PHYSIOLOGICAL AND BIOMECHANICAL DETERMINANTS OF SWIMMING PERFORMANCE

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PHYSIOLOGICAL AND BIOMECHANICAL DETERMINANTS OF SWIMMING PERFORMANCE

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Young Swimmers' Anthropometrics, Biomechanics, Energetics, and Efficiency as Underlying Performance Factors: A Systematic Narrative Review

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Introduction: In youth swimming, researchers are interested in understanding how anthropometry and parameters related to swimming technique (biomechanics, energetics, and efficiency) influence the performance. However, there is not any review in the literature that consolidates the body of knowledge of this topic. The objective of this study was to review systematically the current body of work on the influence of determinant factors related to swimming technique (biomechanics, energetics, and efficiency) and anthropometry in the young performance of swimmers.

Methods: The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines were used to identify relevant studies.

Results: After screening, 240 studies were analyzed and 59 related to swimming performance, and its determinant factors were retained for synthesis. Studies revealed a high-quality index by PEDro scale (mean score was 7.17 ± 1.40). Twenty-five studies were longitudinal designs and the remaining 34 cross-sectional designs. Most of the studies (N = 39, 66.1%) reported concurrently two or more determinant factors (anthropometrics, biomechanics, energetics, and efficiency).

Conclusion: Youth swimming research relies on a multifactorial assessment. From the synthesis, it is possible to conclude that the performance of young swimmers is characterized by a multifactorial, holistic, and dynamic phenomenon. Better performance has always been related to better swimming technique and higher anthropometrics. This suggests that both anthropometrics (i.e., nature) and training (i.e., nurture) play key roles in the swimming performance of young swimmers.

Keywords: talent, identification, development, swimming, determinants, sports career

INTRODUCTION

One of the major topics of interest in sports science is the identification of talented young athletes. This process is based on talent identification and development (TID) programs that aim to identify young athletes with potential for success in adult/elite sport (Blume and Wolfarth, 2019). Detecting talent at an early stage is considered a key factor in increasing a chance of a country of achieving success in sports (Vaeyens et al., 2009). Competitive swimming is one of the three main modern Olympic sports. In competitive swimming, Olympic, and World records are broken on a regular basis, challenging the limits of athletes. Practitioners and researchers are eager to predict the next top-ranked swimmer who will contribute to the superiority of their country at major international competitions.

Talent identification and development programs follow standard steps: (1) identifying the athletes with the potential to deliver the best performances in adulthood and determining the variables responsible for such performances; (2) understanding the development and changes in performance and its determinant factors, according to a training program, and; (3) following up in order to allow to understand the variation of such variables and its relationship with performance over a given time (Morais et al., 2017). To get deeper insights into how determinant factors of swimmers change over time, their interaction and their effect on performance, researchers, and coaches should focus on a long-term approach (Staub et al., 2020a; Zacca et al., 2020). Long-term athlete development (LTAD) programs focus on providing young athletes with fundamental motor skills in tandem to their maturation stage (Martindale et al., 2005; Lang and Light, 2010).

Literature reports that performance in youth swimming is highly dependent on variables related to technique (i.e., nurture) and body dimensions (i.e., nature) (Abbott et al., 2021). Thus, research on young swimmers has been largely focused on the assessment of anthropometrics (Geladas et al., 2005; Nevill et al., 2020), strength and conditioning (Garrido et al., 2010b; Amaro et al., 2017), biomechanics (Morais et al., 2012; Silva et al., 2012), energetics, and efficiency (Denadai et al., 2000; Toubekis et al., 2006), as well as interactions among some or all of them (Morais et al., 2017; Barbosa et al., 2019). Nonetheless, most of these are cross-sectional designs. Such research design does not provide substantial information on the dynamic and complex interactions among the performance determinants over time (Morais et al., 2017). Conversely, longitudinal designs can help gather information on: (1) how determinant factors interplay and affect performance; (2) the dynamic changes that take place at these early ages, and; (3) the change of the partial contribution of each determinant factor in the performance over time (Lätt et al., 2009a,b; Morais et al., 2014a). Notwithstanding, in the last decade, it has been suggested that research on sports performance should adopt a multidisciplinary approach to better understand the athlete (Phillips et al., 2010; Seifert et al., 2013). Moreover, the relationship with the environment must be taken into account, as this relationship is considered under a complex and dynamic system framework (Phillips et al., 2010; Seifert et al., 2013). If so, it will be possible to understand the partial contribution of each determinant factor or set of factors in the performance, which will most likely change over time, as aforementioned (Barbosa et al., 2014; Morais et al., 2015).

Literature reports a review study about the relationship between performance and determinant factors in master swimmers (Ferreira et al., 2016). More recently, Koopmann et al. (2020) have systematically reviewed technical skills in talented youth athletes (which included three articles about swimmers). That said, there is no review that consolidates the available evidence of how different determinant factors can affect youth swimming performance. Therefore, the aim of this study was to review the current body of work on the influence of determinant factors related to swimming technique (biomechanics, energetics, and efficiency) and anthropometrics in the performance of young swimmers.

METHODS

Literature Search and Article Selection

The Web of Science, PubMed, and Scopus databases were searched to identify studies that aimed to identify, analyze, or predict the performance of young swimmers and its determinant factors (anthropometrics, biomechanics, energetics, and efficiency). These electronic search databases were chosen because they are the most used in sports science. As an initial search strategy, the title, abstract, and the studies keywords were identified and read carefully for a first scan and selection of the journal articles. To search the articles, the following fields were used: (1) Web of Science—"Topic"; (2) PubMed—"All fields"; and (3) Scopus—"Article title, abstract, keywords." A Boolean search strategy was used with the operators AND, OR, and a combination of the keywords presented in **Table 1** (whenever suitable). If one of these fields (title, abstract, and keywords) was not clear about the topic under analysis, the complete article was read and fully reviewed to ensure its inclusion or exclusion. After deleting all duplicated and unrelated articles, 59 articles were included. The final search was carried out on March 21, 2021. **Table 1** presents the used PI(E)CO search strategy (P—patient, problem or population; I—intervention; E—exposure; C—comparison, control, or comparator; O—outcomes).

