue effect that could affect the assessment of progress. However, collection of a larger data set would be required to perform a more powerful statistical analysis.

This study shows that the goal metrics calculated from a single sacrum IMU can provide valuable information about performance in different swimming phases. Coaches can forgo measuring lap time with a stopwatch and use the goal metric for lap average velocity, which can be automatically estimated based on IMU as a substitute for traditional lap timing. They can then focus on the goal metric for each phase to get a more detailed analysis of the swimmer's performance. Compared to other studies monitoring swimmers' performance that focused mainly on either overall performance or free-swimming phase parameters (Morais et al., 2013, 2015), our proposed goal metrics allow the coach to track swimming performance in each phase separately. Furthermore, tracking progress using conventional methods such as video-based systems or heart rate and lactate monitors is very time-consuming and only possible at selected times during a season (Ferreira et al., 2021), whereas IMUs have the least impact on swimmers' training and can be used on a daily basis.

The dominance of coaching philosophy and qualitative analysis in training sessions invariably leads to subjective, inaccurate assessments (Mooney et al., 2016a). Therefore, providing phase-based goal metrics serves as an assistant to the coach, allowing him or her to quantitatively monitor each swimming phase and track a swimmer's progress during training sessions. Using this information, the coach can customize training strategies for each swimmer, which usually takes a lot of time and effort. Although wearables induce more drag on the swimmer's body (Magalhaes et al., 2015), they require an extremely small amount of preparation and analysis from the coach to provide personalized feedback. The coach can access performance evaluation reports for the entire team after each training session and plan further training for each swimmer based on their phase-specific progress.

Conclusion

By using IMU based goal metrics to monitor the performance of a team of swimmers, we have demonstrated the possibility of objective evaluation of swimmers' progress during training sessions. Of the goal metrics considered in this study, lap average velocity and Swim average velocity had the highest accuracy, precision, sensitivity, and specificity (≥0.87) to predict swimmers' progress. The goal metrics related to *Push*, *Glid* and *StPr* achieved high specificity and precision (≥0.79) for progress, confirming the role of initial phases in overall swimming performance. Lap average velocity and *Swim* average velocity are as sensitive as lap time to swimming progress and can be used as precise performance-related indicators. Other goal metrics provide additional quantitative information about the swimmer's phase-related performance that is not available in traditional coaching approaches. It is illustrated that the value of changes in goal metrics also correlates with swimmer progress. In summary, the coach can use the phase-based report to obtain a comprehensive view of the swimmer's performance. This study opens new training horizons in swimming by providing objective feedback based on goal metrics and analyzing the effects of feedback on the swimmer's performance.

Data availability statement

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

Ethics statement

The studies involving human participants were reviewed and approved by EPFL human research ethics committee (HREC, No: 050/2018). Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

Author contributions

MH, KA, VG, FM, and FC designed and conceptualized the study and contributed to the analysis and interpretation of the data. MH carried out the measurements and designed the algorithms. KA supervised the study and FD co-advised it. KA and FD have contributed equally to this work and shared last authorship. MH drafted the manuscript, and all other authors revised it critically. All authors confirmed the final version and concurred to be responsible for all aspects of this study.

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Conflict of interest

Author FM is employed by Gait Up S.A. Author FD is employed by Huma Therapeutics Ltd.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fbioe.2022.910798/full#supplementary-material

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Ankle joint flexibility affects undulatory underwater swimming speed

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The movement of undulatory underwater swimming (UUS), a swimming technique adapted from whales, is mainly limited by human anatomy. A greater ankle joint flexibility could improve the imitation of the whale's flap of the fin and therefore enhance USS performance. The aim of this study was to investigate the impact of ankle joint flexibility on swimming velocity and kick efficiency during UUS by comparing kinematics of swimming trials with reduced, normal, and enhanced maximum angles of plantar flexion. Ten well trained swimmers (5m and 5f; 22 ± 4years; 177 ± 7cm; 74 ± 15kg), performed multiple trials of UUS with normal, restricted, and increased ankle joint flexibility on two separate days in randomized order. Kick frequency was controlled by a metronome. Plantar flexion (PF) was restricted by tape application on both feet and increased by passive-dynamic stretching. All trials were filmed. Kinematics were obtained with two-dimensional motion analysis. Tape application restricted maximum PF by 10.42% while stretching increased PF by 6.87% compared to normal PF. Swimming velocity and kick efficiency significantly decreased during swimming with restricted PF (1.13 ± 0.13m*s^{-1}; 0.69 ± 0.09m) compared to normal (1.20 ± 0.14 m*s^{-1}; 0.72 ± 0.10m) and increased (1.22 ± 0.15m*s^{-1}; 0.73 ± 0.10m) PF. Swimming velocity and kick efficiency did not differ between normal and increased PF. Body height normalized swimming velocity correlated significantly with PF angle (r = 0.538). The results suggest that UUS velocity is affected by impaired PF. Particularly swimmers with low or average maximum PF angles may benefit from a long-term ankle joint flexibility program to improve their UUS performance.

KEYWORDS

undulatory underwater swimming, dolphin kick, swimming performance, ankle joint flexibility, plantar flexion, elite swimmers

Introduction

In competitive swimming races, success and failure are often discriminated by milliseconds only (McCullough et al., 2009; Yuan et al., 2019). As a result, biomechanical characteristics affecting swimming stroke efficiency must be identified and optimized to improve the athlete's performances even by marginal gains. Since undulatory underwater swimming (UUS) is often faster than the main swimming strokes (Bissig et al., 2004; Ungerechts et al., 2009; Schneider, 2012), improving dolphin kick efficiency has the potential to improve overall competitive swimming times (Nakashima, 2009; Gonjo and Olstad, 2020). The more streamlined body posture (Schneider, 2012; Zamparo et al., 2012), as well as the smaller up to non-existing wave resistance underneath the water surface allow to maintain the gliding speed after start and turns as long as possible and to reduce the deceleration during the diving phase (Zamparo et al., 2012). Although the optimal distance traveled underwater seems to be individually different and depends on the following swimming stroke (Veiga and Roig, 2015; Veiga et al., 2016; Morais et al., 2019), studies have shown that faster swimmers had longer UUS distances (Veiga et al., 2014) and UUS can have a positive impact on swimming velocity and stroking length on start and turn segments (Veiga and Roig, 2016) as well as total race times (Morais et al., 2019). Thus, the permitted diving distance of 15 m (Fédération internationale de Natation, 2017), which equates to 30% of a long course and 60% of a short course, provides an opportunity to improve overall competitive swimming times by enhancing UUS performance.

To maximize the speed of UUS, the optimized movement must be adapted to human anatomy (Hochstein and Blickhan, 2014). Since the human body has only a few joints that can execute the undulatory movement (hip, knee and ankle), the smooth transition of the body wave is highly limited and the propulsion effect is quite low compared to whales with a larger number of separate joints (Von Loebbecke et al., 2009a,b). However, a greater ankle joint flexibility which allows increased plantar flexion may improve the dolphin kick performance as the greatest propulsion is generated with the kicking movement of the feet (Von Loebbecke et al., 2009b). More flexible ankle joints could thus superiorly imitate the efficient kicking movement of a fin (Reischle, 1988; Wick, 2013). The displacement of water during the down kick would be directed rather backwards than downwards, so there would be a higher propulsion with the same power efficiency (McCullough et al., 2009; Hochstein et al., 2010; Schneider, 2012; Séhel, 2016). Furthermore, the greater range of motion could increase the flipping movement of the feet which would enhance the usable propulsive momentum by faster reversion of the vortices (Strass et al., 2002; Ungerechts et al., 2009). Additionally, a greater ankle joint flexibility could result in a more harmonized and energy-efficient undulatory movement (Hahn, 2013). This could enhance the kicking frequency which, in turn, is positively correlated to swimming speed (Arellano et al., 2003; McCullough et al., 2009). Therefore, elite as well as recreational athletes could improve their swimming performance in different strokes *via* more efficient UUS by enhancing their ankle joint flexibility.

Previous studies of UUS mainly investigated kinematic key parameters as kicking frequency and kick amplitude (Arellano et al., 2002; Connaboy et al., 2009; Cohen et al., 2012; Yamakawa et al., 2017) or the underlying hydrodynamics (Arellano et al., 2002; Connaboy et al., 2009; Von Loebbecke et al., 2009b). The potential benefit of more flexible ankle joints on kicking efficiency and swimming velocity is often mentioned but rarely directly tested. Only a few studies investigated the effect of the ankle joint flexibility on swimming velocity during UUS (Sugimoto et al., 2008; Willems et al., 2014; Connaboy et al., 2016; Shimojo et al., 2019; Wadrzyk et al., 2019). Different methodological approaches (e. g., different swimming distances, different number of analyzed swimming trials and swimming cycles per trial, different magnitude of ankle joint flexibility restriction, dimension of filming and analysis) complicate the direct comparison of the results. A restriction of the plantar flexion (PF) angle by tape application consistently decreased swimming velocity, however, it remained unclear if an increase in the range of ankle movement would enhance the swimming velocity.

The aim of this study was to investigate the impact of ankle joint flexibility on swimming velocity and kick efficiency during UUS by comparing kinematics of swimming trials with different maximum angles of plantar flexion. We hypothesized that a greater ankle joint flexibility (maximum PF angle) is associated with a greater swimming velocity and kick efficiency.

Materials and methods

Subjects

Five male and five female swimmers (age: 22.00 ± 4.19 years, height: 176.90 ± 6.64 cm, weight: 74.20 ± 15.11 kg, training experience: 15.7 ± 4.0 years) were tested within this study. Swimmers who reported former ankle surgery or structural ankle injuries were excluded from participation in this study. The study was reviewed and approved by the Ethics Committee of the Faculty of Humanities and Social Sciences of the Humboldt-Universität zu Berlin. The participants provided their written informed consent to participate in this study.

Experimental setup

Each participant got tested on two separate days at an interval of a week. Anthropometric data (body height and weight) and personal data (age, sex, and training experience) were recorded before starting the swimming trials.

Swimming trials were performed in an indoor swimming pool (8 × 25 m, water temperature: 28 °C, water depth: 1.80 m). Swimmers maintained a depth of ~0.8 m while performing UUS. The participants were instructed to use the push off from the wall only to obtain the correct water depth, and to generate the swimming speed by undulatory swimming only. All trials were filmed, and kinematics were obtained by two-dimensional motion analysis.

Standardization of kicking frequency

After independently warming up for 20 min including UUS, the participants performed three trials (15 m) of underwater dolphin kicks in maximum speed to determine their maximum kicking frequency. Between the trials they had a resting time of 5 min. The duration of three kick cycles were used to calculate the kicking frequency. The highest frequency of the three trials was set as individual maximum (100%).

The following trials were performed with submaximal effort (80% of individual maximum kicking frequency). The submaximal effort should provide an individual competition-like intensity without risking to much muscle fatigue. The constant kicking frequency during all swimming trials should also ensure a consistent power output and prevent an impact of kicking frequency on UUS kinematics. Shimojo et al. (2014) showed no significant difference of kick efficiency (Strouhal number and Froude-efficiency) during swimming with submaximal kicking frequency (85%) compared to swimming with maximum kicking frequency. The calculated velocity was set by a waterproof metronome device (FINIS® Tempo Trainer Pro) which was clipped onto the swimming goggle. The synchronization of the kicking frequency to a metronome device has previously been shown to have no impact on kinematics, movement patterns and muscle activity of the lower extremities during UUS (Yamakawa et al., 2017). The swimmers performed three familiarization trials of 15 m with underwater dolphin kicks trying to synchronize their kicking frequency to the beat of the metronome device.

Swimming trials

The familiarization trials were followed by three trials of swimming with normal, restricted, and increased ankle joint flexibility, respectively. The participants were asked to swim as fast as possible while maintaining the set kick frequency of the metronome device.

The following conditions were tested and compared regarding different kinematic parameters:

(1) Normal PF angle: participants swam with their natural ankle joint flexibility,
(2) Restricted PF angle: plantar flexion was restricted by tape application on both feet by approximately 10% before swimming,
(3) Increased PF angle: plantar flexion was increased by passive-dynamic stretching before swimming.

The condition "normal PF angle" was tested first on both test days. The order of the remaining conditions was individually randomized. Accordingly, there were two possible orders:

(1) 3 x Normal – 3 x Restricted – 3 x Increased,
(2) 3 x Normal – 3 x Increased – 3 x Restricted.

On the second testing day the order of the last two conditions was reversed compared to the first testing day.

There were 3 min rest between trials and 10 min rest between sets. The application of the tape and the passive-dynamic stretching was performed during that resting time.

Taping

The amount of restriction was aimed to be high enough to produce measurable effects on swimming velocity and kick efficiency and low enough to prohibit unwanted effects on swimming technique. Considering previous studies which used either 30 or 4% (Willems et al., 2014; Shimojo et al., 2019), we aimed for a restriction in between of 10% of maximum plantar flexion.

Right before the swimming trials, the active PF angle was measured with a goniometer using the neutral zero method (Freiherr von Salis-Soglio, 2015). A waterproof elastic tape was used to restrict PF and all swimmers got taped by the same person (JK). The feet were held in a position of 80% of maximum PF angle while applying the tape as tightly as possible. The remaining restriction was supposed to result in 90% of maximum PF angle. After tape application, the active maximum PF angle was measured again to verify, that the sought PF restriction was achieved. If the tape loosened partially from the feet during swimming trials the tape application was renewed during the following resting time.

Stretching

Immediately before the swimming trials with increased PF a passive-dynamic stretching of the ankle joints was performed. Swimmers lay on the ground with straightened legs while the researcher (JK) moved the feet from maximum plantar flexion to maximum dorsiflexion within 5 s. This stretching was performed for 60 s and paused for 30 s. Before the first trial, the stretching was repeated three times. During the resting time between trials, the stretching was performed once to maintain the acute stretching effect. After every finished stretching session, the maximum active PF angle was measured. The plantar flexion angle increased on average by 6.87%. To counteract possibly reduced muscle activity after stretching, the swimmers performed three hops before each swimming trial.

Motion analysis

UUS trials of the participants were filmed with an underwater video camera (60 frames per second; GoPro HERO7,

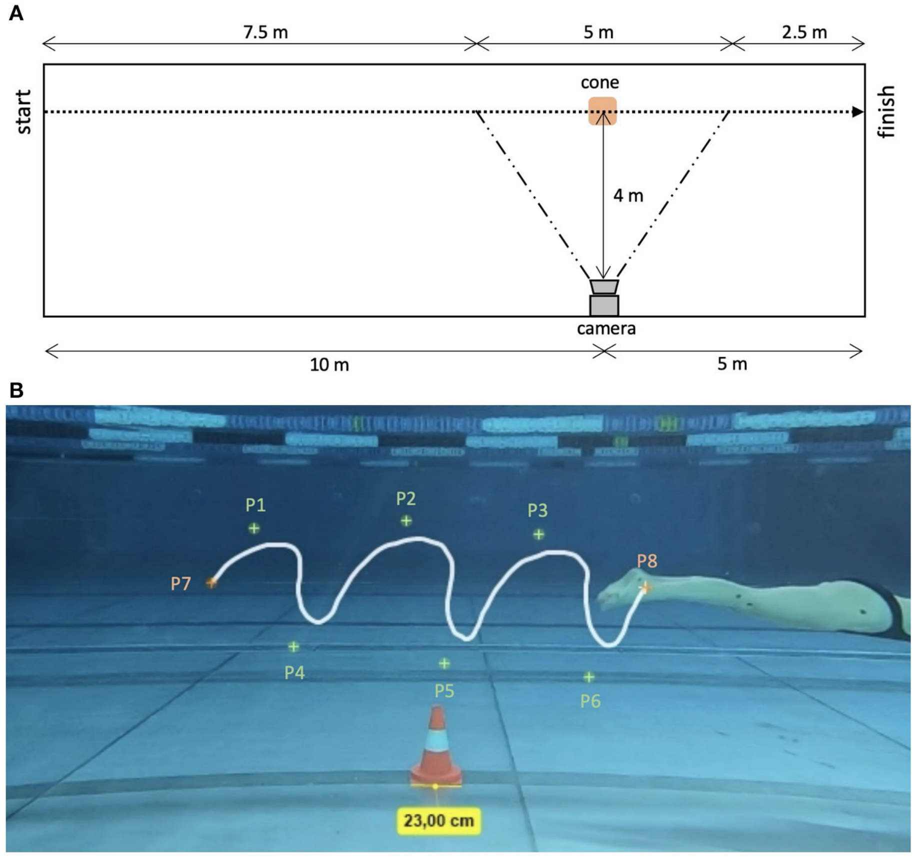

FIGURE 1
Experimental set-up **(A)** and motion analysis of swimming trial by tracking bony landmarks **(B)**. P1–P3 and P4–P6 mark the highest and lowest points of the fifth toe during kicking cycles. P7 and P8 mark the start and end points of three kicking cycles.

GoPro Inc., San Mateo, USA) which was positioned 0.6 m below water surface and 10 m away from the starting point (perpendicular to the swimming direction). The camera was attached to a bar that was pressed against the wall of the pool to ensure a stable camera positioning while filming. The distance between camera and swimmers was 4 m. The recorded area of swimming was from 7.5 m to 12 m after push-off from the wall. A cone was placed 10 m from the starting point (push-off). Its width was used as reference for calibration of the swimming distance in the motion analysis program (see Figure 1).

For motion analysis, six anatomical landmarks were marked with a waterproof pen on the lateral right side of the swimmer's bodies: trochanter major (hip), epicondylus lateralis femoris (knee), caput fibulae (knee), malleolus lateralis (ankle), calcaneus (heel) and caput ossis metatarsalis V (toe). The recorded videos were uploaded to a motion analysis program (Kinovea version 0.9.4) and landmarks of the swimmer's bodies were manually digitized (see Figure 1). A recent study reported that the Kinovea software is a valid and reliable tool that is able to measure accurately at distances up to 5 m from the object and at an angle range of 90–45° (Puig-Divi et al., 2019).

The following kinematic variables were measured, respectively, calculated:

(1) kicking frequency [Hz]: number of finished kicking cycles divided by duration of swimming,
(2) kick amplitude [m]: vertical distance between highest and lowest position of the fifth toe during kick cycles,
(3) horizontal swimming velocity[m^*s^{-1}]: swimming distance divided by swimming duration,
(4) kick efficiency [m/kick]: horizontal swimming velocity divided by kicking frequency, and
(5) minimum knee flexion angle: α [°]: minimum angle between femur and fibula during the down kick.

Three kick cycles of each trial were used to calculate the mean of each variable. For statistical comparison of the three different PF conditions, means were calculated of three trials first and of both testing days afterwards.

Statistical analysis

Statistical analysis was performed using IBM SPSS (version 27). Shapiro-Wilk-tests were used for assessment of normal distribution. All kinematic variables were statistically normally distributed except minimum knee flexion angle during swimming with increased PF angle [$W_{(10)} = 0.83$, $p = 0.036$, $n = 10$]. T-tests for dependent samples were used to compare the kinematics of the two separate testing days. An analysis of variance (ANOVA) for repeated measurements was applied to compare kinematics of the different swimming conditions for all variables, as it is robust against violations of the normal distribution. In case of a significant difference, a Bonferroni *post-hoc* analysis was conducted. The effect size f was evaluated as small (0.10–0.24), moderate (0.25–0.39) and large (>0.40) (Cohen, 1988). Pearson correlations r were used to determine the correlation between maximum PF angle and each kinematic parameter. Classification was made regarding the minimum levels of r: small (±0.1), moderate (±0.3) and large (±0.5). The level of significance was set at $p < 0.05$.

Results

There was no significant effect of testing day on UUS kinematics, thus the mean of both days was calculated and used for analysis of each tested condition (PF angle).

Maximum PF angles were significantly lower during swimming with restricted PF angle compared to swimming with normal or increased PF angle (Table 1). The effect size was evaluated as large ($f = 4.36$).

Kicking frequency, as set by the metronome, did not differ between test conditions as planned (Table 1).

Kick efficiency and horizontal swimming velocity were significantly smaller during swimming with restricted PF angle compared to swimming with normal and increased PF (Figure 2). The effect size was evaluated as large (kick efficiency $f = 1.54$; swimming velocity $f = 1.82$). There were no significant differences regarding kick efficiency and horizontal swimming velocity between swimming with normal and increased PF.

Regarding kick amplitude, the ANOVA for repeated measurements indicated a significant difference in kick amplitude between tested conditions [$F_{(2,18)} = 3.74$, $p = 0.044$, $\eta_p{}^2 = 0.29$]. Mean values for kick amplitude were highest during swimming with increased PF angle followed by swimming with normal PF angle and restricted PF angle (Table 1). However, Bonferroni corrected paired comparisons did not reveal significant differences between conditions.

Minimum knee flexion angle was significantly smaller during swimming with restricted PF compared to swimming with increased PF (Table 1). The effect size was evaluated as large ($f = 0.79$). There was no significant difference of minimum knee flexion angle between swimming with normal PF and restricted PF as well as between swimming with normal and increased PF.

Horizontal swimming velocity significantly correlated with body height in all tested conditions (restricted PF: $r = 0.77$, $p = 0.010$; normal PF: $r = 0.66$, $p = 0.038$; increased PF: $r = 0.64$, $p = 0.046$). Therefore, to account for interpersonal differences

TABLE 1 Kinematic variables of USS with restricted, normal, and increased plantar flexion (mean±SD).

Kinematic variable	Ankle joint flexibility		
	Restricted	Normal	Increased
Maximum plantar flexion angle [°]	57.5 ± 3.51	64.2 ± 3.94*	68.6 ± 4.76*,#
Minimum knee flexion angle [°]	107.9 ± 7.74	108.4 ± 7.97	109.2 ± 7.89*
Kicking frequency [Hz]	1.66 ± 0.17	1.68 ± 0.18	1.67 ± 0.19
Kick amplitude [m]	0.64 ± 0.08	0.65 ± 0.08	0.66 ± 0.09

*Significantly different to restricted PF angle, #significantly different to normal PF angles.

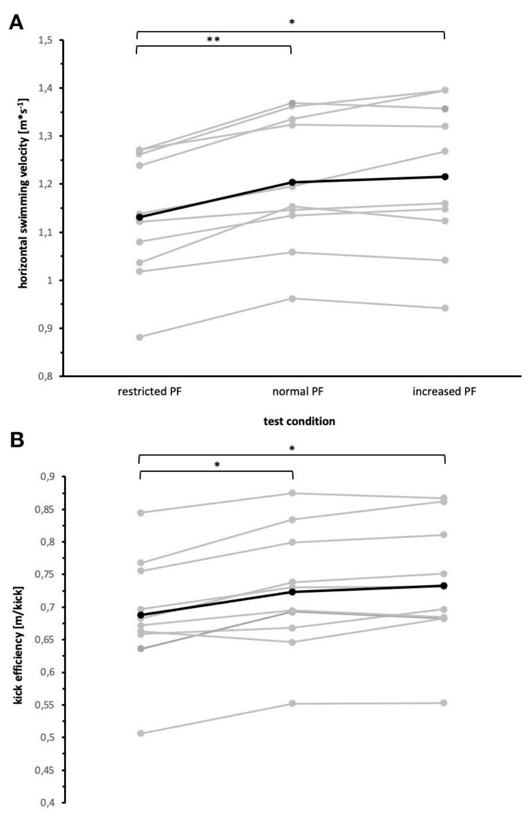

FIGURE 2
Effect of increased, normal, and restricted plantar flexion angle on horizontal swimming velocity **(A)** and kick efficiency **(B)**. Gray lines represent individual swimmers while the black line represents the mean value. *$p < 0.05$, **$p < 0.001$.

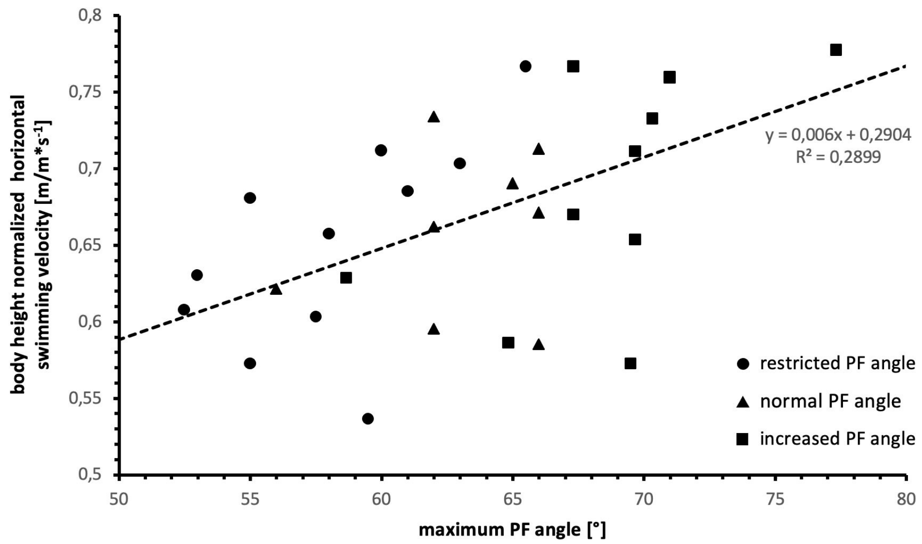

FIGURE 3
Relationship between body height normalized swimming velocity and maximum PF angle.

in body morphology affecting swimming performance and to analyze the effect of maximum PF angle irrespective of body morphology, swimming velocity was normalized to body height for further analysis. Body height normalized swimming velocity significantly correlated with maximum PF angle ($r = 0.538$, $p = 0.002$) which is shown in Figure 3.

There were no significant correlations between maximum PF angle and other kinematic variables.

Discussion

To our knowledge this is the first study that investigated the impact of both restricted as well as increased plantar flexion angles on UUS kinematics. In agreement with our hypothesis, swimming velocity and kick efficiency were affected by ankle joint flexibility. However, it was particularly the restriction of plantar flexion that was negatively affected, while the increase in plantar flexion did not further enhance swimming velocity or kick efficiency.

The negative effect of PF restriction on swimming velocity seems to be at least partially dose dependent. A study on the effect of ankle flexibility on dolphin kick performance in competitive swimmers, which restricted PF by tape application by 30% (Willems et al., 2014), has led to a 19.5% reduction in swimming velocity, while in our study PF restriction was smaller (10%) which has led to a smaller reduction in swimming velocity of 5.8%. In accordance, a small PF restriction of 4% in a study on ankle joint flexibility in UUS (Shimojo et al., 2019) resulted in a small reduction of swimming velocity of 4.7%.

Regarding the reason for the effect of PF restriction on swimming velocity, it has been suggested (Willems et al., 2014) that the area of the feet, which shifts the water backwards and generates the propulsive impulse, decreases with the restriction of the PF angle. Consequently, a higher knee flexion during the down kick has been observed which may be a compensatory strategy for restricted PF flexibility (Willems et al., 2014). The limited vortex generation due to restricted PF and the potentially greater frontal drag due to higher knee flexion were suggested to be the reason for the decreased swimming velocity. Previous studies also described a negative correlation of knee flexion and swimming velocity because of the higher frontal water resistance [$r = -0.70$ (Arellano et al., 2003); $r = -0.53$ (Wadrzyk et al., 2017)]. Our results point in the same direction as the reduction of swimming velocity with restricted PF angle was similarly accompanied by greater knee flexion when compared to swimming with increased PF angle (+1.2%). It is conceivable, that smaller reductions in PF lead to smaller or negligible changes in knee flexion. This is supported by the finding that a 6% reduction in PF (Wadrzyk et al., 2019) did not result in any significant changes in knee flexion angles.

It has also been suggested (Sugimoto et al., 2008; Cohen et al., 2012) that a limited inversion of the feet may cause a reduction in swimming velocity. In the present study, the measurement of the foot inversion angle was not possible due to the lateral and two-dimensional nature of the video analysis. Thus, we cannot test this assumption with our data. A previous study (Matsuda et al., 2021) detected no significant relationship between ankle inversion ROM and UUS velocity. However, this study analyzed the correlation between ankle inversion ROM and UUS velocity in fast and less fast swimmers and thus described interpersonal differences. Those interpersonal differences in UUS velocity can be affected by a huge variety of variables not allowing to conclude on the effect of ankle inversion ROM on UUS velocity within one person. While the combination of maximum plantar flexion and inversion may be important for a perfect propulsion during UUS, we are confident that there is a causal relationship between PF restriction and decreased swimming velocity in our study. In agreement with the literature, the restricted maximum PF angle could have caused a greater frontal drag (Ungerechts et al., 2009). Additionally, the smaller range of motion could have resulted in a limited flipping action of the feet during the down kick so both the size and the rotation velocity of the generated vortices could have been reduced, which, in turn, would have decreased the swimming velocity and kick efficiency. Also, the tape material could have changed the streaming characteristics of the water as well as the vortex generation which could have contributed to the decreased swimming velocity and kick efficiency. However, the extent of this possible impact cannot be determined yet.

In contrast to the negative effect of PF restriction on swimming velocity, it seems that an increase in PF by stretching intervention does not further enhance swimming velocity. It is conceivable, that the increase in PF angle compared to the normal condition may have been too small to result in significant changes in swimming velocity and kick efficiency. It is also possible that other three-dimensional movements of the lower limbs are crucial to achieve higher UUS velocity, as it has been shown that e. g., the peak angular velocities of hip internal and external rotation were significantly correlated with UUS velocity (Matsuda et al., 2021). However, body-height normalized swimming velocity highly significantly correlated with maximum PF angle in the present study which indicates that the ankle joint flexibility affects swimming velocity. This result contrasts with the findings of Willems et al. (2014) who did not find a significant correlation between swimming velocity and PF angle. They assumed that the ankle joint flexibility is a neglectable factor regarding swimming velocity compared to other determinants like muscle power or water drag. While other determinants may affect swimming velocity to a greater extend, we suppose that PF angle has at least a small impact on swimming velocity, which may decline with increasing ankle flexibility. Thus, there can be an optimal condition of plantar flexion flexibility beyond which no further gain in swimming velocity and kick efficiency is realized. Furthermore, the normal PF angles of our participants were with 50° highly above average. It is possible that in swimmers with lower initial values of PF angle a larger effect on swimming velocity and kick efficiency may have been measurable which needs to be confirmed in future studies. However, especially in longer races even small improvements of kick efficiency can have a particular impact on overall performance as a higher kick efficiency can result in lower energy cost and therefore faster racing times (Zamparo et al., 2020). Over a 400 m short course race a time improvement of ~2 s can be calculated based on the within our study detected improvements in kick efficiency and swimming velocity with increased PF (compared to normal PF), when swimming with an intensity of 80% and assuming an UUS distance of 10 m excluding start and turn push offs.

Considering the presented results, it is conceivable that particularly athletes with low or average maximum plantar flexion angles could benefit from of a long-term ankle joint flexibility program to improve their UUS and overall performance.

Although the study was conceived and performed with care to obtain objective, valid and reliable data, there are some points to discuss that may limit the interpretation of the results. The present study investigated acute effects of ankle joint flexibility changes only. However, long-term increases in plantar flexion flexibility may differently affect UUS velocity. For instance, we observed a higher knee flexion, possibly resulting from an acute compensatory mechanism in response to restricted PF but long-term impacts of limited PF on knee flexion cannot be derived from the presented results and may differ from acute effects. Moreover, the elastic material of the tape may not have fully restricted the PF angle during swimming because of the high passive forces underwater. A non-elastic tape could have reduced this potential discrepancy between maximum PF angle on land and during swimming. However, when applying a non-elastic tape the participants of Shimojo et al. (2019) reported pain during swimming. Furthermore, pilot-trials of the present study demonstrated that a non-elastic tape was not waterproof, so the tape got loosened during the swimming trials and PF angle was no longer restricted. For this reason, a waterproof elastic tape was used in the present study and was sticked as tightly as possible onto the skin. In addition, exact measurement of PF angle and inversion during swimming was not feasible due to two-dimensional video analysis and combined movement of PF and inversion during down kick. Thus, future studies should consider a 3D movement analysis to capture foot inversion in addition to PF. Besides, an underwater camera was used to film the swimming trials. While a linear field of view was set, there was a slight distortion at the outer frame of the video. To counteract this effect, analyzed swimming trials were always in the center of the video. Lastly, the study size may have been too small to find small yet significant changes of e. g., kick amplitude and a resulting impact on UUS performance as well as gender-specific effects.

Further research is necessary to determine the magnitude of the impact of ankle joint flexibility on swimming velocity and kick efficiency as well as the threshold level of PF angle upon which swimming performance does not further improve. Kinematics between swimming with normal and increased PF angles should be tested and compared particularly in swimmers with impaired ankle flexibility to observe the effects of increased PF angle on UUS performance.

Implications for practice

Since success in competitive swimming races is often determined by milliseconds, factors affecting swimming stroke efficiency must be identified and optimized to improve the athlete's performances even by marginal gains. As reduced ankle joint flexibility impairs UUS velocity, we recommend that particularly swimmers with low or average PF angles should consider implementing ankle joint flexibility exercises in their training regime to improve their UUS performance.

Data availability statement

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

Ethics statement

The studies involving human participants were reviewed and approved by the Ethics Committee of the Faculty of Humanities and Social Sciences of the Humboldt-Universität zu Berlin. The patients/participants provided their written informed consent to participate in this study.

Author contributions

JK conceived the study and collected the data, performed the analysis, and wrote the first version of the manuscript. JK and KL designed the study and discussed the results and contributed to the final version of the manuscript. KL supervised data collection and analysis and revised the manuscript. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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The characteristics of the breaststroke pullout in elite swimming

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Since the rule change permitting the inclusion of one dolphin kick during the underwater breaststroke pullout phase following a swim start or turn, there has been an emergence of several different pullout techniques adopted by elite swimmers. The aim of this study was to characterize the underwater breaststroke pullout technique trends and to assess the effectiveness of each technique as utilized by elite male and female swimmers. The sample included 60 swimmers ($n = 26$ male, $n = 34$ female) competing across the 50, 100, and 200 m long-course breaststroke final races from the World Championships 2015, 2017, 2019 and Olympic Games 2016. An above-water camera was used to identify and measure the different phases of the underwater pullout techniques, which was found to be a highly accurate methodological approach (ICC = 0.97). From the 150 trials analyzed, three different pullout techniques were identified: the Fly-Kick First technique, the Combined technique and the Pull-Down First technique. Although the most common underwater pullout technique utilized by elite competitive breaststroke swimmers was the Combined technique ($n = 71$), followed by the Fly-Kick First technique ($n = 65$) and the Pull-Down First technique ($n = 14$), it was observed that technical selection deviates according to gender. This indicates that male and female swimmers should not be coached adhering to the same technical model. This study found no significant difference in terms of performance outcome with respect to each of these techniques, indicating that technique selection should be guided by one's individual preference. It was concluded that the results of this study will serve as an up-to-date resource for coaches and swimmers working with elite breaststroke swimmers and as a useful insight to current underwater pullout trends.

KEYWORDS

start, turn, race-analysis, competition, fly-kick placement, underwater, breaststroke

Introduction

In competitive swimming, rules and regulations associated with performing starts and turns have evolved over the decades and are governed by Fédération Internationale de Natation (FINA). A significant amendment in 2005 to the breaststroke event, permitted the inclusion of one butterfly kick during the underwater breaststroke pullout following a start or turn. A pullout is defined as the period from toe immersion following the start, or toe-off at the turn wall, until the swimmer breaks the water surface to commence free breaststroke swimming. After subsequent modifications, the current FINA (2017) SW 7.1. ruling states that: "After the start and after each turn, the swimmer may take one arm stroke completely back to the legs during which the swimmer may be submerged. At any time prior to the first breaststroke kick after the start and after each turn a single butterfly kick is permitted." This latest iteration has resulted in various emerging techniques or movement pattern sequencing of the underwater breaststroke pullout phase, as swimmers aim to determine how best to utilize the butterfly kick (if at all). Considering the rules as prescribed by FINA, swimmers typically execute the underwater breaststroke pullout in the following manner: (1) passive glide with arms outstretched in a streamlined position overhead, (2) perform a pullout action of the arms so that they are extended at the sides of the trunk, (3) recovery of the arms and breaststroke kick toward breaking the surface, (4) that one butterfly kick takes place sometime before the breaststroke kick. It has been observed anecdotally that the placement of the butterfly kick relative to the pullout arm action varies across swimmers. It has been suggested that altering the placement of the kick may have consequences on the physiological demands of the underwater phase, the swimmers body alignment and consequently, resistive drag (McCabe et al., 2012). However, to date, no study within a competition setting has examined the technique trends displayed by elite swimmers or sought to assess the effectiveness of each technique throughout the underwater pullout following a breaststroke start or turn.

The underwater phase has been identified as the most important determinant of start and turn performance, as this is when the swimmer is traveling fastest through the water (Guimaraes and Hay, 1985; Seifert et al., 2007a; Connaboy et al., 2010; Tor et al., 2014a,b,c, 2015). Marinho et al. (2020) examined the underwater characteristics of the breaststroke pullout and reported that elite swimmers tend to spend longer (males 18.24%, females 16.85%), travel further (males 13.10%, females 11.94%), but are slower (males 4.43%, females, 4.03%) in the 200 m breaststroke underwater phases compared to the 100 m event. At the 2013 World Long Course Championships, Veiga and Roig (2016) reported that faster swimmers competing in the 100 m breaststroke, traveled with a faster underwater velocity (not further) compared to slower swimmers. More recently, Gonjo and Olstad (2021) reported that male elite swimmers displayed a faster mean glide velocity after both breaststroke starts and turns compared to sub-elite swimmers during a 100 m short-course time trial performance. On the basis that a faster underwater velocity is important in start and turn performance, researchers have recommended that coaches and swimmers should aim to optimize the underwater phase by executing a "good kinematical organization" and sequencing of the underwater breaststroke pullout movements in the most efficient way possible, i.e. by maximizing propulsion and minimizing resistive drag (Seifert et al., 2007b; Olstad et al., 2020; Sánchez et al., 2021).

The purpose of this study was to (1) ascertain the breaststroke pullout technique trends, as determined by the location of the fly-kick placement, across a range of international competitions, and (2) to assess the effectiveness of these pullout techniques as utilized by elite male and female swimmers across all competitive breaststroke events. It is hypothesized that a range of pullout techniques will be observed across swimmers and based on the findings of previous experimental studies (McCabe et al., 2012; Olstad et al., 2021; Seifert et al., 2021), there will be no significant difference in terms of performance across all breaststroke pullout techniques.

Materials and methods

Participants

Athletes competing in long-course breaststroke final races from World Championships 2015, 2017, 2019 and Olympics 2016 were included in the dataset. This resulted in a sample of 60 swimmers ($n = 26$ male, $n = 34$ female) across the 50 m (male = 26.79 ± 0.34 s, female = 30.25 ± 0.48 s), 100 m (male = 58.87 ± 0.69 s, female = 66.23 ± 0.90 s) and 200 m (male = 128.07 ± 1.00 s, female = 142.71 ± 1.43 s) breaststroke events. This totalled 150 race entries across the 50 m ($n = 22$ male, $n = 18$ female), 100 m ($n = 26$ male, $n = 28$ female) and 200 m ($n = 26$ male, $n = 30$ female) that were analyzed for this study. All the swimmers specialized in breaststroke, and were classified as elite based on the FINA points 'Level 1' qualifying standards (≥875 pts) set by Ruiz-Navarro et al. (2022).

Race analysis

Following ethical approval from Manchester Metropolitan University, British Swimming's bespoke race analysis system, "Nemo" (Sheffield Hallam University), was used for all competition analysis. The system comprised of a single side-on panning Panasonic HC 1500 camera (resolution: 1920x1080, sampling frequency: 50Hz, shutter speed: 1/125-1/180 s), mounted at the highest point possible within the respective venues, usually around the 25 m mark of a 50 m pool to record all swim races. This experimental set-up is typical within a high-performance race analysis competition setting, demonstrating the study's ecologically valid approach (Nicol et al., 2021). To assess the validity of technique identification using a single above-water camera at 25 m, one analyst performed a pilot study analyzing 45 breaststroke starts (independent trials with respect to the current study) comparing technique identification between underwater footage and the single above-water camera approach used in this study. Temporal data corresponding to the key movement positions were identified and recorded (Figure 1). These positions are based on the actions performed by the arms and legs independently during the underwater pullout phase whilst adhering to FINA's regulations. A high intraclass correlation (ICC) was reported (ICC = 0.97; $p < 0.05$), evidencing that this method has excellent agreement with respect to an underwater camera approach.

Similar to previous studies, start time was defined as the duration between the start signal to when the middle of the swimmer's head (goggle line) reached 15 m (Thompson et al., 2000; Cossor and Mason, 2001; Veiga et al., 2013; Tor et al., 2014a,b; Marinho et al., 2020). The start signal was identified as the first frame where the strobe light was visible and is the point at which the video is synchronized. Turn time was defined as the time from when the swimmer's hands touch the wall to the head reaching 15 m out from the wall. The rationale for this definition was to isolate the turn/underwater pullout performance and eliminate any possible influence of the swimmer's approach to the wall.

Determination of underwater breaststroke pullout techniques

To determine the temporal sequencing and the techniques associated with the breaststroke underwater pullout phase, each of the races were firstly visually inspected to identify key movement positions (Figure 1).

The identification of these key movement positions facilitated the classification of the following eight phases throughout the underwater pullout:

1) 1st glide (A.1)—from toe immersion (dive start) / toes having left the wall (turn exit) to first movement deviating from a streamline position (common instances of deviation: hand separation/start of dolphin kick preparation phase/first upper body movement).
2) Dolphin kick (L.1 to L.5).
3) Pull down (A.1 to A.3)—time between beginning of hand separation (breaking the streamline position) to the end of pull down—end of backward movement of hands finishing at the hips (or thighs).
4) 2nd glide (A.3)—time from end of pull down to the start of arm recovery—as the elbow starts flexing and the hands start forward movement.
5) Arm recovery (A.3 to A.4)—time between start of arm recovery to the instance when the arms are fully extended.
6) Leg recovery (L.6 to L.7)—time between first initiation of knee flexion, to position just prior to first backward movement of feet.
7) Propulsive kick (L.8 to L.9)—time between first backward movement of feet, to end of kick—as the feet come together ending inward lateral movement.
8) 3rd glide (A.5 and L.9)—time between feet coming together and first lateral movement of hands or as the head breaks water surface.

Once the phases were defined, the underwater pullout technique could be determined based on the temporal order in which the phases were executed. For example, Figure 2 presents a graphical representation of the interplay between the arm (A.1–A.5) and leg actions (L.1–L.9), connected by three defined glide phases through the duration of the pullout in breaststroke swimming. The sequenced movement pattern observed in Figure 2, will be from hereon referred to as the "Fly-Kick First" technique whereby the fly-kick is initiated and completed prior to the arm pull-down. A key feature of the Fly-Kick First technique is that there is a clear separation/takeover from one action to the next (arms and legs) throughout the underwater pullout.

Through observation of all 150 trials captured across the four competitions within this study, two further technical trends were identified and categorized, relative to the Fly-Kick First technique (Figure 3). The "Combined" technique is characterized by the initiation of the pullout prior to the completion of the fly-kick; consequently a degree of partial overlap between the arm and leg actions is observed. Finally, the "Pull-Down First" is distinguishable due to the arms fully pulling down to the sides of the trunk prior to the completion of the fly-kick. The Pull-Down First technique is unique in that it is the only movement pattern whereby the arms are initiated prior to any leg action.

In defining the three techniques across the participants in this study; a visual representation provided below highlights the primary temporal variation in arm and leg action sequencing during the pullout progression across all techniques. The below representations exclude all actions occurring after the arm action "A.2" (i.e. prior to the 2nd glide), in order to place a greater emphasis on the underwater temporal phase variation between the three techniques.

Statistical analysis

Following key underwater position identification (Figure 1), each swimmer was categorized into a 'technique' sub-group.

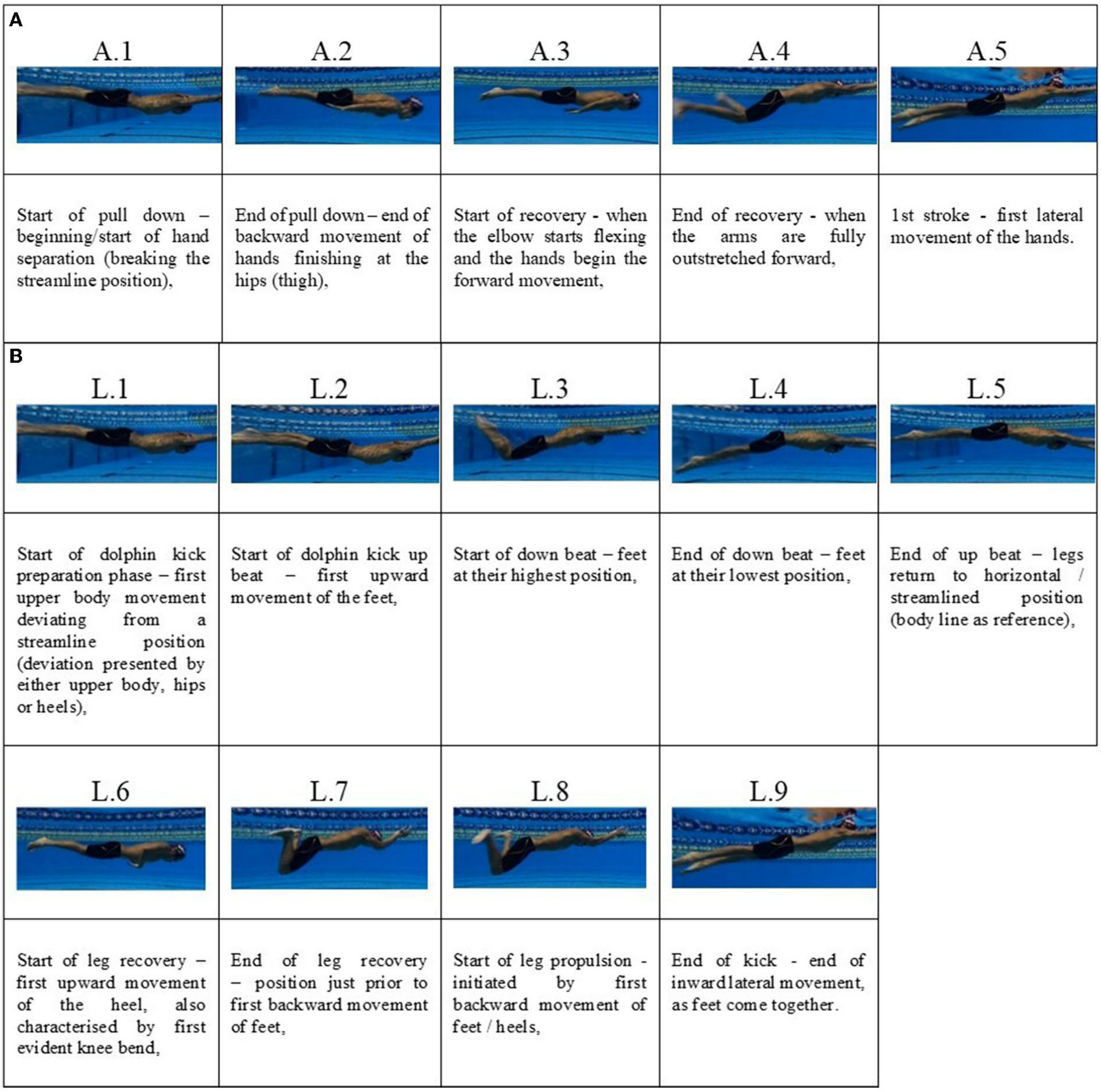

FIGURE 1
(A) Identification of key movement positions during the breaststroke underwater pullout phase with respect to the arm actions (A.1 to A.5) [A = arm]. **(B)** Identification of key movement positions during the breaststroke underwater pullout phase with respect to the leg actions (L.1 to L.9) [L = leg].

Descriptive statistics for each technique, such as time to complete the start and turn per racing event were reported across the combined sample and also separated with respect to gender. Homogeneity of variance was assessed using the Levene's test, before a one-way ANOVA was performed to determine any significant differences between pullout techniques. A Tukey *post-hoc* correction was used to assess the differences between underwater pullout techniques. The significance level across all statistical tests was set at $p < 0.05$. The eta square (η^2) was used to assess the magnitude of the effect size, with: (i) without effect if $0 < \eta^2 \leq 0.04$; (ii) minimum if $0.04 < \eta^2 \leq 0.25$; (iii) moderate if $0.25 < \eta^2 \leq 0.64$; and (iv) strong if $\eta^2 > 0.64$ (Ferguson, 2009). All statistical analysis was conducted using SPSS version 27.0 (Statistical Package for Social Sciences, IBM Corp. Armonk, NY, USA).

Results

A summary of the descriptive statistics calculated for each technique across all race distances is displayed within Table 1. It was found that the most common underwater pullout

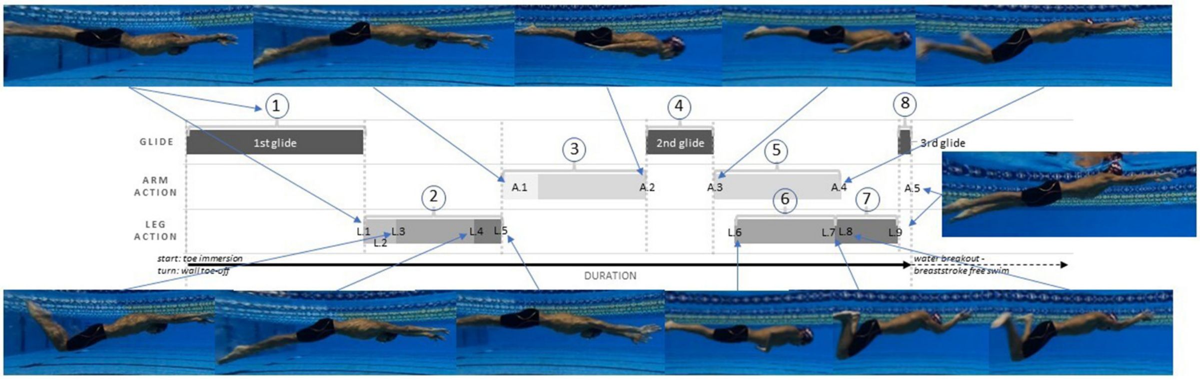

FIGURE 2
A phase duration sequence of the Fly-Kick First Technique. Refer to Figures 1A,B for number and letter annotation information.

technique utilized by elite competitive breaststroke swimmers following a start and turn was the Combined technique (total observations = 71), followed by the Fly-Kick First technique (total observations = 65) and the Pull-Down First technique (total observations = 14). There was no statistical difference found between techniques across the 50m (start: $p = 0.41$, $\eta^2 = 0.05$), 100m (start: $p = 0.06$, $\eta^2 = 0.11$; turn: $p = 0.43$, $\eta^2 = 0.30$) or 200m (start: $p = 0.62$, $\eta^2 = 0.02$; turn: $p = 0.74$, $\eta^2 = 0.01$) breaststroke race events.

Figure 4 illustrates the underwater breaststroke pullout technical trends by elite swimmers competing across major competitions 2015–2019. It is observed that the Fly-Kick First technique has increased in popularity over the years, whilst the Pull-Down First technique has progressively decreased in popularity. Throughout the data collection period, the Combined technique appeared to be the most favored underwater pullout technique until 2019, when the Fly-Kick First was observed to be executed most often during the World Championships.

Tables 2, 3 provide an overview of the start and turn performances for each of the underwater pullout techniques across the 50 m, 100 m, and 200 m breaststroke races events for male and female swimmers respectively. Figure 5 illustrates that male elite breaststroke swimmers tend to favor the Combined technique, followed by the Fly-Kick First technique across all race events. Alternatively, it was observed that elite female breaststroke swimmers tend to favor the Fly-Kick First closely followed by the Combined technique. Statistical analysis revealed there were no significant differences between techniques across the race distances for either male (Table 2) or female (Table 3) swimmers, with one exception. Within the 100 m female event, a significant difference ($p=0.05$) was found between techniques when turning. *Post hoc* results indicated a difference between the Combined technique and Pull-Down First technique ($p = 0.05$).

Observationally, it was noted that nine swimmers changed their underwater pullout technique during the 200 m race event, and three swimmers modified their pullout technique in the 100 m for the start vs. turn. The implications of this observation will be further explored within the discussion.

Discussion

The purpose of this study was to characterize the breaststroke underwater pullout technique trends utilized by elite swimmers within a competition setting across all race events and to assess the effectiveness of each. The context underpinning this study was to consider the inclusion of the fly-kick during the underwater pullout phase as a consequence of (FINA, 2017) SW 7.1 regulatory modification. A unique aspect of this current study was access to a large dataset of elite swimmers which was captured and analyzed using the same methodological approach across four international competitions, including World Championships and Olympic Games, ensuring the capability to provide a rigorous and broad characterization of the underwater breaststroke pullout techniques by elite male and female swimmers.

Using footage from key international competitions, three different pullout techniques were identified in this study: the Fly-Kick First technique (fly-kick is initiated and completed prior to pull-down), the Combined technique (pull-down is initiated before the fly-kick is complete, consequently an overlap of phases is observed) and the Pull-Down First technique (pull-down is completed prior to fly-kick). Therefore, our first hypothesis that a range of pullout techniques will be observed across swimmers was accepted. These three techniques differ slightly with respect to Seifert et al. (2021) who identified three coordination profiles, namely: "Continuity", "Glide" and "Superposition". They defined the Continuity profile as the

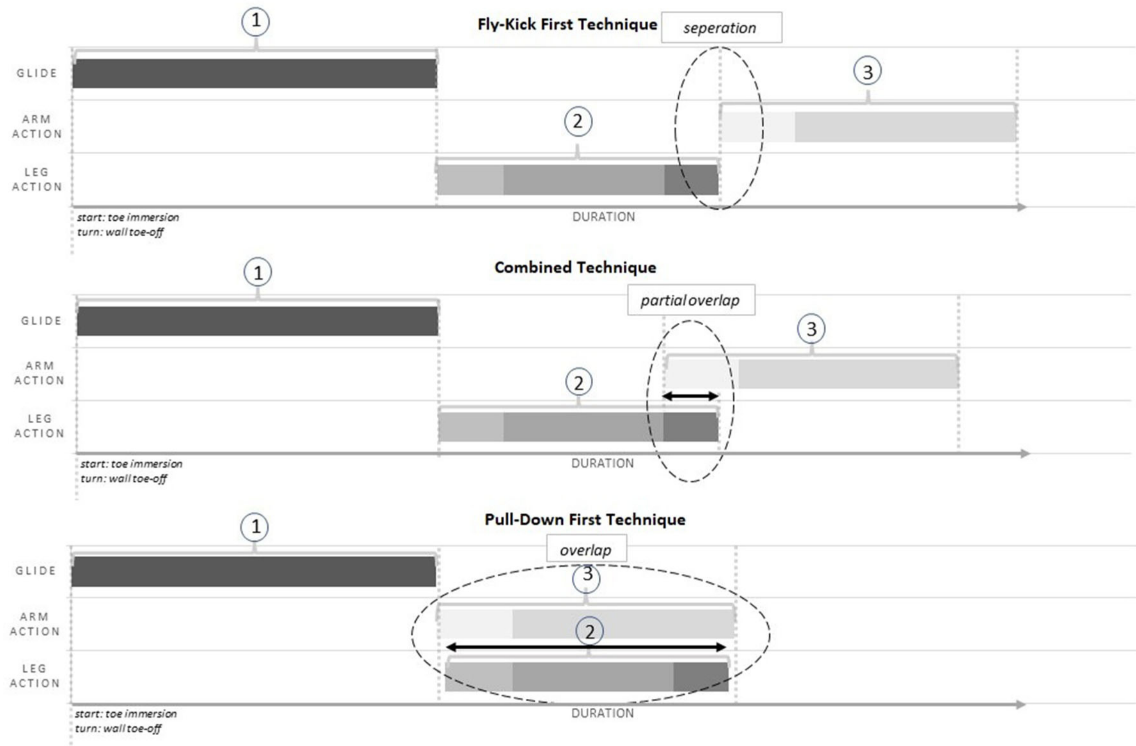

FIGURE 3
Breaststroke pullout phase profile variations; indicating the primary difference in arm and leg action sequence across the Fly-Kick First, the Combined and the Pull-Down First techniques. The numbers 1, 2, and 3 represent the first three phases of the pullout [1st Glide, Dolphin Kick, and Pull Down phase].

TABLE 1 Descriptive statistics for start and turn performances for each of the underwater pullout techniques across the 50, 100, and 200 m breaststroke race events.

Technique	Start 50 m (s)	Count	Start 100 m (s)	Turn 100 m (s)	Count	Start 200 m (s)	Turn 200 m (s)	Count
Fly-Kick First	6.80 ± 0.57	16	7.08 ± 0.68	9.45 ± 0.58	26	7.35 ± 0.70	29.24 ± 21.40	23
Combined	6.67 ± 0.59	20	6.84 ± 0.61	9.34 ± 0.62	22	7.19 ± 0.74	29.36 ± 2.08	29
Pull-Down First	7.11 ± 0.75	4	7.56 ± 0.57	9.68 ± 0.41	6	7.47 ± 0.76	30.18 ± 2.17	4
Avg.	6.77 ± 0.60		7.03 ± 0.67	9.43 ± 0.58		7.28 ± 0.71	29.37 ± 2.19	

This dataset includes all male and female performances combined.

synchronization of the arm pull-down beginning as the fly-kick ends, which is similar to the Fly-Kick First technique as described in the current study. The Glide profile was defined as the initiation of the arm pull-down following a glide phase post completion of the fly-kick. This coordination profile was incorporated within the Fly-Kick First technique in this study, perhaps as a result of no supporting underwater video footage and thus inability to identify a distinct glide portion following the fly-kick completion. The Combined technique and Seifert et al. (2021) Superposition profile are similar in that both identify an overlap of the arm pull-down and completion of the fly-kick. In addition, this study uniquely observed and identified the Pull-Down First technique which was not evident within the Seifert et al. (2021) study. The variation in underwater pullout technique identification between studies may be due to the data being captured in two different environments (research vs. competition setting). The research-based technique identification by Seifert et al. (2021) was conducted using underwater cameras which would have increased the visibility of key points compared to using an above-water camera in the current study. Undoubtedly, underwater footage is beneficial to accurately track key positions associated with the underwater breaststroke pullout. However, this study did report high validity (ICC = 0.97) in terms of

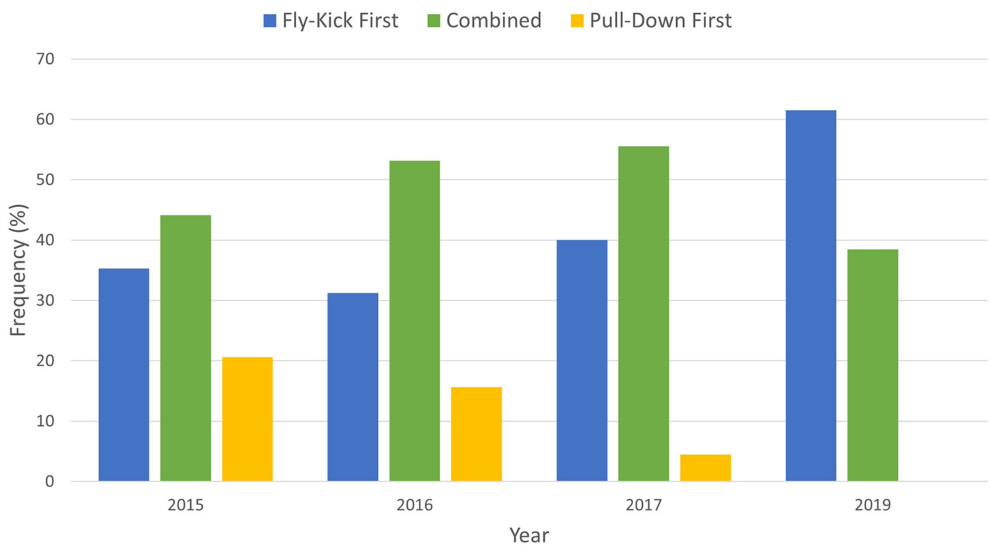

FIGURE 4
Underwater breaststroke pullout technique trends for elite swimmers during the period 2015–2019.

TABLE 2 Male start and turn performances for each of the underwater pullout techniques across the 50, 100, and 200 m breaststroke race events.

Technique	Male start 50 m (s)	Male start 100 m (s)	Male turn 100 m (s)	Male start 200 m (s)	Male turn 200 m (s)
Fly-Kick First	6.27 ± 0.16	6.36 ± 0.28	8.83 ± 0.13	6.48 ± 0.20	26.63 ± 10.61
Combined	6.26 ± 0.15	6.41 ± 0.19	8.92 ± 0.30	6.56 ± 0.20	27.67 ± 1.02
Pull-Down First	6.04	6.52	8.90	6.82 ± 0.14	28.36 ± 0.37
Avg.	6.19 ± 0.15	6.39 ± 0.23	8.88 ± 0.23	6.55 ± 0.21	27.40 ± 1.29
Significance (p)	0.38	0.75	0.72	0.11	0.09
Effect size (η^2)	0.10	0.03	0.03	0.18	0.19

the current methodological approach, thus providing confidence with respect to the dataset obtained. Moreover, it should be highlighted that international competitions restrict the placement of underwater cameras, meaning that above-water camera systems are typically utilized to perform competition race analysis. Therefore it is acknowledged that the method used to obtain data in this study allows direct comparison with the existing literature, whilst also providing an ecologically valid approach that is meaningful to swimmers and coaches in the context of trends and techniques used within a competition environment. Other considerations to explain the differences in technique identification between Seifert et al. (2021) and the current study may be due to the variation of swimmers sampled in terms of magnitude ($n = 14$ vs. $n = 60$) gender ($n = 14$ males vs. $n = 26$ males & $n = 34$ females) and performance level (64.42 ± 3.11 s for 100 m short course vs. males = 58.87 ± 0.69 s, females = 66.23 ± 0.90 s for 100 m long course). Indeed, Seifert et al. (2007b) and Veiga et al. (2014) both reported that the underwater swimming phases differed significantly with respect to expertise, with competitors tending to organize the underwater portion of the race according to the swimmer's skill level which may account for the differences between previous studies and the current one.

The results of this study show that across all race distances, the most common underwater pullout technique utilized by elite competitive breaststroke swimmers (male and female) following a start and turn was the Combined technique, followed by the Fly-Kick First technique and the Pull-Down First technique respectively. This differs from Seifert et al. (2021) who found that based on their population, the Continuity profile (the Fly-Kick First Technique) was more popular followed by the Superposition profile (the Combined Technique). As discussed previously, it is possible that skill level, gender and the length of the pool (short vs. long course), may all be contributing factors that influence the style of underwater technique utilized which requires further investigation. Another consideration is based on the observations in this study that the underwater pullout temporal movement sequences have evolved over the years (Figure 4). Although the Combined technique tended to be favored by swimmers across the period 2015–2017,

TABLE 3 Female start and turn performances for each of the underwater pullout techniques across the 50, 100, and 200 m breaststroke race events.

Technique	Female start 50 m (s)	Female start 100 m (s)	Female turn 100 m (s)	Female start 200 m (s)	Female turn 200 m (s)
Fly-Kick First	7.33 ± 0.14	7.61 ± 0.27	9.94 ± 0.18	7.82 ± 0.24	30.63 ± 1.33
Combined	7.43 ± 0.15	7.60 ± 0.18	10.08 ± 0.14	7.97 ± 0.16	31.44 ± 0.53
Pull-Down First	7.46 ± 0.30	7.77 ± 0.28	9.84 ± 0.17	8.12 ± 0.11	32.01 ± 0.72
Avg.	7.41 ± 0.20	7.63 ± 0.25	9.96 ± 0.18	7.90 ± 0.22	31.08 ± 10.10
Significance (p)	0.42	0.41	0.05*	0.06	0.07
Effect Size (η^2)	0.11	0.07	0.22	0.19	0.18

*Significant difference $p < 0.05$.

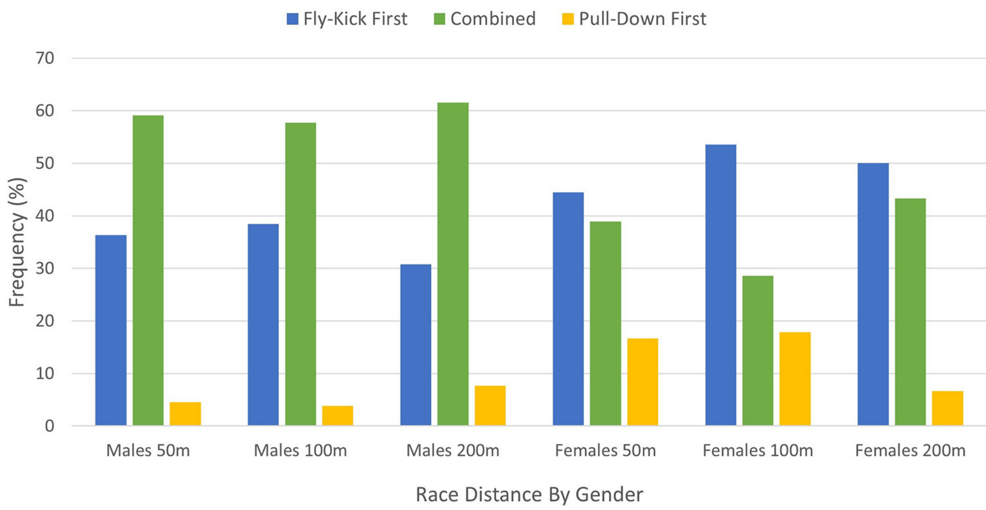

FIGURE 5
Underwater breaststroke pullout trends across all race distances for male and female elite swimmers.

this was superseded by the Fly-Kick First technique in 2019. Therefore, in agreement with Seifert et al. (2021), there are qualitative indications that the Fly-Kick First technique has become most popular in recent years. Continuous competition monitoring is required to confirm this observation; however, it is also possible that elite swimmers are still experimenting with the fly-kick placement to optimize their individual underwater performance.

Interestingly, when the dataset was filtered by gender, it was observed that male and female elite breaststroke swimmers tended to favor different techniques during the underwater pullout phase. Male swimmers were observed to utilize the Combined technique most often followed by the Fly-Kick First technique across all race distances, whereas female swimmers favored the Fly-Kick First technique followed by the Combined technique. It has previously been established that body morphology directly affects a swimmer's hydrodynamic resistance, with the majority of literature suggesting that males experience increased drag compared to females due to differences in body shape (Toussaint et al., 1988). Vilas-Boas et al. (2010) reported that during an underwater breaststroke sequence, females tended to experience lower drag values during the first gliding position (arms overhead in a streamlined position) compared to their male counterparts. In the second gliding position (arms extended by the swimmer's sides) males experienced lower drag values compared to females. The authors suggested that these differences in drag values were linked to differences in cross sectional area, body length and slenderness between the genders. It is therefore possible to extrapolate that the observed differences between genders in terms of favored underwater breaststroke pullout techniques in this study may be due to differences in anthropometry and morphology, thus the hydrodynamic resistance experienced. Although additional investigation is warranted to confirm such associations, a strong "take-home message" from this study is that coaches should not prescribe the same technique across genders.

Our second hypothesis is accepted as when swimmers were combined, this study did not find any significant difference in start or turn performance in relation to the technique used and effect sizes were reported as moderate-small. This is in agreement with McCabe et al. (2012), Seifert et al. (2021), and Olstad et al. (2021) and who all reported similar underwater performance outcomes could be achieved irrespective of the technique used and that the selected technique may be due to individual preference. When examining genders independently, this study found that female swimmers competing in the 100 m event, were 0.24 s or 2% faster using the Pull-Down First compared to the Combined technique. This is interesting in the context of the Pull-Down First technique popularity progressively declining over the years, suggesting that trends or techniques favored by elite swimmers may not always be the most effective techniques to adopt. It is concluded that based on the overall results of this research, no technique appears to be more effective than the other. Rather, the technical choice appears to be driven by individual preference, which may be influenced by anthropometric or morphology factors. If the swimmer can execute the chosen technique effectively, they should be competitive amongst their peers, but this may require experimentation within a training environment.

Another observation found from the qualitative pullout analysis showed that some elite swimmers altered their pullout technique between the start and the turn. There were nine swims in the 200 m races and three swims in the 100 m race where athletes changed their technique. Interestingly, Seifert et al. (2021) also observed that two swimmers changed the way they synchronized their fly-kick and arm pullout between the start and three turns. The statistical analysis conducted in this study was completed based on the technique that the swimmers utilized in the start. Hence, this was a limitation of the study and future studies of this nature should account for this change to reveal further trends amongst elite breaststrokers and perhaps explore why this may occur.

Considering the methodological limitations of this study, the results should be interpreted cautiously until future investigations confirm our technique observations *via* capturing underwater footage (either in a competition or experimental setting). Regardless, this is the first paper to qualitatively report the underwater breaststroke pullout technical trends across multiple competitions and thus provides a novel contribution to the research area and swimming community. Future studies should explore the underwater pullout trends further in terms of spatiotemporal characteristics and examine the potential discriminant factors associated with performing these different techniques. For example, it would be useful to quantify the break-out distances associated with each technique to assess if the time to 15 m was influenced by surface swimming, rather than the differing pull-out techniques. It is also recommended that the velocity profiles of each pullout technique be investigated. As the breaststroke pullout follows the dive and wall push-off phases within a race lap; the primary aim of the pullout should be to maintain the speed generated following these phases. This is achieved by reducing drag in optimizing body form and minimizing velocity degradation through beneficial use of leg and arm actions prior to the free-swimming phase. Velocity profiles could allow for a greater understanding of each of the techniques in relation to these instances and facilitate coaches to make more informed decisions on technique selection for optimizing start and turn performance.

Practical applications

The findings from this study will yield multiple practical implications for coaches and sport scientists. Given the significant contribution of the start and turn in breaststroke performance at the elite level, large importance should be placed on the pullout phase during training practices. This study demonstrates that technique selection is largely individual, but coaches should conduct appropriate biomechanical testing to ensure that the fastest technique is being used for each individual's start and turn performance. The technique used should also consider the physiological cost, as the selection of the Combined technique and Pull-Down First technique may influence the breakout distance (as reported by McCabe et al., 2012), which would have implications on the number of strokes to be taken during the free-swimming phase. Further research surrounding the breakout distances of each pullout technique will enhance the understanding of the underwater phase in breaststroke specific events.

Conclusion

This was the first study of its kind to provide an in-depth analysis focusing solely on the breaststroke pullout using a large cohort of elite swimmers during competition. This study identified three common breaststroke pullout techniques used by elite swimmers during multiple key international competitions. Based on qualitative observations, the most frequent pullout technique was the Combined technique, with indications this was changing toward a Fly-Kick First technique preference in recent years. Male and female swimmers appear to utilize different underwater pullout techniques; therefore, it is recommended they should not be coached adhering to the same technical model. Although there was no difference in performance across techniques, it is important that swimmers are proficient in their chosen technique. The results from this study will serve as a resource for coaches and swimmers working with breaststroke swimmers competing at the highest international level.

Data availability statement

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

Ethics statement

The studies involving human participants were reviewed and approved by Manchester Metropolitan University Ethics Committee. Written informed consent for participation was not required for this study in accordance with the national legislation and the institutional requirements.

Author contributions

CM and ET conceived and designed the study. EM performed all data analysis. RH produced the Figures. CM, ET, and EM carried out the drafting of the manuscript. All authors reviewed the manuscript and approved the submitted version.

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Conflict of interest

Author ET was employed by Forethought Pty Ltd.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Implications of the choice of distance-based measures in assessing and investigating tumble turn performance

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Although the tumble turn in swimming has been studied extensively, no consensus exists about which measure is best suited to capture its performance. The aim of this study was to better understand the implications of choosing a particular distance-based performance measure for assessing and investigating tumble turn performance in freestyle swimming. To this end, a large set of retrospective turn data consisting of 2,813 turns performed by 160 swimmers was analyzed statistically in three steps. First, a mixed-effects model was derived for the entire data set, which showed that both performance level and sex had clear effects on the distance-based performance measures and performance determining variables studied in the literature. Second, repeated measures correlations were calculated for the entire data set and four performance level- and sex-based subgroups to determine the level of association between the performance measures. This analysis revealed that the performance measures were strongly correlated ($r > 0.84$ and $p < 0.05$ for all possible pairs), largely independent of performance level and sex. This finding implies that the choice of performance measure is not very critical when one is interested solely in the overall performance. In the third and last step, mixed-effects models were derived for the performance measures of interest to establish the importance of different turn-related actions for each measure, again for both the entire data set and the four subgroups separately. The results of this analysis revealed that performance measures with short(er) distances are more sensitive to changes in the adaptation time and reflect the wall contact time better than performance measures with long(er) distances, which in contrast are more useful if the focus is on the approach speed prior to the turn. In this final analysis, various effects of performance level and sex were found on the technical execution of the tumble turn.

KEYWORDS

swimming, flip turn, performance measures, turning technique, sex, performance level

Introduction

Turning is an important component of competitive swimming, which determines a substantial portion of the overall swim performance. Research has shown that the accumulated duration of turns amounts to at least 19% of the total race time in long-course races and up to 44% in short-course races (Veiga et al., 2013; Morais et al., 2019a,b; Born et al., 2021). However, no consensus exists in the literature about the most suitable operational measure for capturing the time associated with performing the most common turn in swimming, the freestyle tumble turn.

In the literature, two types of definitions for turning performance are found: one based on the time that elapses between the submerging of the head at turn initiation and its resurfacing after the turn, thus covering a variable distance covered within this interval, and one based on the time that elapses between the head (or another body part) crossing predefined fixed distances toward and away from the wall. The limitation of the first definition is that a lower score on this performance measure (a shorter time) does not necessarily indicate a superior turn performance compared to a higher score (a longer time). This is due to the velocity profile of the swimmer after the push-off from the wall and the subsequent underwater phase. The velocity after the push-off from the wall is higher than the free-swimming speed and decreases over time due to drag until the speed is equal to the free-swimming speed, at which the swimmer ideally transfers to free swimming (Shimadzu et al., 2008). This moment can be postponed by extending the underwater phase [e.g., by making (more) undulatory kicks], however on the first, action-based definition, the performance score becomes lower (better) even if the swimmer resurfaces before the optimal point is reached. The sooner the swimmer resurfaces, the lower (better) the score on this performance measure will be. However, this lower score will typically not translate into a better overall swim performance.

Although the use of fixed distances overcomes this problem, there is quite some variation in the literature regarding the reference distances that are used to measure turning performance (Silveira et al., 2011). This variation exists because there are no distances that naturally limit the turn, except that, according to race regulations, the head must resurface before the 15-m mark after the turn for all swim strokes except the breaststroke. Obviously, the resulting variation in reference distances limits the comparison of results across studies. The performance measures that have been used in the literature are the 5 m round trip time (5mRTT), i.e., the time that elapses between the swimmer crossing the 5 m line away from the wall when approaching it (5 m-in) and crossing it again when moving out of the wall (5 m-out) (Blanksby et al., 1996, 1998; Cossor et al., 1999; Clothier, 2004; Mosavi et al., 2012; Pereira et al., 2015; Smithdorf, 2018; Nicol et al., 2019), the 2.5mRTT (Toshiaki et al., 2001), the 3mRTT (Puel et al., 2010a,b, 2012), the 7.5mRTT (Mason and Cossor, 2001; Tourny-Chollet et al., 2002; Shahbazi et al., 2007; Bahadoran et al., 2012; Veiga et al., 2013; Skyriene et al., 2017), the 5 m-in to 7.5 m-out time (Nicol et al., 2019), the 5 m-in to 10 m-out time (Webster et al., 2011; Nicol et al., 2019) and the 5 m-in to 15 m-out (McCabe et al., 2012; Suito et al., 2015; Morais et al., 2019a,b; Nicol et al., 2019; Marinho et al., 2020) time.

Based on empirical observations, Silveira concluded that the 5mRTT constitutes the best measure to describe turning performance in sub-elite swimmers because it included all turn-related actions and had the lowest percentage of free-swimming compared to other fixed-distance performance measures (Silveira et al., 2011). However, it remains unclear whether the turns of swimmers of different performance levels and/or sex, who might submerge or resurface earlier or later than 5 m from the wall, are also optimally reflected by the 5mRTT.

It is important to note in this context that the freestyle tumble turn is a highly complex skill, which involves many different actions that are performed sequentially in rapid succession. For instance, it takes about 1.1 s from turn initiation to the feet leaving the wall. Within this short time, the swimmer slows down, reverses position, and generates as much speed as possible in the opposite direction by applying a high push-off force to the wall. Immediately thereafter an underwater phase follows involving both passive gliding and active propulsion actions. Hence, in general, it is not realistic to assume that a performance measure that ignores speed and distance and is based on time alone can fully capture the freestyle tumble turn performance with all its performance determining factors.

Nonetheless, time-based performance measures can be used not only to assess the turn performance by itself but also to gain insight into the determinants of turn performance that might be improved through training. Based on previous analyses of the tumble turn, the technical variables that might be relevant in this regard include the approach speed toward the wall (Lyttle and Mason, 1997), the horizontal distance at which the turn is initiated (Blanksby et al., 1996; Lyttle and Mason, 1997), the adaptation time [from head submersion until the feet touching the wall (Lyttle and Mason, 1997; Maglischo, 2003)], the wall contact time (Blanksby et al., 2004; Pereira et al., 2006; Araujo et al., 2010), the push-off angle, the deepest point reached by the hips during underwater swimming (Lyttle et al., 1998), the horizontal distance from the wall at first downbeat (Lyttle et al., 2000), and the break-out distance (i.e., the horizontal distance from the wall at which the head breaks the water surface (Mason and Cossor, 2001).

To our knowledge, no other attempts besides Silveira (Silveira et al., 2011) have been made to examine the relative merits of the turning performance measures used in the literature, nor the information contained in them. The aim of the present study was to fill this lacuna by analyzing a large set of retrospective turn data that were collected from 160 elite and sub-elite swimmers of both sexes during regular training sessions. To this end, three statistical analyses were performed: (1) a foundational analysis to examine the impact of performance level and sex on the performance measures and performance determining variables that have been studied in the literature, (2) a coarse-grained analysis of the correlation strengths between the performance measures of interest, and (3) a fine-grained analysis of the degree to which the aforementioned technical variables account for the variation in each of the performance measures of interest. For all three analyses, we had specific expectations based on a combination of common sense and previous findings.

Considering the well-documented performance differences between male and female swimmers and between elite and sub-elite swimmers (Arellano et al., 1994; McCabe et al., 2012; Veiga and Roig, 2016; Morais et al., 2019b; Nicol et al., 2019; Marinho et al., 2020), we expected both performance level and sex to have a significant effect on the performance measures and performance determining variables of interest. We conducted this preliminary foundational analysis to determine how to treat the effects of performance level and sex in the subsequent statistical analyses (see section Materials and methods for details).

The coarse-grained analysis was motivated by the recognition that the information contained in the different performance measures is overlapping due to their overlapping fixed in and out distances. As a result, the performance measures will be correlated, which raises the question of how critical the choice of a particular performance measure is relative to other possible choices. After all, the higher the association between the performance measures, the less critical the choice of performance measure becomes. Based on logical grounds, we expected the association between measures to be high and largely independent of the performance level and sex of the participants. If so, this would render the choice of performance measure less critical from a statistical point of view.

The fine-grained analysis is based on the recognition that the tumble turn is a highly complex skill. As a result, the choice of a particular performance measure may reflect some turn-related actions more prominently and other turn-related actions less prominently, if at all. In other words, the information contained in a particular performance measure is likely to be a function of its definition. To select a suitable performance measure for answering a certain scientific or practical question, it is necessary to understand which information is contained in the set of (currently) available performance measures. This can be accomplished by deriving linear mixed-effects models to determine which specific turn-related actions account for (most of) the variance of each performance measure.

Based on logical grounds, we expected the technical variables associated with wall contact, notably the adaptation time and wall contact time, to account for more of the variance of the performance measures with a short(er) distance covered (that is, with fixed in and out distances close to the wall) than for performance measures with a long(er) distance covered (that is, with fixed in and out distances far from the wall). Conversely, we expected technical variables associated with the underwater phase, notably the push-off angle, the deepest point of the hip reached underwater and the break-out distance, to account for more of the variance of performance measures with a long(er) distance than performance measures with a short(er) distance covered.

Materials and methods

Participants

For this study, extensive retrospective freestyle turn data from 160 swimmers (85 male, 75 female) were analyzed. The participants, or their legal guardians in case they were 16 years of age or younger, signed an informed consent form stating that their turn data would be used anonymously for the purpose of scientific research. FINA points were determined to assess the performance level of the swimmers. To this end, the race times on any freestyle event (long course or short course) swum during the period from 2010 to 2021 in which the turn data were collected, were converted to FINA points based on the FINA point score of 2021 (FINA World Championships, 2022). The highest FINA point score of all these races was used to quantify the performance level of each swimmer. The 50 m long events were excluded from this procedure as they contain no turn.

The participants were categorized as either elite or sub-elite swimmers, depending on their FINA point score, which enabled making statistical comparisons based on performance level. Swimmers were considered elite swimmers if they had 860 FINA points or more. The 860 FINA points cut-off for elite swimmers was based on the average FINA point score corresponding to the FINA A qualification time for the freestyle events of the World Championships 2022 (Bouget, 2008).

Data acquisition

The tumble turn data for this study were derived from video footage recorded between 2010 and 2022 with a video system in the training pool of InnoSportLab de Tongelreep in Eindhoven. Before the measurements, a marker was placed on the swimmer's trochanter major to capture the position of the hip to derive the technical variables of interest (see below for further details).

The fixed video system in the training pool of De Tongelreep consists of four cameras (scA 1400-30gc, 50 Hz, Basler, Ahrensburg, Germany) that are embedded in the pool's lateral sidewall (at respectively, 2, 5, 10, and 15 m from the turn wall at a depth of 0.55 m below the water surface). The video data from the cameras were acquired using the software package Streampix 7 (Norpix, Montreal, Canada, 2016). The cameras were synchronized by means of an external trigger pulse generator (NI-DAQmx Pulse Generator). During the trials, the swimmers began swimming about 15 m from the wall (before the turn), sprinted toward the wall, turned and sprinted back until they were positioned well beyond the 15-m mark with their hip. All trials were recorded during regular training sessions and performed at maximal or race pace effort to mimic competitive races. Whether or not this was actually accomplished was not considered a major concern since having considerable variation in tumble turn performances is beneficial for the to-be-performed statistical analyses.

All video recordings were analyzed manually using a custom-made software package called Turnanalyzer (Escrito IT, Eindhoven, The Netherlands). The intrinsic parameters of the cameras were determined with the Camera Calibration Toolbox in Matlab (R Core Team, 2022) using image data of a checkerboard from various positions. The extrinsic calibration parameters were obtained by making use of control points at known positions in the pool. The intrinsic and extrinsic camera parameters were combined to reconstruct pixel data in the field of view of the cameras to 2D real-world coordinates on a sagittal plane positioned parallel to the sidewall at a distance of 3.6 m into the pool. The calibration error (root mean squared error) of the cameras was between 0.40 and 0.52 pixels for the cameras positioned at 2, 10, and 15 m, respectively, and 1.82 pixels for the camera positioned at 5 m, which was thus a factor less accurate than the other cameras. The technical variables were then manually extracted from the video and the resulting data were stored in a database.

Data preparation

All front crawl turn data of the included swimmers were extracted from the database and filtered for trials that contained all of the temporal performance measures depicted in Figure 1: from 5 m-in to 3 m-in to the wall (A), from 3 m-in to the wall until the moment the head is completely submerged before the turn (B), the time taken for the tumble turn and push-off [from head under the water surface until the feet losing contact with the wall (C)], the feet losing contact with the wall until hip at 5 m (D), from 5 m-out of the wall until 10 m-out of the wall (E) and 10 m-out of the wall to 15 m-out of the wall (F). The hip was used as the reference point for establishing the time at which the various spatial variables of interest were determined. In the protocol used in De Tongelreep for the measurement and analysis of swimming movements, the hip is routinely chosen for this purpose, because it is always in the field of view of the camera(s), regardless of the swimming stroke used (as opposed to the head, which is continuously visible in freestyle swimming, but not, for example, in the breaststroke and butterfly).

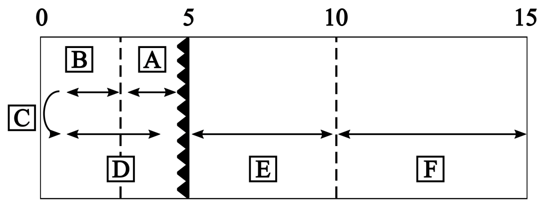

FIGURE 1
Graphical representation of the temporal variables and distances used for calculating the performance measures and the technical variables of interest. A: from 5 m-in until 3 m-in to the wall, B: from 3 m-in to the wall until head down before the turn, C: duration of the tumble turn and push-off (starting with the head underwater until the feet lose contact with the wall), D: the feet having lost contact with the wall until the hip crosses the 5 m mark, E: from 5 m-out of the wall until 10 m-out of the wall and F: 10 m-out of the wall until 15 m-out of the wall.

TABLE 1 Operational definition of the variables of interest.

Speed-in (m/s)	The average approach speed between the 5 and 3 m mark before the turn.
Initiation distance (m)	The horizontal distance of the hip to the wall at the moment the head of the swimmer submerges.
Adaptation time (s)	The time needed to bring the feet to the wall measured from the moment the head completely submerges until the first wall contact.
Wall contact time (WCT) (s)	The time between the first moment the feet are touching the wall until the last moment they are touching the wall.
Push-off angle (°)	The angle in the sagittal plane of the lane between a horizontal line and a line from the toes to fingertips at the moment of last wall contact. An angle of 0 degrees corresponds to a horizontal orientation of the body.
Deepest point (m)	The deepest point of the hips during the underwater swimming phase.
Distance of first kick (m)	The horizontal distance of the hip from the wall at the first downbeat.
Break-out distance (m)	The horizontal distance of the hip from the wall at the moment of resurfacing.

Based on the temporal variables used in the literature, the following temporal performance measures were determined for each turn: 5 m-in to 5 m-out, 3 m-in to 5 m-out, 3 m-in to 10 m-out, 5 m-in to 10 m-out, 3 m-in to 15 m-out and 5 m-in to 15 m-out.

Only swimmers with a minimum of five turns in the database were included in the statistical analyses to limit the impact of swimmers with only a small number of turns in the database satisfying the selection criteria. Furthermore, trials

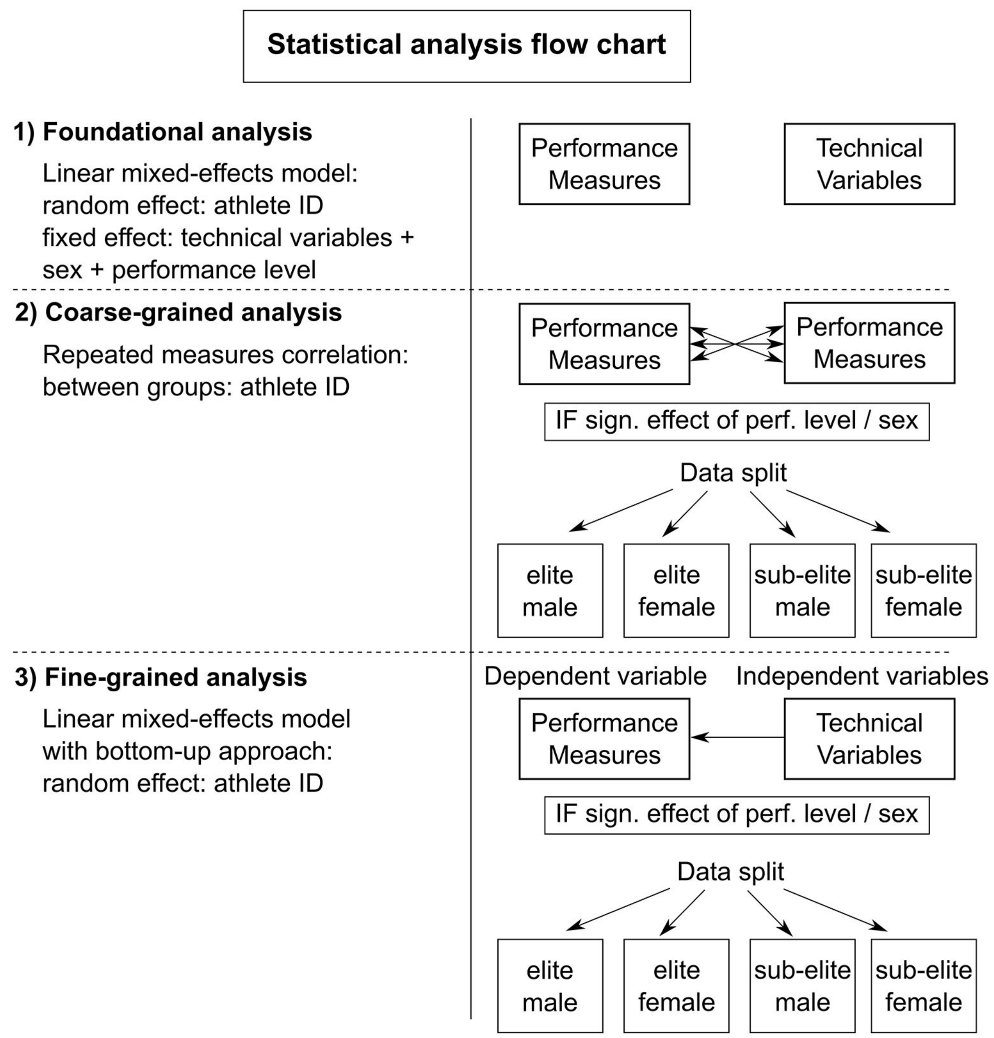

FIGURE 2
Flow chart of the performed statistical analysis. 1) Foundational analysis to investigate the effect of performance level and sex on the performance measures and technical variables. 2) Coarse-grained analysis to determine the level of association between the performance measures. 3) Fine-grained analysis to examine the relationship between each performance measure and the selected technical variables.

were excluded if they did not contain data on all of the eight technical variables of interest, as defined operationally in Table 1.

Statistical analysis

All statistical analyses were performed in R (Bates et al., 2014) using RStudio 4.2.0 (RStudio, Boston, Massachusetts, USA). In particular, the following modules were used: lme4 (Wickham et al., 2022), readxl (Barton, 2022), MuMIn (Long, 2022) and jtools (Bakdash and Marusich, 2022) and rmcorr (Bakdash and Marusich, 2017; Schweinberger, 2022). The statistical analysis of the data consisted of (1) a foundational analysis, followed by (2) a coarse-grained analysis, and (3) a fine-grained analysis (see Figure 2). For all statistical tests, an α-level of 0.05 was assumed.

Foundational analysis

First, the effects of performance level and sex on the performance measures and technical variables were assessed in a foundational analysis of the entire data set by deriving linear mixed-effect models for each of the six performance measures and the eight technical variables separately. In this analysis, the technical variables, performance level and sex were defined as fixed effects and athlete ID as a random effect (Figure 2).

As indicated, the main aim of this analysis was to determine how to treat the effects of performance level and sex in the subsequent statistical analyses. In particular, if a significant main effect of either performance level or sex would be found for (the majority of) the performance measures, the data set would be split into two subgroups (male and female, or elite and sub-elite, depending on the nature of the effect). Similarly, if main effects of both performance level and sex would be found for (the majority of) the performance measures, the data would be split into four subgroups (i.e., elite male, elite female, sub-elite male and sub-elite female, Figure 2). Splitting the data accordingly into subgroups may provide insight into possible group-specific differences in the performance measures and different turn strategies with regard to the technical, performance determining variables of interest. In this regard, the described statistical analysis was foundational for the subsequent coarse-grained and fine-grained analysis of the entire data set, and whether or not they would be complemented by group-specific analyses (Figure 2).

Coarse-grained analysis

To investigate the level of association between the different performance measures, repeated measures correlations were calculated for all possible pairs of performance measures, either for the complete data set alone or also for specific subgroups, depending on the results of the foundational analysis. This method is more suitable than Pearson's correlation analysis to deal with the repeated measures design of this data set and the unequal number of observations per individual. In particular, it is not biased by the mixing of intra- and inter-individual variance, where Pearson's correlation analysis would be (Schweinberger, 2022). The lower the repeated measures correlation coefficient, the more important the choice of one performance measure in favor of the other.

Fine-grained analysis

In the next, in-depth analysis, linear mixed-effect models with a bottom-up procedure (Lyttle et al., 1999) were constructed to determine the relationship between each performance measure and the eight derived technical variables as independent predictors (Figure 2). This was done to estimate the sensitivity of each performance measure with regard to the technical variables (Table 1) that were identified in previous research as potentially important determinants of turn performance (Blanksby et al., 1996, 2004; Lyttle and Mason, 1997; Welham and Thompson, 1997; Mason and Cossor, 2001; Maglischo, 2003; Pereira et al., 2006; Araujo et al., 2010). Again, this was either accomplished for the complete data set alone or also for (two or four) specific subgroups, depending on the result of the foundational analysis (Figure 2).

As a first pass on the data, boxplots and histograms were made and inspected for all independent variables to identify outliers amongst the independent predictors. Following this, collinearity was assessed by calculating the repeated measures correlation coefficients between all independent variables. In case there was a strong repeated measures correlation ($r > 0.7$) between two independent variables, the one with the highest absolute correlation coefficient with the performance measure was preserved as a predictor in the model while the other one was removed.

Finally, a bottom-up procedure (Lyttle et al., 1999) was used to determine which (combination of) independent variables provided the best fit for the model, starting with a model that only contained athlete ID as a random effect, due to the repeated measures design of the data. In each iteration round, a variable was added to the linear mixed-effects model and the new model was compared to the previous one using the likelihood ratio test (Nakagawa and Schielzeth, 2013). If the model was not significantly different from the previous one, the latest added variable was removed from the model. This procedure was continued until the model only contained variables that improved the model's fit. To be able to compare the contributions of the independent variables within and between the models, the same models were constructed with the standardized dependent and independent variables, thereby removing the effect of the scale at which they were measured. The following equation was used to standardize the variables:

$$z_i = \frac{x_i - \mu}{sd_X} \tag{1}$$

where z_i represents the standardized value, x_i represents the unstandardized value, μ represents the sample mean of the variable and *sd* is the sample standard deviation of the variable. Finally, the R^2 values of the linear mixed-effects models were determined using the method of Nakagawa and Schielzet (Lyttle et al., 1998).

Results

Foundational analysis

After application of the inclusion criterion to all turns available in the database, a total of 2,813 turns from 160 individual swimmers remained, out of which 1,154 turns were performed by 38 elite male and female swimmers combined (Table 2). The means and standard deviations of the performance measures and technical variables for both performance level and sex are displayed in Table 2. As expected, there was a significant main effect for both performance level and sex for all performance measures, in the absence of a significant sex by performance level interaction. The male swimmers were significantly faster than the female swimmers on all performance measures in both the elite and sub-elite subgroups. Furthermore, elite swimmers were significantly faster than the sub-elite swimmers on all performance measures in both the male and female subgroups. The results for the technical variables of interest are presented in Table 2. Since

TABLE 2 Descriptive statistics and means and standard deviations of performance measures and technical variables for the elite male and female and sub-elite male and female subgroups separately.