The inclusion criteria were the following: (1) written in English; (2) published in a peer-reviewed journal; (3) related to assessment of the performance of young swimmers (i.e., race events or swim trials/bouts) and its determinant factors (anthropometrics, biomechanics, energetics, and efficiency); (4) included healthy and able-bodied swimmers, and; (5) reported an average sample age limited to the age of 13 (it is considered that children tend to enter the puberty stage from this age onwards—Mirwald et al., 2002). The exclusion criteria were: (1) studies that included disabled swimmers or with any pathology; (2) review papers, conference papers, and books; (3) studies including animal models; (4) publications not related to the topic in question (e.g., in other scientific fields, such as nutrition, psychology, or any other topic not related to performance); (5) studies that recruited several age groups, but did not clearly report the average of at least an age group of 13 years or under.

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*	Talent	Cross-sectional	Performance
Athlete*	Identification	Longitudinal	Velocity/speed
Youth	Development	Experimental	Length
Child*	Long-term development	Exploratory	Area
Boy*	Anthropometrics	Descriptive	Volume
Girl*	Biomechanics	Randomized control trial	Mass
Young	Energetics		Girth
Age-group*	Efficiency		Skinfold
	Motor control		Stroke length
	Strength and conditioning		Stroke frequency
			Stroke rate
			Intra-cyclic variation of velocity/speed
			Passive drag
			Active drag
			Coefficient of drag
			Oxygen uptake
			Oxygen consumption
			Lactate
			Heart rate
			Aerobics
			Anaerobic lactic
			Anaerobic alactic
			Energy cost
			Energy expenditure
			Propelling efficiency
			Froude efficiency
			Stroke Index
			Critical velocity/speed
			Index of coordination
			Strength
			Maximal strength
			Power
			Mechanical power

Truncation to retrieve words with different endings.

Figure 1 depicts the PRISMA flow diagram for identifying, screening, checking eligibility, and inclusion of the articles. There were four articles (**Figure 1**—"Additional records identified through other sources" that were obtained by submissions reviewed and based on references from the articles retained.

Quality Assessment

The PEDro scale was used to assess the quality of the selected articles. It was observed that this scale is a suitable and valid tool to assess the methodological quality (de Morton, 2009). Two reviewers read all the included articles and scored them according to the scale items (poor quality if score ≤3; fair quality if the score is between 4 and 5; high quality if the score is between 6 and 10) (de Morton, 2009). Afterwards, the Cohen's Kappa (K) was computed to assess the agreement between reviewers. It was interpreted as: (1) no agreement if $K \leq 0$; (2) none to slight agreement if.01 $< K \leq 0.20$; (3) fair if.21 $< K \leq 0.40$; (4) moderate if.41 $< K \leq 0.60$; (5) substantial if.61 $< K \leq 0.80$, and; (6) almost perfect if.81 $< K \leq 1.00$. Studies were compared based on the: (1) research design (cross-sectional vs. longitudinal designs), and (2) year of publication (published before or in 2010 vs. published after 2010). In both comparisons, distribution was non-normal. Thus, the Mann–Whitney U test ($p \leq 0.05$) was selected for further inferential analysis.

RESULTS

PEDro mean score was 7.17 ± 1.40 points (i.e., high quality). The Cohen's Kappa yielded an almost perfect agreement between reviewers ($K = 0.937$, $p < 0.001$). There were non-significant differences in PEDRo scores based on research design ($p = 0.651$), or year of publication ($p = 0.477$).

Table 2 summarizes the sample demographics, including the sample size, chronological age, maturation stage, years of experience, and competitive level based on FINA points.

Table 3 presents the summary of the studies purpose, research design, type of collected data (anthropometrics, biomechanics, energetics, and efficiency), and performance. Overall, swimming performance (time or speed) was clearly reported (normative data for time or speed at a given distance) in 51 reviewed studies (86.4%) (**Table 3**). Out of 59 included studies, 25 (42.4%) were based on longitudinal designs, and the remaining 34 (57.6%) were cross-sectional (**Table 3**). Fifty-four studies (91.5%) reported anthropometric parameters, including 34 cross-sectional designs and 20 longitudinal designs. Also, 54 studies (91.5%) analyzed the biomechanics (32 cross-sectional and 22 longitudinal designs), and 42 (71.2%) the energetics and efficiency (25 cross-sectional and 17 longitudinal designs) (**Table 3**). Thirty-nine studies (66.1%) reported anthropometrics, biomechanics, energetics and efficiency, and performance concurrently (i.e., interdisciplinary research). Three studies (5.1%) focused exclusively on tracking the swimming performance from childhood to adulthood.

DISCUSSION

The aim of this study was to review the current body of work on the influence of determinant factors related to swimming technique and anthropometrics in the performance of young swimmers. It was recognized that the performance of young swimmers is not exclusively dependent on one or a small set of determinant factors related to swimming technique and anthropometrics. It is rather influenced by a multidisciplinary interaction of several determinant factors. Furthermore, these factors and their partial contribution to performance can change over time according to the training plan or designed periodization.

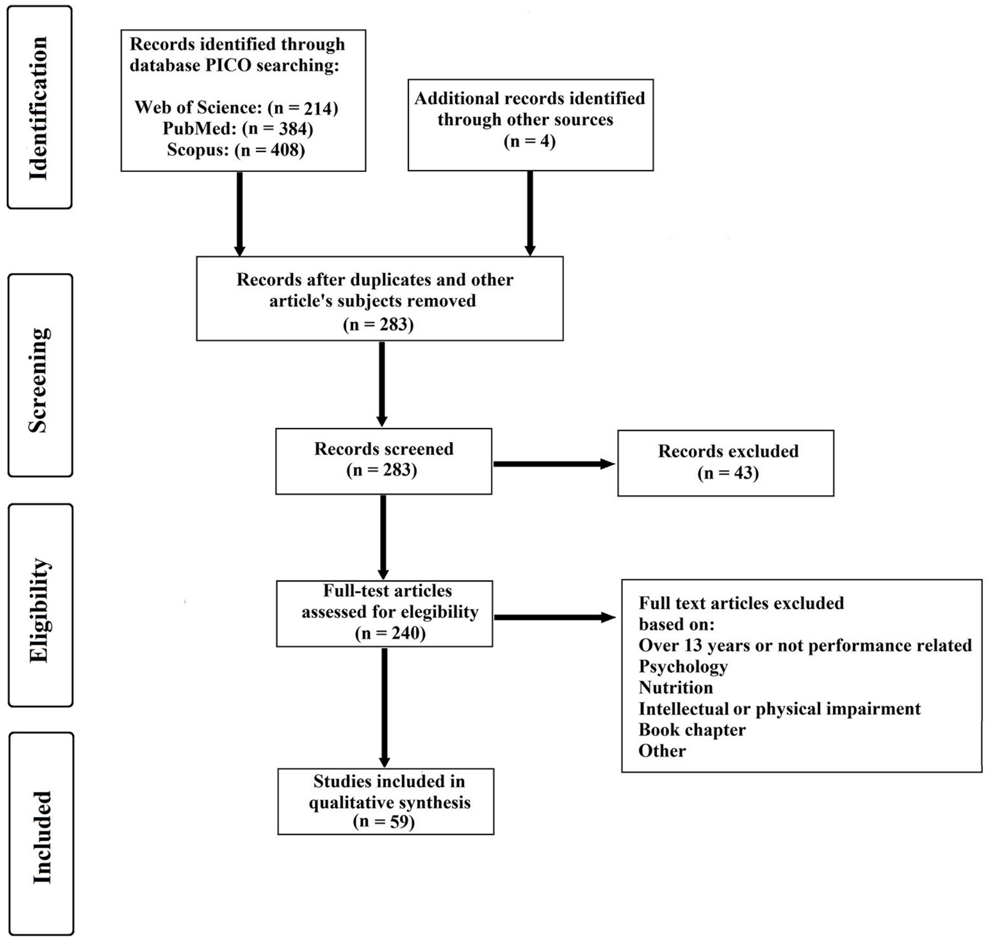

FIGURE 1 | Summary of PRISMA flow for search strategy.

Anthropometrics and Growth

Most studies (N = 55, ∼93%) included in this review assessed the anthropometrics. Body dimensions are related to nature, i.e., genetically determined (Saavedra et al., 2010; Majid et al., 2019; Tijani et al., 2019). Researchers are prone to assess the anthropometrics of young swimmers of both sexes, because these features play one of the major roles in the swimming performance, kinematics, energetics, and efficiency (Geladas et al., 2005; Jürimäe et al., 2007; Lätt et al., 2009a), in addition to hydrodynamics (Kjendlie and Stallman, 2008; Barbosa et al., 2014). Cross-sectional studies showed that variables such as height (H), arm span (AS), and hand length (HL) are strongly and positively correlated to Freestyle sprint performance (i.e., 50 or 100 m) (Geladas et al., 2005; Morais et al., 2012; Bielec and Jurak, 2019). The same trend was verified in breaststroke, in which swimmers with longer upper-limb lengths and wider girths had a significant advantage (i.e., better performance in the 100 m) (Sammoud et al., 2018). In backstroke (25- and 50-m pace), it was observed that postpubertal swimmers were significantly faster than their prepubertal counterparts (Silva et al., 2013). The significant higher body mass (BM), H, and AS shown by the postpubertal swimmers contributed to this (Silva et al., 2013). The same trend was verified in other freestyle distances (100, 200, and 400 m—Mezzaroba and Machado, 2014; 50 and 400 m—Ferraz et al., 2020), in which H, AS/H ratio (Ferraz et al., 2020) and other lengths related to upper- (TUEL) and lower-limbs (TLEL) lengths were significantly longer in mature swimmers (Mezzaroba and Machado, 2014).

Cluster analysis identifies homogeneous subgroups of swimmers within a larger sample (Barbosa et al., 2014; Morais et al., 2015, 2020b). Cluster analysis detects swimmers within a specific cluster that shares similar characteristics but is very different from other swimmers who do not belong to that cluster (Morais et al., 2015). Faster swimmers, competing in the 100-m freestyle, were clustered as a group with larger anthropometric features such as BM, AS, H, chest perimeter (CP), hand surface area (HSA), frontal surface area (FSA), trunk transverse surface area (TTSA), and body surface area (BSA) (Morais et al., 2015, 2020b). A study that aimed to identify key somatic variables in youth swimming recognized that all swimmers benefited from having less body fat (BF), wider shoulders and hips, longer AS, and forearm girth (FG)

TABLE 2 | The summary of the sample demographics of each study included for analysis.