Descriptive statistics	Sex	Elite	Sub-elite
Number of swimmers	Male	23	62
	Female	15	60
Number of trials	Male	600	670
	Female	554	989
Age (years)	Male	21.5 ± 3.2	18.9 ± 3.6
	Female	23.7 ± 5.4	19.5 ± 4.3
FINA points	Male	899 ± 22	684 ± 131
	Female	935 ± 53	750 ± 87

Performance measures	Sex	Elite	Sub-elite	*F*-statistic (sex)	*F*-statistic (performance level)
3 m in–5 m out	Male	3.54 ± 0.30	4.00 ± 0.47	$F_{(1,151.1)} = 43.39$	$F_{(1,151.1)} = 37.43$
	Female	3.88 ± 0.25	4.36 ± 0.42	$P < 0.001$, $\eta_p^2 = 0.22$	$P < 0.001$, $\eta_p^2 = 0.19$
5 m in–5 m out	Male	4.62 ± 0.40	5.14 ± 0.57	$F_{(1,155.47)} = 46.01$	$F_{(1,155.47)} = 35.03$
	Female	5.02 ± 0.30	5.60 ± 0.52	$P < 0.001$, $\eta_p^2 = 0.23$	$P < 0.001$, $\eta_p^2 = 0.18$
3 m in–10 m out	Male	6.37 ± 0.49	7.11 ± 0.80	$F_{(1,155.35)} = 37.66$	$F_{(1,155.35)} = 33.65$
	Female	6.91 ± 0.38	7.71 ± 0.72	$P < 0.001$, $\eta_p^2 = 0.20$	$P < 0.001$, $\eta_p^2 = 0.18$
5 m in–10 m out	Male	7.45 ± 0.58	8.25 ± 0.90	$F_{(1,155.55)} = 39.91$	$F_{(1,155.55)} = 32.74$
	Female	8.05 ± 0.44	8.96 ± 0.82	$P < 0.001$, $\eta_p^2 = 0.20$	$P < 0.001$, $\eta_p^2 = 0.17$
3 m in–15 m out	Male	9.20 ± 0.71	10.18 ± 1.11	$F_{(1,155,75)} = 38.19$	$F_{(1,155.75)} = 31.47$
	Female	9.95 ± 0.54	11.04 ± 1.01	$P < 0.001$, $\eta_p^2 = 0.20$	$P < 0.001$, $\eta_p^2 = 0.17$
5 m in–15 m out	Male	10.28 ± 0.80	11.33 ± 1.21	$F_{(1,155.88)} = 39.72$	$F_{(1,155.88)} = 30.91$
	Female	11.10 ± 0.60	12.28 ± 1.11	$P < 0.001$, $\eta_p^2 = 0.20$	$P < 0.001$, $\eta_p^2 = 0.17$

Technical variables	Sex	Elite	Sub-elite	*F*-statistic (sex)	*F*-statistic (performance level)
Speed-in (m/s)	Male	1.88 ± 0.18	1.77 ± 0.17	$F_{(1,153.99)} = 52.25$	$F_{(1,153.99)} = 21.21$
	Female	1.75 ± 0.12	1.62 ± 0.15	$P < 0.001$, $\eta_p^2 = 0.25$	$P < 0.001$, $\eta_p^2 = 0.12$
Initiation dist. (m)	Male	1.98 ± 0.24	1.82 ± 0.18	$F_{(1,152.26)} = 45.81$	$F_{(1,152.26)} = 11.2$
	Female	1.76 ± 0.14	1.71 ± 0.17	$P < 0.001$, $\eta_p^2 = 0.27$	$P = 0.001$, $\eta_p^2 = 0.08$
Adaptation time (s)	Male	0.85 ± 0.13	0.87 ± 0.12	$F_{(1,143.88)} = 0.02$	$F_{(1,143.88)} = 5.33$
	Female	0.83 ± 0.08	0.89 ± 0.12	$P = 0.88$, $\eta_p^2 < 0.01$	$P = 0.02$, $\eta_p^2 = 0.04$
WCT (s)	Male	0.25 ± 0.07	0.30 ± 0.10	$F_{(1,137.89)} = 0.22$	$F_{(1,137.89)} = 8.97$
	Female	0.26 ± 0.06	0.30 ± 0.11	$P = 0.64$, $\eta_p^2 < 0.01$	$P = 0.003$, $\eta_p^2 = 0.06$
Push-off angle (°)	Male	7.59 ± 3.42	7.73 ± 3.88	$F_{(1,144.86)} = 4.41$	$F_{(1,144.86)} = 0.68$
	Female	8.19 ± 3.65	8.36 ± 3.73	$P = 0.04$, $\eta_p^2 = 0.03$	$P = 0.41$, $\eta_p^2 < 0.01$
dist. First kick (m)	Male	2.72 ± 0.53	1.82 ± 0.40	$F_{(1,141.78)} = 17.82$	$F_{(1,147.78)} = 0.03$
	Female	2.57 ± 0.44	2.55 ± 0.44	$P < 0.001$, $\eta_p^2 = 0.11$	$P = 0.87$, $\eta_p^2 < 0.01$
Deepest point (m)	Male	0.76 ± 0.15	0.70 ± 0.16	$F_{(1,142.2)} = 3.07$	$F_{(1,142.2)} = 5.45$
	Female	0.73 ± 0.15	0.69 ± 0.15	$P = 0.08$, $\eta_p^2 = 0.02$	$P = 0.02$, $\eta_p^2 = 0.04$
Break-out dist. (m)	Male	7.97 ± 1.90	7.24 ± 1.60	$F_{(1,150.14)} = 7.18$	$F_{(1,150.14)} = 7.68$
	Female	7.92 ± 1.63	6.74 ± 1.37	$P < 0.001$, $\eta_p^2 = 0.05$	$P < 0.001$, $\eta_p^2 = 0.05$

Furthermore, the main and interaction effects of the foundational analysis.

both performance level and sex had a significant main effect on all performance measures, both the course-grained and fine-grained analyses were performed on the entire data set and the elite male, elite female, sub-elite male and sub-elite female subgroups separately.

Coarse-grained analysis

As can be appreciated from the repeated measures correlation matrices presented in Table 3, all performance measures were strongly ($r > 0.8$) and significantly ($p < 0.001$) correlated. For the sake of clarity, the repeated measures correlations were presented for the entire data set only, since the results for the four subgroups, which are presented in Table 3, only showed marginal differences. The highest correlation of 0.99 was between the 3 m-in−15 m-out and 5 m-in−15 m-out and the lowest correlation of 0.84 was between the 3 m-in−5 m-out and 5 m-in−15 m-out. As expected, the greater the overlap in distance between the performance measures, the higher the degree of association.

Fine-grained analysis

The boxplots and histograms of the technical variables revealed no outliers. According to the procedure described in the Materials and methods section, the horizontal initiation distance was excluded from the model because it was highly correlated with the adaptation time ($r = 0.73$), indicating collinearity between these variables. Additionally, the absolute repeated measures correlation coefficient with the performance measures was lower (e.g., $r = 0.20$ initiation distance and the 5 m-in−5 m-out time compared to $r = 0.29$ between adaptation time and 5 m-in−5 m-out time). For all six performance measures, a prediction model was derived with athlete ID as a random effect and the seven remaining technical variables as independent predictors.

All the models showed a high R^2 value ranging from 70 to 91% explained variance (see Appendix A). The prediction models of the performance measures that started 5 m before the wall had a higher R^2 than those starting 3 m before the wall. The bottom-up procedure resulted in the intercepts, estimates, and standardized estimates of the independent variables that are collated in Appendix A. All models for the different performance measures across all four subgroups included the speed-in, adaptation time, WCT and break-out distance. Although the break-out distance improved the models' fit significantly, the overall contribution to all models turned out minimal. The estimates of adaptation time and WCT had a positive sign in the model, indicating that an increase in these independent variables was associated with an increased turning time. The opposite was true for the estimates of speed-in and break-out distance, which had a negative sign, indicating that an increase was associated with a faster turn. The distance of the first kick, push-off angle and deepest point in the underwater trajectory were included only in some models. If included, the push-off angle and deepest point had a positive sign, implying slower turn times with greater values.

The estimates of the distance of the first kick had a negative sign for the sub-elite male swimmers, but a positive sign for the elite male and female swimmers and the sub-elite female swimmers. Compared across the different models, the contribution of the speed-in increased with the distance toward the wall covered in the performance measure (Figure 3, Appendix A). In contrast, the contribution of the adaptation time increased mainly for performance measures with an increased distance out-off the wall but decreased when the distance to the wall became longer.

The overall contribution of the WCT seemed higher for the elite swimmers than the sub-elite swimmers, for whom the speed-in was the predictor with the highest contribution to performance, especially for performance measures with long(er) distances. The adaptation time was a stronger performance predictor in the female swimmers than the male swimmers (Figure 3, Appendix A).

In the sub-elite female swimmers, all three main predictors (speed-in, adaptation time, and wall contact time) contributed to a similar degree, unlike the other three subgroups in which one main predictor clearly contributed more than the other two (notably WCT in the elite male and female swimmers and speed-in in the sub-elite male swimmers) (Figure 3, Appendix A).

Discussion

The present study examined the implications of selecting a particular distance-based performance measure for the tumble turn with regard to the overall turn performance and the underlying performance determining variables. To this end, three statistical analyses were performed: (1) a foundational analysis to examine the impact of performance level and sex on the selected performance measures and the performance determining variables, (2) a coarse-grained analysis of the correlation strengths between the performance measures of interest, and (3) a fine-grained analysis of the technical variables that account for the variation in each of those performance measures.

Foundational analysis

As expected, the foundational analysis revealed significant main effects of both performance level and sex on the performance measures and technical variables of interest. Based on these results the data set was divided into four subgroups:

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TABLE 3 The repeated measures correlation coefficient matrix between all possible combinations of performance measures for the entire data set and the elite male and female, and sub-elite male and female swimmers separately.

Repeated measures correlation

3 m in–5 m out	0.92	0.85	0.96	0.90	0.84
0.92	3 m in–10 m out	0.94	0.91	0.98	0.94
0.85	0.94	3 m in–15 m out	0.85	0.93	0.99
0.96	0.91	0.85	5 m in–5 m out	0.94	0.88
0.90	0.98	0.93	0.94	5 m in–10 m out	0.95
0.84	0.94	0.99	0.88	0.95	5 m in–15 m out

Repeated measures correlation elite male

3 m in–5 m out	0.92	0.85	0.92	0.89	0.84
0.92	3 m in–10 m out	0.93	0.88	0.97	0.92
0.85	0.93	3 m in–15 m out	0.82	0.90	0.98
0.92	0.88	0.82	5 m in–5 m out	0.95	0.88
0.89	0.97	0.90	0.95	5 m in–10 m out	0.95
0.84	0.92	0.98	0.88	0.95	5 m in–15 m out

Repeated measures correlation elite female

3 m in–5 m out	0.95	0.85	0.97	0.94	0.86
0.95	3 m in–10 m out	0.91	0.94	0.99	0.92
0.85	0.91	3 m in–15 m out	0.85	0.91	0.99
0.97	0.94	0.85	5 m in–5 m out	0.97	0.89
0.94	0.99	0.91	0.97	5 m in–10 m out	0.93
0.86	0.92	0.99	0.89	0.93	5 m in–15m out

Repeated measures correlation sub-elite male

3 m in–5 m out	0.85	0.79	0.97	0.84	0.79
0.85	3 m in–10 m out	0.95	0.85	0.99	0.94
0.79	0.95	3 m in–15 m out	0.81	0.95	0.99
0.97	0.85	0.81	5 m in–5 m out	0.88	0.84
0.84	0.99	0.95	0.88	5 m in–10 m out	0.96
0.79	0.94	0.99	0.84	0.96	5 m in–15 m out
0.79	0.95	3 m in–15 m out	0.81	0.95	0.99
0.97	0.85	0.81	5 m in–5 m out	0.88	0.84
0.84	0.99	0.95	0.88	5 m in–10 m out	0.96
0.79	0.94	0.99	0.84	0.96	5 m in–15 m out

Repeated measures correlation sub-elite female

3 m in–5 m out	0.94	0.87	0.96	0.91	0.86
0.94	3 m in–10 m out	0.95	0.93	0.98	0.95
0.87	0.95	3 m in–15 m out	0.88	0.94	0.99
0.96	0.93	0.88	5 m in–5 m out	0.95	0.90
0.91	0.98	0.94	0.95	5 m in–10 m out	0.96
0.86	0.95	0.99	0.90	0.96	5 m in–15 m out
0.87	0.95	3 m in–15 m out	0.88	0.94	0.99
0.96	0.93	0.88	5 m in–5 m out	0.95	0.90
0.91	0.98	0.94	0.95	5 m in–10 m out	0.96
0.86	0.95	0.99	0.90	0.96	5 m in–15 m out

All correlation coefficients were significant ($P < 0.001$).

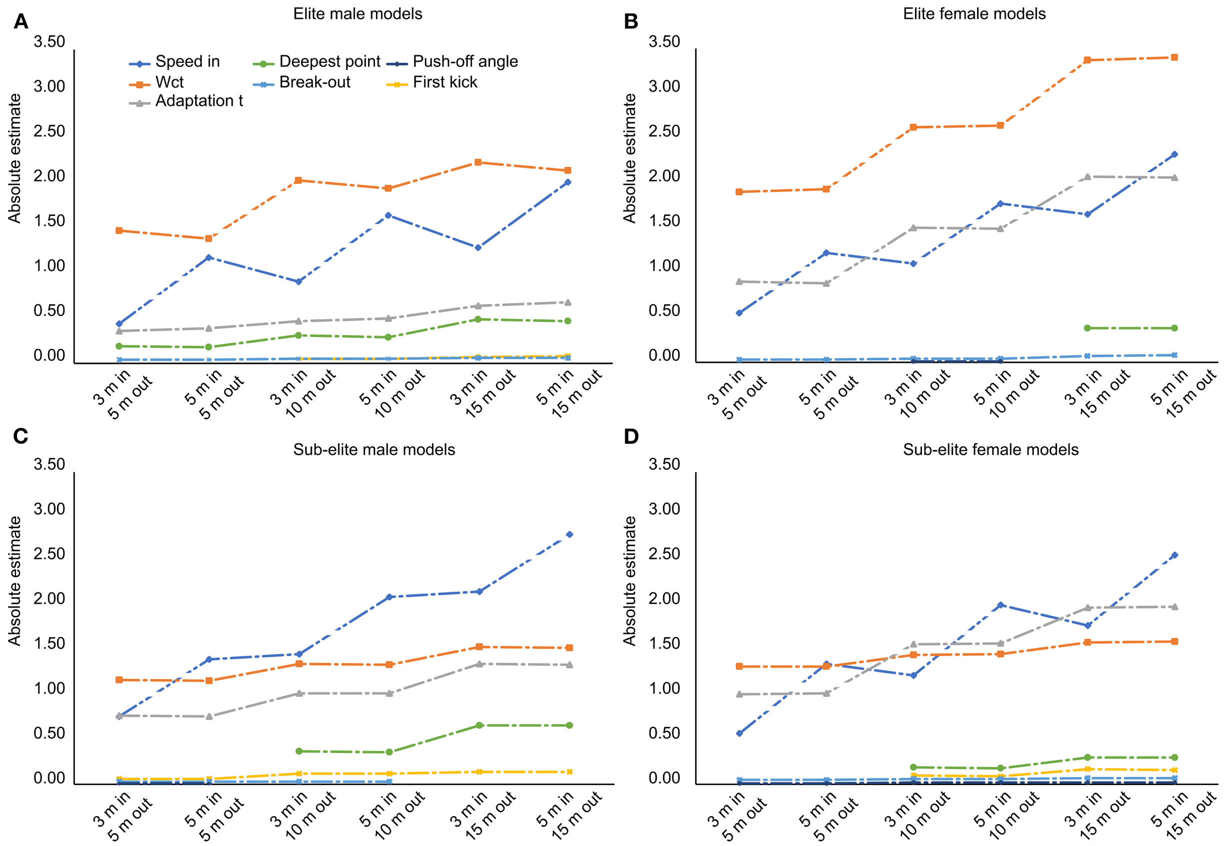

FIGURE 3
(A–D) The absolute estimates of the seven contributors (speed-in, adaptation time, wall contact time (WCT), break-out distance, deepest point in the underwater phase, distance at first kick and push-off angle) to the elite male and female and sub-elite male and female models are presented graphically. The different models are presented on the *x*-axis.

elite male, elite female, sub-elite male and sub-elite female. All subsequent analyses were done on the entire data set and on the four subgroups separately to gain insight into any subgroup-specific differences in performance and the adopted turn technique.

Coarse-grained analysis

The level of association between the fixed-distance performance measures of interest was assessed by calculating repeated measures correlation coefficients for all possible pairs of performance measures, both for the entire set of turn data and the four subgroups. This analysis revealed a high overall level of association with correlation coefficients ranging from 0.84 to 0.99. Although this result was expected on logical grounds since the performance measures covering longer distances overlap with the performance measures covering smaller distances (e.g., 5 m-in—5 m-out is part of the 5 m-in—10 m-out and 5 m-in—15 m-out), it has, to our knowledge, not been established or highlighted before in the literature. The strong correlation between the various performance measures implies that if one is interested solely in assessing the overall turn performance, the choice of performance measures is less critical. This finding was exacerbated by the marginal unsystematic differences in the results obtained between the four subgroups, which showed similar correlation patterns independent of performance level and sex. The small differences in the level of association between the various performance measures may have been due to differences in the turn-related actions and amount of free-swimming covered by the different performance measures (e.g., the moment of head resurfacing and stroke resumption occurring somewhere between 5 and 15 m).

However, even though all correlation coefficients were higher than 0.8, it appeared that the included distance after the turn had a stronger effect than the distance before the turn since the correlation coefficient decreased pair-wise with different out-off-the-wall distances, but not with different to-the-wall distances (see Table 3). This finding can be interpreted by realizing that the speed after the turn is largely determined by an effective push-off, an appropriate time spent on the wall and a properly streamlined position (Welham and Thompson, 1997; Lyttle et al., 1998; Mason and Cossor,

2001) and that some of these variables may be affected by the characteristics of the approach toward the wall. The longer the distance covered, the more variability may be generated by the interaction of all performance determining factors. This might explain why the level of association diminishes faster when correlating performance measures with different out-of-the-wall distances compared to different into-the-wall distances. Therefore, performance measures with longer out-of-the-wall distances seem more informative about the efficiency of turning actions and the transfer to swimming than performance measures with shorter out-of-the-wall distances.

Fine-grained analysis

The fine-grained sensitivity analysis revealed which turn-related actions are reflected predominantly in the performance measures of interest. This was achieved by finding the best fitting linear mixed-effects model for each performance measure using seven (eight minus one) technical variables as independent predictors and athlete ID as a random effect.

All the models showed a high R^2 value ranging from 70 to 91% explained variance. This is in contrast to the findings of Nicol et al., who did not find any of the technical variables to be a significant predictor of the overall turn time (Nicol et al., 2019). This discrepancy might be explained by the size of the included data set and the variability that was introduced in the present study by including swimmers of different performance levels. Interestingly, all models starting 5 m from the wall showed a higher R^2 than models starting 3 m before the wall. Speed-in, adaptation time, WCT, and break-out distance were significant predictors in all models. Of these four variables, speed-in was the only variable whose contribution differed between the 3 m-in and 5 m-in models. However, this is not surprising because the speed-in was measured between the 5 m and 3 m mark before the wall. The difference in contribution, therefore, seems to account for the higher explained variance of the 5 m-in models.

The estimates of speed-in had a negative sign, indicating that a higher swim speed toward the wall was associated with a better turn performance, as has been found in previous studies (Takahashi et al., 1982; Blanksby et al., 1996; Lyttle and Mason, 1997). The amount of variance explained by speed-in increased with increasing the distance covered by the performance measure. Taking an example from the elite male model (see Appendix A), an increase of speed-in of about 1 m/s would be associated with a turn time reduction of 0.44 s in the 3 m-in−5 m-out measure, while the same change would be associated with a turn time reduction of 2.32 s in the 5 m in−15 m out measure. This can be understood from the fact that the longer performance distances included more free-swimming; a higher swimming speed was, therefore, reflected more in the performance measures with longer distances. This could also explain why the contribution of the speed-in increased more strongly with distance in the sub-elite swimmers, who on average traveled a shorter distance underwater than the elite swimmers.

As expected, adaptation time and WCT turned out to be strong positive contributors to the overall turn performance. This finding is in agreement with the results of Blanksby and Puel (Blanksby et al., 1996; Puel et al., 2012), who also found that a reduction of the adaptation time and WCT resulted in faster turns. The adaptation time and WCT were reflected more strongly in the performance measures with shorter distances as indicated by their higher contribution to these models, which was expected as well. The model outcomes further revealed that the overall contribution of the WCT was higher for the elite compared to the sub-elite swimmers (Figure 3), which suggests that focusing the training on the optimization of WCT might have a beneficial effect on turn performance. However, as the WCT is very short (∼0.3 s), easier improvements might be accomplished by shortening the adaptation time (∼0.9 s). Another interesting finding of the fine-grained analysis was that the adaptation time is a stronger predictor in female compared to male swimmers, whereas the adaptation time itself was not significantly different between sexes. This suggests that a different turning technique was employed by male and female swimmers.

The contribution of the adaptation time and WCT decreased compared to the speed-in as the distance covered by the performance measures increased for all subgroups, except for the elite female swimmers. This decrease could be expected since these variables play a role early in the turn; therefore, even if their impact on turn time is large, it will be diluted by the impact of the actions later in the turn. This effect will be especially strong for the adaptation time. Also, the ratio of the WCT and the turn time decreases the longer the distance covered, which automatically reduces the impact. This result confirms our expectation that if the WCT is the focus of interest, a performance measure with short(er) distances should be chosen. The contradictory finding for the elite female swimmers could be explained by looking further into the characteristics of this subgroup, which contained a relatively small number of swimmers (N =15). This could have resulted in an overall higher variability of the included variables and an underestimation of their contribution.

The negative coefficient for the break-out distance is in line with the results of Mason et al., who concluded that a longer underwater phase is beneficial for the speed after the turn, resulting in a better turn performance (Mason and Cossor, 2001). The increase in the contribution of the break-out distance is also in line with our expectations because this variable plays out relatively late in the turn and thus was expected to contribute to the performance measures with longer distances. However, the contribution to the performance measures was generally much smaller than those of the speed-in and the WCT and also the relative impact declined with increasing distance when compared to the speed-in, which can be appreciated from the standardized estimates (see Appendix A).

By comparing the three main contributors (speed-in, adaptation time and WCT) between the subgroups, not one predictor appeared more dominant than the other two predictors in the sub-elite female swimmers. In contrast, WCT stood out as the main contributor in the elite male and female swimmers, while speed-in was the main contributor in the sub-elite male swimmers. This might suggest that the variation of turn strategies was markedly higher in the sub-elite female swimmers than in the other subgroups.

The remaining three technical variables, the push-off angle, the distance of the first kick and the deepest point in the underwater trajectory, were only minor contributors to some of the models. From the literature, a negative estimate was expected for the distance of the first kick (Lyttle et al., 2000). Surprisingly, this was only the case for the sub-elite male swimmers; in contrast, positive estimates of the distance of the first kick were found for the sub-elite male and female swimmers, while it did not even appear as a significant contributor in the elite female swimmers. Besides only playing a minor role to predict turn performance, the negative estimates of the distance of the first kick resulted from the relatively short distance to the wall of the sub-elite male swimmer (∼1.82 m), while the elite male (∼2.72 m) and sub-elite female swimmers (∼2.55 m) might already had reached the optimal distance where a further increase would no longer be beneficial.

The deepest point in the underwater trajectory contributed to all elite male models, but only to the 10 m-out and longer sub-elite male models. Whereas the elite male swimmers reached a significantly greater depth during the underwater phase, their push-off angle was similar to that of their sub-elite counterparts. This suggests that the elite male swimmers held their downward line longer after push-off than the sub-elite male swimmers, which could also explain the later break-out distance. This is in line with the findings of Mason et al., who showed that swimmers with a longer underwater phase after the turn could benefit more than other swimmers from making quicker turns (Puel et al., 2010a).

Interestingly, the underwater phase seemed less important in the elite female swimmers, because none of the variables related to underwater swimming contributed to many of the derived models. This may be the case because the elite female swimmers within the data set adopted a wide variety of turn strategies, which could have obscured finding clear statistical relationships.

When comparing the subgroups with each other it became clear that there are some indications of different turning strategies between the subgroups. Furthermore, depending on the subgroup one is interested in, not all performance measures reflected the turn-related technical variables to the same degree. Therefore, it is important to choose a performance measure that reflects the variable of interest for the specific subgroup or question of interest. More research is needed to clarify these differences and their origins.

Although the standardized estimates enabled comparison, they should be interpreted with caution when comparing them between models. If the standard deviations between models are different, this could jeopardize drawing a valid conclusion based on their relative contributions. One example is the increase of standardized estimates for speed-in for the models for performance measures including a 3 m distance to the wall, while the standardized estimates decreased for models on the 5 m-in distances in elite swimmers. Using the non-standardized estimates showed that the effect of the speed-in variable increased with increasing distance from the wall, which is consistent with the idea that swimmers with a higher performance level have a higher speed-in and also will be faster after the turn.

One of the limitations of the present study is that the data set used contained no information about the underwater swimming ability of the swimmer, apart from the distance at which the head resurfaced after the turn. Although it was found in previous studies that underwater actions are important predictors of turn performance, this was not reflected in the present results (Clothier, 2004; Connaboy et al., 2016). It could be that the selected technical variables did not optimally reflect the underwater actions. The second limitation is that the data set only contained variables that were extractable from video footage. Adding biomechanical variables like the push-off force to the models would have rendered the analysis more comprehensive and should ideally be done in future research. However, most swimming facilities do not have the advanced measurement infrastructure required for this purpose, which precludes them from including other biomechanical variables besides kinematic variables.

The data set used in this study is unique as it contained over 2,800 turns from a broad variety of competitive swimmers, ranging from international Olympic finalists to regional swimmers. A sample size of this magnitude is unique in turn-related swimming research and allowed gaining a better understanding of the implications of choosing particular performance measures for both scientific and practical purposes. In particular, the present results clearly indicate that the various performance measures used in the literature are strongly correlated, they reflect different technical, performance determining variables, that play out differently in a subgroup-specific manner, depending on both performance level and sex. This implies that the choice for a particular performance measure has to be based on how well it is suited to answer the research or practical question of interest, and to which technical variables are reflected in the selected measure. The present results provide a wealth of information in this regard, which allows both researchers and coaches to make better-informed choices on which performance measures to use for their research or training purposes, and hopefully also inspires them to explore new leads in research and training.

Conclusion

The present results suggest that if one is interested solely in the overall turn performance, the choice of performance measure is less critical and can be adapted in accordance with the available facilities or personal preferences of the coach or researcher. Even though all correlation coefficients were higher than 0.8, it has to be taken into account that the included distance after the turn was a stronger contributor than the distance before the turn. When the aim is to identify performance determining variables that could be improved through training, the choice of performance measure matters. The present results showed that choosing a fixed-distance performance measure with short distances reflects the WCT better while performance measures with long distances are beneficial if the focus is on the approach speed prior to the turn. Also, performance measures with short distances before the turn are more sensitive to changes in the adaptation time.

Data availability statement

The data set presented in this article are not readily available because the data set contains elite athletes that can be identified from the data. Requests to access the data set should be directed to p.koster@fieldlabswimming.com.

Ethics statement

The studies involving human participants were reviewed and approved by the Scientific and Ethical Review Board (VCWE) of the Faculty of Behavioural and Movement Sciences of the Vrije Universiteit Amststerdam. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

Author contributions

PK, WA, SS, and PB conceptualized and designed the study. PK, WA, and SD performed the literature search and data processing. SS, PK, and WA were involved in data collection. PK, SD, SS, and PB drafted the current manuscript. All authors contributed substantially to the interpretation of the data, revised it critically and approved the final version of the manuscript before submission.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fspor.2022.958548/full#supplementary-material

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Modeling the expenditure and reconstitution of distance above critical speed during two swimming interval training sessions

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In swimming, the speed-time relationship provides the critical speed (CS) and the maximum distance that can be performed above CS (D′). During intermittent severe intensity exercise, a complete D′ depletion coincides with task failure, while a sub-CS intensity is required for D′ reconstitution. Therefore, determining the balance D′ remaining at any time during intermittent exercise (D'_{BAL}) could improve training prescription. This study aimed to 1) test the D'_{BAL} model for swimming; 2) determine an equation to estimate the time constant of the reconstitution of D′ ($\tau D'$); and 3) verify if $\tau D'$ is constant during two interval training sessions with the same work intensity and duration and recovery intensity, but different recovery duration. Thirteen swimmers determined CS and D′ and performed two high-intensity interval sessions at a constant speed, with repetitions fixed at 50 m. The duration of passive recovery was based on the work/relief ratio of 2:1 (T2:1) and 4:1 (T4:1). There was a high variability between sessions for $\tau D'$ (coefficient of variation of 306%). When $\tau D'$ determined for T2:1 was applied in T4:1 and vice versa, the D'_{BAL} model was inconsistent to predict the time to exhaustion (coefficient of variation of 29 and 28%). No linear or nonlinear relationships were found between $\tau D'$ and CS, possibly due to the high within-subject variability of $\tau D'$. These findings suggest that $\tau D'$ is not constant during two high-intensity interval sessions with the same recovery intensity. Therefore, the current D'_{BAL} model was inconsistent to track D′ responses for swimming sessions tested herein.

KEYWORDS

athletes, performance, critical velocity, critical power, severe domain, aerobic capacity

Introduction

Swimming is widely recognized as a popular sport and it has been part of the Olympic program since the first modern Olympic Games in 1896. Most of the swimming events at the Olympic program are performed between 50 and 200 m (or about 21–150 s), demanding a high rate of ATP resynthesis by aerobic and anaerobic energy systems (Capelli et al., 1998; Pyne and Sharp, 2014). During swimming training, sets of interval exercises at low and high intensities are interspersed with relief periods lasting generally less than 60 s (Nugent et al., 2017). However, the relief time is prescribed by coaches with scarce scientific support. Given environmental and technological constraints in swimming, feasible technologies of training prescription and assessment are helpful to athletes, coaches, and sports scientists.

At the beginning of the last century, Hill (1925) observed a hyperbolic relationship between work rate or speed and performance time. This power/speed-time relationship is characterized by two parameters: critical power (CP) or critical speed (CS) demarcating the boundary between heavy and severe exercise domains, and the maximum amount of work/distance that can be performed above CP/CS represented by the mathematical expression W′ or D′, respectively (Poole et al., 2016). Both CP and CS as well as W′ and D′ are analogous but expressed in different units of measurement. Although the precise mechanisms of W'/D′ have remained elusive (Broxterman et al., 2016; Hureau et al., 2016; Poole et al., 2016), the exercise tolerance provides similar amounts of work/distance performed above CP/CS and similar attainment of a critical level of intramuscular phosphocreatine, inorganic phosphate and/or pH (Fukuba et al., 2003; Vanhatalo et al., 2010; Jones and Vanhatalo, 2017). Therefore, to any severe intensity exercise the task failure coincides with the complete depletion of W'/D′ during constant and intermittent exercises, while the replenishing of W'/D′ necessitates a sub-CP/CS intensity (Coats et al., 2003; Chidnok et al., 2012).

Skiba et al. (2012) proposed a mathematical model to determine the balance of W′ remaining at any given time during an intermittent exercise session (W'_{BAL}) where some amount of W′ is expended and reconstituted during periods performed above and below CP, respectively. This mathematical model was initially developed for cycling exercise and provides a novel approach for coaches to determine the optimal training intervals and intensity (Skiba et al., 2014a) or for athletes to perform the best pace during a competitive race (Patton et al., 2013). Such a model assumes a linear expenditure and a curvilinear reconstitution of W′ comprising two equations: Eq. 1 determines W'_{BAL} considering the work intensity and duration, the relief intensity and duration, and the time constant of the exponential reconstitution of the W' (τW′), whereas Eq. 2 estimates τW′ to be inserted into Eq. 1. In the second equation, the difference between power output at recovery and CP (D_{CP}) is fitted to each relief interval and participant, while the mathematical constants are arbitrary parameters from cycling exercise determined by plotting D_{CP} with actual τW' (found by an iterative process until modeled W'_{BAL} equaled zero at the time to exhaustion) (Skiba et al., 2012). Therefore, in theory, whether CP is unchanged and relief intensity is the same for different interval training sessions, the τW′ should be the same for these exercise sessions regardless of work interval intensity and duration as well as relief interval duration. However, it is unclear whether τW′ remains constant during different interval training sessions with the same work interval intensity and duration as well as relief intensity but different relief interval durations.

$$W'bal = W' - \int_0^t \left(W' exp\right)\left(e^{-(t-u)/\tau W'}\right) \tag{1}$$

$$\tau W' = 546e^{\left(-0.01Dcp\right)} + 316 \tag{2}$$

where the W'_{BAL} at any point during a training session or race is the difference between the known W′ and the total W′ expended, W′ equals the subject's known W′ as calculated from CP model, W'exp is equal to the expended W′, (t - u) is equal to the time in seconds between segments of the exercise session that resulted in a depletion of W′, τW′ is the time constant of the reconstitution of the W′, and D_{CP} is the difference between the recovery power output and the CP.

Although the W'_{BAL} model has been proposed to characterize the expenditure and reconstitution of W′ during intermittent cycling exercises, there are few studies investigating this model for other exercise modalities (Galbraith et al., 2015; Broxterman et al., 2016). Galbraith et al. (2015) applied the W'_{BAL} model during intermittent running (i.e. D'_{BAL}) and showed a D'_{BAL} negative on average (−21.2 m) at interval training session termination. The authors also reported a time constant of the exponential reconstitution of the D' (τD′), determined interactively until modeled D'_{BAL} equaled zero at the time to exhaustion. Apparently the τD′ was lower compared with the previously reported τW′ in intermittent cycling (~376 vs. 578 s) (Skiba et al., 2012). During severe intensity handgrip exercises, τW′ was affected by different contraction–relaxation cycles, ranging between 580 and 2,450 s (Broxterman et al., 2016). In addition, the authors reported an exponential decay relationship between τW′ and CP (Broxterman et al., 2016). Taken together, these data indicated that τW'/τD′ could be modality-specific and should be directly determined.

Based on the aforementioned statements, the application of the D'_{BAL} model for swimming exercise would be useful as a feasible training prescription tool not requiring any sophisticated apparatus. Therefore, the purposes of this investigation were to 1) test the applicability of the D'_{BAL} model for swimming; 2) determine an equation to estimate τD′ for swimming; and 3) verify if τD′ is constant during two swimming interval training sessions with the same work interval intensity and duration as well as recovery intensity but with different recovery interval

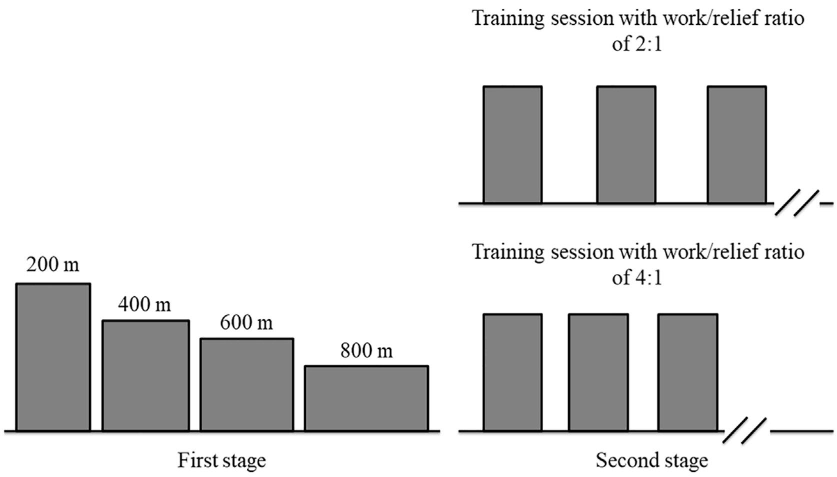

FIGURE 1
Schematic illustration of experimental design.

durations. We hypothesized that 1) D'_{BAL} could be suitable for swimming exercises; 2) $\tau D'$ would be related to CS; and 3) $\tau D'$ would be similar between different interval trainings sessions. The implications of confirming these hypotheses for coaches and sports scientists would be a cost-free practical tool to consistently determine optimal intervals and intensities for swimming improving exercise prescription and experimental designs.

Materials and methods

Participants

Thirteen male trained swimmers (body mass: 71.8 ± 10 kg, height: 177 ± 7.6 cm, age: 21.3 ± 10 years, arm span: 187.3 ± 10 cm) volunteered for this study. Swimmers took part in regional ($n = 4$) and national ($n = 9$) competitions, had 10.8 ± 5.3 years of experience as competitive swimmers and trained 8.9 ± 2.8 times a week (of which 3.1 ± 1.6 were dry-land exercises) with 23.9 ± 5.4 km of volume per week. Swimmers were specialized in freestyle ($n = 7$), breaststroke ($n = 4$), backstroke ($n = 1$), and butterfly ($n = 1$) at 50–200 m ($n = 10$) and 400–1,500 m ($n = 3$) distance events and completed their best swimming performance last year achieving 510 ± 105 FINA points with classification performance ranked at level 4 (Ruiz-Navarro et al., 2022). Swimmers were free from physical limitations, health problems, or musculoskeletal injuries that could affect the tests, as well as reported not using drugs, medication, or dietary supplements that could have any influence on physical performance. Swimmers or their guardians were informed of the benefits and risks of the investigation prior to signing an informed consent. The study was conducted according to the Declaration of Helsinki and was approved by the Institutional Review Board.

Study design

Swimmers visited the swimming pool ten times separated by at least 24 h for 3 weeks. All trials were conducted individually in a 25 m indoor pool (28–30°C). Experimental tests were carried out in two stages. The first stage consisted of four randomly performances for CS and D' determination. The second stage included two high-intensity interval training sessions, in a random order, at a constant speed predicted to lead to exhaustion in 3 minutes during continuous exercise. Between the first and the second stages, the swimmers performed four or five trials to familiarize with this constant speed (Figure 1). All tests were performed in front crawl stroke with a push start and, the swimmers were verbally encouraged to perform the best performance possible (first stage) or continue for as long as possible (second stage). All tests were preceded by a standardized pool warm-up completed in the following order: 300 m freestyle (easy swim); 2 × 100 m freestyle (second faster, higher distance per stroke); 2 × 50 m (25 m kick/25 m easy); 2 × 50 m (25 m drill/25 m easy); 4 × 50 m (25 m at race pace/25 m easy); and 100 m easy swim (Neiva et al., 2014). During the first stage, the race pace warm-up was performed at a speed that swimmers self-selected according to *a priori* expectations about their performances. In the second stage, the race pace warm-up was performed at a constant speed determined for the two interval training sessions. The constant speed was controlled by a pacing device (see below for further details). The warm-up protocol was followed by 10 min of passive rest. All tests started at the same time of day (±1 h) to minimize any effects of diurnal variation (Lisboa et al., 2021). During the study, swimmers were asked to arrive at the swimming pool in a rested and fully hydrated state, abstain from alcohol and strenuous exercise 24 h before testing, and avoid ergogenic aid to enhance performance.

Critical speed and constant swimming speed

Swimmers were instructed to swim distances of 200, 400, 600, and 800 m as quickly as possible and each performance was recorded at the nearest 0.01 s by a manual stopwatch (Raimundo et al., 2020). These performances were used to calculate the CS (slope) and the D' (*y*-intercept) by applying the distance-time linear regression model (Dekerle et al., 2002). The constant swimming speed that would be predicted to lead to exhaustion in 180 s during continuous exercise was calculated according to Eq. 3:

$$Speed = CS + \left(D'/t\right) \tag{3}$$

where Speed is the target swimming speed, CS is the critical speed, D' is the distance coursed above CS from distance-time linear regression model, and *t* is the time to exhaustion (set at 180 s in this case).

High-intensity interval training sessions

Swimmers performed two high-intensity interval training sessions. At each interval training session, the repetitions were fixed at 50 m and were conducted at constant swimming speed. The swimming speed was controlled by matching auditory signals from an electronic speaker (Beat Training & Test, Cefise, Nova Odessa, Brazil) along with nine markers in contrasting colors placed every 2.5 m at the bottom and sides of the 25 m pool. In addition, two investigators walked along the side of the pool at pre-defined pace providing visual feedback when needed. Swimmers were asked to keep their head at the level of the markers for each auditory signal and the test continued until the swimmer's hand was unable to reach the marker despite strong verbal and visual encouragement (Bentley et al., 2005; Libicz et al., 2005). The exercise repetitions were interspersed by a passive rest with duration based on the work/relief ratio. Thus, the training session was performed with a work/relief ratio of 2:1 (training 2:1; T2:1) or 4:1 (training 4:1; T4:1). For example, a swimmer with a constant swimming speed of 1.44 m s^{-1} completed each repetition in approximately 35 s during both training sessions. Therefore, each relief interval lasted approximately 18 and 9 s in T2:1 and T4:1, respectively. The high-intensity interval training sessions were conducted on different days, performed to exhaustion, and continuously recorded using a camera (Sony DCR-SR68, Tokyo, Japan; 30 Hz) to determine the swimming speed and work and relief intervals durations. This camera was positioned near the edge of the swimming pool perpendicular to the lane. Data from recordings were extracted by a software (Kinovea, v. 0.9.5, MA, United States) and used in all subsequent analyses (i.e. time to perform 50 m and recovery time between repetitions).

Data analysis

The D' depletion for each 50 m course and D' reconstitution during relief intervals were computed to calculate the time course of D' for the entire interval training session. Data files were analyzed using the continuous equation previously reported by Skiba et al. (2012):

$$D'bal = D' - \int_0^t \left(D' exp\right)\left(e^{-(t-u)/\tau D'}\right) \tag{4}$$

where D' equals the subject's known D' as calculated from distance-time linear model, D'exp is equal to the expended D', (*t* - *u*) is equal to the time in seconds between segments of the exercise session that resulted in a depletion of D', and $\tau D'$ is the time constant of the reconstitution of the D'. Thus, D'_{BAL} at any point during an interval training session or race is the difference between the starting D' from distance-time linear regression model and the total D' expended, which is being recharged exponentially when speed falls below CS (Ferguson et al., 2010; Skiba et al., 2012). The $\tau D'$ for each participant and interval training session was calculated by an iterative process until modeled D'_{BAL} equaled zero at exhaustion. Actual $\tau D'$ found by iterative process from T2:1 and T4:1 were plotted against the CS to determine the better equation to estimate $\tau D'$. In the present study, as the work intervals were interspersed with passive recovery periods, CS and difference between recovery speed and CS (D_{CS}) were equal.

The $\tau D'$ determined for each participant in each interval training session was applied for the other training session (i.e. the individual $\tau D'$ determined from T2:1 was applied in T4:1 and vice versa) to predict the time to exhaustion (TTE) and the D'_{BAL} value at the point of interval session termination (D'_{END}). As previously noted by Shearman et al. (2016), the D'_{BAL} values can be lower than the D'_{BAL} value at the point of task failure. Therefore, the lowest D'_{BAL} value attained (D'_{LOW}) in each training was also determined.

Statistical analysis

The data are shown as mean ± standard deviation (SD) or 95% confidence interval (CI). Paired *t*-tests assessed possible differences in $\tau D'$, D'_{END}, D'_{LOW}, total D' expended and reconstituted between training sessions, as well as actual and

TABLE 1 The mean and individual values of actual time constant of the reconstitution of the D′ found by an iterative process from T2:1 and T4:1.

Subject	T2:1 (s)	T4:1 (s)	Difference (s)
1	86	86	0
2	75,5	205	129.5
3	73.5	58	15.5
4	81	49.5	31.5
5	68.4	45	23.4
6	70	100	30
7	46	24.5	21.5
8	71.5	51	20.5
9	65	250	185
10	169	500	331
11	78.5	4,000	3,921.5
12	77.7	57	20.7
13	69.5	36.5	33
Mean	79.4	420.2	366.4
SD	28.6	1,083.7	1,072.3

T2:1: Training session with work/relief ratio of 2:1; T4:1: Training session with work/relief ratio of 4:1; SD: standard deviation.

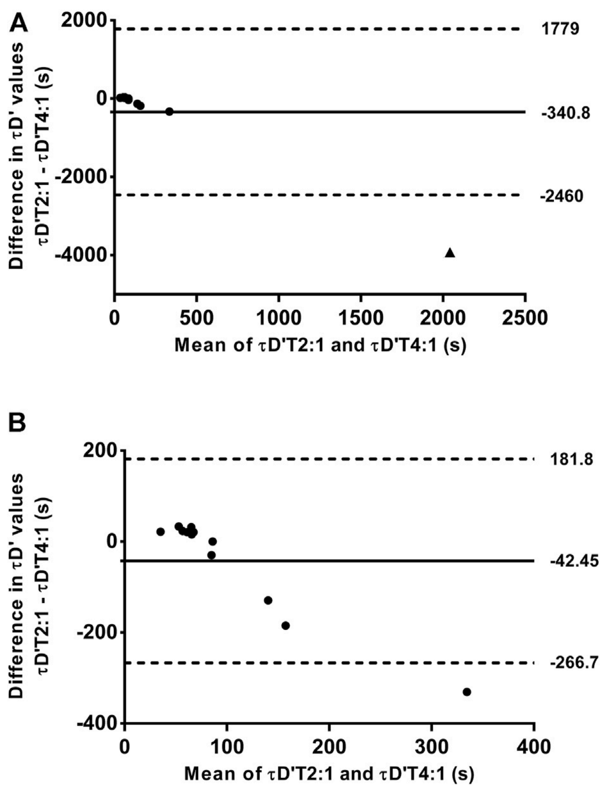

FIGURE 2
Bland—Altman plots between the time constant of the reconstitution of D′ (τD′) found by iterative process from training sessions with work/relief ratio of 2:1 (T2:1) and 4:1 (T4:1). The **(A)** included all swimmers while the **(B)** shows the data analyzed excluding the swimmer 11 (see results session for further details). Horizontal solid line represents the mean difference between τD′ found by iterative process from training sessions with work/relief ratio of 2:1 and 4:1, while horizontal dashed lines represent the 95% limit of agreement. ▲ represents the swimmer 11.

predicted values. Bland and Altman plots (Bland and Altman, 1986) and coefficient of variation (Hopkins, 2000) examined the consistency of τD′ between training sessions and the predictive ability of the D'_{BAL} model. The within-subject coefficient of variation was calculated by dividing the SD of the differences by the square root of two and dividing the result by the grand mean (τD′) or mean of real value (TTE), and expressed as a percentage (Hopkins, 2000). Statistical significance was accepted at $p < 0.05$. The analyses were performed using Statistical Package for Social Sciences (SPSS) Version 20.0 (SPSS Inc, Champaign, IL). The relationships between τD′ and CS were assessed by linear and nonlinear regressions using GraphPad Prism Version 6.01 (GraphPad Prism; GraphPad Software, San Diego, CA).

Results

The performances for 200, 400, 600, and 800 m races lasted 136 ± 8, 297 ± 21, 461 ± 35, and 624 ± 45 s, respectively. The distance-time relationship provided average values of 1.23 ± 0.09 m s^{-1} (91.2 ± 2.7% of the 400 m pace) and 33.69 ± 8.65 m for CS and D′, respectively. The goodness of fit of the distance–time relationship was 0.999 ± 0.001 (range: 0.998—0.999). The mean standard error of the estimate were 0.01 ± 0.01 m s^{-1} (1.1 ± 0.7%) for CS and 5.95 ± 3.87 m (18.7 ± 12.4%) for D'. Using Eq. 3, the constant swimming speed that would result in exhaustion in 180 s during continuous exercise was estimated to be 1.42 ± 0.08 m s^{-1} (105.2 ± 2.3% of the 400 m pace). The work interval duration was 35 ± 2 s, while the recovery durations were 18 ± 1 s for T2:1 and 9 ± 1 s for T4:1. The TTE (work plus recovery intervals) were 856 ± 355 s for T2:1 and 301 ± 72 s for T4:1.