Source	Sample	Tanner stage	Years of experience	Pool length	Race/trial event	FINA points
Abbes et al. (2018)	*n* = 14 boys: 13.00 ± 2.00 years	n.a.	At least 4 years	50 m	50 m Freestyle	520.00 ± 98.00
Abbes et al. (2020)	*n* = 17 boys: 13.00 ± 2.00 years	n.a.	At least 4 years	50 m	50 m Freestyle	520.00 ± 98.00
Abbott et al. (2021)	*n* = 48 boys (between 10 and 13 years)	Maturity status (years pre/post peak height velocity): between −2.4 ± 0.29 and 0.2 ± 0.46	n.a.	50 m	200 m Freestyle	
Alshdokhi et al. (2020)	*n* = 28 boys: 12.60 ± 2.60 years	n.a.	n.a.	25 m	50 m and 100 m Freestyle, Backstroke	n.a.
Amaro et al. (2017)	*n* = 21 boys: 12.70 ± 0.80 years	2.10 ± 0.40	At least 2 years	25 m	50 m Freestyle	n.a.
Barbosa et al. (2010)	*n* = 38 boys: 12.53 ± 0.58 years	1–2	n.a.	25 m	200 m Freestyle	n.a.
Barbosa et al. (2014)	*n* = 34 girls and 33 boys: 12.83 ± 1.26 years	1–2	At least four years	25 m	100 m Freestyle	n.a.
Barbosa et al. (2015)	*n* = 49 boys: 12.51 ± 0.77 years; 51 girls: 12.24 ± 0.71 years	1–2	n.a.	25 m	100 m Freestyle	n.a.
Barbosa et al. (2019)	*n* = 75 boys: 11–13 years	1–2	At least two years	n.a.	100 m Freestyle	n.a.
Bielec and Jurak (2019)	*n* = 26 boys: 12.10 ± 0.50 years; 15 girls: 12.20 ± 0.50 years	Boys: 1.80 ± 0.60 Girls: 2.10 ± 0.70	2.40 ± 0.50	25 m	50 m Freestyle, and 200 m Individual Medley	Boys 50 m: 202.00 ± 64.40 Girls 50 m: 279.20 ± 58.30 Boys 200 m: 211.50 ± 55.90 Girls 200 m: 280.60 ± 46.40
Costa et al. (2011)	*n* = 242 boys	n.a.	n.a.	n.a.	50 m, 100 m, 200m, 400 m, 800 m, and 1500 m Freestyle	n.a.
de Mello Vitor and Böhme (2010)	*n* = 24 boys: 13.00 ± 0.70 years	3–4	3 to 4 years	50 m	100 m Freestyle	n.a.
Denadai et al. (2000)	Beginners: *n* = 4 boys and 6 girls: 11.20 ± 0.90 years Trained: *n* = 3 boys and 3 girls: 11.10 ± 0.90 years	n.a.	Beginners: 1–2 years; Trained: 3–5 years	25 m	50 m, 100 m, and 200 m Freestyle	n.a.
Duché et al. (1993)	*n* = 25 boys: 11.30 ± 1.00 years	1	2 years	n.a.	50 m, 100 m, 200m, and 400 m Freestyle	n.a.
Ferraz et al. (2020)	Under 12 level: *n* = 25 girls (12.48 ± 0.30 years); *n* = 24 boys (12.69 ± 0.26 years) Under 13 level: *n* = 23 girls (11.63 ± 0.28 years)	n.a.	n.a.	25 m	50 m, and 400 m Freestyle	n.a.
Ferreira et al. (2019)	n = 14 boys: 11.90 ± 1.08 years; 29 girls: 10.74 ± 0.91 years	Boys: 2.93 ± 0.95 Girls: 2.71 ± 1.15	n.a.	25 m	400 m Freestyle	n.a.
Ferreira et al. (2021)	*n* = 24 boys: 12.51 ± 0.99 years; 10 girls: 11.24 ± 0.88 years	Boys: 2.94 ± 1.04 Girls: 3.05 ± 1.10	n.a.	n.a.	400 m Freestyle	n.a.
Figueiredo et al. (2016)	*n* = 51 boys and 52 girls: 11.80 ± 0.80 years	n.a.	n.a.	25 m	25 m Freestyle trial	n.a.
Garrido et al. (2010a)	*n* = 16 boys and 12 girls: 12.01 ± 0.56 years	1–2	n.a.	25 m	25 m and 50 m Freestyle	n.a.
Garrido et al. (2010b)	*n* = 14 boys and 11 girls: 12.08 ± 0.76 years	1–2	n.a.	25 m	25 m and 50 m Freestyle	n.a.
Geladas et al. (2005)	*n* = 178 boys: 12.78 ± 0.05 years; 85 girls: 12.68 ± 0.06 years	Boys' biological age: 14.17 ± 0.13 Girls' biological age: 13.47 ± 0.13	n.a.	50 m	100 m Freestyle	n.a.
Hue et al. (2013)	*n* = 61 boys and 65 girls: 12.00 ± 1.30 years	1–2	n.a.	50 m	400 m Freestyle	n.a.
Jürimäe et al. (2007)	*n* = 15 boys: 11.90 ± 0.30 years	1–2	3.00 ± 1.10	25 m	400 m Freestyle	n.a.
Kjendlie et al. (2004a)	*n* = 10 boys: 11.70 ± 0.80 years	n.a.	4.30 ± 1.40	25 m	50 m and 100 m Freestyle	n.a.
Kjendlie and Stallman (2008)	*n* = 9 boys: 11.70 ± 0.80 years	n.a.	n.a.	25 m	25 m Freestyle trial	n.a.