The mean and individual values of actual τD′ found by an iterative process from T2:1 and T4:1 are shown in Table 1. The τD′ was similar between T2:1 and T4:1 [t (12) = -1.13, $p > 0.05$; 95% CI = -994 to 312 s] but it showed a within-subject coefficient of variation of 306%. Figure 2A shows the bias ±95% limits of agreement of actual τD′ found interactively in T2:1 and T4:1. The D'_{LOW} was lower in T2:1 (−1.86 ± 1.73 m) compared with T4:1 (−0.06 ± 0.23 m) [t (12) = −4.13, $p < 0.05$; 95% CI = −2.74 to—0.85 m]. The D'_{LOW} was lower than zero for twelve swimmers in T2:1 and for two swimmers in T4:1, consequently it was equal to zero for one swimmer in T2:1 and eleven swimmers in T4:1. The Total D′ reconstituted during the passive rests was higher in T2:1 (105 ± 63 m) compared with T4:1 (20 ± 17 m) [t (12) = 5.76, $p < 0.05$; 95%

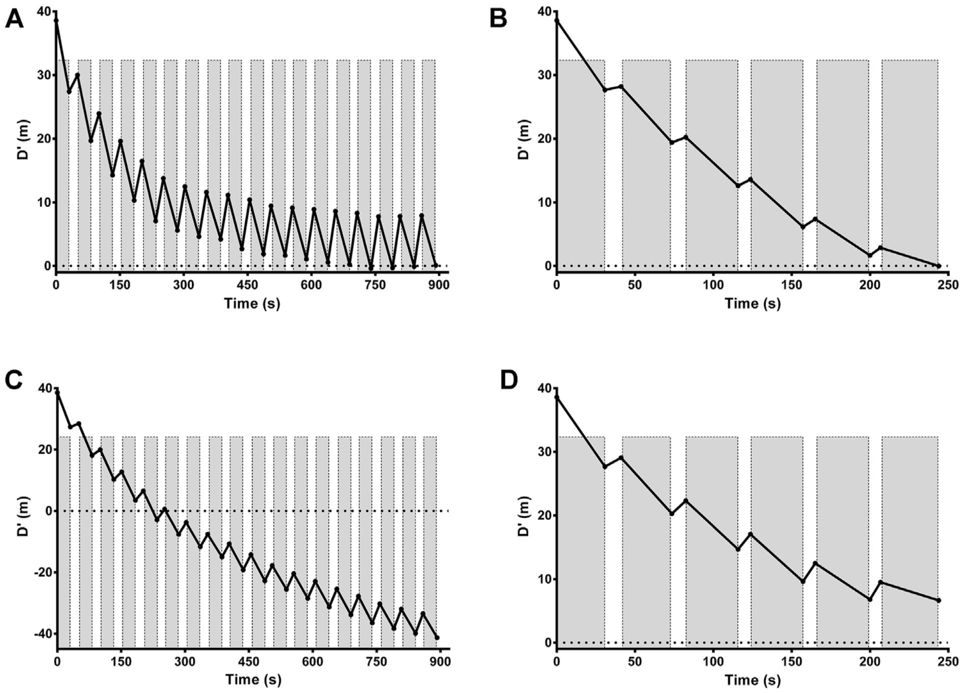

FIGURE 3
Modeled D'_{BAL} depletion and reconstitution for a representative swimmer in training sessions with a work/relief ratio of 2:1 **(A)** and 4:1 **(B)**. An example for the same representative swimmer of individual D'_{BAL} model when τD′ were inverted in training sessions with a work/relief ratio of 2:1 **(C)** and T4:1 **(D)**. Gray bars indicate work intervals with D′ depletion while white space indicates recovery intervals with D′ reconstitution. Black line shows D′ during depletion and reconstitution cycles. Horizontal dotted line represents D′ equals zero and, in theory, the moment when the swimmer reaches volitional exhaustion.

CI = 52–117 m], as well as total D′ expended during exercise was higher in T2:1 (138 ± 64 m) compared with T4:1 (53 ± 18 m) [t (12) = 5.77, $p < 0.05$; 95% CI = 52–117 m]. An example of individual D'_{BAL} model data for a single swimmer in both training sessions is shown in Figures 3A,B (as these τD′ were calculated by iterative processes D'_{END} has to be equal to zero).

When the τD′ determined for T2:1 was applied in T4:1 and vice versa, the D'_{END} were similar between T2:1 (-10.8 ± 35.8 m; 95% CI = −32.5 to 10.8 m) and T4:1 (−2.6 ± 7.4 m; 95% CI = −7.0 to 1.9 m) [t (12) = −0.71, $p > 0.05$; 95% CI = −33.5 to 16.9 m]. The bias and 95% limits of agreement between actual D'_{END} (i.e. interactively determined and equal to zero) and estimated D'_{END} (i.e. τD′ inverted) was 10.8 m and -59.3–81.0 m for T2:1 and 2.6 m and −11.8–17.0 m for T4:1, respectively.

An example of individual D'_{BAL} model data when the τD′ was inverted for a single swimmer in both training sessions is shown in Figures 3C,D. It was not possible to predict the TTE with τD′ inverted in T2:1 for seven swimmers because the D'_{END} did not approach zero. In the other six swimmers, the actual TTE was 653 ± 267 s, while the predicted TTE was 261 ± 71 s. The bias and 95% limits of agreement between actual and predicted TTE for T2:1 are shown in Figure 4A and the coefficient of variation was 29%. For T4:1 it was possible to predict the TTE (261 ± 75 s) for all swimmers when applied the τD′ found by an iterative process from T2:1. The bias and limits of agreement between actual and predicted TTE for T4:1 are shown in Figure 4B and the coefficient of variation was 28%. No linear or nonlinear relationships were found between τD′ and CS (all $R^2 <$ 0.04 or not converged; Figures 5A,B).

The swimmer 11 showed a very different τD′ value in T4:1 (4,000 s) compared with T2:1 and other swimmers (Table 1). This swimmer exhibited no difference during the data collect. Thus, the source for this discrepancy is unclear (e.g. physiological response or random error), but results remain similar when reanalyzed excluding this swimmer. As a result of such reanalyzing, the within-subject coefficient of variation of τD′ was 80.4% with no agreement between the two τD′ values (Figure 2B). The bias and 95% limits of agreement between actual and predicted TTE was 339 s and −186–863 s for T2:1 ($n = 5$) as well as 49 s and −182–281 s for T4:1. Coefficient of variation between actual and predicted TTE was 43% for T2:1 ($n = 5$) and 29% for T4:1. No linear or nonlinear relationships between τD′ and CS were found without the swimmer 11 (all $R^2 < 0.03$ or not converged; Figures 5C,D).

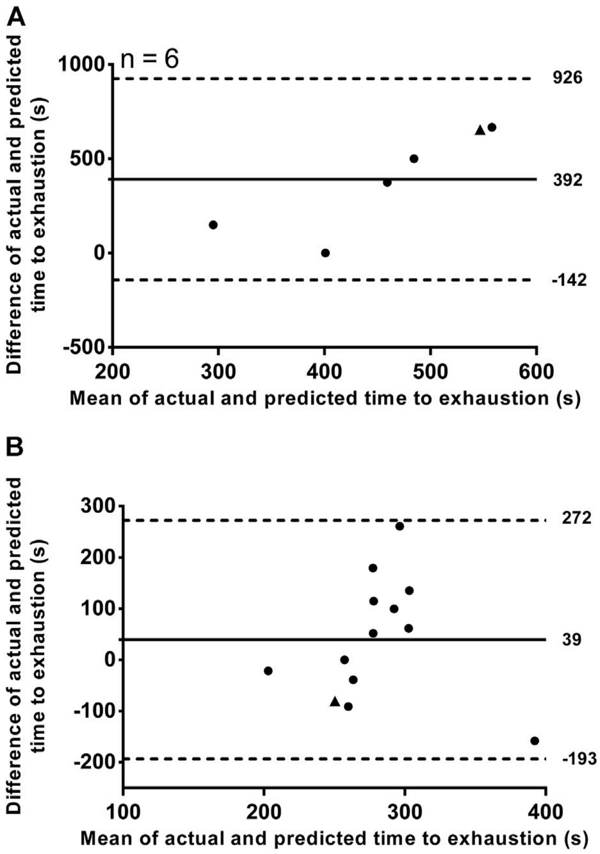

FIGURE 4
Bland–Altman plots showing individual differences between actual and predicted time to exhaustion plotted against their individual mean values. Training sessions with a work/relief ratio of 2:1 **(A)** and with a work/relief ratio of 4:1 **(B)**. Horizontal solid line represents the mean difference and while horizontal dashed lines represent the 95% limit of agreement. ▲ represents the swimmer 11 (see result section for bias and 95% limit of agreement analyses without this swimmer).

Discussion

This was the first study to model the D′ expenditure and reconstitution during swimming exercise. The main finding of this study was that τD′ is not constant during two similar high-intensity interval trainings, showing high variability between sessions. Thus, when the τD′ determined for T2:1 was applied in T4:1 and vice versa, the D'_{BAL} model was inconsistent to predict the exhaustion of swimmers. In addition, τD′ was not related to CS regardless of the linear or nonlinear equations used. The initial hypothesis has been refuted, suggesting that the current form of D'_{BAL} model is inconsistent to track the dynamic response of D′ during intermittent swimming exercises.

Skiba et al. (2012) were the first to develop the CS/CP model for intermittent exercise using linear expenditure and curvilinear reconstitution of W′ during cycling. According to model theory, the curvilinear reconstitution of the D'/W′ occurs below CS/CP and it is dependent on the difference between recovery intensity and CS/CP (Chidnok et al., 2012; Skiba et al., 2012). Therefore, different training sessions with the same recovery intensity should produce the same τD'/τW'. However, Skiba et al. (2014b) reported that decreasing the recovery duration from 30 to 20 s resulted in an additional reduction of τW′ during cycling exercise with the same recovery intensity. Recently, Caen et al. (2019) and Lievens et al. (2020) confirmed that recovery characteristics can affect W′ reconstitution during cycling exercise. In particular, the model seems to underestimate the reconstitution of W′ after shorter recovery intervals (Caen et al., 2019). In addition, Chorley et al. (2019) and Chorley et al. (2020) reported that the reconstitution of W′ is subject to fatigue following successive bouts of maximal exercise and related to aerobic fitness. Taken together, these results demonstrate that the reconstitution of D'/W′ is more complex than the current model considers (Equations (1) and (4)). As τD′ represents the rate of D′ reconstitution, any physiological changes related to D′ reconstitution should affect τD'. However, the physiological parameters related to D'/W′ have yet to be fully elucidated (Broxterman et al., 2015; Vanhatalo et al., 2016; Raimundo et al., 2019) to improve understanding of D'/W′ reconstitution. In the present study, although not statistically different, τD′ had high variability between training sessions, which resulted in low predictability of D'_{END} and TTE when the τD′ determined for T2:1 was applied in T4:1 and vice versa. Notably, most studies reporting τD′ and the predictive ability of the D'_{BAL} model have only reported systematic changes (Skiba et al., 2014b; Broxterman et al., 2016; Shearman et al., 2016). Despite being an important component for analyzing the robustness of the model, systematic changes do not indicate the consistency of τD′ and D'_{BAL} model as a coefficient of variation and limits of agreement (Hopkins, 2000). Therefore, the dynamics of D′ reconstitution need to be better understood and mathematically described for τD′ to be widely applicable during different swimming interval trainings.

The present study observed that τD′ was not related to CS regardless of linear or nonlinear equations used. On the other hand, τW′ was previously related to D_{CP} or CP in cycling, running, and handgrip exercises (Skiba et al., 2012; Broxterman et al., 2016; Vassallo et al., 2020). As previously mentioned, it is possible that no relationship was found because of the high within-subject variability of τD'. Also, the discrepancies between results might, to a large extent, be due to these studies employing recovery intensity based on different exercise domains (Skiba et al., 2012; Vassallo et al., 2020) or different contraction–relaxation cycles (Broxterman et al., 2016). In accordance, when performing a visual inspection in figures presented by Skiba et al. (2012), Vassallo et al. (2020), and Broxterman et al. (2016), the relationships would likely have a worse or no fit if only one exercise domain were used for recovery intensity

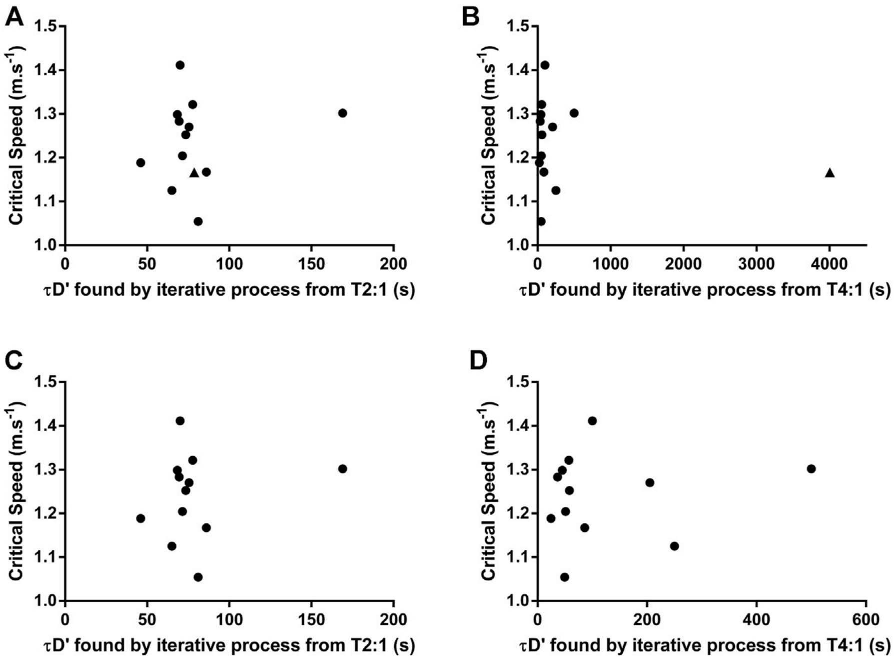

FIGURE 5
Relationship between Critical Speed and τD′ found by iterative process from training sessions with a work/relief ratio of 2:1 (T2:1) or 4:1 (T4:1). **(A)** and **(B)** show data analysis with all swimmers included. **(C)** and **(D)** show data analysis excluding the swimmer 11 (see results session for further details). ▲ represents the swimmer 11.

(Skiba et al., 2012; Vassallo et al., 2020) or contraction–relaxation cycle (Broxterman et al., 2016). Therefore, although passive rests are usually employed during swimming interval trainings, future studies should relate τD′ and D_{CS} with recovery intensities of different exercise domains.

Considering the aspects mentioned above, the current form of D'$_{BAL}$ model was inconsistent for the swimming interval training sessions tested herein. Before incorporating the D'$_{BAL}$ model into common practices of swimming teams, this model should include other physiological variables as τD′ not being constant during a training session (Chorley et al., 2019). For instance, phosphocreatine seems to be one of the determinants of D'/W' (Miura et al., 1999) as intramuscular phosphocreatine is depleted during high-intensity exercise (Vanhatalo et al., 2010). However, a model for phosphocreatine resynthesis showed a higher concentration of phosphocreatine after exercise, with the phosphocreatine concentration rising ~5% above that recorded at rest (Nevill et al., 1997). Furthermore, priming exercise can increase CS/CP and/or D'/W' (Miura et al., 2009; Burnley et al., 2011), overestimating the amount of D'/W′ depleted during exercise above CS/CP and underestimating the replenishment during exercise below CS/CP. Collectively, all these physiological factors should be considered to provide a greater practical application of D'$_{BAL}$ model in swimming.

Limitations

The present study and others reported a high standard error of the estimate for D' (Dekerle and Paterson, 2016), which is usually higher in swimming than in other exercise modes (e.g. running and cycling). While the best practices to determine CS and D′ were used (Muniz-Pumares et al., 2019; Raimundo et al., 2020), we acknowledge that a high standard error of the estimate for D′ can decrease D'$_{BAL}$ model accuracy in swimming. In addition, the swimmers were asked to swim at a constant pre-determined speed, in which there could be some little variation. This possibility was considered prior to the study, we accounted for potential pacing variability by cuing participants according to pre-programmed audio signals, *a priori* familiarization with the protocol, and data analyses performed by video. Lastly, we did not notice any visual difference between pre-determined and real speed during the data collect.

Practical applications

Based on the findings of the present study, the D'$_{BAL}$ model should be further explored and improved to consistently track the dynamic response of D′ during intermittent swimming exercise. Thus, the D'$_{BAL}$ model needs to take into account other more complex physiological mechanisms that are not currently incorporated as $\tau D'$ not being constant during different training sessions with the passive recovery. Hence, athletes and coaches should be aware that the current D'_{BAL} model may not predict the balance of D' remaining at any given time during swimming interval training. Overcoming these shortcomings, the D'_{BAL} model could contribute to the training prescription in different exercise modalities, especially in swimming which has limitations imposed by the aquatic environment. Lastly, it would be interesting to estimate $\tau D'$ based on only passive rests, which are mostly used for swimming.

Conclusion

In summary, this study confirmed that $\tau D'$ is not constant during two swimming interval training sessions, although the same recovery intensity has been used. Consequently, when the $\tau D'$ determined for T2:1 was applied in T4:1 and vice versa, the D'_{BAL} model was not able to predict the exhaustion of swimmers. Therefore, the current form of D'_{BAL} model was inconsistent to track the dynamic response of D' during swimming, at least for the interval workouts tested herein.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the corresponding author on reasonable request, without undue reservation.

Ethics statement

The studies involving human participants were reviewed and approved by Santa Catarina State University Institutional Review Board on Humans Research. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

Author contributions

JR: Conceptualization, Methodology, Investigation, Data Curation, Writing—Original Draft. RD: Methodology, Formal analysis, Writing—Review and Editing. FL: Formal analysis, Writing—Review and Editing. GR: Investigation, Data Curation, Writing—Review and Editing. FC: Conceptualization, Resources, Writing—Review and Editing. All authors approved the final version of the study.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Time limit and $\dot{V}O_2$ kinetics at maximal aerobic velocity: Continuous vs. intermittent swimming trials

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The time sustained during exercise with oxygen uptake ($\dot{V}O_2$) reaching maximal rates ($\dot{V}O_{2peak}$) or near peak responses (i.e., above second ventilatory threshold [t@VT_2) or 90% $\dot{V}O_{2peak}$ (t@90%$\dot{V}O_{2peak}$)] is recognized as the training pace required to enhance aerobic power and exercise tolerance in the severe domain (time-limit, t_{Lim}). This study compared physiological and performance indexes during continuous and intermittent trials at maximal aerobic velocity (MAV) to analyze each exercise schedule, supporting their roles in conditioning planning. Twenty-two well-trained swimmers completed a discontinuous incremental step-test for $\dot{V}O_{2peak}$, VT_2, and MAV assessments. Two other tests were performed in randomized order, to compare continuous (CT) vs. intermittent trials (IT_{100}) at MAV until exhaustion, to determine peak oxygen uptake (Peak-$\dot{V}O_2$) and $\dot{V}O_2$ kinetics ($\dot{V}O_2$K). Distance and time variables were registered to determine the t_{Lim}, t@VT_2, and t@90%$\dot{V}O_{2peak}$ tests. Blood lactate concentration ([La^-]) was analyzed, and rate of perceived exertion (RPE) was recorded. The tests were conducted using a breath-by-breath apparatus connected to a snorkel for pulmonary gas sampling, with pacing controlled by an underwater visual pacer. $\dot{V}O_{2peak}$ (55.2 ± 5.6 ml·kg·min^{-1}) was only reached in CT (100.7 ± 3.1 %$\dot{V}O_{2peak}$). In addition, high $\dot{V}O_2$ values were reached at IT_{100} (96.4 ± 4.2 %$\dot{V}O_{2peak}$). $\dot{V}O_{2peak}$ was highly correlated with Peak-$\dot{V}O_2$ during CT ($r = 0.95$, $p < 0.01$) and IT_{100} ($r = 0.91$, $p < 0.01$). Compared with CT, the IT_{100} presented significantly higher values for t_{Lim} (1,013.6 ± 496.6 vs. 256.2 ± 60.3 s), distance (1,277.3 ± 638.1 vs. 315.9 ± 63.3 m), t@VT_2 (448.1 ± 211.1 vs. 144.1 ± 78.8 s), and t@90%$\dot{V}O_{2peak}$ (321.9 ± 208.7 vs. 127.5 ± 77.1 s). $\dot{V}O_2$K time constants (IT_{100}: 25.9 ± 9.4 vs. CT: 26.5 ± 7.5 s) were correlated between tests ($r = 0.76$, $p < 0.01$). Between CT and IT_{100}, t_{Lim} were not related, and RPE (8.9 ± 0.9 vs. 9.4 ± 0.8) and [La^-] (7.8 ± 2.7 vs. 7.8 ± 2.8 mmol·l^{-1}) did not differ between tests. MAV is suitable for planning swimming intensities requiring $\dot{V}O_{2peak}$ rates, whatever the exercise schedule (continuous or intermittent). Therefore, the results suggest IT_{100} as a preferable training schedule rather than the CT for aerobic capacity training since IT_{100} presented a significantly higher t_{Lim}, t@VT_2, and t@90%$\dot{V}O_{2peak}$ (~757, ~304, and ~194 s more, respectively), without differing regards to [La^-] and RPE. The $\dot{V}O_2K$ seemed not to influence t_{Lim} and times spent near $\dot{V}O_{2peak}$ in both workout modes.

KEYWORDS

maximal aerobic velocity, interval training, VO_2 response, time-limit, swimming

Introduction

The maximal aerobic velocity (MAV), which corresponds to the minimal velocity at which the maximal oxygen consumption of an athlete occurs, is one of the most important variables of study in sports physiology since it combines exercise economy and maximal $\dot{V}O_2$ rates into a single factor, being well related with performance (Billat and Koralsztein, 1996; Demarie et al., 2000; Reis et al., 2012; Espada et al., 2015; Almeida et al., 2021). This velocity, associated with the 3,000 m running (Lacour et al., 1990; Demarie et al., 2000) or the 400 m swimming (Espada et al., 2015; Zacca et al., 2019) velocities, is usually used by coaches for training intensity prescriptions (Demarie et al., 2000; Fernandes and Vilas-Boas, 2012; Espada et al., 2015; Zacca et al., 2019,2020). Therefore, studying the time to exhaustion (t_{Lim}) at MAV (t_{Lim}-MAV) is extremely important, primarily to provide insightful information regarding the athletes' capacity at this intensity, aiming for better planning of the training sets (Fernandes et al., 2008). Moreover, it is generally accepted that exercise intensities between 70% and 100% of $\dot{V}O_2$ maximal rates, as well as training sets sustained near $\dot{V}O_2$ maximal rates have been reported to improve the aerobic power (Billat and Koralsztein, 1996; Demarie et al., 2000; Millet et al., 2003; Almeida et al., 2021), and therefore also improve long term performance (Bentley et al., 2005; Libicz et al., 2005).

It is well recognized that how fast an athlete can reach each exercise's energetic requirements will contribute to its oxidative response, reducing metabolites accumulation, and delaying the fatigue process (Jones and Poole, 2005). In this sense, faster primary $\dot{V}O_2$ responses have been associated with higher conditioning levels (Jones and Burnley, 2009; Reis et al., 2012; Espada et al., 2015), as well as related to the time spent near $\dot{V}O_2$ maximal values during interval training (IT) running sessions (Millet et al., 2003). However, only two studies analyzed continuous $\dot{V}O_2$ response in IT swimming sessions (Bentley et al., 2005; Almeida et al., 2021).

Previous studies which analyzed the exercise tolerance around MAV have shown an interesting inverse relationship between t_{Lim}-MAV with the MAV and the velocity of the second ventilatory threshold (vVT_2), which seems to suggest that high-level athletes could have a lower capacity to deal with this relative intensity (Billat et al., 1996; Billat and Koralsztein, 1996; Faina et al., 1997; Fernandes et al., 2008; Fernandes and Vilas-Boas, 2012). Also, the relationship between t_{Lim}-MAV with the $\dot{V}O_2$ slow component and $\dot{V}O_{2peak}$ seems not to be a consensus in the literature regarding the positive relationship between higher $\dot{V}O_2$ slow component and $\dot{V}O_{2peak}$ with longer times to exhaustion (Billat and Koralsztein, 1996; Billat et al., 1998; Demarie et al., 2001; Fernandes et al., 2003, 2008; Fernandes and Vilas-Boas 2012). Furthermore, there is a lack of studies that can translate the t_{Lim}-MAV characteristics to other real training situations such as interval training in swimming; but being one of the few, the study of Demarie et al. (2000) reported higher t_{Lim} and times spent near $\dot{V}O_2$ maximal values in IT compared to the continuous running trial.

The current study aimed to compare physiological responses during two different training modes—continuous (CT) vs. intermittent (IT_{100}) swimming sets both performed until exhaustion (t_{Lim}), in order to verify the differences regarding the t_{Lim} and times spent near $\dot{V}O_{2peak}$. We hypothesize that: 1) both time-limit tests will promote a high $\dot{V}O_2$ response near $\dot{V}O_2$ maximal values, and therefore recognize both conditions as suitable schedules for training to improve maximal cardiorespiratory conditioning; 2) the IT_{100} will present a higher t_{Lim} and a longer time spent near $\dot{V}O_2$ maximal values, which is an expectance when considering the recognized effect of IT mode of exercise on reducing metabolites accumulation (Zuniga et al., 2011; Rønnestad & Hansen, 2016; Almeida et al., 2021); and 3) faster $\dot{V}O_2$ responses will be related with longer times to exhaustion in the time-limit tests, since the assumption relating t_{Lim} to $\dot{V}O_2$ kinetics considers that fast $\dot{V}O_2$ response to target muscle O_2 requirements would reduce O_2 deficit and metabolite accumulation, and increase oxidative contribution (Bailey et al., 2009).

Materials and methods

Participants

Twenty-two well-trained swimmers (9 females and 13 males), were informed about the procedures and experimental risks and gave their written informed consent (and the respective legal guardians, when they were under 18 years old) in order to participate in this study. *A priori* sample N was determined with G*Power 3 from data

TABLE 1 Mean ± SD of the descriptive characteristics of the swimmers.

Variables	Female	Male	Group
Age (years)	15.3 ± 1.2	16.5 ± 1.9	16.1 ± 1.7
Height (cm)	165.0 ± 6.5	178.6 ± 8.4	173.0 ± 10.2
Body Mass (kg)	58.4 ± 6.0	70.4 ± 10.3	65.5 ± 10.6
PB 200 (s)	122.2 ± 5.9	136.8 ± 5.7	65.5 ± 10.6
% to WR	~19.6	~21.2	-

including five participants (three males and two females) of time above VT_2 (CT: 146.5 ± 120.3 vs. IT_{100}: 268.6 ± 88.4 s), and specifying $\alpha = 0.05$ and $1\text{-}\beta = 0.80$ (Faul et al., 2007). The output N = 20 was further increased by 10% to consider possible withdrawal from the study, totalizing 22 participants.

The swimmers showed time performance within 20% of the world record, therefore the "highly trained/national level" matched the conditioning profile of the current sample of participants, as recommended in McKay et al. (2022). In addition, the current swimmers planning includes seven to eight training sessions which total ~32 km per week in water, as well as dry land workouts. Also, the current swimmers had been regularly involved with competitive events for at least 3 years prior the study. All swimmers were fully familiarized with the equipment and the test procedures before the test sessions, being frequent participants in similar experimental studies that our research group has undertaken. This study was approved by the local University Ethical Committee (CEFMH: 39/2015) and conducted following the 1964 Declaration of Helsinki (Harriss et al., 2017). The descriptive characteristics of the swimmers are presented in Table 1.

Experimental design

All swimmers performed three testing sessions, separated by at least 48 h: 1) a discontinuous incremental step-test; and 2) two time-limit sessions at the MAV intensity, a continuous test (CT) vs. an intermittent test (IT_{100}). All subjects performed the same pre-test warm-up protocol, which followed the schedule suggested in Almeida et al. (2020), e.g., dry land stretching exercises for upper- and lower-limbs, and 800 m swimming at a comfortable and effortless pace, including whole-body, and only arms and legs swimming practices. The swimmers were instructed to avoid strenuous exercise in the preceding 24 h before each session, attend well hydrated and fed, and abstain from caffeine and alcohol in the preceding 24 h. In order to minimize the effect of circadian rhythms or differences in prior exercise, the same environmental conditions were applied to all tests, namely the time of day (±2 h), water temperature (~28°C), and relative humidity (~50%).

A telemetric portable breath-by-breath gas analyzer (K4b[2], Cosmed, Italy), connected to the swimmer by a respiratory snorkel and valve system (new-AquaTrainer®, Cosmed, Italy), was used in all tests in order to measure the respiratory and gas exchange variables for cardiorespiratory analysis (Reis et al., 2010; Baldari et al., 2013). The K4b[2] was calibrated before each test according to the manufacturer's instructions. All tests were performed in front crawl swimming with in-water starts and open turns without underwater gliding.

The heart rate (HR) was telemetrically recorded during exercise with an HR monitor (Polar®, Finland) coupled to the snorkel and synchronized with the K4b[2] system. For the blood lactate concentration $[La^-]$ analysis a biochemistry analyzer was used (YSI, 2300 STAT, Yellow Springs, United States), and capillary blood samples (25 µl) were collected from the earlobe before the start of each test, during the breaks of the discontinuous incremental step-test and at 1, 3, 5, and 7 min after all tests. The option for the earlobe site considered the assumption that the $[La^-]$ analysis did not differ between sample sites, particularly when movement involved both legs and arms, and is performed at high exercise intensity (Forsyth and Farrally, 2000). The rate of perceived exertion (RPE) was also recorded through the Borg's CR-10 scale (Borg, 1990).

An underwater visual pacer (Pacer2Swim®, KulzerTEC, Portugal) was placed along the bottom of the pool for the swimming velocity control. This system is composed of 26 lights that subsequently light up, giving the swimmer an accurate notion of the correct velocity for each test. For time-limit tests, a tolerance of 2% of the overall time was given to the swimmers. Tests were finished when the swimmers exceeded the tolerance or when individual voluntary exhaustion was observed.

The sessions were performed in a 25 m swimming pool at the beginning of the preparatory period of the second macrocycle of the swimmers' competitive season, after 2 weeks of training adaptation.

Incremental step-test

This test was composed of six sets of 250 m, plus one set of 200 m at maximal intensity, with 30 s rest for $[La^-]$ collection (Espada et al., 2015; Almeida et al., 2020, 2021; Massini et al., 2021), in order to allow the determination of maximal oxygen uptake ($\dot{V}O_{2peak}$), VT_2, vVT_2, and MAV. The velocity of the first repetition was set at 50% of the swimmers' 200 m trial velocity (performed 48 h before the beginning of the tests), and increments of 5%–10% were imposed in the remaining repetitions until swimmers' voluntary exhaustion. $\dot{V}O_{2peak}$ was recorded as the highest 30 s average of the $\dot{V}O_2$, and MAV was considered the minimal velocity at which the $\dot{V}O_{2peak}$ values were reached (both reached in the last two repetitions).

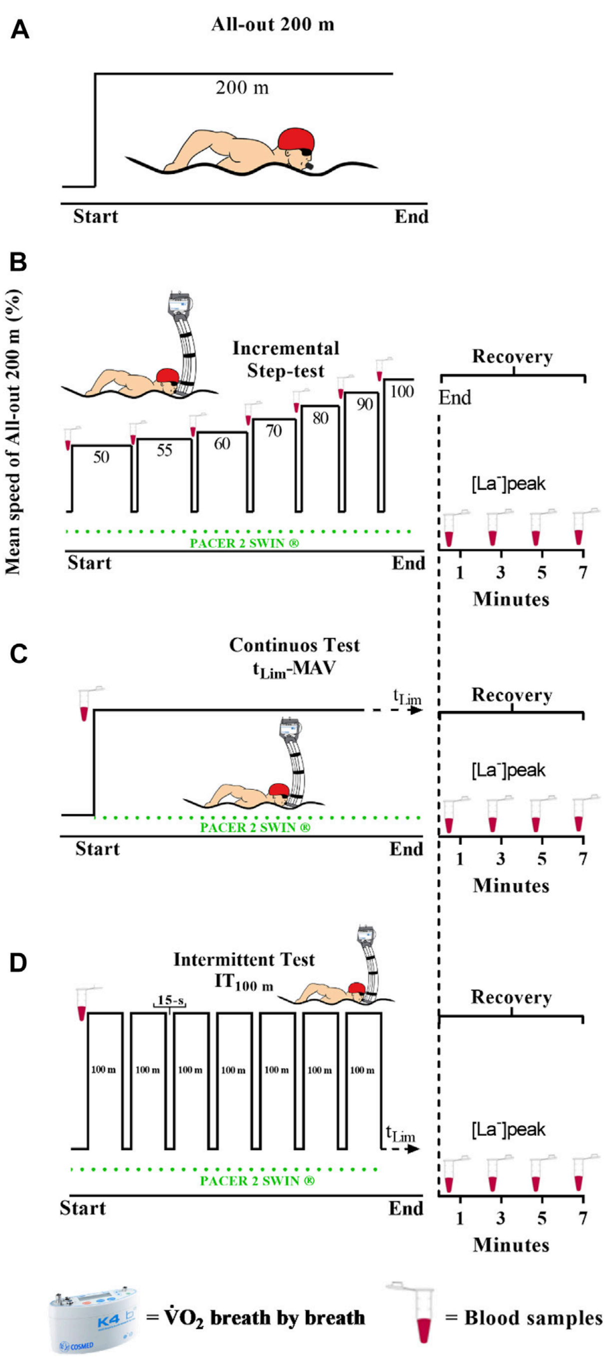

FIGURE 1
Overview of experimental design for 200 m performance **(A)**, discontinuous incremental step-test **(B)**, continuous test **(C)**, and intermittent test **(D)**.

Time-limit sessions

In subsequent days, in a randomized order, the swimmers performed two time-limit sessions at MAV until exhaustion: 1) a constant load set (CT); 2) and an interval set composed of 100 m repetitions (IT_{100}), with 15 s breaks with passive rest. In both sessions, the t_{Lim} and distance were recorded. The selected planning for the IT protocol was supported by the findings that short (i.e., 100 m) or long (i.e., 200 m) work intervals did not differ with regard to physiological and temporal responses at MAV condition in swimming, but the shortest is perceived as less difficult to perform and therefore suitable to ensure swimmer engagement at such an exhaustive training condition (Almeida et al., 2021). Apart from the option for the ideal IT distance, the work:rest ratio for IT_{100} followed the recommendations of Billat, (2001), which suggested 10–30 s of rest to training for high intensity aerobic short-intervals, considering that 1) rest should be long enough to ensure the restoration of the O_2 reserve and phosphocreatine sources partially, but 2) short enough to avoid considerable reduction of $\dot{V}O_2$. The maximal $\dot{V}O_2$ response (Peak-$\dot{V}O_2$), oxygen deficit at the onset of exercise ($O_{2InitialDef}$), maximal [La^-], and the $\dot{V}O_2K$ parameters were determined (we use the first bout in the IT_{100} session to compare with the CT). Additionally, the time spent at or above the VT_2 (t@VT_2) and 90% of the $\dot{V}O_{2peak}$ (t@90% $\dot{V}O_{2peak}$), and the corresponding percentage values for the total duration of the sessions, were registered (%t@VT_2 and % t@90%$\dot{V}O_{2peak}$, respectively). For the IT_{100}, the mean Peak-$\dot{V}O_2$ (MPeak-$\dot{V}O_2$) as the average value of the Peak-$\dot{V}O_2$'s of each repetition was calculated. The swimmers were encouraged to give their maximal effort in the incremental test and perform the maximal distance in the time-limit tests. Figure 1 depicts the overall view of all testing protocols.

Data analysis

Breath-by-breath $\dot{V}O_2$ data were first cleaned by the exclusion of values lying more than three standard deviations from the local mean for the exclusion of outliers caused by abrupt breaths or coughing. For maximal oxygen uptake determination, a 30 s moving average of data was used for the incremental and time-limit tests considering the highest value as the peak. For the t@VT_2, t@90%$\dot{V}O_{2peak}$, and respective percentage values for the total duration of the sessions, $\dot{V}O_2$ data was further interpolated into 1 s values, and all the above values were registered.

$\dot{V}O_2K$ parameters [time delay (TD), time constant (τ), and amplitude (A)] of the time-limit tests were determined by using: 1) bi-exponential modelling for the CT, since after a primary rise of the $\dot{V}O_2$ values, a secondary rise (slow component) was observed (except for two swimmers); or 2) by monoexponential modelling for the IT_{100}, since due to the short duration of the sets we did not observe the secondary rise of the $\dot{V}O_2$ values, in accordance with previous studies (Rodríguez et al., 2003; Sousa et al., 2013; Almeida et al., 2020, 2021). To remove the influence of the cardiodynamic phase on the subsequent $\dot{V}O_2$ response, we chose to remove the first 20 s of data from the analysis (Pessôa Filho et al., 2012;

TABLE 2 Mean ± SD of the conditioning parameters assessed during incremental test, by sex and group.

	Sex			Power	
Variables	Group	Female	Male	ρ	Hedges' g
$\dot{V}O_{2peak}$ ($ml{\cdot}kg^{-1}{\cdot}min^{-1}$)	55.2 ± 5.6	52.5 ± 4.2	57.0 ± 5.7	0.054	0.80 [large]
VT₂ ($ml{\cdot}kg^{-1}{\cdot}min^{-1}$)	48.4 ± 5.0	46.4 ± 4.3	49.9 ± 4.8	0.107	0.71 [medium]
%VT₂ (%$\dot{V}O_{2peak}$)	87.9 ± 3.2	88.3 ± 2.5	87.6 ± 3.5	0.603	0.20 [trivial]
vVT₂ ($m{\cdot}s^{-1}$)	1.19 ± 0.08	1.11 ± 0.04	1.24 ± 0.06*	<0.001	1.99 [very large]
MAV ($m{\cdot}s^{-1}$)	1.26 ± 0.09	1.20 ± 0.07	1.30 ± 0.07*	0.007	1.37 [very large]
Peak [La⁻] ($mmol{\cdot}l^{-1}$)	8.4 ± 3.3	7.9 ± 2.5	8.8 ± 3.6	0.178	0.27 [small]
Peak HR ($b{\cdot}min^{-1}$)	184.1 ± 9.4	188.7 ± 9.2	180.4 ± 7.8	0.059	0.95 [large]

$\dot{V}O_{2peak}$, maximal oxygen uptake; VT₂ and %VT₂, $\dot{V}O_2$ at the second ventilatory threshold and corresponding percentage value for $\dot{V}O_{2peak}$; vVT₂, velocity at VT₂; MAV, maximal aerobic velocity; Peak [La⁻], maximal blood lactate concentration; Peak HR, maximal HR; *, statistical differences for the female group ($p < 0.05$). The observed sample power for the differences between sexes with regards to vVT_2 and MAV are 100 and 88%, respectively. For the other variables, The differences between sexes neither attained statistical significance or sufficient sample power (i.e., <80 %).

Reis et al., 2012; Espada et al., 2015; Almeida et al., 2020, 2021). We also calculated an individual "snorkel delay" (ISD) for each test, as described previously by Reis et al. (2012), adapted to the specific characteristic of the snorkel device used in this study.

$\dot{V}O_2K$ parameters were calculated through an iterative procedure by minimizing the sum of the mean squares of the differences between the modelled and the measured $\dot{V}O_2$ values. Therefore, we modelled the $\dot{V}O_2K$ according to the equation (Jones and Poole, 2005):

$$\dot{V}O_{2(t)} = \dot{V}O_{2(b)} + A_p \bullet (1\text{-}e^{-(t-TDp)/\tau p}) + A_{sc} \bullet (1\text{-}e^{-(t-TDsc/\tau sc)})$$

Where $\dot{V}O_{2(t)}$ represents the relative $\dot{V}O_2$ at a given time; $\dot{V}O_{2base}$ represents the $\dot{V}O_2$ at rest, which was calculated as the average of the first 30 s of the last minute before the start of the exercise (after 10 min of passive rest); TD, τ, and A represent the time delay, the time constant (time that is needed to complete 63% of the $\dot{V}O_2$ response), and the amplitude of the exponential response of the $\dot{V}O_2$, respectively for the primary (p) and the slow component (sc) phases.

Statistical analysis

Firstly, normality and homogeneity of data were confirmed with Shapiro-Wilk and Levene tests; secondly, independent T-tests were applied to variables to check the differences between sexes. The differences between $\dot{V}O_{2peak}$ values observed during the discontinuous incremental step-test and the CT and IT_{100} tests were tested for statistical significance using one-way ANOVA with Sidak post-hoc analysis. The independent Student's t-test analyzed the differences between sexes with regards to conditioning parameters, as well as being used to test for differences between the time-limit tests. The effect size for each Student's *t*-test comparison was determined by Hedges' g, which is considered: <0.19 (trivial), 0.20–0.49 (small), 0.50–0.79 (medium), 0.80–1.29 (large), and >1.30 (very large) (Rosenthal, 1996). The sample power was determined considering the security level at 95% ($\alpha = 0.05$), and a minimal power at 80% ($1 - \beta = 0.80$) to satisfy the confidence of the differences between sexes and training trials, when observed. Lastly, Pearson's linear correlation coefficient was used to establish the significant associations between physiological measures and swimmers' performance in the time-limit tests. Statistical significance was accepted at $p < 0.05$. All statistical comparisons were performed with the Statistical Package for the Social Sciences (version 25.0; SPSS, Chicago, IL, United States), and power analysis was estimated with G*Power 3 software.

Results

The physiological responses of the swimmers in the incremental test are depicted in Table 2. Except for the swimming velocities, as expected, no differences were found between sexes with regards to the conditioning parameters.

The physiological responses during CT and IT_{100} are presented in Table 3 and a typical response of $\dot{V}O_2$ is demonstrated in Figure 2.

The CT presented no significant Peak-$\dot{V}O_2$ than the IT_{100} test, but the %Peak-$\dot{V}O_2$ is higher in CT. However, the IT_{100} test presented significantly higher values for t_{Lim}, distance, t@VT₂, and t@90%$\dot{V}O_{2peak}$. Regarding the time spent near $\dot{V}O_{2peak}$, when the percentage values for the total duration of the sessions were considered, no differences were observed between tests. Also, none of these variables seem to be related between tests.

No differences were found in the $\dot{V}O_2K$ parameters and $O_{2InitialDef}$ between the CT and the first bout of the IT_{100} test, nor for the peak [La⁻]. However, RPE response is lower for CT than IT_{100}. However, both the time constants and the $O_{2InitialDef}$ were correlated between tests (r = 0.77 and r = 0.67, p < 0.01, respectively) and the time constants seem to be highly

TABLE 3 Mean ± SD of the physiological and performance responses during training trials. N = 22 (9 F, 13 M).

Variable	Training trial		Power	
	Continuous	Intermittent	ρ	Hedges' g
Peak-$\dot{V}O_2$ (ml·kg^{-1}·min^{-1})	55.4 ± 5.1	53.1 ± 5.3	<0.149	0.44 [small]
%Peak-$\dot{V}O_2$ (%$\dot{V}O_{2peak}$)	100.7 ± 3.1	96.4 ± 4.2*	0.001	1.14 [large]
MPeak-$\dot{V}O_2$ (ml·kg^{-1}·min^{-1})	—	50.6 ± 4.9		
%MPeak-$\dot{V}O_2$ (%$\dot{V}O_{2peak}$)	—	91.8 ± 4.2		
Peak HR (b·min^{-1})	183.2 ± 7.4	182.2 ± 10.4	0.725	0.11 [trivial]
Peak [La$^-$] (mmol·l^{-1})	7.8 ± 2.7	7.8 ± 2.8	0.839	0.00 [trivial]
RPE (0–10 units)	8.9 ± 0.9	9.4 ± 0.8	0.051	0.58 [medium]
Distance (m)	315.9 ± 63.3	1,277.3 ± 638.1*	<0.001	2.08 [very large]
t_{Lim} (s)	256.2 ± 60.3	1,013.6 ± 496.6*	<0.001	2.10 [very large]
t@VT₂ (s)	144.1 ± 78.8	448.1 ± 211.1*	<0.001	1.87 [very large]
%t@VT₂ (%)	53.4 ± 20.1	45.8 ± 17.3	0.194	0.40 [small]
t@90%$\dot{V}O_{2peak}$ (s)	127.5 ± 77.1	321.9 ± 208.7*	<0.001	1.21 [large]
%t@90%$\dot{V}O_{2peak}$ (%)	47.3 ± 19.6	34.1 ± 20.9*	0.040	0.64 [medium]
A_p (ml·kg^{-1}·min^{-1})	42.7 ± 5.3	42.2 ± 3.8	0.758	0.11 [trivial]
TD_p(s)	12.6 ± 2.2	11.8 ± 2.3	0.297	0.35 [small]
τ_p (s)	26.5 ± 7.5	25.9 ± 9.4	0.838	0.07 [trivial]
$O_{2InicialDef}$ (ml)	1,658.5 ± 372.2	1,652.0 ± 601.2	0.967	0.01 [trivial]
A_{SC} (ml·min^{-1})	266.2 ± 178.4			
A_{SC} (ml·kg^{-1}·min^{-1})	4.0 ± 2.6			
TD_{SC}(s)	132.5 ± 20.5			
τ_{sc} (s)	39.6 ± 26.4			

Peak-$\dot{V}O_2$ and %Peak-$\dot{V}O_2$, maximal $\dot{V}O_2$ in the test and corresponding percentage to $\dot{V}O_{2peak}$; MPeak-$\dot{V}O_2$ and %MPeak-$\dot{V}O_2$, average value of the maximal $\dot{V}O_2$ achieved in each repetition of the set and corresponding percentage to $\dot{V}O_{2peak}$; Peak [La$^-$] and Peak HR, maximal blood lactate concentration and HR, respectively; RPE, rate of perceived exertion; Distance and t_{Lim}, maximal distance and time performed by the swimmers; t@VT₂ and t@90%$\dot{V}O_{2peak}$, time spent by the swimmers with $\dot{V}O_2$ values above the VT₂ and 90% of the $\dot{V}O_{2peak}$, and corresponding percentage values for the total duration of each test, respectively; A, TD and τ, amplitude, time delay and time constant parameters of the $\dot{V}O_2$K, for the primary (p) and slow component phase (Asc); *, statistical differences for the continuous test ($p < 0.05$). The observed sample power for the differences between CT and IT_{100} with regards to %Peak-$\dot{V}O_2$, Distance, t_{Lim}, t@VT₂, and t@90% $\dot{V}O_{2peak}$ are 96, 100, 100, 100, and 98%, respectively. For the other variables, The differences between CT and IT_{100} did not attain statistical significance, nor sufficient sample power (i.e., <80%).

correlated with the corresponding $O_{2InitialDef}$ (r = 0.82 and r = 0.92, p < 0.01) for CT and IT_{100}, respectively.

Both time-limit tests achieve high values of Peak-$\dot{V}O_2$, however, only CT reached the $\dot{V}O_{2peak}$ of the incremental test. Moreover, $\dot{V}O_{2peak}$ was highly correlated with Peak-$\dot{V}O_2$'s (r = 0.95 and r = 0.91, p < 0.01, for CT and IT_{100}, respectively), and Peak-$\dot{V}O_{2peak}$ were also correlated between CT and IT_{100} tests (r = 0.88, p < 0.01).