(Continued)

TABLE 2 | Continued

Source	Sample	Tanner stage	Years of experience	Pool length	Race/trial event	FINA points
Lätt et al. (2009a)	$n = 29$ boys: 13.0 ± 1.80 years	2.30 ± 1.00	3.00 ± 1.10	25 m	400 m Freestyle	n.a.
Lätt et al. (2009b)	$n = 26$ girls: 12.70 ± 2.20 years	2.30 ± 0.80	3.70 ± 1.00	25 m	400 m Freestyle	n.a.
Majid et al. (2019)	$n = 4$ boys: 11.15 ± 0.96 years	n.a.	n.a.	50 m	50 m Breaststroke	n.a.
Marinho et al. (2011)	$n = 12$ boys and 8 girls: 12.10 ± 0.72 years	n.a.	3.70 ± 1.26	n.a.	50 m, 100 m, and 200 m Freestyle, Backstroke, Breaststroke, and Butterfly	n.a.
Marinho et al. (2020)	$n = 75$ boys and 76 girls: 13.02 ± 1.19 years	n.a.	3.36 ± 0.77 years	25 m	100 m Freestyle	n.a.
Mezzaroba and Machado (2014)	$n = 13$ boys: 10.70 ± 0.90 years; $n = 11$ boys: 13.00 ± 0.50 years	2.20 ± 0.80 and 3.60 ± 0.80	3.50 ± 1.90 and 5.70 ± 3.30 years	50 m	100 m, 200 m, and 400 m Freestyle	n.a.
Morais et al. (2012)	$n = 73$ boys: 12.72 ± 1.03 years; 64 girls: 11.47 ± 0.66 years	1–2	n.a.	25 m	100 m Freestyle	n.a.
Morais et al. (2013a)	$n = 62$ boys: 12.76 ± 0.72 years; 64 girls: 11.89 ± 0.93 years	1–2	n.a.	25 m	100 m Freestyle	n.a.
Morais et al. (2013b)	n = 15 boys: 12.30 ± 0.63 years; 18 girls: 11.77 ± 0.92 years	1–2	3.18 ± 0.52 years	25 m	100 m Freestyle	n.a.
Morais et al. (2014a)	$n = 14$ boys: 12.33 ± 0.65 years; 16 girls: 11.15 ± 0.55 years	1–2	3.40 ± 0.56 years	25 m	100 m Freestyle	Boys: 284.85 ± 67.48 Girls: 322.56 ± 45.18
Morais et al. (2014b)	$n = 14$ boys, 7 high skill: 12.83 ± 0.37 years, 7 average skill: 11.83 ± 0.37 years; 16 girls, 8 high skill: 11.42 ± 0.49 years, 8 average skill: 10.83 ± 0.37 years	1–2	3.40 ± 0.56 years	25 m	100 m Freestyle	Boys (high skill: 294.40 ± 40.00; average skill: 166.20 ± 17.50) Girls (high skill: 334.30 ± 39.50; average skill: 229.10 ± 33.90
Morais et al. (2015)	$n = 15$ boys: 12.30 ± 0.60 years; 18 girls: 11.70 ± 0.90 years	1–2	3.18 ± 0.52 years	25 m	100 m Freestyle	Boys: 227.90 ± 69.80 Girls: 291.10 ± 66.20
Morais et al. (2016)	$n = 49$ boys: 12.50 ± 0.76 years; 51 girls: 12.20 ± 0.71 years	1–2	3.10 ± 0.71 years	25 m	100 m Freestyle	n.a.
Morais et al. (2017)	$n = 47$ boys: 12.04 ± 0.81 years; 47 girls: 11.22 ± 0.98 years	n.a.	3.18 ± 0.62 years	25 m	100 m Freestyle	Boys: 217.70 ± 69.50 Girls: 277.70 ± 68.70
Morais et al. (2020a)	$n = 22$ boys: 12.79 ± 0.71 years; 32 girls: 11.78 ± 0.85 years	1–2	n.a.	25 m	100 m Freestyle	Boys: 297.58 ± 87.72 Girls: 330.35 ± 79.80
Morais et al. (2020b)	$n = 14$ boys: 12.70 ± 0.63 years; 16 girls: 11.72 ± 0.71 years	1–2	n.a.	25 m	100 m Freestyle	Boys: 234.86 ± 69.76 Girls: 288.75 ± 67.01
Moreira et al. (2014)	n = 12 boys: 12.80 ± 0.90 years; 13 girls: 12.00 ± 0.90 years	1–2	3.18 ± 0.52 years	n.a.	25 m Freestyle trial	n.a.
Nevill et al. (2020)	$n = n = 39$ boys: 11.50 ± 1.30 years; n = 20 girls: 12.10 ± 1.00 years; $n =$ 13.00 ± 1.00 years	2.33 ± 1.10, 0.04 ± 1.00, 0.82 ± 0.96 maturity offset years	n.a.	n.a.	100 m Breaststroke and Backstroke	n.a.
Ozeker et al. (2020)	$n = 15$ girls: 11.18 ± 0.80 years; $n =$ 15 girls: 11.16 ± 0.83 years	n.a.	At least 3 years	50 m	50 m and 400 m Freestyle	n.a.
Poujade et al. (2003)	$n = 3$ girls and 8 boys: 12.40 ± 0.50 years	n.a.	4–5 years	50 m	400 m Freestyle	n.a.
Poujade et al. (2002)	$n = 3$ girls and 8 boys: 12.40 ± 0.50 years	n.a.	5–6 years	n.a.	400 m Freestyle	n.a.
Saavedra et al. (2013)	$n = 67$ girls: 11.51 ± 0.55 years	n.a.	n.a.	n.a.	Best score according to the LEN table of competitive performance level	n.a.

(Continued)

TABLE 2 | Continued

Source	Sample	Tanner stage	Years of experience	Pool length	Race/trial event	FINA points
Saavedra et al. (2010)	*n* = 67 girls: 11.50 ± 0.60 years	2.99 ± 1.19	n.a.	25 m	Fastest of three competitive events swum in one of the four strokesat any of four different race distances (i.e., 100 m, 200 m, 400 m, and 800 m)	n.a.
Sammoud et al. (2018)	*n* = 39 boys: 11.50 ± 1.30 years; 20 girls: 12.00 ± 1.00 years	Boys: −2.30 ± 1.10; girls: 0.04 ± 1.00 maturity offset years	n.a.	25 m	100 m Breaststroke	n.a.
Sammoud et al. (2019)	(*n* = 26 boys) two groups: 10.30 ± 0.40 and 10.50 ± 0.40 years	−3.10 ± 0.30 and −2.80 ± 0.30 years until peak height velocity	2.00 ± 1.60 years	50 m	15 m, 25 m, and 50 m Freestyle trial	n.a.
Sammoud et al. (2021)	(*n* = 22girls) two groups: 10.01 ± 0.57 and 10.50 ± 0.28 years	−1.50 ± 0.50 and −1.34 ± 0.51 maturity offset	2.00 ± 1.40 years	50 m	25 m, and 50 m Freestyle trial	n.a.
Seffrin et al. (2021)	*n* = 16 boys: 11.50 ± 0.52 years; 6 girls: 11.67 ± 0.52 years	n.a.	n.a.	n.a.	100 m and 400 m Freestyle	n.a.
Silva et al. (2012)	(*n* = 36 boys: 12.42 ± 0.08 years; and 24 girls: 11.08 ± 0.08 years)	Boys: 2–3 Girls: 2–3	3.75 ± 0.87 and 3.38 ± 0.77 years	n.a.	25 m Backstroke trial	n.a.
Silva et al. (2013)	Pubertal: n = 36 boys: 12.42 ± 0.08 years; 24 girls: 11.08 ± 0.08 years Post-pubertal: *n* = 20 boys: 12.65 ± 0.11 years; 34 girls: 11.71 ± 0.08 years	Pubertal: 1–2 Post-pubertal: 3–5	Pubertal boys: 3.75 ± 0.87 years; girls: 3.38 ± 0.77 years Post-pubertal boys: 3.75 ± 1.25 years; girls: 3.35 ± 1.07 years	n.a.	25 m Freestyle trial	n.a.
Staub et al. (2020b)	*n* = 952 boys and 936 girls: 11 years	n.a.	n.a.		50 m, 100 m, 200 m, 400 m Freestyle; 50 m, 100 m, 200 m Breaststroke and Backstroke; 50 m and 100 m Butterfly; 200 Individual Medley	Swimmers ranked at 18 years: 321.90 ± 75.20 Swimmers not ranked at 18 years: 313.80 ± 73.70
Staub et al. (2020a)	*n* = 842 boys and 863 girls: 11 years	n.a.	n.a.		50 m, 100 m, 200 m, and 400 m Freestyle; 50 m, 100 m, and 200 m for both Breaststroke and Backstroke; 50 m, and 100 m Butterfly; 200 m Individual Medley	Relationships between success at age 18 (1–1000 FINA points), to within-sport specialization and age of entry
Tijani et al. (2019)	*n* = 22 boys and 18 girls12.30 ± 0.56 years	n.a.	7.10 ± 0.50 years	25 m	50 m Freestyle	n.a.
Tsalis et al. (2012)	*n* = 8 girls: 10.40 ± 0.60 years	n.a.	n.a.	50 m	50 m, 100 m, 200 m, and 400 m Freestyle	n.a.
Zarzeczny et al. (2013)	*n* = 24 boys: 12.20 ± 0.10 years	n.a.	n.a.	25 m	50 m, and 400 m Freestyle and Breaststroke	n.a.

n.a., not applicable (i.e., not reported).

in the 100-m breaststroke and backstroke events (Nevill et al., 2020). This review only includes data related to breaststroke and backstroke from this article (Nevill et al., 2020) because only these strokes met the inclusion criteria (i.e., under 13 years of average age). Nonetheless, the authors agreed that such characteristics were common in the whole sample (over 13 years

TABLE 3 | The summary of the purpose, design, type of data collected (anthropometrics, biomechanics, energetics/efficiency), and performance of the studies included.