The t_{Lim} in the CT presented 1) direct relations with: %t@VT₂ (r = 0.56, p < 0.01) and %t@90%$\dot{V}O_{2peak}$ (r = 0.55, p < 0.01); and 2) inverse relations with: MAV (r = −0.69, p < 0.01) and vVT₂ (r = −0.53, p < 0.05), which also correlate with each other (r = −0.87, p < 0.01).

Discussion

The current study contributed to the literature with the evidence that, as shown previously in running (Demarie et al., 2000), also in swimming the IT_{100} allows the athletes to perform for longer the MAV intensity with longer times spent near the $\dot{V}O_{2peak}$ when compared to the CT, without demanding different blood lactate accumulation and perceived rate exertion. The main evidence of the present study are: 1) both time-limit tests promote high values of $\dot{V}O_2$ with considerable times, similar to previous literature findings (Demarie et al., 2000; Almeida et al., 2021), spent near $\dot{V}O_2$ maximal values (i.e., ~53 % and ~46% of t@VT₂, for CT and IT_{100}, respectively), evidencing the training sets efficacy for aerobic improvement, and therefore confirming our first hypothesis; 2) IT_{100} presented a significantly higher t_{Lim} (~757 s higher), contributing to a significantly higher amount of time spent at or above VT₂ and 90% of $\dot{V}O_{2peak}$ (~304 and ~194 s higher, respectively) confirming our second hypothesis; 3) our third hypothesis was not confirmed since faster $\dot{V}O_2$ kinetics were not associated with higher t_{Lim}, however both time constants were highly associated with the O_2 initial deficits, suggesting that swimmers with

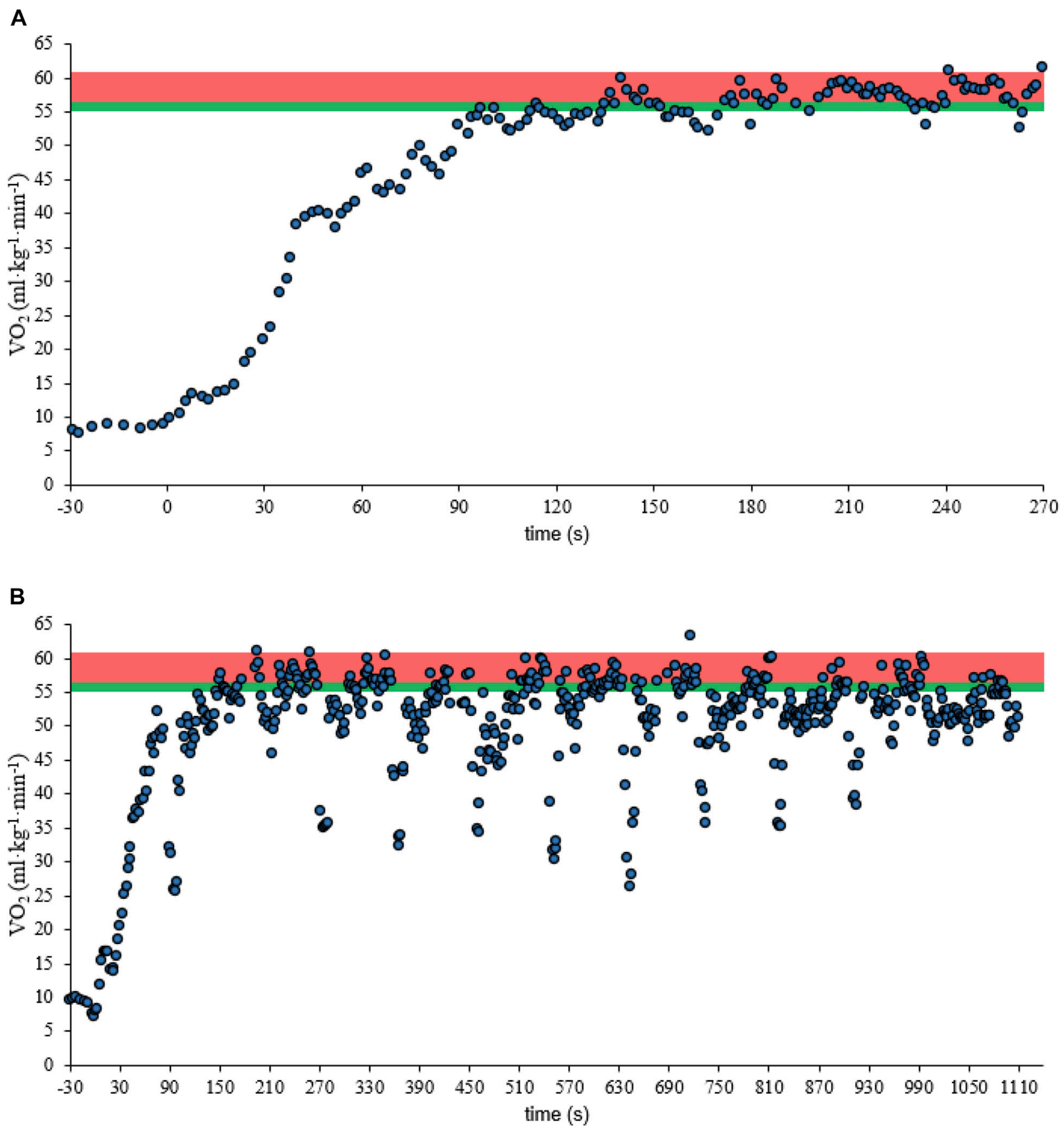

FIGURE 2
Example of the $\dot{V}O_2$ response profiles of the swimmer no 12 in the CT **(A)** and IT_{100} **(B)**. Green and red shadow areas highlight the swimmer t@VT_2 and t@90 %$\dot{V}O_{2peak}$.

faster kinetics could reduce the anaerobic contribution at the beginning of the exercise.

Demarie et al. (2000), comparing the $\dot{V}O_2$ of intermittent and continuous running at 92.2% of MAV, concluded that both have efficacy for endurance training performance, however the authors demonstrated that subjects were truly able to run for a significantly longer time during the intermittent test (~555 s more), with a significantly longer time with $\dot{V}O_2$ values near maximal values (~316 s more), suggesting that the intermittent test is the best to stimulate the aerobic metabolism at its maximum value. The current results corroborate the reports from Demarie et al. (2000) for running, suggesting that interval training in swimming is more beneficial for developing aerobic power than continuous training. Even though the percentage of $\dot{V}O_{2peak}$ was higher in the continuous test and the percentage of the time performed near maximal $\dot{V}O_2$ values was similar between the two training modes in study, the swimmers were able to perform the requested intensity for a significantly longer time in the interval training, which consequently contributed to significantly higher times spent near their $\dot{V}O_2$ maximal values. This evidence suggests interval training as the best for stimulating the oxidative system, promoting better chronic adjustments to the aerobic conditioning level of swimmers (Demarie et al., 2000; Bentley et al., 2005; Libicz et al., 2005; Helgerud et al., 2007).

Previous studies reported inverse correlations between the tLim-MAV with MAV and vVT₂ for several exercise modalities (Billat et al., 1996; Billat and Koralsztein, 1996; Faina et al., 1997; Fernandes et al., 2008; Fernandes and Vilas-Boas, 2012). This fact suggests that swimmers with higher aerobic power could not perform an exercise at this intensity for such long times, when compared to swimmers with lower conditioning levels, probably because higher velocities imply a more strenuous effort, leading to fatigue in an earlier stage by the higher anaerobic energy requirements, as suggested by Fernandes et al. (2008). According to Fernandes et al. (2003), this could be explained by distinct phenotypes, which probably influenced the motor unit's recruitment patterns during the conducted tests, suggesting that swimmers with higher values of second lactate threshold and MAV should use less extensive training sets for aerobic power improvement purposes. Also, Fernandes and Vilas-Boas (2012) reported that the t_{Lim}-MAV is influenced by stroking parameters, having a direct relationship with stroke index and stroke length and an inverse correlation with stroke rate. Even though the kinematic parameters were not monitored in this study, it is logical to believe that the same should occur since these variables will influence the swimming economy and contribute to fatigue delay in an earlier test stage. The current study corroborates the inverse relationship between t_{Lim}-MAV with MAV and vVT₂, suggesting that high-level swimmers should train with short-distance IT trials at MAV to avoid premature performance deterioration with fatigue in the first trials.

The $\dot{V}O_2$ slow component is another factor that can influence the t_{Lim}-MAV, however its impact is still an open issue since the literature has been giving contradicting results regarding the relation with the time to exhaustion. Demarie et al. (2001) were the first group to highlight that, as well as in running or cycling, swimming athletes also present $\dot{V}O_2$ additional adjustments, as reported in more recent studies (Pessôa-Filho et al., 2012; Reis et al., 2012; Espada et al., 2015) probably because of the effect of fatigue induced by the exercise on the increase in muscle temperature, on muscular contraction characteristics, higher recruitment of motor units (particularly "fast-twitch" fibers), lower mechanical efficiency (associated with the changes on stroking technique), and the energy cost of breathing (which has a higher relevance in swimming) (Fernandes et al., 2003; Espada et al., 2015). Despite the relationships between higher $\dot{V}O_2$ slow component with t_{Lim}-MAV were not often reported, as in swimming (Demarie et al., 2001) and other modalities (Billat and Koralsztein, 1996; Billat et al., 1998), or in the current study, there are reports showing a direct relationship, suggesting that longer times to exhaustion lead to higher $\dot{V}O_2$ slow components (Fernandes et al., 2003; Fernandes et al., 2008; Fernandes and Vilas-Boas, 2012). Such results and the inverse relationship between t_{Lim}-MAV and MAV emphasized that the lower maximal aerobic metabolic rate level of swimmers might be related to a larger tolerance at this intensity. Furthermore, this hypothesis suggests that the inverse relationship might be explained by the reliance on anaerobic release, as this is also pointed out by Billat and Koralsztein (1996) and Faina et al. (1997).

Based on the current results, the $\dot{V}O_2$K did no influence MAV tolerance nor on the time spent near $\dot{V}O_{2peak}$ during both the continuous and intermittent training modes. This result was unexpected since fast $\dot{V}O_2$K response should, theoretically, contribute to the exercise tolerance. However, the correlation found between time constants during continuous and intermittent training modes reinforces the idea that the rate of $\dot{V}O_2$ adjustments per se did not influence the tolerance at this intensity, since neither in the continuous nor in the intermittent exercise, no relations with the t_{Lim} were observed. In swimming, several studies also presented no correlation between these two variables for a t_{Lim}-MAV test (Fernandes et al., 2003, 2008; Sousa et al., 2014). Moreover, Bailey et al. (2009), testing the effect of an all-out sprint interval training program, concluded that even though both the tolerance to exercise and the $\dot{V}O_2$K presented improvements after the program, those two variables were not correlated. In swimming, Almeida et al. (2021) and Bentley et al. (2005) also tested the relation between the time spent near $\dot{V}O_{2peak}$ during intermittent exercise with $\dot{V}O_2$K rate of adjustment with no relations found, in agreement with the current findings.

The relation between $\dot{V}O_{2peak}$ and t_{Lim} is also inconsistent in the literature since reports support a direct relationship (Billat and Koralsztein, 1996) and no relationship at all (Demarie et al., 2000; Fernandes and Vilas-Boas, 2012). The lack of a significant correlation shown in the current study is consistent with the assumption that $\dot{V}O_{2peak}$ is directly related to MAV, which is inversely related to the t_{Lim} (Billat et al., 1996; Billat and Koralsztein, 1996; Faina et al., 1997; Fernandes et al., 2008; Fernandes and Vilas-Boas, 2012), as observed in this study.

With regard to the use of the new-Aquatrainer® for the sampling of gas exchange response, it could not be recognized as a limitation for physiological analysis, even when considering that this system delays the actual swimming velocity through the modification of swimming tasks such as turning and gliding (Ribeiro et al., 2016), and supposedly allows a higher contribution of oxidative energetic system than expected during high-intensity short-and middle-trials performances (Campos et al., 2017). Indeed, there are reports stating that a swimmer is able to stroke at a maximum rate when required while wearing new-Aquatrainer®, and therefore no impairments are expected for the level of exertion during swimming tests (Ribeiro et al., 2016) and energetic contribution (Almeida et al., 2020; Massini et al., 2021).

Conclusion

In conclusion, our results suggest: 1) the intermittent training set of 100 m repetitions, with 15 s of rest, is the best training set in order to promote the longest times spent near $\dot{V}O_2$ maximal values, and therefore promote gains in $\dot{V}O_{2peak}$; 2) testing the tolerance of swimmers at MAV provides an individualized reference of training intensity, which might assist coaches to manage training for the entire team in conformity with the findings of the current study that higher level swimmers could not perform the MAV intensity longer than swimmers with lower conditioning levels; and 3) that $\dot{V}O_2K$ seemed not to influence the tolerance at MAV or times spent near $\dot{V}O_{2peak}$ during the continuous and intermittent training modes.

From the current findings, some practical applications are:

- Continuous and intermittent exercises mode at MAV are both able to elicit maximal $\dot{V}O_2$ response before exhaustion, and therefore both might be considered suitable training conditions to improve maximal aerobic power.
- The IT_{100} planned at MAV increases considerably the time-limit and time spent near $\dot{V}O_{2peak}$ when compared to continuous longer distances, and therefore considered an advisable exercise mode to preclude earlier exhaustion during such high intensity training.
- The t_{Lim} at MAV might be considered a suitable index of the enhancement of swimming tolerance, and therefore able to parametrize either training efficacy or planning adjustments to engender the physiological chronic alterations required to perform successfully at high aerobic intensities.

When planning training at MAV to improve maximal aerobic power, coaches should consider that the time sustained during CT (~256 s, in the current study) can be enhanced with IT (~1,014 s performing ~12 to 13 bouts of 100 m with a 15 s interval), therefore engendering a longer swimming time with oxidative rates close to maximal values. Following other studies (Billat, 2001; Zuniga et al., 2011; Buchheit and Larson, 2013; Wen et al., 2019; Almeida et al., 2021) this is an effective condition for improving $\dot{V}O_{2peak.}$

Data availability statement

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

Ethics statement

The studies involving human participants were reviewed and approved by Faculty of Human Kinetics Ethics Council—University of Lisbon CEFMH: 39/2015. Written informed consent to participate in this study was provided by the participants and the respective legal guardian/next of kin (just for under 18 years old participants).

Author contributions

TAFA, MCE, JFR, FBA, and DMPF conceived and designed the study. TAFA, DAM, OTSJ, RVJ, JFR, AGM, and DMPF conducted experiments and analyzed the data. TAFA, DAM, OTSJ, RVJ, MCE, JFR, FBA, and DMPF wrote the manuscript. All the authors read and approved the manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Numerical and experimental methods used to evaluate active drag in swimming: A systematic narrative review

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Introduction: In swimming, it is necessary to understand and identify the main factors that are important to reduce active drag and, consequently, improve the performance of swimmers. However, there is no up-to-date review in the literature clarifying this topic. Thus, a systematic narrative review was performed to update the body of knowledge on active drag in swimming through numerical and experimental methods.

Methods: To determine and identify the most relevant studies for this review, the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) approach was used.

Results: 75 studies related to active drag in swimming and the methodologies applied to study them were analyzed and kept for synthesis. The included studies showed a high-quality score by the Delphi scale (mean score was 5.85 ± 0.38). Active drag was included in seven studies through numerical methods and 68 through experimental methods. In both methods used by the authors to determine the drag, it can be concluded that the frontal surface area plays a fundamental role. Additionally, the technique seems to be a determining factor in reducing the drag force and increasing the propulsive force. Drag tends to increase with speed and frontal surface area, being greater in adults than in children due to body density factors and high levels of speed. However, the coefficient of drag decreases as the technical efficiency of swimming increases (i.e., the best swimmers (the fastest or most efficient) are those with the best drag and swimming hydrodynamics efficiency).

Conclusion: Active drag was studied through numerical and experimental methods. There are significantly fewer numerical studies than experimental ones. This is because active drag, as a dynamical phenomenon, is too complex to be studied numerically. Drag is greater in adults than in children and greater in men than in women across all age groups. The study of drag is increasingly essential to collaborate with coaches in the process of understanding the fundamental patterns of movement biomechanics to achieve the best performance in swimming. Although most agree with these findings, there is disagreement in some studies, especially when it is difficult to define competitive level and age. The disagreement concerns three main aspects: *1*) period of the studies and improvement of methodologies; *2*) discrimination of methodologies between factors observed in numerical vs. experimental methods; *3*) evidence that drag tends to be non-linear and depends on personal, technical, and stylistic factors. Based on the complexity of active drag, the study of this phenomenon must continue to improve swimming performance.

KEYWORDS

active drag, water resistance, biomechanics, assisted swimming, resisted swimming

Introduction

Swimming performance concerning humans is poor compared to species whose habitat is aquatic. In fact, the maximum swimming speed performed by humans represents about 16% of the maximum speed obtained by aquatic species (Toussaint et al., 2004). One of the reasons for this difference in speed is the greater resistance humans encounter when moving through the water (Toussaint et al., 2004).

A swimmer's displacement relies on the net balance between propulsion and drag (Zamparo et al., 2020):

$$a = \frac{T - D}{m} \tag{1}$$

In which a is the acceleration (in m/s^2), T is the total propulsive force, i.e., thrust (in N), D is the total drag force (in N), and m is the total mass (i.e., swimmer's body mass plus the added mass of water, in kg). This is critical to understanding the biomechanical needs that determine better swimming performance. Therefore, when performing swimming strokes, the goal is to optimize speed by increasing propulsion and reducing drag (Zamparo et al., 2020). Drag is the force that swimmers must overcome to maintain the translation of their center of mass (Kjendlie and Stallman, 2008). It can be expressed by Newton's equation as:

$$D = \frac{1}{2} \cdot v^2 \cdot \rho \cdot S \cdot C_d \tag{2}$$

In which D is the drag force (in N), ρ is the density of water (in kg/m^3), v is the swimming speed (in m/s), S is the projected frontal surface area (FSA) of the swimmers (in m^2) and C_d is the coefficient of drag (changing according to shape, orientation, and Reynolds number).

The total drag consists of three components: *1*) friction drag (depends on the friction between the skin and the water); *2*) pressure drag (depends on body surface area); *3*) wave drag (depends on the water surface deformation) (Toussaint and Beek, 1992). Based on these components, total drag can be computed as:

$$F = F_f + F_p + F_w \tag{3}$$

In which F (in N) is the total drag force, F_f is the friction component (in N), F_p is the pressure component (in N), and F_w is the wave component (in N). Overall, it is generally accepted that frictional drag is the component with the smallest contribution to total drag, especially at higher swimming velocities (Bixler et al., 2007). Nonetheless, friction drag should not be disregarded in elite level swimmers. On the other hand, pressure drag and wave drag represent the most important part of the total drag, especially when performing a swimming stroke (Toussaint and Beek, 1992). Therefore, swimmers must intensify the most hydrodynamic postures during swimming.

Indeed, the literature reports two types of drag: *1*) passive drag; *2*) active drag. Passive drag (D_p) is the evaluation of the drag produced during the displacement of a towed body (i.e., without relative movement of the body segments in the aquatic environment) (Pendergast et al., 2006). Active drag (D_a) is the water resistance induced to a body while swimming (Kolmogorov and Duplishcheva, 1992). Studies on D_a are more common because during a race swimmers spend most of their time performing strokes (Morais et al., 2019).

In 1974, di Prampero et al., developed and used a method to evaluate drag during real swimming conditions through an energetic approach. All recent overviews of a swimmer's drag have confirmed this statement (Keys and Lyttle, 2007; Sacilotto et al., 2014; Morais et al., 2019; Zamparo et al., 2020; González-Ravé et al., 2022). Both types of drag and its components can be measured by numerical and experimental methods. The former (i.e., numerical methods) is a virtual prototype of the product of interest represented by a system of equations based on a mathematical theory, such as computational fluid dynamics (CFD) (Takagi et al., 2016). The latter (i.e., experimental methods) is a method in which the variables are manipulated in a pre-established way and their effects are sufficiently controlled and known by the researcher for the observation of the study (Takagi et al., 2016). CFD is one of several methods that have been applied in sports research to observe and understand the water flow activity around the human body and its application to improve swimming technique, equipment, and performance (Keys and Lyttle, 2007; Marinho et al., 2011). Smooth particle hydrodynamics (SPH) is a numerical method without a Lagrangian mesh, which allows a detailed quantitative analysis of swimming stroke variations and kinanthropometric variations. It is important to mention that there are few studies that use numerical methods to study D_a. Bixler and Schloder (1996) introduced two-dimensional CFD applied to swimming science. More recently, Cohen et al. have made progress in this method as they are the authors of some studies on numerical methodology that provide some interesting data (Cohen et al., 2015; Cohen et al., 2018; Cohen et al., 2020). However, in one of their studies, they mention that the angles of attack of the hands were compared with the contribution of lifting and dragging the hands to generate thrust in the direction of the current. This study allowed the investigation of possible connections between performance and asymmetries during swimming. Efficiency is negatively affected because periods of very high velocity consume exaggerated amounts of energy, considering that drag is non-linearly dependent on instantaneous velocity. Thus, a greater coefficient of variation of the swimmer's speed suggests a lower swimming efficiency (Cohen et al., 2018; Cohen et al., 2020).

Based on experimental methods, D_a can be measured through three approaches: *1*) measurement of active drag (MAD) (Hollander et al., 1986); *2*) velocity perturbation method (VPM) (Kolmogorov and Duplishcheva, 1992); *3*) assisted towing method (ATM) (Alcock and Mason 2007), and; *4*) measurement of residual thrust (MRT) (Narita et al., 2017). To determine D_a through experimental studies, it was found that MAD, VPM, and ATM are now commonly used to obtain D_a values accurately to assess swimmer technique (Toussaint et al., 2004; Formosa et al., 2012; Hazrati et al., 2016). The MAD system consists of pushing pads while the swimmer moves in the water performing the natural swimming movement (as much as possible) (Hollander et al., 1986). The thrust pads fixed below the water allow for the generation of propulsion without loss of energy (Formosa et al., 2012). The ATM system is relatively new compared to the MAD and VPM systems (Hazrati et al., 2016). The ATM system was developed identically to the bases of the VPM, except that it uses assisted towing and resisted swimming (Toussaint et al., 2004), as similar conditions are required in both tests. The main difference between the two is that the ATM produces D_a profiles and intra-course propulsion, rather than just an average measure of D_a (Formosa et al., 2012). The MRT method, which was recently developed, allows the estimation of drag in swimming using measured values of residual thrust (Narita et al., 2017; Narita et al., 2018b; Gonjo et al., 2020). Through this method, it is possible to investigate D_a at various speeds without neglecting the influence of stroke length.

As stated by Toussaint et al., 2004, it is known that human performance in water is dependent on many variables in addition to innate ones. In this way, we must consider all the variables that can compromise a better performance. Thus, these variables depend not only on their propulsive abilities but also on their ability to reduce to a minimum the drag forces that involve the body in a hydrodynamic way (Taïar et al., 1999). Studying active drag becomes relevant simply because it corresponds to the very act of swimming in a cyclical way, which consists almost of the entire race in high competition (Kolmogorov and Duplishcheva, 1992). Considering the importance that the measurement of drag has on swimming performance, it can be said that the evidence in the literature has not been systematically or narratively summarized, specially including studies based on both numerical and experimental measurements. It must be mentioned that Sacilotto et al. (2014) underwent a literature review on drag that also included numerical studies. The authors performed a biomechanical review of the techniques used to estimate or measure resistive forces in swimming. Therefore, the aim of this study was to carry out a systematic narrative review focusing on D_a (and its components) measured by numerical and experimental methods.

Methods

Literature search and article selection

Studies that analyzed D_a in swimming were searched in the following databases: Web of Science, Scopus, PubMed, and Science Direct. These electronic search databases were chosen as the most common databases related to methodological approaches in biomechanics applied to sport (framework, methodology, performance, and engineering). The studies that were selected met the following pre-defined inclusion criteria: *1*) follow the criteria defined in Table 1; *2*) are observational or intervention studies, *3*) are written in English, *4*) are published in a peer-reviewed journal; *5*) involve fully healthy real human swimmers (or their three dimensional scans – 3D); *6*) include tests performed to determine D_a in swimming; *7*) are related to the analysis of human movement in the aquatic environment; *8*) use numerical and experimental methods. Review articles, conference articles and books, studies including animals, and publications not related to the topic in question were excluded from the analysis. Studies with disabled swimmers were also excluded from this review. The Preferred Reporting Items for Systematic Reviews flow diagram (PRISMA in Figure 1) characterizes the identification, screening, verification of eligibility, and inclusion of the studies. PRISMA describes the flow of information through the different phases of a systematic review and includes maps or number of identified, included, and excluded records and reasons for exclusion.

The Patient/Problem, Intervention, Comparison and Outcome (PICO) search strategy is shown in Table 1. It presents the words used to carry out the research, supported by the words most used by the authors to describe their studies. Each title, abstract, and keyword field of the text was identified and carefully read for the first selection of journal articles. If any of these fields (title, abstract, and keywords) was not clear on the topic under analysis, it was necessary to read and review the entire article in question to ensure its inclusion. For the initial research, a Boolean search strategy was used based on a combination of keywords that can be seen in Table 1. After excluding all unrelated and duplicate articles, 75 articles were

TABLE 1 PI(E)CO (P – patient, problem or population; I – intervention; E – exposure; C – comparison, control, or comparator; O – outcomes) search strategy.

Population	Intervention or exposure	Comparison (design)	Outcome
Swimmer[a]	Development	Cross-sectional	Active drag
Athlete[a]	Long-term development	Longitudinal	Drag
Boy[a]	Biomechanics	Experimental	Performance
Girl[a]	Strength and conditioning	Descriptive	Coefficient of drag
Young[a]	Performance	Randomized control trial	Mechanical power
Men[a]	Competitive	Numerical	Assisted swimming
Women[a]		CFD	Resisted swimming
Male[a]		MAD-System	Forces
Female[a]		VPM	Drag forces
		Computational fluid dynamics	Biomechanic
		Quantitative analysis	Power input
		ATM	Power output
			Mechanical
			Water resistance
			Coefficient
			Friction
			Inverse dynamics
			Posture
			Hydrodynamic
			Resistance
			Balanced position
			Alternative fluid dynamic
			Underwater
			Body position
			Breaststroke
			Backstroke
			Front crawl
			Freestyle
			Butterfly
			Balance

[a]truncation to retrieve words with different endings.

selected for the final published review (Figure 1), comprising studies from 1986 until the end of the review research on 31 January 2022, as this was the latest study framed within the pre-defined selection model. From the selected articles, the reviewers extracted information about the aim of the study, the participants, the methods to measure the D_a in swimming, the characteristics of the numerical and experimental method (s), the measured variables, and the data analysis used.

Quality assessment

The Delphi method was used to assess the quality of the selected articles (knowing that Delphi is a process to develop a scale suitable for the purpose). It was noted that this approach (i.e., applying and creating a group scale) is an indicator of methodological quality (de Meyrick, 2003; de Morton, 2009). The Delphi method aims to structure a process of collective communication allowing a group of researchers to deal with a complex problem (de Meyrick, 2003). This method allows the creation of an evaluation scale for the articles selected for this study (de Meyrick, 2003; de Morton, 2009). Particularly when accessing numerical studies, there is a need to create a specific questionnaire and scale. Thus, it was agreed among the authors to create a questionnaire that would make the decision on the classification of the studies selected for this narrative review unanimous. In this way, through the Delphi method, the authors attempted to evaluate the following questions: *1*) Does the contemplated content meet the objective?; *2*) Was there a logic in the used methods?; *3*) Were the methods and subjects well defined?; *4*) Was there writing, language and clarity in the presentation of the contents covered?; *5*) Was the presentation of

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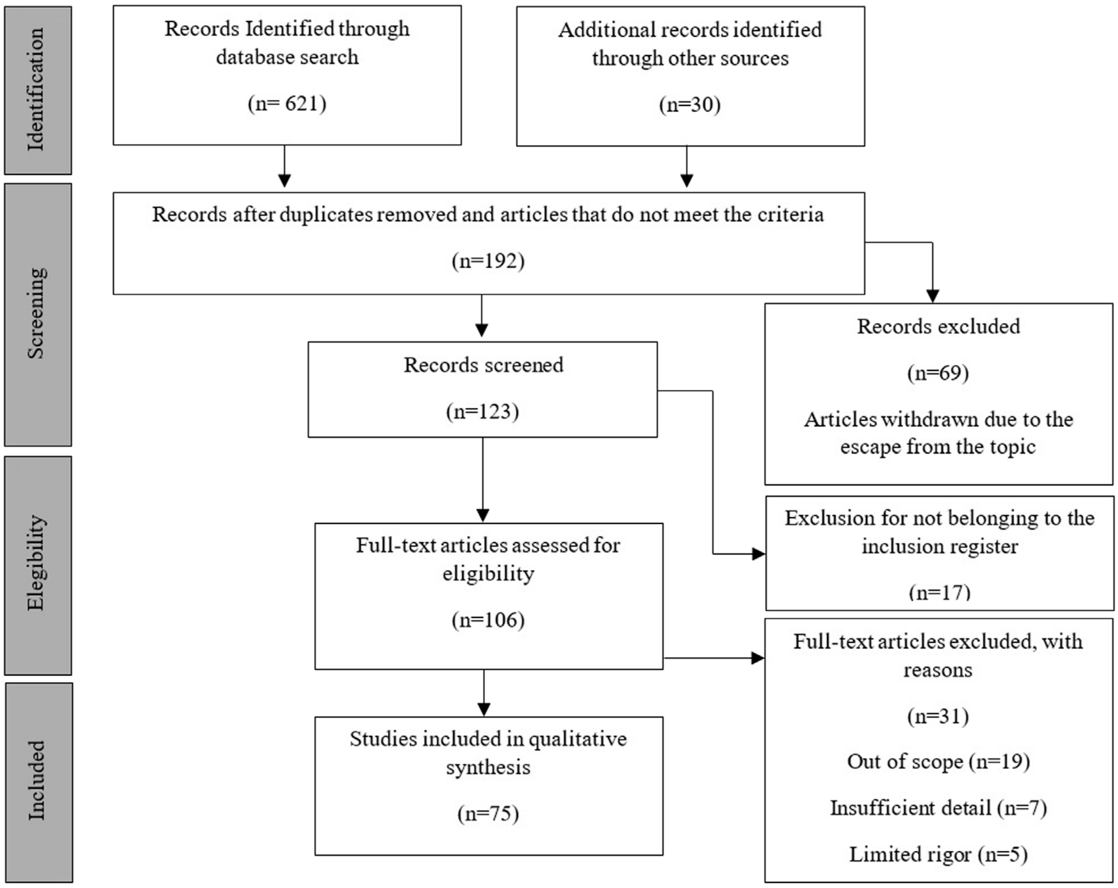

FIGURE 1
Summary of PRISMA flow for search strategy.

the results clear?; *6)* Are the results consistent with the culture of the study? Two independent reviewers read all articles and scored according to the items on the scale (poor quality if scored ≤2; fair quality if scored 3 to 4; high quality if scored 5–6) (de Meyrick, 2003; de Morton, 2009). Subsequently, Cohen's Kappa (K) was calculated to assess agreement between reviewers. It was interpreted as *1)* no agreement if K ≤ 0; *2)* none to slight if 0.01 < K ≤ 0.20; *3)* fair if 0.21 < K ≤ 0.40; *4)* moderate if 0.41 < K ≤ 0.60; *5)* substantial if 0.61 < K ≤ 0.80; *6)* almost perfect if 0.81 < K ≤ 1.00 (McHugh, 2012). After reviewing all articles, the Delphi scale showed a mean score of 5.85 ± 0.38 (i.e., high quality if scored), and Cohen's Kappa an almost perfect agreement between reviewers (K = 0.651, $p < 0.001$). The Delphi scores are presented in Table 2 for each article.

Results

A total of 75 studies met the inclusion criteria, of which seven used the numerical method and 68 the experimental method. The criterion for defining which studies to include was unanimous, and so it was decided to consider all studies regardless of their type of method. However, it was essential that the topic of the study followed the needs described in Table 1.

Table 2 present a summary of the included studies, indicating the authors, year of publication, objective, number of participants, if applicable, and main results, for studies based on numerical and experimental methods, respectively.

Seven studies analyzed D_a based on numerical methods (including five studies on front crawl, two on backstroke, four on butterfly, and one on breaststroke (considering front crawl and dolphin kick), in which some studies include several techniques) (Table 2). All studies used swimmers as a sample, despite being models (scans of athletes or three-dimensional programming of at least one or more swimmers as their sample). Sixty-eight studies analyzed D_a based on experimental methods (including 64 studies on front crawl, six on backstroke, two on butterfly, and six studies on breaststroke (considering front crawl and dolphin kick)) (Supplementary Table S1). They used human swimmers in their entire sample, all with effective experience in the modality and training.

TABLE 2 Summary of the objective, sample demographics, and main results of the studies related with D_a for numerical methods.

Study (year)	Objective	Subjects (age and competitive level)	Results	Delphi score Mean ± 1 SD
Cohen et al. (2012)	Determine the relative importance of the extension kick (often called downbeat) compared to the flexion kick (often called upbeat) in dolphin kick swimming	Smoothed Particle Hydrodynamics (SPH). Laser scans of athletes are used to provide realistic swimmer geometries in a single anatomical pose. These are rigged and animated to closely match side-on video footage	Swimmer strength depends on kick frequency and is insensitive to ankle flexibility. The maximal drag force occurs in the direction of the current, corresponding to the periods before the inversions of strokes, and swimmers must pay attention to the rapid inversions of direction	5.0 ± 0.0
Cohen et al. (2014)	Determine the pitching effects of buoyancy during all competitive swimming strokes (front crawl, backstroke, butterfly, and breaststroke)	Laser body scans of national-level athletes and synchronized multiangle swimming footage were used in a novel markerless motion capture process to produce three-dimensional biomechanical models of the swimming athletes	Variation in buoyancy torque is much larger during breaststroke and butterfly than during front crawl and backstroke; pitching swimmer moment of inertia varies much more for butterfly and breaststroke than for front crawl and backstroke; that buoyancy torque and pitching swimmer moment of inertia are anticorrelated during butterfly and breaststroke	5.0 ± 00
Cohen et al. (2015)	A combination of kinematic data and SPH-based flow modeling was used to explore the degree to which the instantaneous impulse generated by the arms is controlled by the trajectories of the hands, their orientation and speeds during the front crawl stroke	SPH fluid model is used to analyze the thrust and drag generation of a front crawl swimmer. The swimmer model was generated using a three-dimensional laser body scan of the athlete and digitization of multi-angle video footage (CFD)	Two large distinct peaks in liquid thrust coincide with underwater strokes. The movement of the hands generates vortex structures that travel along the body (there is the production of lift and drag)	6.0 ± 0.0
Cohen et al. (2018)	Investigate how the streamwise speed and net streamwise forces of the swimmer vary throughout the phases of the stroke. The dependence of the relative thrust from the arms compared to the legs on the stroke rate was also investigated	A dynamic biomechanical model of a female national-level swimmer was generated from a three-dimensional laser body scan of the athlete and multi-angle videos of sub-maximal swimming trials (CFD)	The Froude number varies from 0.40 to 0.31, meaning that the swimmer swims close to Fr = 0.42 (hull speed), consequently the drag of waves on the surface is significant	6.0 ± 0.0
Cohen et al. (2020)	The asymmetrical front crawl swimming performance of a male elite level swimmer who breathed every second arm stroke (unilaterally) was investigated	A laser body scan and multi-angle video footage of the athlete were used to generate a swimming biomechanical model (one male elite level)	The natural asymmetrical performance with the swimming movement acquired through the frontal area results in a greater D_a (swimmer's technique) are the main findings. These will help improve athletes' performance and coaches' decision making	6.0 ± 0.0
Keys and Lyttle, (2007)	Sought to discriminate between the D_a and propulsive forces generated in underwater dolphin and flutter kicking using the CFD technology	A 3D image of an elite swimmer was animated using results from a kinematic analysis of the swimmer performing two different patterns of underwater dolphin kick (large/slow kicks *versus* small/fast kicks) and the underwater flutter kick	Advantage in using the swim kick in the underwater flutter kick over the small/fast or large/slow kick at 2.18 m/s There are benefits in prescribing techniques through the use of CFD models	6.0 ± 0.0
Yuan et al. (2019)	Find the mechanism of the hydrodynamic interaction between human swimmers and to quantify this interactive effect by using a steady potential flow solver	Only interested in the wave drag component. No attempt is made here to analyze the other drag components due to the viscosity of the fluid One passive swimmer; three swimmers in competitive swimming; and another observations	Showed that the hydrodynamic interaction made a significant contribution to the drafter's wave drag. By following a leading swimmer, a drafter at wave-riding positions could save up to 63% of their wave drag at speed of 2.0 m/s and lateral separation of 2.0 m/s. When a drafter is following two side-by-side leaders, the drag reduction could even be doubled	5.0 ± 00

D_a, active drag; CFD, computational fluid dynamics; SPH, coupled biomechanical-smoothed particle hydrodynamics; F_r, froude number; C_d, coefficient of drag; SD, one standard deviation.

Discussion

The aim of this study was to perform a systematic narrative review on the up-to-date body of knowledge on D_a and its components through numerical and experimental methods. In the studies that used numerical methods for the D_a analysis, it was found that the main focus was to: *1*) confirm whether the drag measured the same force throughout the entire path; *2*) verify the variation within the stroke cycle or between stroke cycles. Overall, the studies that focused on the experimental methods to assess D_a tended to: *1*) present the comparison between the determining factors of performance; *2*) emphasize the comparison between the drag variation at different swimming speeds and between sexes and age groups.

Numerical methods – D_a

Most studies were focused on the front crawl stroke for submaximal speeds (Cohen et al., 2012; Cohen et al., 2018; Yuan et al., 2019). It was found that the ratio of arm thrust to leg thrust increases with a higher stroke rate (Cohen et al., 2018). However, the attempt at specificity is also evident, i.e., they investigate specific movements such as kicks and arm strokes (cycles). Another study also analyzed the effects of buoyancy during swimming and the drafting as a parameter performance for competition (Cohen et al., 2014). Additionally, the authors observed that at different flow velocities, the hydrodynamic coefficients considered were not constant, knowing that the variation for different hand positions was examined for different phases of the path (Cohen et al., 2018). Regarding D_a using numerical methods (Table 2), it was noted that the coefficient of variation (CoV) decreases from 4.8% at the lowest frequency to 3.9% at the highest frequency, indicating that velocity fluctuations decrease with the stroke rate (Cohen et al., 2018). It also highlights the asymmetries in the duration of the different phases of the strokes. The right arm had a 33% shorter impulse period and a 14% longer recovery period than the corresponding periods of the left arm. The duration of the traction phase was similar for both arms (Cohen et al., 2018). There are differences between the use of the underwater flutter kick over the large/slow kick or small/fast kick at 2.18 m/s (Keys and Lyttle, 2007), confirming that the D_a, in relation to all these variables, is entirely influenced by the great variation between asymmetries, type of stroke, type of kick, and considering the type of style the swimmer is performing.

During the movements, vortex structures are generated by the arms, which then pass along the body towards the movement of the legs (using a female swimmer at submaximal speed in front crawl). These structures dissipate quickly due to the high-frequency kicking of the legs. There are earlier and more recent references (Cohen et al., 2018; Cohen et al., 2020) that suggest that generated vortices can be used to increase propulsion through vortex recapture. Another study that determined the pitching effects of buoyancy during all competitive swimming strokes (front crawl, backstroke, breaststroke, and butterfly) with a male swimmer and a female swimmer at constant submaximal speed verified that the average thrust torque tended to increase in the legs and decrease in the head (Cohen et al., 2014). However, the instantaneous torque had an opposite effect during part of the throttle stroke. In addition, the alternating techniques (front crawl and backstroke) showed smaller variations in the positions of the center of mass, thrust torques and positions of the center of thrust (Cohen et al., 2014). The simultaneous techniques (butterfly and breaststroke) showed greater variations in buoyancy torques, directly influencing the swimmer's ability to maintain a horizontal inclination to perform the strokes. This helps athletes swim efficiently by minimizing their frontal areas and the consequent pressure drag (Cohen et al., 2014). The CoV values were moderate for front crawl (53% for women and 26% for men, respectively, this order will be used from now on) and backstroke (52% and 28%), with female values being approximately twice than those of males. The CoV values for butterfly (132% and 133%) and breaststroke (130% and 127%) were significantly higher than for the other strokes. The CoV is higher for strokes with synchronized limb movement. The CoV, and consequently D_a, change depending on the movement or swimming phase, being different between kicks and strokes (Cohen et al., 2015). Regarding dolphin kicks, it was observed that the CoV of swimming velocity remains small (7–9%) in experiments with dolphin kicks even when the frequency increases. The amplitude of velocity fluctuations increases, which turns out to be much lower than other intracycle simulations (28–59%). The extension kick proved to be more important than the flexion kick (extension can also be known as down in prone swim and up in dorsal swim) for generating momentum (Cohen et al., 2012). The study by Keys and Lyttle (2007) also demonstrated that it is beneficial to use the underwater flutter kick over the large/slow kick or the small/fast kick using the CFD method.

In all techniques, but mostly in front crawl, swimmers should focus on maximizing their leg extension (it can be called the whiplash effect), as this generates most of the impulse (Cohen et al., 2012). Additionally, they should focus on decreasing D_a, even knowing that these values change according to important multivariable and that they derive from the variation of swimming along the swimming path. For example, the full dolphin kick strikes a balance between minimizing drag and maximizing thrust while minimizing the physical effort required of the swimmer (Cohen et al., 2012). The periods before course reversals correspond to the maximum drag forces in the direction of the current, so swimmers should be aware of rapid reversals of direction (turns). After starting and turning, increasing stroke frequency (SF) automatically results in a linear increase in speed. All these recommendations described can be useful to optimize the swimmer's stroke technique (Cohen et al., 2012). It can be assumed that studies with numerical methods have a higher percentage of studies variability (83.3% focus on the front crawl technique), despite a low number of articles that consider D_a. Most studies that focus on front crawl try to evaluate multivariable (strokes, kicks, and stroke frequency), but always at constant speed (submaximal). In a way, studying the drag while considering these variables has become crucial in these studies. In butterfly, studies focused on the analysis of underwater dolphin kicks concluded that cases of higher kick frequency produced higher peaks of both thrust and drag, as already mentioned in a study by the same author that focuses on the front crawl technique. The extension kick proved to be more important for generating momentum than the flexion kick. The only study that showed a greater range of study was the one by Cohen et al., 2014 in which they compared all swimming techniques for a constant submaximal speed. The authors confirmed that the variation in buoyancy torque is much greater during breaststroke and butterfly than during front crawl and backstroke, having a peak of D_a in this phase compared to the other techniques.

It should be noted that numerical methods that measure D_a have some limitations. A main limitation of the laser body scanned method is that the volume enveloped by the triangular surface mesh is assumed to be of uniform density on the entire swimmer's internal volume, which requires a very detailed reproduction of the swimmer's body, as well as specific kinematics to be accurate (Cohen et al., 2012; Cohen et al., 2015). Another limitation is the approximation of the free surface as a horizontal plane (Cohen et al., 2012; Cohen et al., 2015). Swimming involves rapid accelerations and decelerations of the limbs and the estimates obtained are highly limited (Cohen et al., 2015). Regarding the numerical methods, the body position was limited to a single angle to prevent the swimmer's model from deviating from its course, which ended up conditioning the trajectory, and the results obtained (Cohen et al., 2020). These limitations constitute a solid basis to be considered in future studies (Cohen et al., 2015; Yuan et al., 2019).

Experimental methods – D_a

Effects of D_a on elite/adult swimmers

Historically, D_a was first measured in adult swimmers (e.g., di Prampero et al., 1974; Kolmogorov et al., 1997). Overall, studies noted that drag and C_d are about 1.5–2 times greater in D_a than in passive conditions (di Prampero et al., 1974; Kolmogorov and Duplishcheva, 1992). In addition, such studies confirmed that better swimming technique reduced D_a essentially due to reduced C_d. Indeed, Kolmogorov et al. (1997) supported the idea that elite swimmers have a greater ability to reduce D_a than non-elite swimmers. More recently, Neiva et al. (2021) analyzed the effects of a swimming training mesocycle on the performance and D_a of master swimmers in front crawl. The authors concluded that there is an improvement in the performance of master swimmers after 4 weeks of aerobic training. This also resulted in the reduction of D_a while swimming mainly at submaximal speeds. Therefore, based on the literature, it can be stated that technical training plays a key role on reducing D_a. Nonetheless, adult/elite swimmers tend to present greater D_a and power needed to overcome drag, especially when the competitive level increases (Zamparo et al., 1996; Takagi et al., 1999; Toussaint et al., 2004; Zamparo et al., 2009; Seifert et al., 2010; Morais et al., 2020a; Kolmogorov et al., 2021). Furthermore, it is known that there are several variables that can directly influence the drag of a swimmer, as expressed in Eq. 3. Such variables are also dependent on external variables and in adults become even more important (Kolmogorov et al., 1997; Kjendlie and Stallman, 2008). Adult/elite swimmers tend to have a larger FSA and a fastest swimming speed than other age groups (Gatta et al., 2015; Kolmogorov et al., 2021; González-Ravé et al., 2022). Body position may also affect the hydrodynamic position and, consequently, D_a. For example, Formosa et al. (2014) aimed to quantify the influence of the breathing action on D_a during swimming. This variation is reported to be large when compared to non-breathing, with a 16%–26% difference in drag force during swimming. The simple act of breathing changes D_a, so this variable must also be considered. Others aimed to study D_a in a completely different way, examining relationships between IdC and D_a assuming that at a constant speed, the average drag is equal to the average propulsion, expressing the idea presented in Eq. 1 (Seifert et al., 2015). In front crawl swimmers, changes in inter-arm coordination were linked to changes in resistance forces when swimming at different speeds. A significant and positive linear regression between IdC and D_a was observed (Seifert et al., 2015). Overall, adult/elite swimmers present greater values of D_a, mainly based on the assumption that they generate a greater metabolic power and mechanical power (Gatta et al., 2016; Kolmogorov et al., 2021).

Effects of D_a on young swimmers

Active drag has been largely studied in young swimmers over the last decade, specifically in front-crawl (Kjendlie et al., 2004; Barbosa et al., 2010b; Marinho et al., 2010a; Morais et al., 2012; Morais et al., 2021). In studies on this topic, the authors noted that the best performers were also those with the highest D_a and CD_a (Morais et al., 2015; Barbosa et al., 2019). As expressed in Eq. 2, drag variables are highly dependent on swimming velocity and FSA. This indicates that bigger and faster swimmers are more likely to be under more drag (Barbosa et al., 2019; Silva et al., 2019; Morais et al., 2021). For example, top performers in freestyle sprinting events (front-crawl swim) not only had faster swimming velocity and better kinematics and swimming efficiency but also higher D_a (Barbosa et al., 2013; Ribeiro et al., 2017; Barbosa et al., 2019). Thus, D_a should be analyzed with some caution in young swimmers. That is, not always an increase in D_a can be related to a decrease in performance. As young swimmers go through growth and maturation processes, they increase their body features, more specifically their FSA (Morais et al., 2020a; Morais et al., 2021). Therefore, an increase in body features leads to an increase in swimming velocity as well as in D_a. Indeed, even in detraining periods this phenomenon occurs. It was noted that during an 11-week detraining period, swimmers increased their FSA (as well as other anthropometric features), and their swimming velocity and D_a (Morais et al., 2020a). This highlights the importance that anthropometrics have on swimming velocity and D_a. On the other hand, performing specific training to improve swimming technique may have a positive impact on the swimmers' D_a. For instance, Marinho et al. (2010a) aimed to assess the effects of 8-week of training in young swimmers' D_a. Although non-significant differences were found over time, the authors observed that later on, D_a and CD_a

decreased in both genders. Authors argued that 8 weeks of specific swimming training were not sufficient to allow significant improvements on swimming technique (Marinho et al., 2010a). A reason for this non-significant effect can be the anthropometric factor, as young swimmers tend to increase their body dimensions. Furthermore, others aimed to understand the effect of D_a on swimming performance during an entire competitive season (Morais et al., 2014). It was noted that depending on the season moment and training periodization, the effect of D_a on swimming performance changes. At the beginning of the season, when the main aim is to increase energy, D_a is the main determinant of performance. Again, as D_a is strongly related to swimming velocity, an increase in swimming velocity will lead to an increase in D_a. This indicates that coaches of young swimmers should be aware that when the goal is to build energy quickly, this can lead to an increase in D_a and CD_a (variables related to swimming technique).