Source	Purpose	Design	Anthropometrics	Biomechanics	Energetics/ Efficiency	Performance	
						Initial	Final
Abbes et al. (2018)	To investigate whether tethered swimming before a 50 m freestyle swimming sprint could be an effective post-activation potentiation method to improve performance	Longitudinal	BM, H	CMJ, SL	RPE, Bl	50 Free CG: 32.48 ± 3.35 s 50 Free EG: 32.68 ± 3.68 s	
Abbes et al. (2020)	To investigate performance, biomechanical, physiological, and psychophysiological effects of a simple and easily organized post-activationpotentiation re-warm-up performed before a 50m freestyle swimming sprint	Longitudinal	BM, H	SF, SL	RPE, Bl, HR	50 Free Push-ups group: 32.62 ± 2.81 s 50 Free Squat jump group: 32.42 ± 2.32 s 50 Free Burpees group: 32.46 ± 2.26 s 50 Free CG: 32.84 ± 2.53 s	
Abbott et al. (2021)	To examine the longitudinal relationships between maturity status, technical skill indices, and performance in male youth competitiveswimmers. To determine whether individualdifferences in maturation influenced relationships between technicalskill level and swim performance.	Longitudinal (4 months)	BM, H	v	SI, η_F	200 Free (10 years): 1.08 ± 0.08 m·s^{-1} 200 Free (11 years): 1.16 ± 0.08 m·s^{-1} 200 Free (12 years): 1.21 ± 0.09 m·s^{-1} 200 Free (13 years): 1.23 ± 0.12 m·s^{-1}	200 Free (11 years): 1.20 ± 0.12 m·s^{-1} 200 Free (12 years): 1.26 ± 0.08 m·s^{-1} 200 Free (13 years): 1.28 ± 0.07 m·s^{-1} 200 Free (14 years): 1.23 ± 0.12 m·s^{-1}
Alshdokhi et al. (2020)	To quantify and compare the transfer of dryland strength gains to adolescent backstroke and freestyle swimming performance	Longitudinal (8 weeks)	BM, H, RH	SF, VJ, BJ, PC, LF_{ext}, RF_{ext}, LF_{int}, RF_{int}, BE	HR, RPE	50 Free CG: 43.93 ± 7.11 s 50 Free EG: 44.23 ± 10.27 s 50 Back CG: 49.58 ± 6.31 s 50 Back EG: 49.18 ± 7.00 s 100 Free CG: 104.60 ± 12.35 s 100 Free EG: 102.58 ± 21.72 s 100 Back CG: 119.48 ± 18.69 s 100 Back EG: 113.81 ± 22.02 s	50 Free CG: 42.78 ± 7.13 s 50 Free EG: 42.19 ± 10.23 s 50 Back CG: 47.87 ± 6.88 s 50 Back EG: 47.08 ± 7.41 s 100 Free CG: 102.98 ± 12.33 s 100 Free EG: 99.08 ± 22.32 s 100 Back CG: 118.01 ± 18.89 s 100 Back EG: 112.01 ± 21.77 s
Amaro et al. (2017)	To analyze the effects of a period of swim training alone (CG), a dryland SC program based on sets/repetitions (EG1), plus swim training alone or a dryland SandC program that focused on explosiveness plus swim training alone (EG2)	Longitudinal (10 weeks)	BM, H	MF, MMI, VJ, BT	n.a.	50 Free CG: 33.76 ± 3.14 s 50 Free EG1: 33.92 ± 1.47 s 50 Free EG2: 33.43 ± 2.83 s	50 Free CG: 33.64 ± 3.04 s 50 Free EG1: 34.02 ± 1.61 s 50 Free EG2: 31.65 ± 2.53 s
Barbosa et al. (2010)	To develop a model for young swimmers' performance based on biomechanical and energetic parameters	Cross-sectional	BM, H, FM	SL, SF, v	CV, SI, η_F	200 Free: 156.80 ± 17.30 s	
Barbosa et al. (2014)	To develop a classification system for young talented swimmers based on kinematical, hydrodynamic, and anthropometrical characteristics	Cross-sectional	FSA	v, dv, dv/v, C_{Da}	n.a.	100 Free: 71.30 ± 6.12 s	
Barbosa et al. (2015)	To compare swimming power output between boys and girls, and model the relationship between swimming power output and sprinting performance	Cross-sectional	BM, H, AS, FSA	SF, SL, SL/AS, v, dv, dv/v, D_a, C_{DA}, P_d, P_k, P_{ext}	SI, η_F	Boys 100 Free: 1.44 ± 0.16 m·s^{-1} Girls 100 Free: 1.30 ± 0.12 m·s^{-1}	
Barbosa et al. (2019)	To compare the anthropometrics, biomechanics and energetics in young swimmers of different competitive levels	Cross-sectional	BM, H, AS, FSA	SF, SL, SL/AS, v, D_a, C_{DA}, P_d, P_k, P_{ext}, E_{tot}, F_r, v_h, R_e	SI, η_F, dv	100 Free Tier 1: 1.75 ± 0.07 m·s^{-1} 100 Free Tier 2: 1.53 ± 0.11 m·s^{-1} 100 Free Tier 3: 1.38 ± 0.13 m·s^{-1}	
Bielec and Jurak (2019)	To describe the anthropometric characteristics of prepubescent swimmers and to determine the contribution of chosen anthropometric factors to sports achievements	Cross-sectional	H, HW, HL, AS, BM, BMI, BF	v	n.a.	n.a.	

(Continued)