Sex effect

Studies have compared D_a between genders, whether among adults (Pendergast et al., 1977; Kolmogorov et al., 2021) or young swimmers (Barbosa et al., 2013; Barbosa et al., 2015a). In adults, D_a and the hydrodynamic coefficient at maximum speed in front crawl showed significant differences between genders (Xin-Feng et al., 2007; Kjendlie and Stallman, 2008; Marinho et al., 2010b). Based on the literature, it can be stated that front crawl is the most analyzed stroke and boys/men are more studied than girls/women. In any case, studies corroborate the idea that the values presented by men compared to women are always higher, in regard to strength and D_a (Kolmogorov and Duplishcheva, 1992; Kolmogorov et al., 1997). Initially, Toussaint et al. (1988), who analyzed D_a in relation to speed in male and female swimmers, observed that differences in drag force and C_d are significant regardless of the speed in question. In addition these differences are also strongly present when all techniques other than front crawl are evaluated, ranging from 48.57 N to 105.88 N in men and 36.25 N–77.01 N (Xin-Feng et al., 2007). In another recent study, in all swimming techniques regarding metabolic power, men showed higher values of metabolic power and greater mechanical efficiency than women (P_{ai} = 3346–3560 W and e_g = 0.062–0.068 vs. P_{ai} = 2248–2575 W and e_g = 0.049–0.052, correspondingly in this order) (Kolmogorov et al., 2021). In all swimming techniques and for both sexes, values of metabolic power and mechanical power increased with exercise intensity (Pendergast et al., 1977; Kolmogorov et al., 2021). The opposite effect can be observed when technical components are analyzed, namely the influence of breathing on the effect of D_a during swimming. Formosa et al. (2014) demonstrated that male participants who exhibited a breathing action caused a greater net drag force (26%) compared to females (16%). This confirms once again that these authors agree with others who state that the increase in D_a is not synonymous with worse performance, but simply a natural increase in D_a when the performance is also better (Seifert et al., 2010).

In an approach aimed at young swimmers, in relation to all swimming techniques but mostly front crawl, studies show that several anthropometric, kinematic and efficiency variables were significantly higher in boys than in girls (Morais et al., 2012; Barbosa et al., 2013; Barbosa et al., 2015a). Comparing both sexes, Barbosa et al., 2015a indicated that most of the studied variables showed non-significant differences (controlled for sprint performance). Nonetheless, boys performed better than girls due to their larger constitution and natural physical development at these ages (Barbosa et al., 2015a; Barbosa et al., 2015b). Thus, it is evident that adults present much more solid results regarding the comparison between genders because young swimmers are in the process of maturation and growth. These changes in the morphology of young swimmers can constantly affect their hydrodynamics (Morais et al., 2015; Morais et al., 2020a). Likewise, Barbosa et al. (2015b) when analyzing the changes in the hydrodynamic profile of young swimmers throughout a season, realized that no variable had a significant sex effect, due to the fact that throughout the season the hydrodynamic changes occurred in a non-existent linear way. This is clear when analyzing the differences between the beginning and the end of the epoch, as the drag decreased when comparing these moments (−4.37 ± 39.36%). Additionally, the study by Morais et al. (2014) corroborates this statement, confirming that the latent growth curve shows high variability in performance growth and that there is a significant effect on performance growth between genders.

Determinants of D_a

As shown in Eq. 2, D_a is dependent of speed, FSA, and C_d (in water density, which is constant). Initially di Prampero et al. (1974), pioneered the study of body drag and mechanical efficiency during swimming at speeds of 0.55 and 0.9 m/s. It was shown that the basic approach and the quantitative analysis of swimming proficiency were promising for the study of different forms of locomotion on and under the water surface. The studies by Zamparo et al. (1996) and Clarys (1985) found out that drag in the prone position under the water surface was greater than on the water surface, but the D_a reached twice the values of drag in relation to passive drag during swimming. The actual strategy implemented by swimmers to neutralize underwater torque tolerates a large increase in D_a (Zamparo et al., 1996; Zamparo et al., 2009). Lyttle et al. (1999) and Lyttle et al. (2000) aimed to analyze the variability and amount of drag at different speeds and depths. They showed that for speeds between 1.6 and 3.1 m/s there were no significant differences in drag forces recorded between the speeds indicated in front crawl, although the coefficient of the measures of variation for these tests indicated high reliability. However, although the differences are not significant, there is a tendency for the drag force to present a difference between the speeds, and it is evident that this force constantly increases (Lyttle et al., 1999; Lyttle et al., 2000). This may be because the applications of the towing device for swimming trawl research are widespread (Lyttle et al., 1999). It is necessary to take specific variables such as establishing the improved speed to start the underwater movement (Lyttle et al., 2000), in which results show that experienced swimmers should glide after pushing the wall until they decelerate to speeds between 2.2 and 1.9 m/s for maximum D_a reduction benefits at higher glide speeds.

When comparing the drag/velocity relationship, it was shown that greater drag forces promoted a greater intracycle variation of horizontal velocity (di Prampero et al., 1974; Lyttle et al., 1999). However, as drag depends on the square of velocity, a comparison between swimmers is only relevant when: *1*) it is done at the same absolute velocity, or *2*) the effect of velocity is somehow controlled later (Barbosa et al., 2014). The same authors revealed that there were positive and moderate to strong associations between D_a and velocity (intracycle variation) when controlling for the effect of swimming velocity alone in each test (i.e., slip decay velocity method and perturbation velocity method) and swimming speeds in young swimmers as well. Thus, empirical research confirms the theoretical relationship defined for the intracycle variation of horizontal velocity and drag. It can be mentioned that this topic was first argued in the study by di Prampero et al. (1974). The authors reinforced the idea that a change in velocity affects mechanical efficiency because a change in velocity leads to a change in the body's reaction to water and similar variations in the mechanical efficiency and strength of the body. Another study indicated one relevant technique to estimate D_a (Shimonagata et al., 1999). The aim was to clearly show the relationship between swimming speed and D_a in front crawl swimming. This study was innovative at the time because the subjects were towed with the D_a system (a towing device like the ATM and VPM) in a hydrodynamic position and the subjects swam several attempts at maximum speed (with additional resistance and with towing by the D_a system) (Shimonagata et al., 1999). The propulsion, D_a, and swimming speed present a significant correlation, showing that swimming performance depends both on propulsion and D_a. Thus, it was essential to verify the existence of a balance between the power generated by the thrust forces and the power needed to overcome the drag forces in front crawl, evaluating the thrust and estimating D_a at maximum speed (Gatta et al., 2016). The authors noted that the swimmer's buoyancy force is very close to the force needed to reduce D_a (Gatta et al., 2016; Gatta et al., 2018). Furthermore, another study by Gatta et al. (2018) explored the relationships between mechanical power, thrust power, propulsion efficiency and sprint performance in elite swimmers, reporting that maximum speed in sprint swimming depends on the interaction between power in dry conditions (using a full-body swimming ergometer) and propulsion efficiency. Furthermore, the relationship between maximum velocity and power data was observed with the first method used (in the pool by measuring full tethered swimming force and maximum swimming velocity). The propulsion efficiency is about 40% and the drag is about 1.5 times greater than the values generally reported during passive drag measurements (Gatta et al., 2018). Furthermore, studies such as the one by Shimonagata et al. (1999) showed that swimming speed progresses with increasing propulsion and decreasing D_a (Seifert et al., 2010; Gatta et al., 2016; Gatta et al., 2018).

Frontal surface area is another major determinant of D_a. Knowing that FSA can dynamically change (i.e., variation) during the swimming stroke, researchers set out to assess whether a single FSA measure is adequate to obtain estimates of D_a and mechanical power (Morais et al., 2020b; González-Ravé et al., 2022). The authors noted that, in addition to FSA, swimming speed also changes during arm pull in front crawl, in young swimmers of both sexes (Morais et al., 2020b). There was a significant effect on the variation of the two variables of mechanical power and total input power, as well as on the measure of D_a (Morais et al., 2020b). Thus, it is worth mentioning that the variation of the FSA throughout the course cycle must be considered in the assessment of D_a (Gatta et al., 2015; Morais et al., 2020b; González-Ravé et al., 2022). Furthermore, Kolmogorov et al. (2021) recently determined that the FSA as a component of D_a force is the main reason for the differences in maximum speed among the swimming techniques, as there were no relevant differences for the mechanical and propulsion efficiencies. The body position and swimming coordination parameters have an important influence on performance in different swimming strokes (Zamparo et al., 2009; Stosic et al., 2021). In addition, the body position and coordination between the limbs of competitive swimmers during the transition from underwater to surface swimming represented important factors in swimming speed, explaining 15–30% of the variation during the first stroke cycle (Stosic et al., 2021). This reinforces the idea that swimmers must carefully control the inclination and depth of the body and its coordination between the limbs, especially in the first stroke cycle after swimming underwater. Another study showed that waist indentation and buttock curvature can result in greater drag force and influence swimming performance. When differences in C_d exist, it may be due to the assumption used in D_a methodologies that a swimmer's velocity remains constant throughout the stroke cycle, rather than fluctuating, particularly in front crawl (Papic et al., 2020). D_a and C_d had a negative effect on performance, being related to the increase in speed during the act of swimming (Morais et al., 2021). There are also significant correlations between anthropometric variables and D_a (Barbosa et al., 2019). In addition, this also happens in front crawl, which results in 69% of the performance in young swimmers, for kinematic variables (efficiency), power in the water and strength on dry land (Morais et al., 2016). After a 10-week break, young swimmers show biomechanical improvements that are mainly explained by their normal growth. SF, D_a, and CD_a remained unchanged, however, improving performance while maintaining D_a is a success factor (Moreira et al., 2014). An earlier study by Sharp and Costill (1989) found that the removal of body hair when swimming in breaststroke reduces the D_a, and, thus, the physiology cost of swimming. which directly influences the biomechanical performance of swimming.

Checking the external determinants that directly influence the performance and D_a of swimmers, Benjanuvatra et al. (2002) concluded that D_a values are lower in swimmers who wear competitive suits (Fastskin ™) when compared to traditional swimwear ($p < 0.01$), not adopting a specific swimming technique, but a prone position. This variation occurred between 4.8% and 10.2%, and when the underwater flutter kick condition was excluded, all these differences were significant ($p < 0.05$). Moriyama et al. (2021) showed that Jammer-type race swimsuits improve sprint performance to accompany the increase in maximum swimming speed compared to the conventional training swimsuit, in front crawl. In a relatively recent and innovative study, researchers showed that the AquaTrainer® snorkel does not lead to an increase in D_a during the front crawl performed over a wide range of speeds (Ribeiro et al., 2016). In addition, other studies have highlighted the importance of analyzing D_a as an important variable to be considered in training (Supplementary Table S1), since the most advantageous pulling distance between members of the same team is between 0 and 50 cm from the lead swimmer, where drag is reduced by 21% and 20%, and in which 6% and 7% represent 50 and 100 cm from the lead swimmer. This is true for front crawl, in which maximal and submaximal speeds were analyzed (Kjendlie et al., 2004; Kjendlie and Stallman, 2008; Barbosa et al., 2013).

Drafting is certainly an underdeveloped subject in the literature, but it is known that the effect of distance between swimmers directly influences metabolic and hydrodynamic responses (Chatard and Wilson, 2003). A 4% body difference in underwater volume ($p < 0.001$) between the two techniques in the 3D motion analysis also confirmed that the pressure drag and the friction drag were higher between the techniques (Gonjo et al., 2020). In a pioneering study by Yuan et al. (2019), it was shown that the hydrodynamic interaction between human swimmers can best be described and explained in terms of the interference effect of the wave on the surface of free water.

Overview and practical applications

It is important to mention that all experimental methods that exist to measure and evaluate D_a indicate that there is no agreement among each other regarding the values presented (Toussaint et al., 2004; Formosa et al., 2012). Nonetheless, all authors stated that all equipment measure the same phenomenon, and it can be said that none is more effective than the other (i.e., no gold-standard exists). They simply measure the effects differently and give different results. Some of the methods used were not completely reliable, as there is some margin of error; however, they highlight some issues that coaches should keep in mind not to apply in training or even to apply in an improved way, putting into practice some of the positive points applied in these studies, even if they present some margin of error. For example, the error in the Kolmogorov method can be attributed to the theoretical basis of the equal power assumption (Toussaint et al., 1988; Strojnik et al., 1999). Another analysis corroborated this by showing that the methods used measured essentially the same phenomenon of D_a (Toussaint et al., 1988; Toussaint et al., 2004; Formosa et al., 2012). It is probably more appropriate to state that these methods coincidentally underestimate the D_a coefficient by a similar magnitude.

D_a is defined by the change in characteristics resulting from the flow around different parts of the body following the movement performed. That is why it is essential to have a strategic notion of body movements throughout the stroke cycles, performing in continuous, active and less passive movements. This confirms the need of D_a to be further studied and transmitted to coaches. It is also necessary to understand the implications of D_a on performance in a homogeneous way. However, it is believed that decomposing total drag into pressure drag, friction drag and wave drag is useful to understand the physical mechanisms that determine drag.

The study of drag is increasingly essential to collaborate with coaches in the process of understanding the fundamental patterns of movement biomechanics to achieve the best performance in swimming (Pendergast et al., 1977). Thus, through the D_a research, it was possible to perceive that most studies present very important aspects of swimming technique, more practical movements and easy-to-maneuver variables, such as the distance between swimmers in a training session (aspiration cone), which can be changed depending on the group and type of work considered (Kjendlie et al., 2004; Kjendlie and Stallman, 2008; Barbosa et al., 2013). Furthermore, it will be essential to understand the drag variables regarding each of the four swimming techniques (Xin-Feng et al., 2007; Kjendlie and Stallman, 2008; Marinho et al., 2010b), observing that the values of drag and drag coefficient change completely (highlighting their oscillation and main difference).

Morais et al. (2011) showed that swimming performance in young swimmers is influenced by their swimming efficiency. Therefore, coaches and practitioners of young swimmers should design training programs with a focus on improving technical training (i.e., improving swimming efficiency), indicating that there are data showing that swimming performance is dependent on the SI (an efficiency estimator) and this, in turn, on dv, SL, AS, and D_a (Morais et al., 2011). Considering the performance, latent modeling (modeling a latent growth curve) is a comprehensive way of collecting information about the performance of young swimmers over time. The performance improvement was influenced by the different variables, as well as showing an intra and inter subject variability between genders (Morais et al., 2014; Morais et al., 2015). Otherwise, cluster stability is a feasible, comprehensive and informative method of obtaining information about changes in young swimmers over time. Swimmers can be classified into different clusters based on their performance and determinant factors (Morais et al., 2015).

Finally, it can be confirmed that the resistive or drag images found during swimming greatly influence the swimming performance of swimmers of different age groups, including those in elite competition. The benefits of understanding the factors that affect drag are found to improve performance in this sport in different ways that can be analyzed (Sacilotto et al., 2014). However, current techniques used to measure or experimentally estimate drag values are questioned as to their consistency, thus limiting investigations to certain factors. A recent problem is to understand the best method to be applied to study and analyze the variables considered and to determine a context and purpose. Knowing that the range of methodology is wide but not specific, it can bring some confusion to the process, despite being multifaceted (Sacilotto et al., 2014).

Conclusion

Regarding numerical studies, considering all swimming strokes for a constant submaximal and maximum speed, it was found that the variation in buoyancy torque is much greater during breaststroke and butterfly than during front crawl and backstroke. Experimental studies observed that D_a is greater in adults than in children. It is also meaningfully different between sexes with greater values achieved by males. Furthermore, it is evident that speed and FSA are the biggest contributors to the increase in D_a (adults have a higher D_a value because males and adults tend to have higher speed and FSA). Finally, the technical training dedicated for this purpose makes it possible to reduce D_a and CD_a and thus improving performance. Through longitudinal studies with pre and post-test it is possible to understand the variability of drag throughout the season and to understand the progression and changes in performance. The intensity of the drag force depends on some factors, among which it is possible to highlight the swimming technique and the morphological characteristics of the subject. The FSA appears as the main morphological characteristic of the subject, having a preponderant role in the determination of the drag force intensity.

It is necessary to understand how the resistive forces in swimming are measured and calculated, because like any method they demonstrate strengths and weaknesses in the evaluation of the techniques described in swimming. Furthermore, it can be indicated that D_a is higher in men than in women, while CD_a is not clear in the literature as to its significance between genders. Nevertheless, it is known that the CD_a between the sexes cannot behave in a different way, because swimming efficiency depends on the drag coefficient. In this sense, the drag coefficient will also show a significant result. Notwithstanding, it should be mentioned that these results and outputs are based on discrete variables measured during an entire trial. Future studies should be conducted to understand how D_a and CD_a can change within a stroke cycle in all four swimming strokes.

Data availability statement

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

Author contributions

TL, JM, and DM conceived and designed the study. TL and JM performed the search and data analysis. JM and DM performed the quality assessment. TL and MP carried out the drafting of the manuscript. All authors reviewed the manuscript and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fphys.2022.938658/full#supplementary-material

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Glossary

ρ density of water

a acceleration

AIS assisted towing method

AP pitch angle

AS arm span

ATM assistant towing method

C_d coefficient of drag

CD_a coefficient of active drag

CFD computational fluid dynamics

CoV coefficient of variation

C_x hydrodynamic coefficient

D drag force

D_a active drag

D_p passive drag

dv speed fluctuation

EM experimental method

F total drag force

F_d active drag force

F_f friction component

F_p pressure component

F_r froude number

FSA frontal surface area

F_w wave component

ICC intra-class correlation coefficients

IdC coordination index

IVV intra-cyclic velocity variations

K Cohen's Kappa

M total mass

MAD measuring D_a system

MRT residual thrust measured values

NM numerical method

P_{ai} metabolic power (power input)

P_k mechanical power to transfer

S projected frontal surface area

SB sweep-back angle

SE stroke efficiency

SF stroke frequency

SI stroke index

SL stroke length

SPH Coupled biomechanical-smoothed particle hydrodynamics

T total propulsive force

TDI technique drag index

TTSA trunk transverse surface

v swimming speed

VO_{2max} maximal oxygen uptake

VPM speed perturbation method

WS whole stroke

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Reliability of using a pressure sensor system to measure in-water force in young competitive swimmers

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The aim of this study was to analyze the reliability of using a differential pressure system to measure in-water force in young competitive swimmers. Ten boys and five girls (12.38 ± 0.48 years, 49.13 ± 6.82 kg, 159.71 ± 7.99 cm) were randomly assigned to perform two maximum bouts of 25 m front crawl on different days (trial one, T1; trial two, T2), one week apart. A differential pressure system composed of two hand sensors (Aquanex System, v.4.1, Model DU2, Type A, Swimming Technology Research, Richmond, VA, United States) was used to measure the peak (RF_{PEAK}) and the mean (RF_{MEAN}) resultant force of the dominant and non-dominant hands (in Newton, N). Reliability was analyzed by computing the intraclass correlation coefficient (ICC), typical error (TE), smallest worthwhile change (SWC), coefficient of variation (CV%), standard error of measurement (SEM), and the minimal detectable change (MDC). Bland–Altman plots with 95% limits of agreement were also analyzed. The results showed no differences between T1 and T2 in all variables ($p > 0.05$). The ICC showed "excellent" reliability (ICC > 0.90) for the RF_{PEAK} and RF_{MEAN} in both hands. The CV% was rated as "good" (<5%) and TE was smaller than SWC in all variables. The Bland-Altman plots showed high reliability with a small bias (RF_{PEAK} dominant, -0.29 N; RF_{PEAK} non-dominant, -0.83 N; RF_{MEAN} dominant, 0.03 N; RF_{MEAN} non-dominant, 0.50 N). The pressure sensor system (Aquanex System) seems to be a reliable device for measuring the hand resultant force during front crawl in young swimmers and can be used to monitor the changes over time.

KEYWORDS
swimming, kinetics, differential pressure, accuracy, hand force

Introduction

Deterministic models of swimming performance have highlighted kinetics as an important domain to be studied (Barbosa T. M. et al., 2013). The ability of swimmers to move through the water depends on the amount of propulsive force applied and the drag force opposed to a forward motion. With that in mind, individual force profiles were used to understand propulsive mechanics in the water (Santos et al., 2021).

In the last couple of years, some progress has been made on how propulsive forces are retrieved (Santos et al., 2021). Methods with humans or robotic models based on numerical simulations (e.g., Marinho et al., 2010) or tethered swimming (e.g., Amaro et al., 2014) were used for that purpose; but those kind of approaches were quite heavy to handle or too much time consuming. Thus, the use of differential pressure sensors has been growing in interest. The method of assessing pressures differences between the palmar and dorsal surfaces, along with underwater motion analysis, allows to estimate the propulsive forces (Takagi and Wilson, 1999) and interpret those possible effects on performance (Tsunokawa et al., 2018; Koga et al., 2022). This straightforward method allows the assessment of swimmers in a more ecologically valid environment (i.e., similar to "free-swimming").

Studies using the differential pressure method reported the measurement of in-water forces using two (e.g., Pereira et al., 2015; Bartolomeu et al., 2022) or four to eight sensors (e.g., Takagi and Wilson, 1999; Koga et al., 2020) in swimming strokes. Despite the number of sensors in play, the Aquanex System (a two-hand set-up) showed to be an easy-to-use procedure without encompassing a heavy set-up. This is an important advantage of the system when compared to other differential pressure sensors reported in the swimming science literature (e.g., Takagi and Wilson, 1999; Tsunokawa et al., 2018; Koga et al., 2022). Still, should point out that each sensor only measures the hand resultant force instead of the effective propulsive force. Although some studies reported the use of Aquanex System, the system accuracy and the reliability of the measurements has not yet been investigated. Meanwhile, young swimmers seem not to be constrained in stroke mechanics or stroke efficiency when using this system (Santos et al., 2022).

The peak and mean forces retrieved by this pressure sensors system have been regularly used to understand acute responses to different stimulus (e.g., Morais et al., 2020), the relationship to swimming velocities (e.g., Bartolomeu et al., 2022), upper-limb imbalances (e.g., Morais et al., 2020), or warm-up effects (e.g., Barbosa T. M. et al., 2020). Both kinetic variables appear to be highly reliable in young swimmers when using the tethered-swimming method (Amaro et al., 2014). However, it is still unclear whether the same happens when a pressure system with two hand sensors is used for this purpose. Thus, ensuring the reliability of the Aquanex System would help researchers and practitioners to perform a proper assessment over time and monitoring swimmers' progress.

Thus, the aim of this study was to analyze the reliability of using a differential pressure system to measure in-water force during front crawl in young competitive swimmers. It was hypothesized that pressure sensors would present excellent reliability to measure the peak and the mean of hand resultant force.

Materials and methods

Participants

Fifteen highly trained (Mckay et al., 2022) swimmers including 10 boys and 5 girls [mean ± one standard deviation: 12.38 ± 0.48 years-old, 49.13 ± 6.82 kg, 159.71 ± 7.99 cm, 309.17 ± 58.13 FINA Points at 50-m freestyle (short course)] volunteered to participate in this study. Swimmers were recruited from a local swimming squad and assessed at the end of the first macrocycle (peak form). The inclusion criteria were defined as follows: 1) having a minimum of two years in competitive swimming in regional or national events; 2) practicing more than four swim training sessions per week; 3) being previously familiar with the hand differential pressure system; and 4) not having suffered any injuries in the past 6 months.

Swimmers' parents or guardians were informed about the benefits and experimental risks before signing a written informed consent form. All procedures were in accordance with the Declaration of Helsinki and approved by the Institutional Ethics Committee of the University of Beira Interior (code: CE-UBI-Pj-2020-058).

Data collection

A single group repeated measures design was selected for this study. The in-water experimental testing was carried out in a 25 m indoor swimming pool (water temperature: 27.5°C) and the swimmers attended two sessions on different days, 1 week apart. A standardized 1000 m warm-up for sprint events (Neiva et al., 2015) was performed individually by each swimmer. For the in-water data collection, swimmers were randomly assigned for the first maximum bout of 25 m front crawl (Trial 1, T1) and followed the same order in the second session (Trial 2, T2). All maximum bouts started by a push-off without gliding and swimmers were instructed to maintain their normal breathing pattern for sprint events.

Swimmers wore only a textile swimsuit and a cap during the anthropometric tests. Height (in cm) and body mass were measured with a digital stadiometer (SECA, 242, Hamburg, Germany) and a scale (TANITA, BC-730, Amsterdam, Netherlands), respectively. Hand dominance of the swimmers was assessed by self-report.

Pressure sensors test

A differential pressure system composed of two hand sensors (Type A, Swimming Technology Research, Richmond, VA, United States) positioned between the third and fourth proximal phalanges and metacarpals was used to measure the pressure between the palmar and dorsal surfaces of both hands. Inside each sensor, there is a diaphragm that flexes and is sensed as an electrical signal that is proportional to the difference in the two pressures. Each sensor measures the pressure component acting perpendicular to it. The hand resultant force (in N) was derived by the system from the product of differential pressure by the hand surface area of each swimmer (i.e., differential pressure · hand surface). The sensors (3.18 cm × 1.91 cm x 2.54 cm; 0.226 kg) were attached by a cable (15 m of length) to a two channel A/D interface connected to a laptop with the Aquanex software (v.4.1, Model DU2, Swimming Technology Research, Richmond, VA, United States). Swimmers carried the system with shoulders and arms elastic straps. An illustration of the experimental set-up can be found in Santos et al. (2022). Before each bout, swimmers kept their hands immersed (10 s) at the waistline to calibrate the system with the hydrostatic pressure values. Data was acquired with a sampling frequency of 100 Hz for each maximum bout.

Data analysis

Data was imported into a signal-processing software (AcqKnowledge v.3.7.3, Biopac Systems, Santa Barbara, CA, United States) and the signal was handled with a 5 Hz cutoff low-pass fourth order Butterworth filter. The peak (RF_{PEAK}, in N) and the mean (RF_{MEAN}, in N) resultant force of the dominant and non-dominant hands were assessed during the underwater paths. The recovery phase was discarded for all cycles The RF_{PEAK} was defined as the maximum value achieved on the three consecutive stroke cycles analyzed between the 11th and 24th meter, as suggested elsewhere (Santos et al., 2022). The distance covered by the swimmers was recorded (Sony, HDR-CX 240, Japan) and a visual mark was applied in the defined interval. The RF_{MEAN} was defined as the mean of the values obtained from the force-time curve where the RF_{PEAK} was retrieved.

Statistical analysis

The normality and homoscedasticity of the data were checked using the Shapiro-Wilk and Levene tests, respectively. The mean and one standard deviation (M ± 1SD) were computed as descriptive statistics. A paired sample *t*-test was used to compare the outcome variables between the T1 and T2. Relative test-retest reliability of each variable was assessed using the intraclass correlation coefficient (ICC) plus 95% confidence intervals (95%CI) with two-way mixed effects model (absolute agreement, single measures). The ICC was classified as poor if ICC < 0.50, moderate if 0.50 ≥ ICC < 0.75, good if 0.75 ≥ ICC < 0.90, and excellent if ICC > 0.90 (Koo and Li, 2016). The absolute test-retest reliability was analyzed by estimating the typical error (TE), coefficient of variation (CV%), standard error of measurement (SEM), and the minimal detectable change (MDC) based on a 95% confidence level (Atkinson and Nevill, 1998) The CV% values were interpreted as poor if CV% > 10%, moderate if 5% ≥ CV% ≤ 10%, and good if CV% < 5% (Scott et al., 2016). Additionally, the ability to detect a change was rated as "good", "OK", or "marginal" when the TE was below, similar, or higher than the smallest worthwhile change (SWC), respectively (Buchheit et al., 2011). Bland–Altman plots with 95% limits of agreement (LoA) were used to display the within-subject variation and systematic differences between the two sessions trials. The bias (mean difference), standard deviation (SD), and upper and lower LoA were calculated (Bland and Altman, 1986).

All statistical analyses were performed in the SPSS software (v.27, IBM, SPSS Inc., Chicago, IL, United States) and GraphPad Prism (v.9, GraphPad Software, San Diego, CA, United States). The statistical significance was set at $p \leq 0.05$.

Results

Test-retest reliability of the Aquanex System is shown in Table 1. No differences were found between T1 and T2 in all propulsive force variables. The ICC showed an "excellent" relative reliability for the RF_{PEAK} and RF_{MEAN} in both upper limbs, despite the 95%CI (i.e., lower and upper bound) of ICC demonstrating a "good" to "excellent" relative reliability. TE was rated as "good" when compared to the SWC and CV% revealed a "good" absolute reliability in all variables.

The Bland-Altman plots are presented in Figure 1. Biases (mean differences) were small, approaching zero, and most data points were within the LoA on all resultant force variables.

Discussion

This study analysed the reliability of using a differential pressure system to measure the hand resultant force during front crawl in young competitive swimmers. The main results show that the pressure sensor system has excellent reliability through the measurement of peak and mean resultant force.

TABLE 1 Test-retest reliability of the Aquanex System in young competitive swimmers.

Variable	T1 (M ± 1SD)	T2 (M ± 1SD)	*p*-value	TE	SWC	CV%	ICC	$ICC_{95\%CI}$	SEM	MDC
RF_{PEAK} D (N)	50.02 ± 7.81	50.31 ± 8.29	0.65	0.96	1.61	2.70	0.96	0.88, 0.99	1.67	4.63
RF_{PEAK} ND (N)	49.85 ± 10.10	50.68 ± 9.87	0.17	0.99	1.99	2.95	0.97	0.92, 0.99	1.64	4.55
RF_{MEAN} D (N)	16.54 ± 3.49	16.51 ± 3.34	0.93	0.47	0.68	4.30	0.95	0.86, 0.98	0.75	2.07
RF_{MEAN} ND (N)	16.92 ± 3.44	16.42 ± 3.79	0.19	0.56	0.71	4.64	0.92	0.79, 0.97	1.00	2.76

D, dominant hand; CI, confident interval; CV%, coefficient of variation in percentage; ICC, intraclass correlation coefficient; $ICC_{95\%CI}$, lower and upper bound of ICC; MDC, minimal detectable change; N, newton; ND, non-dominant hand; RF_{PEAK}, peak resultant force; RF_{MEAN}, mean resultant force; SEM, standard error of measurement; SWC, smallest worthwhile change; T1, trial 1; T2, trial 2; TE, typical error.

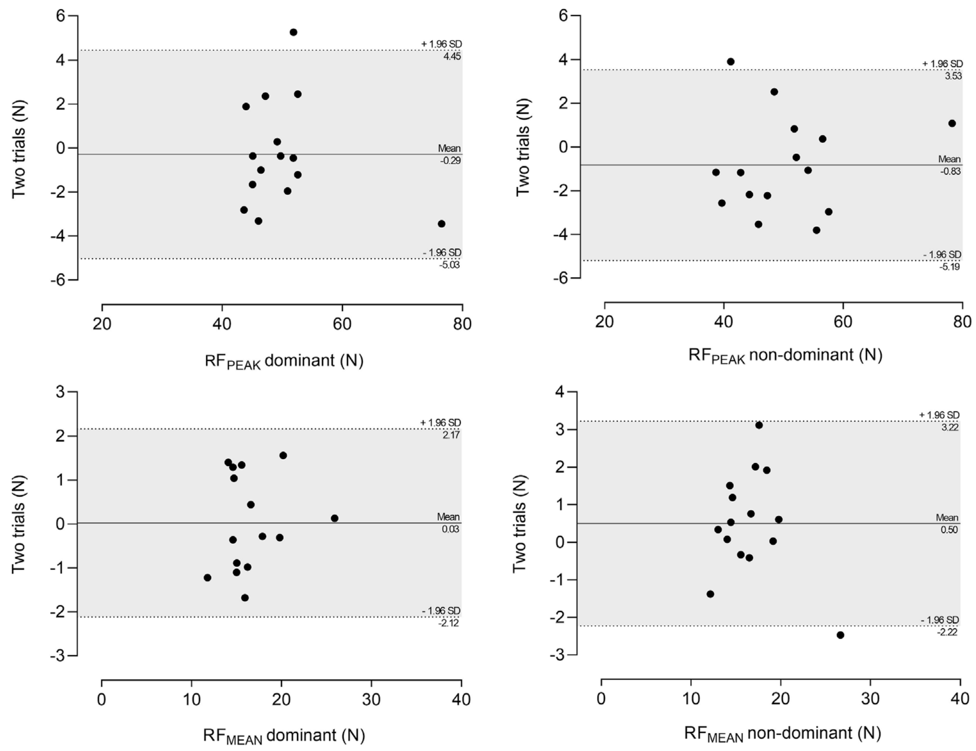

FIGURE 1
Bland-Altman plots of the difference between T1 and T2 (y-axis) and mean of measurements (x-axis) for all variables. Dotted lines represent the upper and lower 95% LoA (mean differences ± 1.96 SD of the differences) and solid lines represent the mean differences between the two trials (bias). N, newton; RF_{PEAK}, peak resultant force; RF_{MEAN}, mean resultant force.

Previous studies using the Aquanex system determined the peak and the mean as the most frequent variables to be studied (Santos et al., 2021). Our results showed values of ≈50 N for RF_{PEAK} and ≈17 N for RF_{MEAN}. These values are lower than previous findings in front crawl stroke, but the age range reported was different from those used in the present study (e.g., Barbosa T. M. et al., 2020; Morais et al., 2020). Furthermore, studies reporting hand resultant force with multi-pressure system also found higher values (e.g., Tsunokawa et al., 2018; Koga et al., 2022).

The reliability of different devices/apparatus in swimming has been extensively investigated. Inertial measurement units (IMU) to assess in-water kinematics (Mooney et al., 2015) and dynamometers for dry-land strength assessment (e.g., Conceição et al., 2018) have already been tested. As far as we know, the reliability of devices to directly measure in-water forces have only been done using the tethered swimming method (Amaro et al., 2014; Nagle Zera et al., 2021). Hence, this study is the first to provide data about test-retest reliability with hand pressure sensors.

The ICC values observed in the present study were classified as "excellent" (range: 0.92–0.97) in both variables for the dominant and non-dominant hands. These results are in agreement with those observed in front-crawl in tethered swimming (Amaro et al., 2014; Barbosa A. C. et al., 2020; Dos Santos et al., 2017; Loturco et al., 2015; Morouço et al., 2014). For instance, Amaro et al. (2014) reported high reliability for peak (ICC: 0.94) and mean forces (ICC: 0.96) in young swimmers. Although tethered swimming is considered a reliable apparatus, some concerns have been raised as swimmers remain in stationary conditions with no forward motion (Soncin et al., 2017). Furthermore, it is expected that with such method swimmer's hand would experience much larger pressure than in a free-swimming condition. On the other hand, the pressure sensors allow a displacement throughout the water without mechanical and efficiency constraints in young swimmers (Santos et al., 2022).

Although the reliability of the two pressure sensors has not been investigated in previous studies, Havriluk (1988), who introduced the first version of the Aquanex System, reported an ICC value of 0.91 for the variable "effective hand movement with respect to the body" (in m). Nevertheless, in-water force values were not analyzed, therefore, no conclusions were drawn about reliability.

The absolute reliability demonstrated a "good" CV% without systematic changes between trials. The CV% ranged from 2.70 to 4.64% and the TE was below 1N being rated as "good" when compared to the SWC. The SEM was less than 2N in all variables. Thus, the differential pressure system (Aquanex System) might be a reliable apparatus to monitor changes in hand resultant force over the season. Meanwhile, different CV% values have been reported for tethered swimming, being lower (Barbosa A. C. et al., 2020; Loturco et al., 2015) or higher (Amaro et al., 2014) than those found in the present study. Different settings, such as the competitive level of the sample, swimmers' age, or data analysis, can help explain these differences.

Some limitations can be addressed: 1) equal pressure assumption on the hand surface, although it has been shown that the pressure is not the same across the whole surface of the hand; 2) only the resultant force was considered; 3) only the reliability of the hands was considered, although the in-water forces of the feet's has also been investigated through pressure sensors. Thus, testing its reliability alone or using the set-up of the hand should be a priority in the future; 4) only peak and mean forces of young swimmers were considered; the use of other measures (e.g., impulse) and type of swimmers (e.g., elite or master) would be essential; and 5) front-crawl is not representative of all swimming strokes, so future studies should try to understand whether systematic changes are the same for butterfly, backstroke, and breaststroke.

Practical applications

Defining the most important factors of swimming performance within the biomechanical domain is still a challenge. This is mainly due to the aquatic environment, which is the biggest obstacle to be overcome in the search for more accurate assessments. Within this rationale, new technologies, such as pressure sensors, make a great contribution to this area. The potentiality of monitoring the hand force continuously during the free-swimming without spatial limitations is an advantage of the Aquanex system with two sensors. As far as we know, this is not possible with other methods that assume the swimmer's kinetic variables. However, the accuracy of such system has not been previously demonstrated. Furthermore, it would be appreciable as a future perspective the wirelesses of these sensors (i.e., telemetry). So, this study is the first to show the reliability of using the Aquanex system for measurements of peak and mean forces in water. This will allow for a deeper understanding of how swimmers generate in-water forces and it will help coaches redefining training programs at some point of the competitive season, if necessary. For researchers, the link between hand forces retrieved by Aquanex and the remaining determinant domains of performance (e.g., anthropometric, biomechanical, physiological) should be a focus in a near future.

Conclusion

The pressure sensor system (Aquanex System) can be considered a reliable set-up to obtain peak and mean hand resultant force in young competitive swimmers. This reinforces the idea that the use of pressure sensors remains the assessment method that most closely resembles free-swimming and can be used to monitor kinetic changes over time.

Data availability statement

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

Ethics statement

The studies involving human participants were reviewed and approved by Institutional Ethics Committee of the University of Beira Interior (code: CE-UBI-Pj-2020-058). Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

Author contributions

Research concept and study design, CS and MC Data collection, CS and MC, Data analysis and interpretation: CS and DM Writing of the manuscript: CS Reviewing the manuscript, DM and MC.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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The reliability of back-extrapolation in estimating $\dot{V}O_{2peak}$ in different swimming performances at the severe-intensity domain

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The amount of anerobic energy released during exercise might modify the initial phase of oxygen recovery (fast-O_{2debt}) post-exercise. Therefore, the present study aimed to analyze the reliability of peak oxygen uptake ($\dot{V}O_{2peak}$) estimate by back-extrapolation (BE – $\dot{V}O_{2peak}$) under different swimming conditions in the severe-intensity domain, verifying how the alterations of the $\dot{V}O_2$ recovery profile and anerobic energy demand might affect BE – $\dot{V}O_{2peak}$ values. Twenty swimmers (16.7 ± 2.4 years, 173.5 ± 10.2 cm, and 66.4 ± 10.6 kg) performed an incremental intermittent step protocol (IIST: 6 × 250 plus 1 × 200 m, IIST_v200m) for the assessment of $\dot{V}O_{2peak}$. The $\dot{V}O_2$ off-kinetics used a bi-exponential model to discriminate primary amplitude, time delay, and time constant (A_{1off}, TD_{1off}, and τ_{off}) for assessment of fast-O_{2debt} post IIST_v200m, 200-m single-trial (v200 m), and rest-to-work transition at 90% delta (v90%Δ) tests. The linear regression estimated BE – $\dot{V}O_{2peak}$ and the rate of $\dot{V}O_2$ recovery (BE-slope) post each swimming performance. The ANOVA (Sidak as *post hoc*) compared $\dot{V}O_{2peak}$ to the estimates of BE – $\dot{V}O_{2peak}$ in v200 m, IIST_v200 m, and v90%Δ, and the coefficient of dispersion (R^2) analyzed the association between tests. The values of $\dot{V}O_{2peak}$ during IIST did not differ from BE – $\dot{V}O_{2peak}$ in v200 m, IIST_v200 m, and v90%Δ (55.7 ± 7.1 vs. 53.7 ± 8.2 vs. 56.3 ± 8.2 vs. 54.1 ± 9.1 ml kg^{-1} min^{-1}, $p > 0.05$, respectively). However, the $\dot{V}O_{2peak}$ variance is moderately explained by BE – $\dot{V}O_{2peak}$ only in IIST_v200 m and v90%Δ (R^2_{Adj} = 0.44 and R^2_{Adj} = 0.43, $p < 0.01$). The TD_{1off} and τ_{off} responses post IIST_v200 m were considerably lower than those in both v200 m (6.1 ± 3.8 and 33.0 ± 9.5 s vs. 10.9 ± 3.5 and 47.7 ± 7.9 s; $p < 0.05$) and v90%Δ (10.1 ± 3.8 and 44.3 ± 6.3 s, $p < 0.05$). The BE-slope post IIST_v200m was faster than in v200 m and v90%Δ (-47.9 ± 14.6 vs. -33.0 ± 10.4 vs. -33.6 ± 13.8 ml kg^{-1}, $p < 0.01$), and the total anerobic ($Anaer_{Total}$) demand was lower in IIST_v200 m (37.4 ± 9.4 ml kg^{-1}) than in 200 m and 90%Δ (51.4 ± 9.4 and 46.2 ± 7.7 ml kg^{-1}, $p < 0.01$). Finally, the τ_{1off} was related to Anaer$_{Total}$ in IIST_v200m, v200 m, and v90%Δ (r = 0.64, r = 0.61, and r = 0.64, $p < 0.01$). The initial phase of the $\dot{V}O_2$ recovery profile provided different (although reliable) conditions for the estimate of $\dot{V}O_{2peak}$ with BE procedures, which accounted for the moderate effect of anerobic release on $\dot{V}O_2$ off-kinetics, but compromised exceptionally the $\dot{V}O_{2peak}$ estimate in the 200-m single trial.

KEYWORDS

swimming, back-extrapolation, peak oxygen uptake, oxygen uptake kinetics, oxygen uptake recovery

Introduction

Back-extrapolation (BE) has been demonstrated to be a suitable procedure for estimating the peak oxygen uptake ($\dot{V}O_{2peak}$) at the very end of exercise by applying the linear $\dot{V}O_2$-time relationship to the primary response of the $\dot{V}O_2$ recovery phase (i.e., fast $\dot{V}O_2$ off-kinetics) (Léger et al., 1980; Rodríguez et al., 2017; Monteiro et al., 2020). In swimming, BE is a reliable procedure for estimating $\dot{V}O_{2peak}$ attained in an incremental exercise (Lavoie et al., 1981; Montpetit et al., 1981), and even BE affords a reliable estimate of $\dot{V}O_{2peak}$ during middle-distance swimming performances (i.e., 200 and 400 m), in which the attainment of the maximal rate of aerobic energy is recognized (Chaverri et al., 2016; Rodríguez et al., 2017). Therefore, the $\dot{V}O_{2peak}$ estimate from BE is supposed to provide the assessment of maximum $\dot{V}O_2$ response from submaximal to supramaximal swimming circumstances (Monteiro et al., 2020), and thus BE is also considered a procedure enabling the overcome of contextual constraints imposed by the apparatus for the assessment of $\dot{V}O_2$ response in the aquatic environment (Chaverri et al., 2016).

However, the linear $\dot{V}O_2$-time model has been the source of controversial findings on the reliability of BE to estimate $\dot{V}O_{2peak}$ in swimming (Lavoie et al., 1985; Chaverri et al., 2016). For example, the overestimation of $\dot{V}O_{2peak}$ assessment of a post 400-m single-trial swimming performance (Lavoie et al., 1981) conflicts with the post incremental step-test values (Montpetit et al., 1981), despite both being swimming circumstances with a recognized maximum $\dot{V}O_2$ demand (Zacca et al., 2019). Probably, this mismatch in comparing BE estimate vs. incremental test assessment of $\dot{V}O_{2peak}$ might account for the impairments on physiological response during high-intensity constant work-rate exercise, including either oxidative inertia or the anerobic energy relying on the onset of exercise since both these physiological mechanisms are supposed to modulate $\dot{V}O_2$ off-kinetics acutely (i.e., slowing or speeding $\dot{V}O_2$ exponential response post-exercise) (Özyener et al., 2001; Rossiter et al., 2002; Sousa et al., 2015). However, these physiological mechanisms are assumed to impair the attainment of $\dot{V}O_{2peak}$ during constant-phase exercise, if the reference value for comparison (usually assessed from an incremental exercise protocol) might be considered a reliable $\dot{V}O_{2peak}$ in swimming (Sousa et al., 2014; Pessôa Filho et al., 2017).

Despite the factors influencing BE reliability to estimate $\dot{V}O_{2peak}$, previous reports suggested both the 200- and 400-m performances in swimming as typical middle-distance events, eliciting high aerobic energy release and, therefore, the attainment of $\dot{V}O_{2peak}$ response, in spite of the differences between each other regarding the aerobic/anerobic energetics balance (Pyne and Sharp, 2014; Almeida et al., 2020; Zacca et al., 2020). In addition, it has been demonstrated that velocities between 95 and 105% of $\dot{V}O_{2peak}$ in swimming also elicited the $\dot{V}O_{2peak}$ (Sousa et al., 2014) and showed a similar profile of $\dot{V}O_2$ response when compared to 200- and 400-m performance (Sousa et al., 2011; Chaverri et al., 2016; Rodríguez et al., 2017). Therefore, the 200- and 400-m trials might be considered suitable for estimating $\dot{V}O_{2peak}$ by applying BE procedures post all-out performances in swimming (Rodríguez et al., 2017; Zacca et al., 2019).

From these studies, the main lessons are that the BE procedure might overestimate the $\dot{V}O_{2peak}$ according to the dataset fitting strategies, the exercise intensity during a trial performance (Rodríguez et al., 2017), and exercising conditions previous to the target trial estimating $\dot{V}O_{2peak}$ (Rodríguez et al., 2017; Zacca et al., 2019). In other words, the mechanisms that affect the reliability of the $\dot{V}O_{2peak}$ estimate by BE are likely related to the physiological response during exercise that also affects the $\dot{V}O_2$ kinetic responses in the recovery phase. This is if other sources capable of impairing the accuracy of the BE estimate (e.g., temporal resolution of data sampling, treatment of the dataset, and mathematical curve fitting) are dis-regarded. (for further information on these other sources, see Monteiro et al., 2020; Rodríguez et al., 2017). Such a relationship was theoretically supposed to explain the modification of the constants of the linear function with the increase of the delay for the onset of $\dot{V}O_2$ recovery, which was in turn, linked to the velocity of $\dot{V}O_2$ adjustment during exercise (i.e., $\dot{V}O_2$ on-kinetic) (Rodríguez et al., 2017).

In fact, experimental results have postulated that a high and rapid increase of $\dot{V}O_2$ during exercise is related to a similar high and rapid reduction in the muscle phosphocreatine (PCr) content, the restoration of which inhibits the rapid decline of oxidative phosphorylation in the initial phase of recovery after exercise (i.e., slow time constant of $\dot{V}O_2$ off-kinetic—τ_{off})

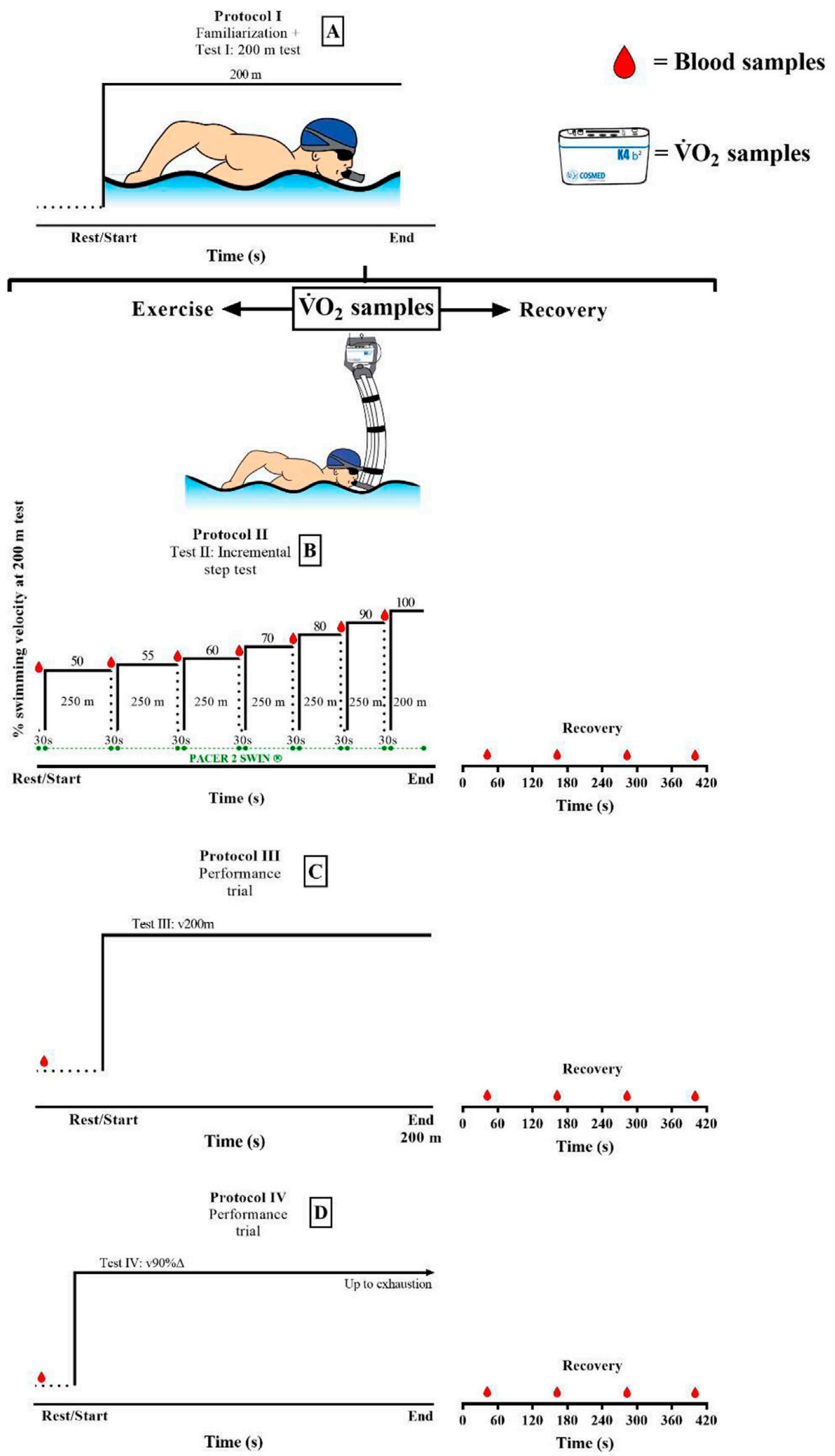

FIGURE 1
Illustration of the protocols: **(A)** familiarization with snorkel and 200-m single-test trial both with no gas sampling; **(B)** incremental intermittent test including 200-m last-step performance (IIST_200m); **(C)** single-trial performance during 200 m (v200m) and **(D)** rest-to-work transition to the limit of tolerance at delta 90% velocity (v90%Δ).

(Rossiter et al., 2002; Korzeniewski and Zoladz, 2013). Indeed, this assumption might also support the overestimation of $\dot{V}O_{2peak}$ when applying BE procedures post 400 m rather than post 200 m (Rodríguez et al., 2017). Despite not ever being addressed, the τ_{off} might play an important role for explaining how the reliability of BE to estimate $\dot{V}O_{2peak}$ is affected by performing exercises in different circumstances, leading to the attainment of the maximal aerobic rate.

Thus, the current study aimed to address the $\dot{V}O_2$ recovery response and anerobic energy demand post different swimming circumstances in the severe-intensity domain to ascertain whether transients of $\dot{V}O_2$ off-kinetics account for alterations of the linear adjustments of $\dot{V}O_2$ response during the initial phase of $\dot{V}O_2$ off-kinetics. Hence, the gathering of information to analyze the reliability of BE in estimating $\dot{V}O_{2peak}$ values with correspondence to the maximal $\dot{V}O_2$ elicited whatever the swimming demand upon anerobic energetics during performances in the severe-intensity domain and correspondence to the maximum $\dot{V}O_2$ response assessed in incremental exercise. In addition, this study explored whether a 200-m single-trial performance would be a feasible reference for the estimation of $\dot{V}O_{2peak}$, adding information to support (or not) that the value estimated by BE is similar to either the $\dot{V}O_{2peak}$ assessed in an incremental test and/or the maximal $\dot{V}O_2$ elicited at the end of the trial.

Methods

Subjects

Twenty swimmers (16.7 ± 2.4 years, 173.5 ± 10.2 cm, and 66.4 ± 10.6 kg; men = 12 and women = 8) were voluntarily recruited to participate in the study. The swimmers had at least three annual competitive training seasons and 200-m performances corresponding to 533 ± 83 and 502 ± 75 FINA points in a 25-m swimming pool, respectively, for men and women. The experimental procedures were performed in an indoor 25-m swimming pool, with a water temperature of ~28°C. The swimmers were evaluated after familiarization with the procedures and devices. They were instructed to refrain from exhaustive training, alcohol, and caffeinated drinks the day before testing and to arrive well-fed and hydrated for the tests. All swimmers (and their legal guardians when they were under 18 years of age) signed a written consent form for their participation. This research was approved by the local ethics committee (CAEE: 54372516.3.0000.5398).

Performance tests and incremental intermittent step test (IIST)

The familiarization phase with the snorkel system took place 24 h before testing procedures, which included all components of a regular training session, emphasizing middle-distance conditioning. All swimmers performed three swimming tests, with the duration between them being at least 48 h (Figure 1), with the second and third tests performed in a randomized order. The tests were 1) an incremental intermittent step-test (IIST) composed of six sets of 250 m in addition to one set of 200 m (IIST_v200m) at 50, 55, 60, 70, 80, 90, and 100% of velocity for 200 m, with 30 s between each step for blood sampling analysis (Almeida et al., 2021). The 200-m test was performed just after familiarization had been accomplished and 24 h before the IIST, following: 1) 1 h of rest from the previous exercise bout and 2) executed maximally with water starting, open turns, and no underwater gliding, as suggested by Massini et al. (2021); 2) a maximal 200-m single-trial performance (v200m); and 3) a transition from rest to the velocity corresponding to 90%Δ (v90%Δ, Eqn. (1)) performed until volitional exhaustion.

$$v90\%\Delta = v_{LT} + \left[\left(v\dot{V}O_{2\,max} - v_{LT}\right) \times 0.9\right], \qquad [1]$$

where v_{LT} is the velocity corresponding to the lactate threshold (LT), defined as the first increase of blood lactate concentration ($[la^-]$) above the resting levels, and determined from log–log bi-segmented plots of $[la^-]$ vs. velocity during the IIST (Faude et al., 2009). The swimming speed during all tests was controlled by visual information using an underwater visual pacer placed along the bottom of the pool (Pacer2Swim®, KulzerTEC, Portugal).

Measurements

Breath-by-breath gas exchange was sampled during and after the following experimental conditions: IIST, v200 m, and v90%Δ. For all conditions, the portable CPET unit (K4b², Cosmed, Italy) was attached to the swimmer by a specific snorkel (new-AquaTrainer®, Cosmed, Italy), which was validated for gas analysis in swimming by Baldari et al. (2013). The CPET unit was calibrated before each test following the manufacturer's recommendations. Blood samples (25 ul) were obtained from the swimmers' earlobe at rest and at 1, 3, 5, and 7 min post-exercise, which were diluted in 75 ul 1% NaF solution. The samples were immediately analyzed for $[la^-]$ evaluation (YSI, 2300 STAT, Yellow Springs, United States).

For assessment of $\dot{V}O_{2peak}$ and peak aerobic velocity ($v\dot{V}O_{2peak}$) during the IIST, the $\dot{V}O_2$ data were smoothed (3-data point filter) and time-aligned to the discernibility of exercise and recovery phases. Moving average (30 s) processing was applied to the exercise $\dot{V}O_2$ raw data, and the highest averaged value was considered the $\dot{V}O_{2peak}$ (Robergs et al., 2010; Reis et al., 2012). The velocity corresponding to the step of $\dot{V}O_{2peak}$ occurrence was defined as $v\dot{V}O_{2peak}$. For modeling of $\dot{V}O_2$ off-kinetics, the 420-s rough $\dot{V}O_2$ dataset from each transition at v200 m, v90%Δ, and IIST_v200m was time-aligned, and the noise was excluded and interpolated second-to-second for the analysis of $\dot{V}O_2$ off-kinetics, as suggested by Özyener et al. (2001), Keir et al. (2014), and Benson et al. (2017). The mathematical modeling of $\dot{V}O_2$ off-kinetics used a bi-exponential equation, with time delay (TD) (Eqn. (2)), according to the recommendations of Özyener et al. (2001) for the modeling of $\dot{V}O_2$ off-kinetics in severe exercise:

$$\dot{V}O_{2off}(t) = EE\dot{V}O_2 - A_{1off}\left[1 - e^{-\left(t - TD_{1off}/\tau_{1off}\right)}\right] - A_{2off}\left[1 - e^{-\left(t - TD_{2off}/\tau_{2off}\right)}\right] \quad [2]$$

where $EE\dot{V}O_2$ corresponded to the final 30 s averaged $\dot{V}O_2$ increase during exercise (in ml min^{-1}). A_{1off} and A_{2off} are the net amplitude of $\dot{V}O_2$ response for each phase of recovery (in ml·min^{-1}); t is exercise time; τ_{1off} and τ_{2off} are time constants (in seconds, s); and TD_{1off} and TD_{2off} are the time delays (in seconds, s) for $\dot{V}O_2$ response for each phase of recovery (Özyener et al., 2001). The cardiopulmonary component was excluded by adjusting $\dot{V}O_2$ response ~15 s after the onset of exercise recovery (Özyener et al., 2001). The fast-O_{2debt} (i.e., the amount of $\dot{V}O_2$ response up to a particular time of the initial $\dot{V}O_2$ recovery phase) was calculated from Eqn. (3), as recommended by Stirling et al. (2005):

$$Fast - O_{2debt} = A_{1off} \cdot \tau_{1off}\left(1 - e^{\left(t_f - TD_{1off}\right)/\tau_{1off}}\right) + A_{1off} \times \left(TD_{1off} - t_f\right)e^{\left(t_f - TD_{1off}\right)/\tau_{1off}}, \quad [3]$$

where t_f is the time (s) at the end of the recovery sampling protocol. The blood lactate accumulation in equivalents of O_2 ($O_2[la^-]$, in ml·min^{-1}) was calculated following the recommendations of Prampero and Ferretti (1999) from $O_2[la^-] = \beta \cdot [la^-]_{net}$, where β is equivalent to 2.7 ml kg^{-1} per 1 mmol L^{-1} of $[la^-]_{net}$, which is the algebraic difference between rest $[la^-]$ and peak $[la^-]$ post-exercise. The fast-O_{2debt} (in ml·kg^{-1}) and $O_2[la^-]$ variables indicated the phosphagen and glycolytic components of total anerobic ($Anaer_{Total}$) response, respectively, during each swimming performance trial. The mean response time for the fast-O_2debt curve was calculated ($MRT_{1off} = TD_{1off} + \tau_{1off}$, s) according to the previous studies in swimming (Almeida et al., 2020; Massini et al., 2021).

The BE method was applied to estimate the $\dot{V}O_{2peak}$ ($BE - \dot{V}O_{2peak}$, in ml min^{-1}) and $\dot{V}O_2$ recovery rate (BE-slope, in ml kg^{-1}) from post-exercise $\dot{V}O_2$ response (Montpetit et al., 1981) in IIST_v200m, v200 m, and v90%Δ. This procedure adjusted 20 s of the $\dot{V}O_2$ vs. recovery time dataset by a linear function (f(y) = ax + b) (Léger et al., 1980), in which the delay of $\dot{V}O_2$ recovery response (i.e., ~15 s) was excluded before the linear adjustment of the dataset (see details on cardiopulmonary component exclusion for mathematical modeling of $\dot{V}O_2$ off-kinetics) to the zero-recovery time.

Statistical analysis

The $\dot{V}O_{2peak}$, $EE\dot{V}O_2$, and $BE - \dot{V}O_{2peak}$ values (in ml·kg^{-1} min^{-1}) for each trial were checked for normality with the Shapiro–Wilk test. The one-way ANOVA (Sidak as *post hoc*) compared $\dot{V}O_{2peak}$ to $BE - \dot{V}O_{2peak}$ and $EE\dot{V}O_2$ in the IIST_v200m, v200m, and v90%Δ and the values of τ_{1off}, TD_{1off}, MRT_{1off}, A_{1off}, $EE\dot{V}O_2$, fast-O_{2debt}, BE-Slope, and $O_2[la^-]$ between each of the swimming performance conditions. The coefficient of dispersion (R^2) and standard error of estimate (SEE) analyzed the variance between $\dot{V}O_{2peak}$ and $BE - \dot{V}O_{2peak}$. Eta squared (η^2) was calculated to determine the effect size for ANOVA, considering the threshold values as <0.04 [trivial], 0.04–0.24 [small], 0.25–0.63 [medium], and >0.64 [large] (Fergusson, 2009).

Pearson's coefficient (r) analyzed the correlation of $\dot{V}O_2$ off-transients, fast-O_{2debt}, and $O_2[la^-]$ with $EE\dot{V}O_2$, $BE - \dot{V}O_{2peak}$, BE-slope, and $\dot{V}O_2$ off-kinetic components under each swimming condition. The magnitudes of Pearson's correlation were expressed as weak (0.00–0.29), low (0.30–0.49), moderate (0.50–0.69), strong (0.70–0.89), or very strong (0.90–1.00) (Mukaka, 2012); while R^2 was considered <0.04 [trivial], 0.04–0.24 [small], 0.25–0.63 [medium], and >0.64 [strong] (Fergusson, 2009). For all analyses, the significance level was set at $\rho \leq 0.05$. Sample power for the observed correlations was calculated considering the sample size ($n = 20$), correlation coefficient (r) $Z\alpha = 1.96$ to a security index of $\alpha = 0.05$, and expected sample power of 80% ($\beta = 0.20$). The statistical analysis was performed with SPSS Statistics for Windows (v18.0, IBM®, Chicago, IL, United States), and $\dot{V}O_2$ data processing and modeling were both performed using OriginPro (OriginLab Corporation®, Northampton, MA, United States).

Results

The $\dot{V}O_{2peak}$ attained in the IIST was 55.7 ± 7.1 ml·kg^{-1}·min^{-1}, and $v\dot{V}O_{2peak}$ corresponded to 1.26 ± 0.08 m × s^{-1}. The v90%Δ and v200m were performed at 96.3 ± 4.4 and 101.1 ± 5.1% of $v\dot{V}O_{2peak}$, respectively Figure 2 illustrates the $\dot{V}O_2$ response profile during exercise and recovery of IIST_v200m, v200 m, and v90%Δ for a male swimmer, which also exemplifies the "off-kinetics" and linear "back-extrapolation" modeling.

The variables of $\dot{V}O_2$ off-kinetics and BE are shown in Table 1. Differences were observed for TD_{1off}, τ_{1off}, and MRT_{1off} (p < 0.01, η^2= 0.251, 0.397, and 0.479, all

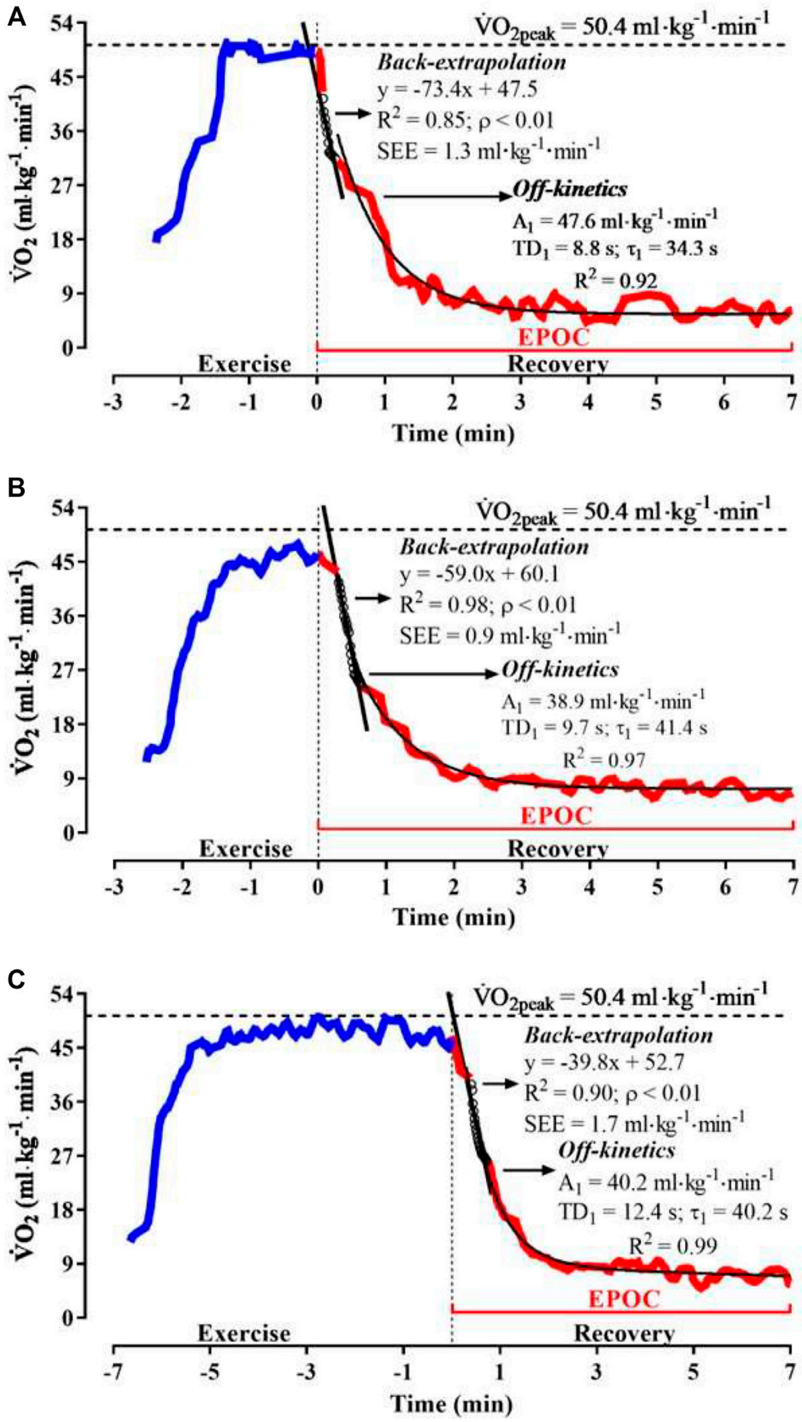

FIGURE 2
Illustration of the procedures applied to adjust recovery $\dot{V}O_2$ "on" (blue) and "off" (red) profiles during IIST_200m **(A)**, v200m **(B)**, and v90%Δ **(C)** for the subject #7.

considered [medium] effect size), which were lower in IIST_v200m than in v200 m and v90%Δ, but not between v200 m and v90%Δ (ρ = 0.84, 0.45, and 0.35). No differences were observed for A_{1off} ($F_{[2,57]} = 0.18$, $p = 0.83$, $\eta^2 = 0.006$ [trivial]) and $EE\dot{V}O_2$ ($F_{[2,57]} = 0.04$, $p = 0.96$, $\eta^2 = 0.001$ [trivial]) between trials.

TABLE 1 Mean ± SD values for $\dot{V}O_2$ off-transients and constants of BE in IIST_200m, v200 m, and v90%Δ. Measurements of the goodness and variability for linear fitting are also shown. N = 20.

	IIST_v200m	v200m	v90%Δ
$\dot{V}O_2$ off-kinetics			
TD_{1off} (s)	6.1 ± 3.8	10.9 ± 3.5*	10.1 ± 3.8*
τ_{1off} (s)	33.0 ± 9.5	47.7 ± 7.9*	44.3 ± 6.3*
MRT_{1off} (s)	39.1 ± 10.8	58.7 ± 8.3**	54.3 ± 7.6**
A_{1off} (ml·kg^{-1}·min^{-1})	44.0 ± 8.5	45.0 ± 6.8	45.3 ± 6.3
$EE\dot{V}O_2$ (ml·kg^{-1}·min^{-1})	53.7 ± 7.0	53.2 ± 6.9	53.5 ± 6.3
$\%\dot{V}O_{2peak}$	96.5 ± 3.5	96.2 ± 12.4	96.5 ± 7.4
R^2	0.96 ± 0.03	0.98 ± 0.01	0.98 ± 0.01
Linear coefficients			
$BE-\dot{V}O_{2peak}$ (ml·kg^{-1}·min^{-1})	53.7 ± 8.9	56.3 ± 8.3	54.1 ± 9.1
SEM (ml·kg^{-1}·min^{-1})	2.0	1.9	2.0
BE-slope (ml·kg^{-1})	-47.9 ± 14.6	-33.0 ± 10.4*	-33.6 ± 13.8*
SEM (ml·kg^{-1})	3.3	2.3	3.1
$\%\dot{V}O_{2peak}$	96.6 ± 11.5	101.7 ± 14.3	96.5 ± 7.4
R^2	0.91 ± 0.08	0.95 ± 0.04	0.96 ± 0.04

(*) significantly different from IIST_200m at ρ ≤ 0.05. (**) significantly different from IIST_200m at ρ ≤ 0.01. SEM: standard error of mean.

In addition, $BE-\dot{V}O_{2peak}$ values did not differ between trials (p = 0.62), despite BE-slope being higher (p < 0.01, η^2= 0.227, considered [small] effect size) in the IIST_v200m than in the v200m and v90%Δ (p < 0.01 for both comparisons), but no difference was observed between v200m and v90%Δ (ρ = 1.00). The values of $BE-\dot{V}O_{2peak}$ assessed for IIST_v200m, v200m, and v90%Δ (Table 1) were not different from those of $\dot{V}O_{2peak}$ (p = 0.73), neither were differences observed when comparing the $EE\dot{V}O_2$ during each trial for $BE-\dot{V}O_{2peak}$ (p = 0.84) or $\dot{V}O_{2peak}$ (p = 0.65).

Small-to-medium R^2 coefficients were observed between $\dot{V}O_{2peak}$ and $BE-\dot{V}O_{2peak}$ for IIST_v200m, v200 m, and v90%Δ (Figure 3, panels A, C, and E, respectively), but a non-significant R^2 coefficient was observed between $\dot{V}O_{2peak}$ and $BE-\dot{V}O_{2peak}$ for v200 m. Also, the R^2 coefficients were medium to strong between $EE\dot{V}O_2$ and $BE-\dot{V}O_{2peak}$ for IIST_v200m, v200m, and v90%Δ (Figure 3, panels B, D, and F, respectively).

Pearson's coefficients between parameters of both models (i.e., $\dot{V}O_2$ off-kinetics vs. BE) attained satisfactory sample power and showed moderate-to-strong correlations between A_{1off} with $BE-\dot{V}O_{2peak}$ and BE-slope for the IIST_v200m and v90%Δ trials, whereas for the v200 m trial, these correlations ranged from low to moderate (Table 2).

The τ_{1off} correlated, exceptionally, to BE-slope for the v200 m trial, with low level and unsatisfactory sample power, and the MRT_{1off} correlated to BE-slope for both v200 m and v90%Δ trials, but with low level and unsatisfactory sample power. The variability of $EE\dot{V}O_2$ (at IIST_v200m and v90%Δ) values is closer to that observed for $\dot{V}O_{2peak}$ values when compared to the variability observed for $EE\dot{V}O_2$ at v200 m and $BE-\dot{V}O_{2peak}$ estimates in all trials, with the largest shown in v200 m (Figure 4).

The fast-O_{2debt}, $O_{2[la^-]}$ and AnaerTotal demands assessed during the IIST_v200m, v200 m, and v90%Δ trials are shown in Figure 5. The fast-O_{2debt} post IIST_v200m was lower (p < 0.01, η^2= 0.281, considered [medium] effect size) than those post v200 m and v90%Δ. However, the values of $O_{2[la^-]}$ were not different (p = 0.11) between IIST_v200m, v200 m, and v90%Δ. The $Anaer_{Total}$ also was lower (p < 0.01, η^2= 0.294, considered [medium] effect size) than those post v200m and v90%Δ. No correlations were observed between fast-O_{2debt} and $O_{2[la^-]}$ values with the responses of $EE\dot{V}O_2$, $BE-\dot{V}O_{2peak}$, and BE-slope for IIST_200m, v200 m, and v90%Δ, respectively. However, τ_{1off} and MRT_{1off} were moderately related to $Anaer_{Total}$ post IIST_v200m (r = 0.64 and r = 0.66; p < 0.01), v200 m (r = 0.61 and r = 0.52; p < 0.01 and p = 0.02), and v90%Δ (r = 0.64 and r = 0.57; p < 0.01).

Discussion

The assumption that maximal $\dot{V}O_2$ response (i.e., $\dot{V}O_{2peak}$) can be elicited, and therefore assessed, during the trials was evidenced from the comparison between mean values of $\dot{V}O_{2peak}$, $EE\dot{V}O_2$, and $BE-\dot{V}O_{2peak}$. In contrast, whether $\dot{V}O_{2peak}$ can be assessed with reliability by BE procedures applied under different recovery conditions in the severe-intensity domain requires further considerations. For example, the estimated $BE-\dot{V}O_{2peak}$ showed low-to-moderate coefficients for the explained variance of the $\dot{V}O_{2peak}$ values assessed in the incremental test, with lowest coefficients observed for the 200-m single trial, which means that BE might mismatch actual $\dot{V}O_{2peak}$ between swimmers irrespective of the trial condition, but mainly in the

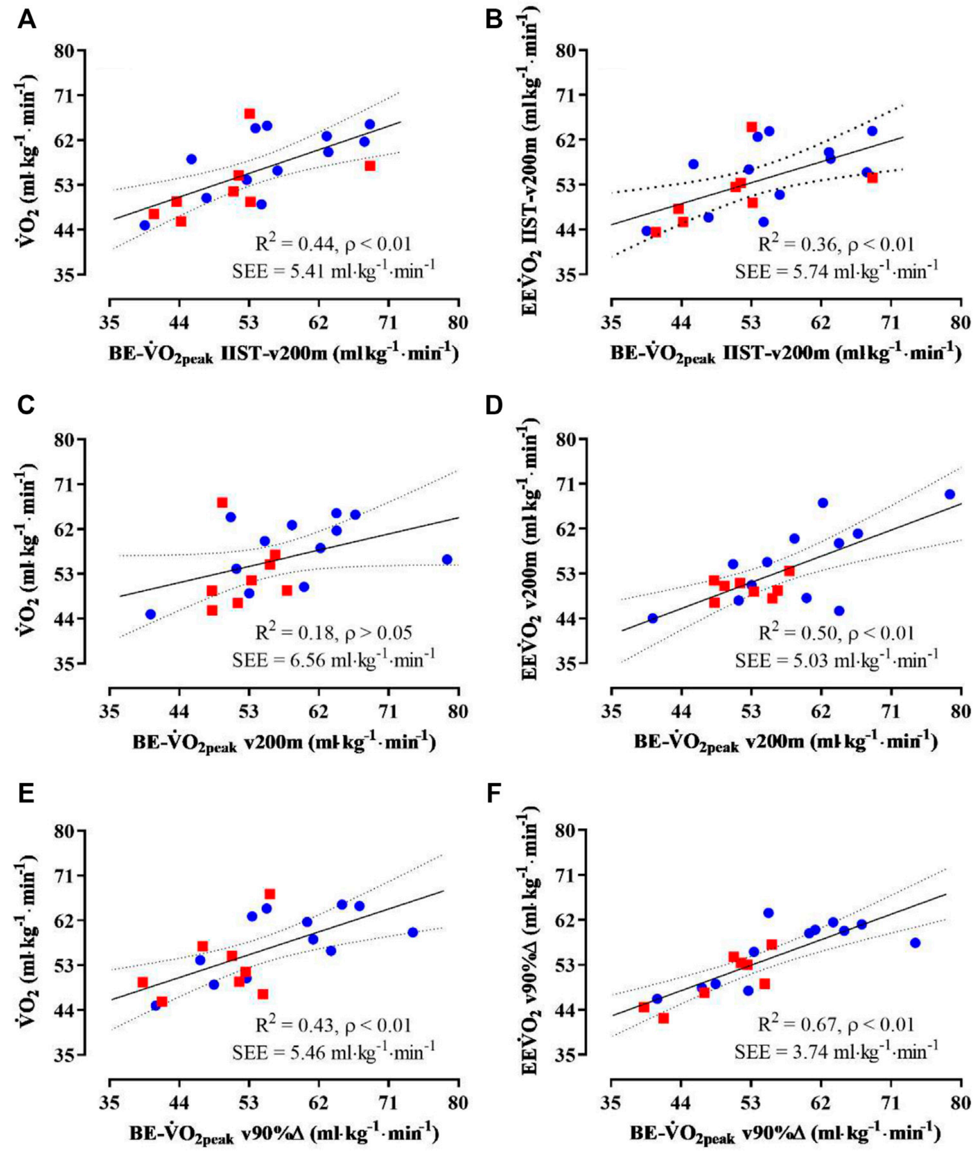

FIGURE 3
Linear regression analysis between the values of VO_{2max} and BE – $\dot{V}O_{2peak}$ for IIST_v200m **(A)**, v200m **(B)**, and v90%Δ **(C)** and between EE$\dot{V}O_2$ and BE – $\dot{V}O_{2peak}$ for IIST_v200m **(D)**, v200m **(E)**, and v90%Δ **(F)**. Red-filled square: women (N = 8) and blue-filled circle: men (N = 12). SEE: standard error of estimate.

200-m trial. Also, when BE – $\dot{V}O_{2peak}$ is estimating EE$\dot{V}O_2$, an improved coefficient of explanation is observed for single-trial conditions, which means that BE provides a satisfactory assessment of $\dot{V}O_2$ elevation during swimming in the severe-intensity domain. Moreover, the transients of $\dot{V}O_2$ off-kinetics played an important role on the reliability of BE – $\dot{V}O_{2peak}$ estimate since delayed and slowed time courses of $\dot{V}O_2$ recovery overshoot the BE values, which seemed to be a direct and positive effect of $Anaer_{Total}$ release on the transients of $\dot{V}O_2$ off-kinetics.

First, it is important to note that linear fitting underlying the BE mathematical procedure showed high adjustment coefficients for the 20 s dataset (with fixed TD = 15 s), irrespective of the trial performance in the severe-intensity exercise domain. Hence, the current finding indicating possible mismatching between $\dot{V}O_{2peak}$ and BE – $\dot{V}O_{2peak}$ should not be addressed to the robustness (i.e., reduced regression power) of the linear procedure applied to the current estimates. The concerns when a fixed delay is considered in the initial phase of $\dot{V}O_2$ recovery are related to the accuracy of the estimate. Commonly,

TABLE 2 Pearson's coefficients between the variables of $\dot{V}O_2$ off-kinetics with EE$\dot{V}O_2$, BE – $\dot{V}O_{2peak}$, and BE-Slope for IIST_200m, v200 m, and v90%Δ. N = 20.

	$\dot{V}O_2$ off-kinetics			
	TD_{1off} (s)	τ_{1off} (s)	MRT (s)	A_{1off} ($ml \cdot kg^{-1} \cdot min^{-1}$)
IIST_v200m				
EE$\dot{V}O_2$ ($ml{\cdot}kg^{-1}{\cdot}min^{-1}$)	ns	ns	ns	0.74**
BE – $\dot{V}O_{2peak}$ ($ml{\cdot}kg^{-1}{\cdot}min^{-1}$)	ns	ns	ns	0.55*
BE-slope ($ml{\cdot}kg^{-1}$)	ns	ns	ns	ns
v200m				
EE$\dot{V}O_2$ ($ml{\cdot}kg^{-1}{\cdot}min^{-1}$)	ns	ns	ns	0.67**
BE – $\dot{V}O_{2peak}$ ($ml{\cdot}kg^{-1}{\cdot}min^{-1}$)	ns	ns	ns	0.48*
BE-slope ($ml{\cdot}kg^{-1}$)	ns	*-0.45**	*-0.44**	ns
v90%Δ				
EE$\dot{V}O_2$ ($ml{\cdot}kg^{-1}{\cdot}min^{-1}$)	ns	ns	ns	0.82**
BE – $\dot{V}O_{2peak}$ ($ml{\cdot}kg^{-1}{\cdot}min^{-1}$)	ns	ns	ns	0.83**
BE-slope ($ml{\cdot}kg^{-1}$)	ns	ns*	*-0.47**	ns

(*) coefficient with significance at $\rho \leq 0.05$; (**) coefficient with significance at $\rho \leq 0.01$; (*ns*) coefficient with no significance.

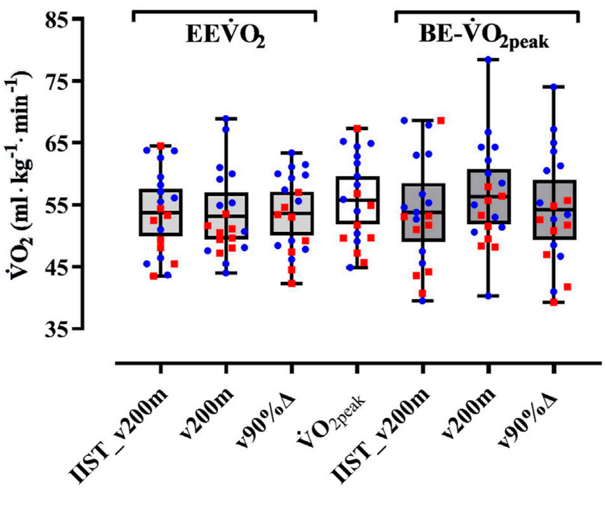

FIGURE 4
Box plots illustrating the variability of maximal and peak $\dot{V}O_2$ measurements (EE$\dot{V}O_2$ and $\dot{V}O_{2peak}$) and estimates (BE – $\dot{V}O_{2peak}$) during each trial (IIST_v200m, v200m, and v90%Δ). The central horizontal line inside squares depicts the mean values, the bottom and top lines of squares indicate the lower and upper boundaries for 95% confidence interval, and bars depict the maximal and minimum range of values. Red-filled square: women (N = 8) and blue-filled circle: men (N = 12).

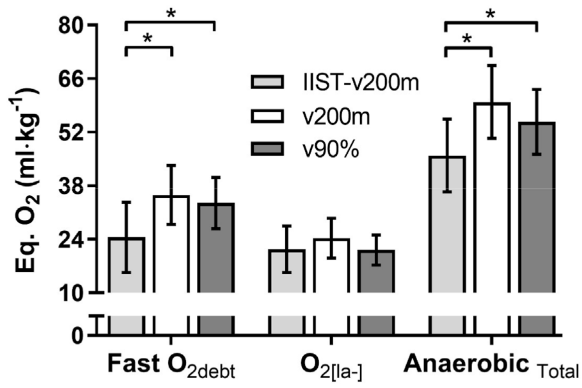

FIGURE 5
Anerobic energy demand during IIST_v200m, v200m, and v90%Δ trials: comparison between each trial regarding the responses of phosphagen (fast-O_{2debt}), glycolytic ($O_{2[la-]}$), and total anaerobic ($Anaer_{Total}$).

studies have demonstrated that the accuracy of the BE model is increased when selecting 20 s of data (Chaverri et al., 2016; Rodíguez et al., 2017; Monteiro et al., 2020), applying a linear fit strategy, and considering a short delay (e.g., ~5–10 s) before dataset fitting, which is, however, not a consensus for BE estimates in different exercise domains (Monteiro et al., 2020) and the exertion level or performance condition at a given exercise domain (Chaverri et al., 2016; Rodíguez et al., 2017). The current finding did not disagree with the aforementioned recommendations for the application of BE procedures but instead suggested that such an arbitrary delay of 15 s shall ensure that the $\dot{V}O_2$ recovery post-swimming performance in severe-intensity domains has already been initiated, and, indeed, the linear fitting strategy on the 20-s dataset still presents high accuracy for the BE estimate.

Second, there is robust statistical evidence from the comparisons between mean values of $\dot{V}O_{2peak}$ and BE – $\dot{V}O_{2peak}$ that these measurements are interchangeable, irrespective of the trial in which the BE – $\dot{V}O_{2peak}$ was estimated. Similar evidence was also observed comparing mean values of $EE\dot{V}O_2$ and $BE - \dot{V}O_{2peak}$. However, dispersion plots of $\dot{V}O_{2peak}$ vs. $BE - \dot{V}O_{2peak}$ refuted the interchangeable use between each other, showing that the power with which $\dot{V}O_{2peak}$ was estimated from $BE - \dot{V}O_{2peak}$ in the post IIST_v200m, v90%Δ, and v200 m trials attained, respectively, moderate (44 and 43%) or low (18%) rates, with just the first two rates with satisfactory statistical confidence. Therefore, the $BE - \dot{V}O_{2peak}$ post v200 m seems to be an unreliable assessment of $\dot{V}O_{2peak}$, which might be attributed to the tendency (not significant) to overestimate actual values.

However, the $\dot{V}O_2$ final response during all trials (i.e., $EE\dot{V}O_2$) attained maximal rates, and hence it did not account for the mismatching between $\dot{V}O_{2peak}$ vs. $BE - \dot{V}O_{2peak}$ either post v200 m or post IIST_v200 m and v90%Δ. Indeed, the assumption that maximal $\dot{V}O_2$ response is elicited during a 200-m single-trial performance has been well-reported (Almeida et al., 2020; Sousa et al., 2011; Rodríguez et al., 2017) and thus also contributing to recognize no constraints to the attainment of $\dot{V}O_{2peak}$ in 200 m. Furthermore, the current and previous reports on $\dot{V}O_2$ response in 200 m also contribute to the typification of the severe-intensity domain in such distance and recognized for swimming conditions ranging from 95 to 105% of $v\dot{V}O_{2max}$ (Sousa et al., 2014), or even for swimming velocity corresponding to 70%Δ (Reis et al., 2012), and just above the respiratory compensation point (Pessoa-Filho et al., 2012).

Third, whether there are no mathematical or physiological concerns about the reliability of BE procedures after all trials, why were the estimates considered poor (and unsatisfactory) for v200 m and moderate (but satisfactory) for IIST_v200m and v90%Δ? The effect of the energetics components during trial performances on the $\dot{V}O_2$ initial recovery phase might provide new insights into the reliability of BE. Despite the lack of information regarding the effect of aerobic/anerobic energy release on $\dot{V}O_2$ off-kinetics post-swimming performance in the severe-intensity domain since previous studies just analyzed the $\dot{V}O_2$ recovery profile in response to exercises at or around maximal aerobic values (i.e., 100% or ranging from 95 to 105% $\dot{V}O_{2peak}$, Sousa et al., 2014, 2015) or even at a given distance (i.e., 200 m; Sousa et al., 2011; Almeida et al., 2020), the current findings evidenced that total anerobic energy (i.e., phosphagenic in addition to glycolytic components) released during each trial showed a moderate and positive relationship with the transients τ_{1off} and MRT_{1off}. This means that the trials demanding higher anerobic release might also be associated to slower $\dot{V}O_2$ recovery, as observed when comparing the slow responses post v90%Δ and v200 m with the fast post IIST_v200m.

In other sports than swimming, longer transients for $\dot{V}O_2$ off-kinetics were associated with different intramuscular mechanisms such as 1) the rate of phosphocreatine resynthesis (i.e., a higher amount of phosphocreatine to restore requires a longer $\dot{V}O_2$ decrement phase; Rossiter et al., 2002; Korzeniewski and Zoladz, 2013); 2) lactate clearance (i.e., parallel lactate oxidation and transportation slow the time course of $\dot{V}O_2$ recovery; (Cunningham et al., 2000;; Özyener et al., 2001); and 3) the pattern of type II fiber recruitment (i.e., the inefficiency of oxidative phosphorylation also accounts to increase the time course of $\dot{V}O_2$ recovery (Cunningham et al., 2000; Rossiter et al., 2002).

Particularly, in swimming, longer $\dot{V}O_2$ time course during recovery has also been reported after the trial (200 m) and time-limited performance (Sousa et al., 2011, 2015), which was attributed to both the slower $\dot{V}O_2$ response until maximal values and to the accumulation of fatigue-related metabolites while performing each swimming condition. Although the current study has no information on the time course of $\dot{V}O_2$ on-kinetics response, which is therefore a limitation to be more assertive regarding the symmetry between on- and off-transients of $\dot{V}O_2$ response, the current findings are best aligned with the statement that a longer $\dot{V}O_2$ decrease is also probably linked to the anerobic reliance during swimming performance in the severe-intensity domain.

Moreover, the $EE\dot{V}O_2$ did not differ between IIST_v200m, v200m, and v90%Δ, and no differences were observed for A_{1off} after each trial. In cycling, the similarity of $\dot{V}O_2$ values and $\dot{V}O_2$ on-kinetics between different performances in high-intensity exercise is consistent with the assumption that the attainment of a maximal oxidative response is not affected by the pattern of fast/slow fiber type recruitment, and its particular metabolic profile for each trial, i.e., cost of O_2, rate of phosphate utilization, amplitude of slow component, and accumulation of metabolites (Cunninghan et al., 2000; Özyener et al., 2001; Rossiter et al., 2002). Therefore, there are also no physiological arguments to suppose that $\dot{V}O_{2peak}$ was not attained while performing v200m, IIST_v200m, and v90%Δ, even considering that differences were observed between them regarding total anerobic demand.

However, the aforementioned metabolic statement in cycling also inferred that longer transients of the initial $\dot{V}O_2$ recovery phase are probably related to the reliance on type II fibers during the performance in the severe-intensity domain, as suggested by higher anerobic release and slow component occurrence, respectively, for higher-intensity short trials (i.e., fast fiber contribution is promptly established) and longer-term trials (i.e., fast fiber contribution is progressively established) (Cunninghan et al., 2000; Özyener et al., 2001; Rossiter et al., 2002). While the current finding on the positive correlation between A_{1off} with $BE - \dot{V}O_{2peak}$ and $EE\dot{V}O_2$ in all trials is aligned with the symmetry between the amplitude of $\dot{V}O_2$ recovery and its values attained during exercise, the positive correlation in all trials between total anerobic energy and MRT (even if in the moderate level) is also consistent with the muscular bioenergetics (with high reliance on anaerobic energy) having influence on $\dot{V}O_2$ recovery time course, which therefore accounted for the observation of MRT relationship to BE-slope only in v200 m and v90%Δ.

Finally, the findings suggested that the initial amplitude of $\dot{V}O_2$ off-kinetics does not account for the possible mismatch between $\dot{V}O_{2peak}$ and BE – $\dot{V}O_{2peak}$, unless the attained value of $EE\dot{V}O_2$ is lower than that of $\dot{V}O_{2peak}$ (i.e., therefore the assumption of maximal $\dot{V}O_2$ cannot be ensured). Moreover, the anerobic energy released contributes moderately to the longer transients of $\dot{V}O_2$ off-kinetics, which suggests that the muscular metabolism is one among other variables with effect on BE – $\dot{V}O_{2peak}$ reliability. However, the current results cannot address the reasons underpinning the better matching between $\dot{V}O_{2peak}$ and BE – $\dot{V}O_{2peak}$ in v90%Δ than in v200 m. Although the aerobic contribution to each trial (i.e., total demand of $\dot{V}O_2$) was not measured in the current study, it is expected to be higher in v90%Δ than in v200 m as supported when comparing previous reports on the energetics for swimming at velocities surrounding maximal aerobic velocity (Sousa et al., 2014) or at 200 m (Massini et al., 2021).

From the results of these previous studies, the reliance on oxidative metabolism during the performance of v90%Δ is supposed to be higher than that of v200 m, and thus the attainment of a given value of $EE\dot{V}O_2$ not different from $EE\dot{V}O_2$ not different from $\dot{V}O_{2peak}$ is expected for each swimmer and can be accounted to the low variability of BE – $\dot{V}O_{2peak}$ estimate during v90%Δ. Therefore, the lack of information on aerobic contribution is another limitation of the current study, which should be overcome in future studies aiming to address whether the muscular energetics influence $\dot{V}O_2$ on-kinetics when comparing distance-limited and time-limited performances in swimming. It can be argued that the poor matching between $\dot{V}O_{2peak}$ and BE – $\dot{V}O_{2peak}$ in v200 m is a feature of the fixed delay (15 s) applied to the BE procedure. Despite the reliability of the $\dot{V}O_{2peak}$ estimate being susceptible to different time delays (Rodígues et al., 2017; Monteiro et al., 2020), the initial $\dot{V}O_2$ recovery seems to differ from 15 s only for IIST_v200m, in which the BE – $\dot{V}O_{2peak}$ estimate was not suspicious.

Although the scope of the current study was not the analysis of the effect of data treatment on the measurements of the transients and amplitudes of $\dot{V}O_2$ kinetics and BE, an unstudied issue in swimming physiology is whether breathing mechanics (i.e., ventilatory frequency and volume) is disturbed with the AquaTrainer® apparatus by comparing to actual free-swimming condition (e.g., producing larger set of aberrant $\dot{V}O_2$ data). It is important to investigate whether swimming has an intrinsic characteristic of ventilatory mechanics, which is different from other sports, hence requiring proper $\dot{V}O_2$ dataset treatment.

When analyzing the practical applications of the current findings, three major comments are discernible: 1) BE is a feasible procedure for the assessment of $\dot{V}O_2$ response at the end of exercise conditions in the severe-intensity domain (represented by IIST_v200m, v200m, and v90%Δ in the current study), which approached a maximal aerobic value despite the lack of endorsement on its interchangeability with $\dot{V}O_{2peak}$; 2) such a maximal aerobic value is, however, meaningful for coaches as it represents the muscular oxidative profile in the severe-intensity domain, and hence enabling the management of aerobic response in middle-distance performance, the adjustments with cardiorespiratory conditioning during training demanding maximal aerobic responses, and the pace reference for training in the severe-intensity domain; and 3) the BE protocol with best reliability to assess the $\dot{V}O_2$ response that matches $\dot{V}O_{2peak}$ should allow a proportionally higher reliance on aerobic than anerobic energy contribution, as is probably the case either during longer trials in the severe-intensity domain (e.g., 300–400 m) or shorter distances preceding a similar trial (e.g., 2 × 200 m).

Conclusion

The major contribution of the current study was to determine the effect of anerobic response on the reliability of the estimation of $\dot{V}O_{2peak}$ by BE, demonstrating that the anerobic demand might also be associated to longer transients of $\dot{V}O_2$ off-kinetics (i.e., slowed $\dot{V}O_2$ recovery), which in turn are associated to the alterations of the slope of the regression line (e.g., reducing the inclination), and therefore compromising the reliability of $\dot{V}O_{2peak}$ estimate, in spite of the strength of these associations observed to be low to moderate. Considering the fact that performance in a single effort with significant contribution of anerobic energy (as observed for v200m and v90%Δ) should probably demand a significant time constant or average response time of $\dot{V}O_2$ recovery; a useful solution is to ensure faster responses of the transients of $\dot{V}O_2$ off-kinetics, with the performance of an exercise with the same characteristics of effort intensity as the one where the test is intended to be carried out, as observed in the ISST_v200m situation. In addition, the findings also reinforce that the time delay for $\dot{V}O_2$ recovery should be considered to apply BE procedures in trials in the severe-intensity domain, being recommendable to encompass a dataset no larger than 15 s. Finally, another important piece of evidence is the response of $\dot{V}O_2$ at the end of IIST_v200m, v200 m, and v90%Δ corresponding to that typical of the severe-intensity domain, despite the estimation of $\dot{V}O_{2peak}$ by BE giving no confident value from the v200m test, and hence the estimates from IIST_v200m and v90%Δ are preferable for planning trials, controlling oxidative response, and monitoring the conditioning adjustment needed to perform in the severe-intensity domain.

Data availability statement

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

Ethics statement

The studies involving human participants were reviewed and approved by São Paulo State University Ethics Committee (CAEE: 54372516.3.0000.5398). Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

Author contributions

DM, AS, TA, JR, FB, ME, and DPF conceived and designed the study. DM, AS, TA, AM. ME, JR, and DPF conducted experiments and analyzed the data. DM, AS, TA, AM, ME, JR, FB, and DPF wrote the manuscript. All the authors read and approved the manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Kinematic, arm-stroke efficiency, coordination, and energetic parameters of the 400-m front-crawl test: A meta-analysis

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Several studies have investigated biomechanical and energetic parameters in competitive swimming. Among these studies, it is possible to identify the 400-m front crawl as a useful test to assess these parameters. The present study provided a meta-analysis assessing representative variables for the kinematic, arm-stroke efficiency, coordination, and energetic parameters of the 400-m front crawl test. *PubMed*, *Embase*, *Web of Science*, and *SPORTDiscus* were the databases used to select the studies published between January 1970 and December 2022. Forty studies ($n = 651$ swimmers) were selected according to the eligibility and inclusion criteria. The variables chosen to represent each parameter were: clean swim speed (kinematics); index of coordination (coordination); arm-stroke efficiency (efficiency); and oxygen consumption (energetic). Swimming speed was moderate (1.34 m s^{-1}) compared to the world's records performers. Thus, this speed contributed for the swimmers in remaining at high efficiency (35%), imposing a capture coordination model (index of coordination: –11%) with high oxygen consumption (58.8 ml·kg^{-1} min^{-1}). High heterogeneity (>75%) was found among the outcome parameters in the studies. The different average speeds that represented the kinematic parameters seem to be the most responsible and influential in the arm-stroke efficiency, coordination, and energetic parameters for high 400-m freestyle (front crawl) performance. This meta-analysis can help researchers, coaches, and swimmers improving competitive performance, and developing further research in the sports sciences area, specifically in the swimming.

KEYWORDS
swimming, biomechanics, systematic review, performance, middle-distance

Introduction

The swimming performance is influenced by kinematic, arm-stroke efficiency, coordination, and energetic parameters (1) and those have been investigated in scientific research (2–5). The synthesis of scientific research results on such parameters can be useful for coaches and researchers to monitor, improve performance, and develop future research. The 400-m, even test (front crawl) or competitive event (freestyle), is a middle-distance swimming distance (6). The descriptive and quantitative summary of 400-m front crawl test specific performance parameters (such as kinematic, arm-stroke efficiency, coordination, and energetic) seems to have not been explored yet.

The 400-m test and competitive event has a prevalence of a parabolic pacing patterns or a fast-even of swimming speed (7), and is performed under the severe intensity domain (8). The mean swimming speed is the product of the mean stroke rate (SR) and mean stroke length (SL), without the effect of the wall push-off, turns and start effects (2). In a middle-distance event, SR and SL can vary (9) according to gender (male and female), categories (age-groups or adults), training experience, and levels of swimming technical skills. The 400-m front-crawl test is widely used in different competitive levels and the elite swimmers in this event can reach speeds ranging from 1.58 to 1.76 m s^{-1} (10). In addition, to reach such speeds, a refined technique can help the swimmer in reduce hydrodynamic drag and generating propulsion. The relation between the swimmer's applied force and effective propulsion is the arm-stroke efficiency (ηp). There are different possibilities to estimate ηp (11) as the percentage of the force generated by the swimmers that is actually propulsive. A model previously proposed (3) considers the stroke cycle as a paddle wheel producing force to propel the swimmer forward. With this method, the ηp values for the 400-m front crawl were around 30%–40% (12–14). Three dimensional (3D) ηp analysis, which considers both the 3D centre of mass speed and 3D hand speed, can be applied too (11). The coordination parameters can be represented, in the front crawl, by the index of coordination (IdC) (4). The IdC characterizes what coordination model the swimmer adopts, i.e., the IdC negative (catch-up model), null (opposition model), and positive (superposition model). In the 400-m front crawl test, studies (14–16) indicated that swimmers adopt a non-propulsive interval between the actions of the arm-stroke, the catch-up model. Expert swimmers in this distance present an IdC from −20% to −10% (17, 18).

However, performing any swimming stroke, under any coordination model, to reach a certain swimming speed requires an amount of metabolic energy. In this way, the bioenergetics profile can be determined by VO_2 in supra-maximal tests (to reach the VO_2 peak) or by exhaustive protocols (to achieve maximum O_2 consumption—VO_2max—even with an increase in intensity, VO_2 does not increase) (19). Previous studies have identified the 400-m front crawl as a reliable test to assess the maximum aerobic power and anaerobic contribution (20–22). As the average speed in the 400-m front crawl test is similar to the minimum speed to reach the VO_2max, the energy profile of this test deserves attention in relation to the possibilities of its use to prescribe training intensities, for example (20). Meta-analysis and systematic reviews are scarce in research concerning observational studies related to sport performance, and specifically swimming (23, 24). Therefore, the purposes of this study were to summarize, analyse, and evaluate results of studies involving 400-m front crawl kinematic, arm-stroke efficiency, coordination, and energetic parameters, tthrough a systematic review with meta-analysis. This meta-analysis can provide to coaches and sports scientists an overview of the 400-m front crawl test.

Methods

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement check list was used for this meta-analysis, following the established criteria (25).

Data strategy and sources

The search strategy used in the PubMed, Embase, SPORTSDiscus and Web of Science databases for study collections were: swimmer AND swimming OR "front crawl" OR "middle distance" OR "400 m" AND energy OR kinematic OR coordination OR efficiency. Only complete original articles were selected and they were published between January 1970 and December 2022. The Boolean operators "AND" and "OR" were used for tracing during the searches in the electronic databases.

Eligibility criteria

The meta-analysis included studies that: (i) performed observational analysis; (ii) analyzed competitive swimmers of both sexes; (iii) used the 400-m crawl test as a protocol. On the other hand, studies were excluded when: (i) participants' age were equal and less than 12 years old and did not clearly show the age mean; (ii) results were incomplete for standard deviation on the results; (iii) were without information from anthropometric data; (iv) described paralympic swimmers; (v) duplicate from the same authors and sample size.

Performance outcomes parameters

To facilitate the construction of the meta-analysis, only one main outcome representing each performance parameter was determined in agreement with the research team. Therefore, the performance outcomes extracted from these studies were: (i) kinematics (clean swim speed); (ii) arm-stroke efficiency; (iii) coordination (index of coordination); (iv) energy (peak and maximal oxygen consumption). The swimming speed was chosen to represent the kinematic parameters by representing the performance in the 400-m front crawl test. The extraction of the values ($m{\cdot}s^{-1}$) for meta-analysis were of the studies that evaluated the clean swim speed either by photogrammetry or by the chronometer. The ηp ($(v{\cdot}0.9)/(2\pi{\cdot}SR{\cdot}l){\cdot}2/(\pi)*100$) in %) was obtained by the paddle wheel method in all the selected studies (3).

The selection of studies regarding coordination parameters were those that presented the results of the IdC (%). All selected studies used the qualitative class model previously proposed (4).

The representative variable of the energy parameters was the VO_2peak or VO_2max obtained in the 400-m front crawl test. The methodological protocols for obtaining VO_2 peak values were by retro-extrapolation and direct method during the test. The first is obtained after the end of the test. The second consists of obtaining the VO_2 breath-by- breath during the entire test. The VO_2peak is the highest value considered until the end of the test and the VO_2max is derived from incremental protocols to exhaustion. Both methods have already been previously reported (20, 21).

Results extraction and assessing risk of bias

The data were extracted by two independent researchers with experience in systematic review and meta-analysis. In the first phase, the studies were selected and gathered by analyzing the databases described in the search strategy. In the second phase, the exclusion criteria established in the previous extraction were applied. First, duplicates were excluded and then, by reading the abstract and, if necessary, the full paper, which did not include the eligibility criteria. A third researcher was requested when there were divergences in the inclusion and exclusion criteria. All researchers maintained the same pattern in the extraction of meta-analysis data.

In addition, the researchers evaluated the methodological quality of the selected articles. For this, the Downs and Black Quality Assessment Checklist (26) for studies with and without randomization was used. The original version of the scale includes 27 items referring to the classification of the methodological quality of the studies. However, some adaptations were made to better fit the focus of this research: (i) item 27 was not used for evaluating whether the negative findings from the study could be due to chance; (ii) replacement of "patient" by "participant" and "treatment" by "testing". These changes in the assessment of the quality were also carried out in previous studies (24, 27, 28). The points obtained were totaled (fraction between the total number of points reached and total number of applicable points), followed by conversion into percentages, like previous study (24).

Data analysis

The kappa index was used to demonstrate the reliability between the researchers in the scoring procedure. The interpretations of the degrees are: (i) very low: $0 < K < 0.19$, (ii) considerable: $0.20 < K < 0.39$, (iii) moderate: $0.40 < K < 0.59$, (iv) substantial: $0.60 < K < 0.79$, and (v) excellent: $0.80 < K < 1.00$ (29). For the meta-analysis, the mean and standard deviation of kinematics, arm-stroke efficiency, coordination, and energy parameters obtained from the selection of studies were used. When necessary, a conversion to equal units of measure was performed. A random effect model was developed for the data statistics (30). The heterogenicity, represented by the inconsistency test (I^2), was applied among the selected studies whose results represent: 0%–25% low; 25%–50% moderate; 50%–75% high, over 75%, very high (30). The weight quality of the studies (31) was calculated by the inverse of the square standard error ($1/SE^2$) and converted into per cent. The risk of data bias was observed by the forest plot (developed manually in Graph Prism 8.0) and statistic results (I^2, SE and CI95%) were provided by the software Open Meta Analyst (32). Subgroup analyses were performed to minimize the effect of inconsistency. The alpha was set at 5%.

Results

The research first identified 6,323 studies, of which, after the exclusion of duplicates, 4,488 remained. With the analysis by means of the titles and abstracts, 2,591 studies were excluded (1,897 studies included). Subsequently, 68 studies were identified in the analysis of the complete articles following the eligibility criteria. Afterwards, 28 studies were excluded for the following reasons: (i) results did not correspond to the maximum 400-m front crawl test; (ii) swimmers of very young age; (iii) when it was not possible to identify the described results; (iv) articles that did not provide sample characterisation data (for example: body mass to convert the unit of measurement of oxygen consumption); (v) articles by the same author, but with the same sample characterisation (in this case only one was chosen). Thus, 40 studies completed the final analysis and inclusion criteria for the meta-analysis (**Figure 1**).

In total, 40 articles were examined extensively because they fitted the previously established inclusion criteria. Of these, 28 studies were classified as moderate and 12 as high quality. No studies were considered low or very high quality. The reliability between both reviewers showed an almost perfect agreement ($k = 0.85$—excellent; $p \leq 0.001$). **Table 1** describes the studies with the quality score, swimmers' competitive level, sample size, time trial, swimming speed, ηp, IdC and VO_2.

Kinematic, arm-stroke efficiency, coordination, and energetic parameters

Due to the large number of studies describing swimming speed, it was possible to carry out subgroup analyses to verify the mean swimming speed responses, as well as the variability of the studies divided into categories. **Figure 2** shows the forest plot with the inclusion of the 40 overall studies ($n = 611$) representing the clean swim speed in the 400-m front crawl. The mean swimming speed was considered moderate ($1.34\ m{\cdot}s^{-1}$ and $SE = 0.02$; 95% CI: 1.31 to $1.37\ m{\cdot}s^{-1}$). The heterogeneity was considered high ($I^2 = 98\%$, $p < 0.01$), which shows a high variability across the studies.

Next, an analysis by subgroup of the gender (male and female) for swimming speed (**Figure 3A,B**) was developed. So, the meta-analyses were performed with 22 studies for male swimmers ($n =$

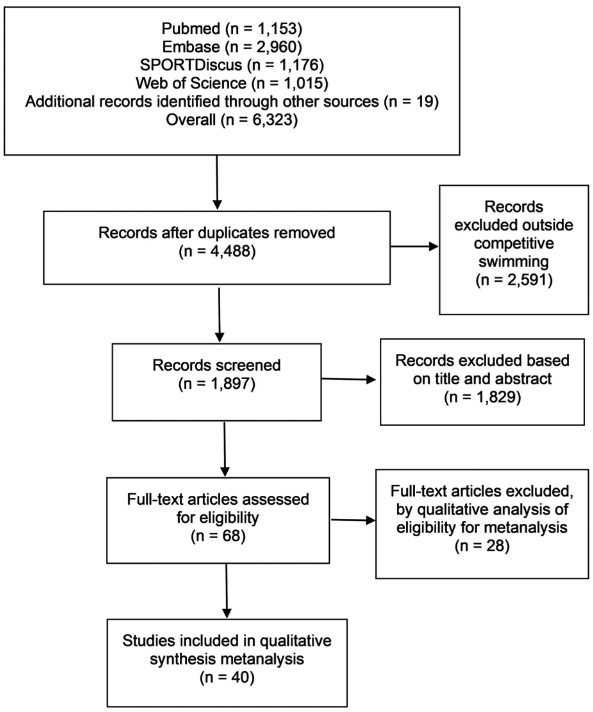

FIGURE 1
Flowchart summary of the studies selection process.

TABLE 1 Studies, quality score, swimmers' competitive level, sample size, time trial, swimming speed, arm-stroke propelling efficiency (*np*), index of coordination (IdC) and oxygen consumption (VO_2).

Studies	Score (%)	Swimmers (competitive level)	Sample	Time trial (s)	Swimming speed ($m \cdot s^{-1}$)	*Hp* (%)	IdC (%)	VO_2 ($ml \cdot kg^{-1} \cdot min^{-1}$)
Arsoniadis, Bogdanis (13)	53.8	Regional and national swimmers	♂$N = 12$	-	1.28 ± 0.10 (experience group)	34.0 ± 4.0 (experience group)	-	44.0 ± 6.0 (experience group)
Barbosa, de Jesus (14)	42.3	Sub elite	♂$N = 22$	254.9 ± 20.4	1.28 ± 0.40	30.0 ± 5.0	−13.0 ± 7.0	-
Bassan, César (33)	34.6	Competitive	♂$N = 15$		1.35 ± 0.15	-	-	-
Bentley, Roels (34)	57.7	Elite	♂♀$N = 8$	265.0 ± 15.0	1.30 ± 0.06	-	-	51.2 ± 5.8
Campos, Kalva (35)	34.6	Competitive	$N = 9$ (♂$N = 6$ ♀$N = 3$)	-	1.34 ± 0.13	-	-	62.3 ± 13.7
Chatard, Collomp (36)	42.3	Competitive	♂$N = 9$		♂1.49 ± 0.07	-	-	-
Chatard, Chollet (37)	50.0	Triathletes	♂$N = 8$	297.25 ± 7.24	1.35 ± 0.01	-	-	64.8 ± 2.9
Chollet, Hue (38)	42.3	Competitive	♂$N = 6$	-	1.34 ± 0.02 (no drafting)	-	-	65.2 ± 1.2 (no drafting)
Correia, Feitosa (20)	42.3	Competitive	♂$N = 14$	316.36 ± 0.21	1.26 ± 0.11	-	-	68.1 ± 9.7
Dalamitros, Zafeiridis (39)	53.8	Competitive	(control group; $N = 8$)	control group 324.13 ± 16.97	control group 1.25 ± 0.01	-	-	-
Dekerle, Sidney (40)	53.8	Well trained	♂$N = 8$ ♀$N = 2$	-	♂♀1.42 ± 0.10 (second part)	-	-	-
Deminice, Gabarra (41)	42.3	Competitive	♂$N = 9$ ♀$N = 5$	-	1.38 ± 0.09	-	-	-
Fernandes, Sousa (42)	42.3	Long distance	♂$N = 17$	-	1.29 ± 0.16	-	-	-
Franken, Figueiredo (43)	42.3	Competitive	♂$N = 11$	-	1.45 ± 0.08	-	-	-
Funai, Matsunami (44)	42.3	Well-trained national-level	♂$N = 7$	264.98 ± 8.94	1.46 ± 0.05	-	-	-
Gay, López-Contreras (12)	53.8	Triathletes and open water	♂$N = 33$	-	1.17 ± 0.16 swim	40 ± 6.2	-	-
Greco, Pelarigo (45)	42.3	Trained	♂$N = 22$; ♀$N = 14$	-	Overall = 1.38 ± 0.09; ♂ = 1.32 ± 0.10; ♀ = 1.21 ± 0.10	-	-	-
Jurimae, Haljaste (46)	34.6	Competitives Youngs	♂$N = 29$	378.3 ± 53.5	1.05 ± 0.14	-	-	62.0 ± 19.4

(*continued*)

TABLE 1 Continued

Studies	Score (%)	Swimmers (competitive level)	Sample	Time trial (s)	Swimming speed ($m \cdot s^{-1}$)	*Hp* (%)	IdC (%)	VO_2 ($ml \cdot kg^{-1} \cdot min^{-1}$)
Kalva-Filho, Campos (22)	42.3	Competitive	♂*N* = 12	-	1.40 ± 0.10	-	-	63.2 ± 13.7
Laffite, Vilas-Boas (9)	38.5	Trained	♂*N* = 7	256 ± 7	1.56 ± 0.04	-	-	67.2 ± 5.6
McCabe and Sanders (47)	46.2	Sprint and specialists' middle distance	♂*N* = 15 (*N* = 7 sprints, *N* = 8 middle distance)	242.59	Overall: 1.45 ± 0.05	-	-	-
Mezzaroba, Papoti (48)	42.3	Trained	*N* = 33 (♂*N* = 17 and ♀*N* = 16)	-	♂ = 1.18 ± 0.19; ♀ = 1.01 ± 0.10; Y: 1.09 ± 0.14	-	-	-
Obert, Falgairette (49)	42.3	Regional	*N* = 13 (♂*N* = 12 and ♀*N* = 8)	352 ± 52	1.06 ± 0.10 (*N* = 13)	-	-	-
Oliveira, Caputo (50)	42.3	Trained	♂*N* = 13	-	1.29 ± 0.05	-	-	-
Papoti, Silva (51)	50.0	National	*N* = 21 (♂*N* = 5 and ♀*N* = 9)	-	Y: 1.24 ± 0.09	-	-	-
Petibois and Deleris (52)	46.2	Competitive	♂*N* = 7	255.9 ± 6.8	1.54 ± 0.06	-	-	
Ribeiro, Cadavid (6)	42.3	Competitive	♂*N* = 15	296 ± 68	1.44 ± 0.05	-	-	56.0 ± 6.0
Rodríguez and Mader (53)	42.3	Young	♂♀*N* = 10	-	♂1.44 ± 0.01; ♀1.36 ± 0.04	-	-	63.2 ± 6.0
Rodriguez (54)	65.4	National Spanish	serie A *N* = 15 (♂*N* = 10 and ♀*N* = 5; serie B *N* = 33 (♀*N* = 22 and ♂*N* = 11)	serie *A* = 265.60 ♂; 280.30 ♀; serie *B* = 272.11s ♂, 294.33s ♀(time trial based on high speed reported in study)	serie A: ♂1.51 ± 0.07, ♀1.43 ± 0.09;	-	-	62.2 ± 10.0
Samson, Monnet (55)	34.6	Regional and national	*N* = 17 (♂*N* = 9 and ♀*N* = 8)	-	1.51 ± 0.08 (*N* = 17)	-	-	-
Schnitzler, Ernwein (56)	46.2	National, international and recreational	*N* = 34 (recreational: ♂*N* = 8 and ♀*N* = 9; expert ♂*N* = 8 and ♀*N* = 9; overall ♀ = 18	-	Recreational: ♂1.21 ± 0.06, ♀ = 1.02 ± 0.07; Expert: ♂1.45 ± 0.05, ♀ = 1.35 ± 0.07; Overall♀ = 1.18 ± 0.07	-	-	-
Schnitzler, Seifert and Chollet (15)	50.0	Competitive	♂*N* = 16 (G1 *N* = 8 expert swimmers; G2 *N* = 8 students with lower performances.	G1 = 267.6 ± 9.9 G2 = 344 ± 14.9	G1: V50 = 1.49 ± 0.08; G2: 1.18 ± 0.11; ♂1.33 ± 0.05	-	−12.5 ± 3.7	-
Schnitzler, Seifert (16)	42.3	French highly trained	♂*N* = 9	280 ± 5.6	Trial 2: 1.39 ± 0.1	-	−13.8 ± 4	-
Strzala, Tyka (18)	34.6	Competitive	*N* = 26		1.42 ± 0.07		−5.9 ± 6.55	

(*continued*)

TABLE 1 Continued

Studies	Score (%)	Swimmers (competitive level)	Sample	Time trial (s)	Swimming speed (m·s^{-1})	*Hp* (%)	IdC (%)	VO_2 (ml·kg^{-1}·min^{-1})
Tsalis, Toubekis (57)	42.3	Different years	*N* = 11 young; *N* = 7 adults	*Y* = 332.3 ± 23; *S* = 315.2 ± 14.6	*Y* = 1.16 ± 0.11); *S* = 1.21 ± 0.08	-	-	-
Wakayoshi, Ikuta (58)	38.5	College	♂*N* = 9		1.54 ± 0.07	-	-	57.8 ± 6.6
Zacca, Fernandes (59)	30.8	Competitive	*N* = 10 (♂*N* = 7 and ♀*N* = 3)	278 ± 16 0.9	1.44 ± 0.08	-	-	64.5 ± 8.6
Zacca, Azevedo (60)	57.7	Young	*N* = 24 (♂*N* = 10, ♀*N* = 14)	315 ± 22 (E4)	1.21 ± 0.08	-	-	49.9 ± 5.2
Zacca, Azevedo (21)	57.7	National level	*N* = 11 (♂*N* = 6, ♀*N* = 5)	311 ± 17	1.28 ± 0.07; Y: 1.21 ± 0.09	-	-	54.4 ± 6.6
Zacca, Toubekis (61)	57.7	Young	*N* = 15 (♂*N* = 6, ♀*N* = 9)	358 ± 21 (Pós)	1.11 ± 0.07; Y: 1.29 ± 0.07	-	−8.5 ± 4.1	42.3 ± 6.6; Y: 45.4 ± 5.7

♂, male; ♀, female; S, senior swimmers; Y, young swimmers.

244) and five studies for female ($n = 70$). The mean swimming speed of male swimmers was 1.39 m·s^{-1} (SE = 0.02; 95% CI: 1.35 to 1.43 m·s^{-1}), higher when compared to the mean swimming speed of female swimmers: 1.24 m·s^{-1} (SE = 0.07; 95% CI: 1.11 to 1.37 m·s^{-1}). The heterogeneity was considered high for both genders (male: $I^2 = 97.0\%$, $p < 0.01$; female: $I^2 = 97.6\%$, $p < 0.01$), while the high variability between studies in each category remained.

Subsequently, the analysis by subgroup was developed by senior (over 18 years old) and junior (under 18 years old) categories for swimming speed (**Figures 3C,D**, respectively). The criteria used by the junior and senior categories was the age group based on the previous study (62). Twenty-six studies were included in the senior category ($n = 205$) and 14 studies in the junior category ($n = 242$). The senior category showed a higher mean swimming speed of 1.36 m·s^{-1} (SE = 0.03; 95% CI: 1.32 to 1.40 m·s^{-1}) compared to the junior category swimming speed, which had a mean of 1.28 m·s^{-1} (SE = 0.03; 95%CI: 1.21 to 1.34 m·s^{-1}). The heterogeneity remained large for both categories (senior category: $I^2 = 98.2\%$, $p < 0.01$; junior category: $I^2 = 97.3\%$, $p < 0.01$), demonstrating a large variability of studies in both categories.

Figure 4A,B shows the ηp and the IdC's meta-analysis (respectively). There was a total of three studies with ηp ($n = 67$) and five with IdC ($n = 73$). The ηp was considered high, with mean of 35% (SE = 2.97; 95% CI: 28.8% to 40.5%). The heterogeneity was considered high ($I^2 = 95.4\%$, $p < 0.001$) due to the high variability of the studies. The IdC showed that swimmers have adopted the catch-up coordination model, with an IdC mean of −11% (SE = 1.65; 95% CI: −14.3% to −7.8%). The heterogeneity was high ($I^2 = 89.5\%$, $p < 0.001$ for IdC).

Figure 5A shows 17 studies ($n = 211$) that were selected in the VO_2 meta-analysis. The overall mean of VO_2 was high, corresponding to 58.5 ml·kg^{-1}·min^{-1} (SE = 2.06). The heterogeneity was considered high ($I^2 = 96.7\%$, $p < 0.01$) due to the variability of studies. **Figure 5B,C** shows the analysis of subgroups by age category (senior and junior, respectively). In the senior category, nine studies were included ($n = 82$), and the VO_2 mean was higher, 60.4 ml·kg^{-1}·min^{-1} (SE = 2.06; 95% CI: 54.7 to 64.2 ml·kg^{-1}·min^{-1}) when compared with the junior category (eight studies; $n = 129$), where VO_2 average was 56.9 ml·kg^{-1}·min^{-1} (SE = 2.5; 95% CI: 52.0 to 61.8 ml·kg^{-1}·min^{-1}). The heterogeneity remained high for both subgroups (senior: $I^2 = 96.2\%$, $p < 0.01$; junior: $I^2 = 93.3\%$, $p < 0.01$).

Discussion and implications

The purposes of this study were to summarize, analyse, and evaluate results of studies involving 400-m front crawl kinematic, arm-stroke efficiency, coordination, and energetic parameters, through a systematic review with meta-analysis. This study tried to demonstrate an overview of the performance parameters of the 400-m front crawl test. Swimming speed, ηp, IdC, and VO_2 results were analyzed. In an overall analysis of the results, independent of gender, the results indicated that the 400-m front crawl mean speed was moderate (1.34 m·s^{-1}), with large ηp (35%), IdC was in the catch-up coordination model (−11%), and swimmers reached high VO_2 values (59 ml·kg^{-1}·min^{-1}). However, when compared with only the best results found, these mean results are below of

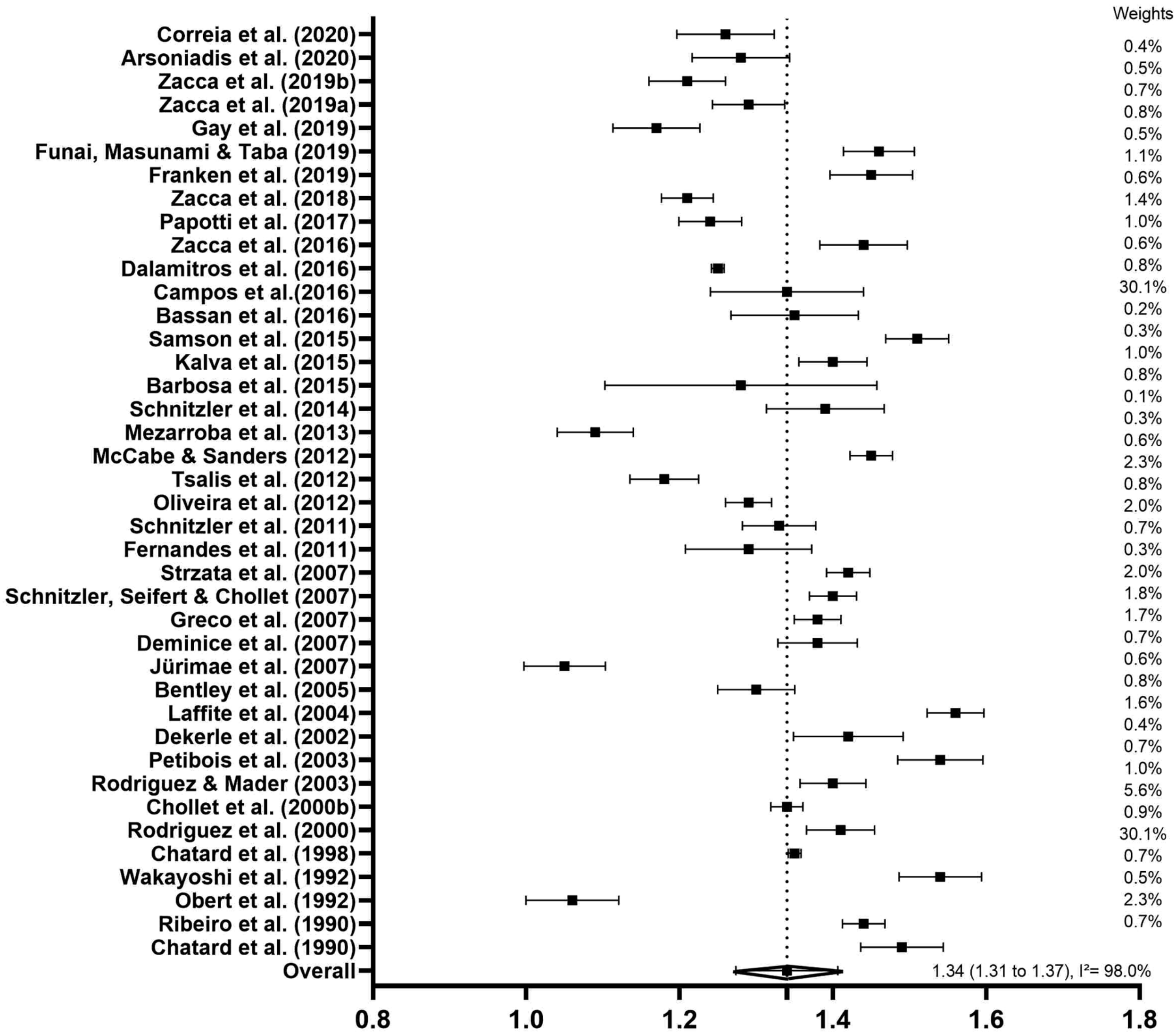

FIGURE 2
Forest plots derived from continuous random-effects models depicting the kinematics parameters represented by clean swim speed ($m \cdot s^{-1}$) in 400-m front crawl test.

those reported previously: speed 1.56 $m \cdot s^{-1}$ of seven trained male swimmers (9); ηp: 40.0% of 33 open water and triathletes, male and female swimmers (12); IdC: −5.9% in 26 competitive male swimmers (18); $VO_2 = 68.1$ $ml \cdot kg^{-1} \cdot min^{-1}$ in 14 competitive male swimmers (20). This comparison is limited by the gender, but the cited values were the highest of each parameter analyzed in this meta-analysis.

The assessment of bias risk from the selected studies was performed with the checklist previously reported (26). The score results (converted to percentage for better understanding of the parts by the whole) of study similar (27) to the present one were approximately 45%. Studies related to swimming performance (27, 63) obtained from 35% to 41%. This can be explained by the fact that most studies were not as rigorous in terms of delineation (e.g., clinical and randomized trials). Implications of group analysis, intervention and blinding of participants, for example, common to these types of trials mentioned, had to be considered null within the scale score. In addition, some items had to be adapted to better suit observational studies (24). Therefore, the meta-analysis pointed to a lack of studies with better methodological quality. It is clear that randomized, clinical, and longitudinal studies can provide better cause and effect responses of parameters that are responsible for the performance of a given event in any type of competitive sport, as previously pointed out (27, 64). Research in the area of sport performance, and swimming, has the difficulties of recruited high sample sizes, making studies with more robust qualities difficult (63). On the other hand, it is understood that such methodologies are often not in accordance with the aims of the studies that were analyzed in the present meta-analysis. Future researches should use more directed to the area scales of evaluation of the quality of studies and that encompass the reality of studies related to sports performance, specifically in competitive swimming.

Over the decades, the 400-m front crawl test has been investigated to help swimmers and coaches improve performance in competitive events (20, 59). It is already known that swimming

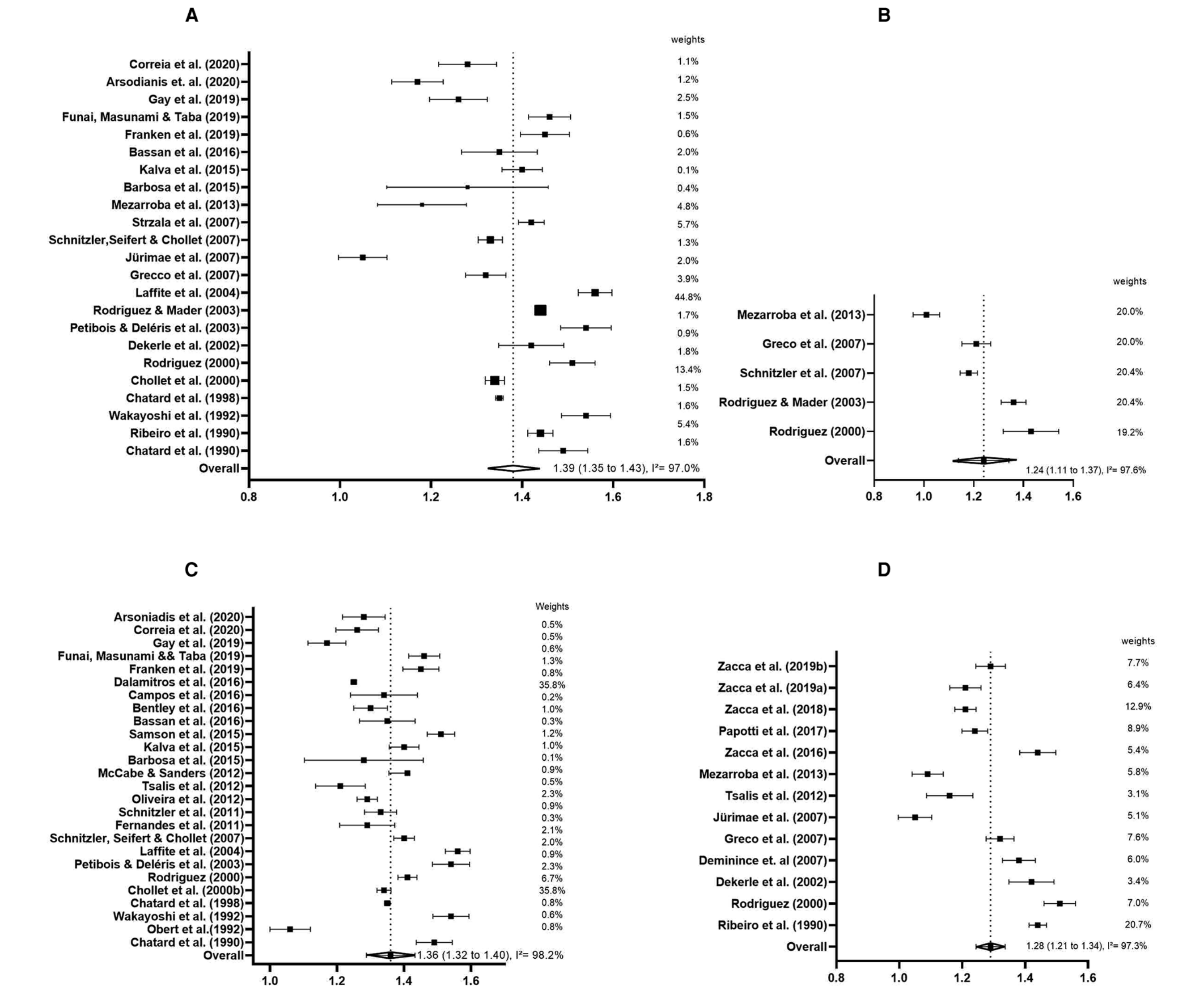

FIGURE 3
Forest plots and subgroup analyses (gender category = **A**: male and **B**: female, respectively; divided by age category = **C**: senior and **D**: junior swimmers derived from continuous random effects models depicting the swimming speed (m·s^{-1}) in 400-m front crawl test.

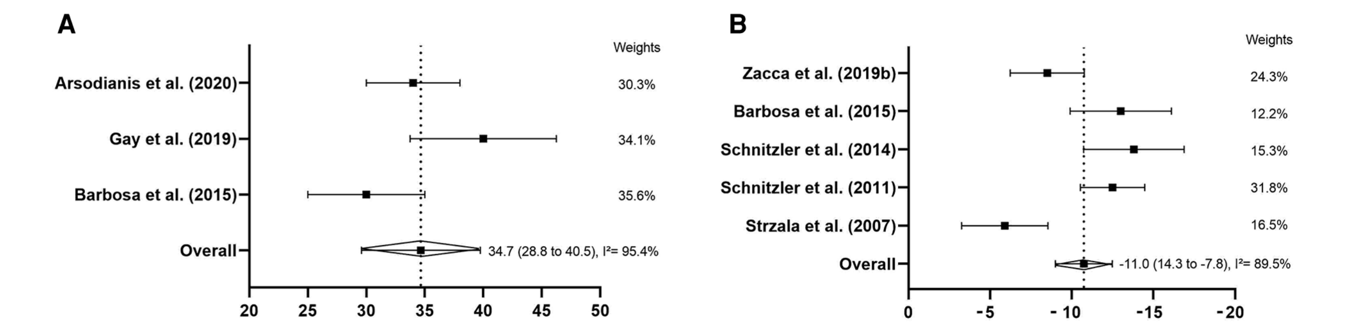

FIGURE 4
Forests plots derived from continuous random-effects models depicting the efficiency (**A**: % *ηp* = arm-stroke propelling efficiency) and coordination (**B**: % IdC = index of coordination) parameters in 400-m front crawl test.

speed is the parameter that best represents a swimmer's performance (46). The faster the swimmer is (and the more able to sustain high speed), the shorter the time to complete the desired distance, which is reflected in the best performance. Thus, the swimming speed was chosen to represent the kinematic parameters. The average result of the swimming speed (male and female together)

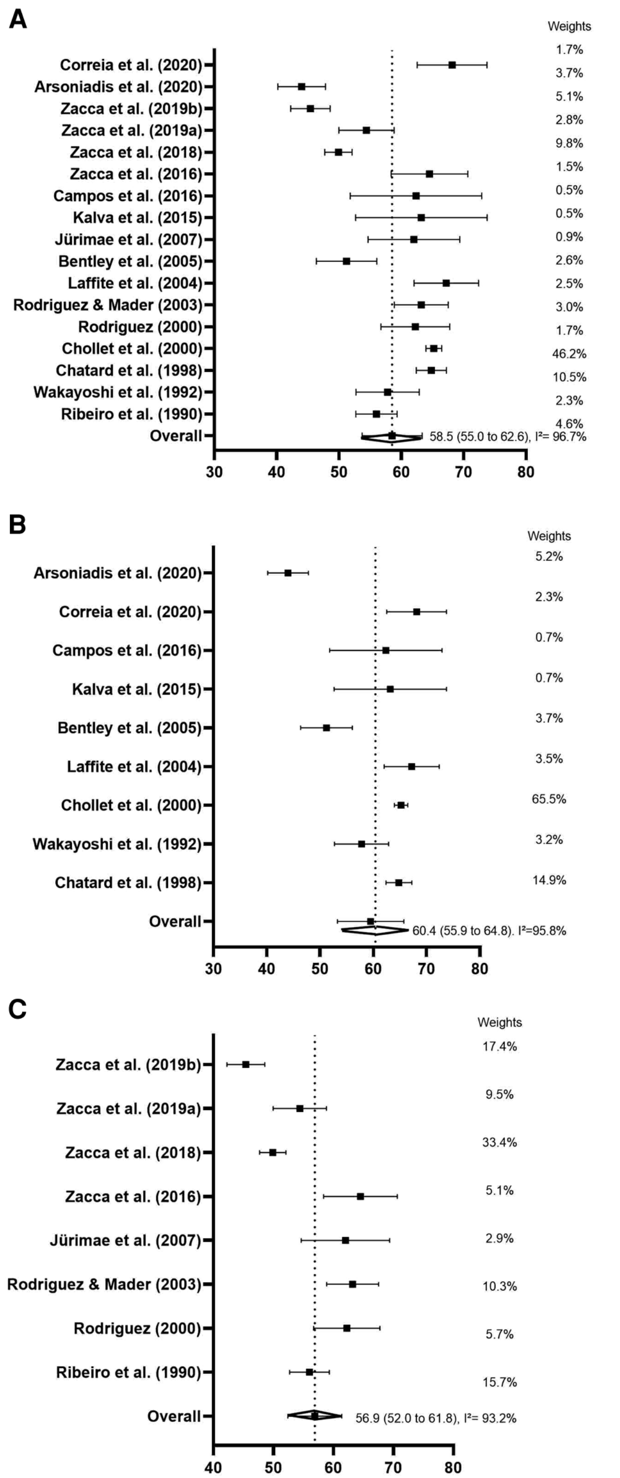

FIGURE 5
Forest plots and subgroups analysis (**A**: mean overall VO_2; **B**: senior category and **C**: junior category, respectively) derived from continuous random-effects models depicting the energy parameters (VO_2: oxygen consumption expressed in $ml \cdot kg^{-1} \cdot min^{-1}$).

reached ≈75.7% of the average speed of the world records of the 400-m freestyle (this speed was calculated as the average of the speeds, with start and turn contributions, of the world records of the 400-m freestyle in 50 and 25-m swimming pools for male and female, retrieved from www.fina.org). This result could be explained by: (i) lower competitive level swimmers are more available to assess in laboratories; (ii) test conditions that do not provide a competitive environment; (iii) the open turns and lacking underwater phase after turns when using a snorkel with valve for respiratory gas analysis. Therefore, a subgroup analysis was conducted to identify whether any factor would reduce heterogeneity and raise mean swimming speed values. Following the eligibility criteria, it was possible to divide the studies into two subgroups: (i) gender (male and female); (ii) age-group categories (senior and junior). No analysis was able to reduce heterogeneity and there was still great variability among the studies (however, as expected, male swimmers reached higher speeds than female swimmers).

Male swimmers can achieve higher speeds than female swimmers in competitive swimming events (65). This is explained by the fact that male swimmers have larger body segments and increased muscle strength. In addition, male swimmers can perform higher SR and SL, to overcome hydrodynamic drag (66). About the subgroup of competitive categories, senior swimmers reached higher swimming speeds (even higher than the mean of all general studies) compared to junior swimmers. This can be explained by the training and competitive experience over the years in the sport (67). In one of the studies that showed the highest speed in the 400-m was (9), the swimmers selected were part of the French national team and obtained high performance in the test (≈256 s). The study that reported the poorest test (≈378 s) (46) assessed male junior swimmers. Furthermore, only in five studies (9, 52, 54, 55, 58) swimmers reached swimming speeds over $1.50\ m \cdot s^{-1}$; however, the swimmers of these cited studies were of optimal technical level. Therefore, more studies are needed to include high-performance swimmers and separated groups to perform analysis of performance (e.g., technical level, genders, and competitive categories), and to verify which performance parameters reflect the actual performance.

It was not possible to carry out an analysis of subgroups in ηp, due to the small number of studies. The mean result (34.6%) shows that expert swimmers, in the 400-m front crawl test, keep their ηp high and close to the values previously referenced of ≈40% (3). In addition, one of the studies included (12) reported the same ηp with the use of a swimsuit by the swimmers and concluded that the high ηp obtained at this event is due to the large SL. Only five selected studies evaluated coordination parameters with the IdC. The mean result (−11.0%) indicated the catch-up model, previously described (4), as that performed by the swimmers. It is already known that the different coordination models do not represent the best or the worst performance, but can be an adaptation that swimmers acquire to overcome hydrodynamic drag oscillations, mainly when speed is increased. However, two studies obtained higher IdC compared to the mean. Previous study (18) reported IdC = 6%. However, the same study reported a mean speed of $1.42\ m \cdot s^{-1}$, which does not represent the best test performance among the studies included in the meta-analysis. Possibly, the high IdC value is related to the increased SR. Regarding both, ηp and IdC, more studies that verify this parameter are needed for a better understanding of the results.

VO_2 was the chosen energy parameter. Seventeen studies were selected and the VO_2 mean was $58.8\ ml \cdot kg^{-1} \cdot min^{-1}$, which represents great aerobic power. The division of the subgroup indicated that the VO_2 of senior swimmers was like that of junior swimmers. So, the age difference has no influence on the values achieved. However, one should consider the swimming speed related to the VO_2 values. In the study (9) that reported the highest swimming speed, the swimmers reached up to 67.0 $ml \cdot kg^{-1} \cdot min^{-1}$ at 1.56 $m \cdot s^{-1}$. Study with junior male competitive swimmers (46) reported 62.0 $ml \cdot kg^{-1} \cdot min^{-1}$ at 1.05 $m \cdot s^{-1}$, with high VO_2, but low swimming speed. High VO_2 values could be related to test duration (from ≈ 242 s to ≈ 378 s). Improved buffering conditions (68), recruitment of fast-contractile muscle fibres, and aerobic power development (69) are some examples of the high VO_2 values' importance in swimming performance. In addition, high swimming speed and high VO_2 are targets to be reached in training for middle- and long-distance specialist swimmers, mainly to develop improved metabolic power. Therefore, future studies should direct a better analysis to the speed reached in the permanence of VO_2 next to maximum.

The results indicated that the 400-m front crawl test presented sub-maximum speeds, required a high arm-stroke efficiency, is performed under catch-up coordination model, and reached high energy demand. However, arm-stroke efficiency and aerobic power do not support the best 400-m front crawl test performance (here represented by the swimming speed). The analysis of subgroups (to identify which factors influence the heterogeneity of the studies), showed that swimmers can reach higher speeds and, consequently, by swimming technical level and specialty, they can decrease the test time and increase performance. Thus, we understand that the swimming speed seems to be the more influential in changing other parameters (efficiency, coordination, energy) in the 400-m front crawl performance.

However, many researchers of sport sciences get stuck in the sample size requirements to have robust and demanding inferential statistics. In this context, the individuals selected to participate in the research are swimmers with easy accessibility, so it is possible to reach the required sample number (for example: university, regional, and national swimmers of age categories, master swimmers). Those of international and elite level are more difficult to assess due to competitive and training schedules. In this regard, the present meta-analysis also pointed out that these level differences determine the high heterogeneity found in the performance parameters. Moreover, the results demonstrated the 400-m front crawl performance parameters' characteristics. Thus, this meta-analysis results can help coaches and researchers to monitor and improve performance, and develop further research in the field of swimming. On the other hand, we can indicate the lack of appropriate evaluation scales for studies with the characteristics of those that fit the eligibility criteria of the present study. Such studies respond very well to the proposed objectives but end up having moderate evaluation in recognized scales.

Data availability statement

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

Author contributions

RC and FC contributed to the conception and design of the study. RC and WF organized the database. RC performed the statistical analysis. RC, WF and FC wrote sections of the manuscript. All authors contributed to the revision of the manuscript, read and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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