TABLE 3 | Continued

Source	Purpose	Design	Anthropometrics	Biomechanics	Energetics/ Efficiency	Performance	
						Initial	Final
Costa et al. (2011)	To track and analyze freestyle performance during elite-standard male swimmers' careers, from 12 to 18 years of age	Longitudinal (12 to 18 years-old)	n.a.	n.a.	n.a.	50 Free: $\Delta = 5.85 \pm 2.66\%$ 100 Free: $\Delta = 4.89 \pm 2.70\%$ 200 Free $\Delta = 5.54 \pm 2.23\%$ 400 Free: $\Delta = 5.47 \pm 2.23\%$ 800 Free: $\Delta = 5.74 \pm 3.24\%$ 1500 Free: $\Delta = 5.34 \pm 2.69\%$	
de Mello Vitor and Böhme (2010)	To assess the relationship among anthropometric variables, specific physical conditioning, swimming techniques and 100 m Freestyle performance	Cross-sectional	BM, H, AS, HL, HW, FL, FW, Biacr B, Biiliac B, AS/H, Biacr B/Biiliac B, TS, SS, BF	SF, SL, SI	AnP, CV	100 Free: 1.46 ± 0.07 m·s^{-1}	
Denadai et al. (2000)	To verify whether critical speed can be used as a non-invasive method for the determination of speed at a blood lactate concentration of 4 mmol·l^{-1}	Cross-sectional	BM, H	v	CV, Bl, V4	Beginner CV: 0.78 ± 0.25 m·s^{-1} Beginner V4: 0.82 ± 0.09 m·s^{-1} Trained CV: 1.08 ± 0.4 m·s^{-1} Trained V4: 1.19 ± 0.11 m·s^{-1}	
Duché et al. (1993)	To determine the influence of anthropometric and bio-energetic parameters on swimming performance	Cross-sectional	H, SH, BM, BF, Biacr B, Biiliac B, TSA, BA, ULL, AL, ForL	v	VO_{2max}, AnP, MP_{30}	50 Free: 40.60 ± 7.20 s 100 Free: 85.60 ± 14.70 s 200 Free: 187.70 ± 30.60 s 400 Free: 399.00 ± 78.50 s	
Ferraz et al. (2020)	To verifyassociations between the anthropometriccharacteristics of young swimmers ofdifferent genders and different competitive levels with sports performance in the 50m and400m freestyle races at different levels.	Cross-sectional	BM, H, BMI, AS, AS/H	SF, SL	SI	Boys (U12) 50 m Free: 33.20 ± 1.98 s Boys (U12) 400 m Free: 326.48 ± 16.94 s Girls (U13) 50 m Free: 34.48 ± 2.34 s Girls (U13) 400 m Free:330.75 ± 25.92 s Girls (U12) 50 m Free:36.52 ± 1.85 s Girls (U12) 400 m Free: 364.18 ± 26.36 s	
Ferreira et al. (2019)	To examine the physiological and biomechanical responses related to the 400m swimming performance	Longitudinal (11 weeks)	BM, H	SF, SL	SI, HR, Bl, Bg	400 Free: 444.40 ± 76.95 s	400 Free: 408.95 ± 61.40 s
Ferreira et al. (2021)	To describe the evolution of middle-distance swimming performancealong with physiological and biomechanical changes in young swimmers during a trainingseason including three macrocycles.	Longitudinal (45 weeks)	BM, H, BMI	SF, SL	SI, HR, Bl, Bg, RPE	400 Free: 432.37 ± 71.78 s	400 Free: 366.66 ± 47.70 s
Figueiredo et al. (2016)	To evaluate the determinants of front crawl swimming sprint performance	Cross-sectional	BM, H, AS, HL, HW, FL, FW	SF, SL, SL/AS, dv, IdC	CV, SI, η_F	25 Free Cluster 1: 1.52 ± 0.16 m·s^{-1} 25 Free Cluster 2: 1.47 ± 0.17 m·s^{-1} 25 Free Cluster 3: 1.40 ± 0.15 m·s^{-1}	
Garrido et al. (2010a)	To identify the dryland strength and power tests that can better associate with sprint swimming performance	Cross-sectional	BM, H	LE, BP, CMJ, BT, BR	n.a.	25 Free: 16.12 ± 0.67 s 50 Free: 35.21 ± 1.98 s	
Garrido et al. (2010b)	To examine the effects of combined dryland strength and aerobic swimming training for increasing upper and lower body strength, power and swimming performance	Longitudinal (8 weeks)	BM, H	D_a, C_{Da}, LE, BP, CMJ, BT, BR	n.a.	EG 25 Free: Δ =6.95% EG 50 Free: Δ =4.77%	
Geladas et al. (2005)	To examine the relationship between anthropometry, some physical capacity traits and sprint swimming performance	Cross-sectional	BM, BF, H, TUEL, HL, FL, CC, Biacr B,Biiliac B, AFlex, SFlex,	HJ, HG	n.a.	Boys 100 Free: 65.52 ± 0.25 s Girls 100 Free: 68.10 ± 0.22 s	

(Continued)

TABLE 3 | Continued

Source	Purpose	Design	Anthropometrics	Biomechanics	Energetics/ Efficiency	Performance	
						Initial	Final
Hue et al. (2013)	To investigate the anthropometric and physiological characteristics of young Guadeloupian competitive swimmers	Cross-sectional	BM, BF, H, AS, LL	CMJ, HL, Glide	eVO_{2max}, MAV	Boys 15 Free: 10.25 ± 0.33 s Boys 400 Free: 363.75 ± 20.16 s Girls 15 Free: 10.63 ± 0.21 s Girls 400 Free: 359.25 ± 14.86 s	
Jürimäe et al. (2007)	To examine the influence of energy cost of swimming, anthropometrical, body composition, and technical parameters on swimming performance	Cross-sectional	BM, BF, BMI, BMM, H, FM, FFM, AS, TBMD, SBMD	SF, SL, v	SI, C_s, VO_2, ΔLa	400 Free: 401.50 ± 53.80 s	
Kjendlie et al. (2004a)	To investigate the differences in the energy cost at submaximal velocities in boys, and to study the differences in the energy cost at different size scaled submaximal velocities	Cross-sectional	BL, BM, BSA	Bu, Vol	C_s, VO_2	50 Free: 33.70 ± 2.90 s 100 Free: 75.10 ± 5.50 s	
Kjendlie and Stallman (2008)	To compare drag in swimming children, quantify technique using the technique drag index, anduse the Froude number to study whether children reach hull speed at maximal swim speed	Cross-sectional	BL, BM, BSA, H	R_e, F_r, D_a, C_{Da}, D_p, C_{Dp}, TDI, v	n.a.	25 Free: 1.42 ± 0.12 $m{\cdot}s^{-1}$	
Lätt et al. (2009a)	To examine the development of specific physical, physiological, and biomechanical parameters during swimmers' maturing and the influence of such parameters on swimming performance	Longitudinal (2years)	BM, BMI, BF, H, AS, FM, BMM, FFM, TBMD, SBMD	v, SF, SL	SI, C_s, VO_2, ΔLa	400 Free: 373.30 ± 53.50 s	400 Free: 351.50 ± 50.40 s
Lätt et al. (2009b)	To examine the development of anthropometrical, physiological, and biomechanical parameters during swimmers' maturing and the influence of such parameters on swimming performance	Longitudinal (2years)	BM, BMI, BF, H, AS, FM, BMM, FFM, TBMD, SBMD	v, SF, SL	SI, C_s, VO_2, ΔLa	400 Free: 373.90 ± 39.20 s	400 Free: 354.20 ± 34.40 s
Majid et al. (2019)	To recognize the effect of special exercises in the development of the rapid strength of the muscles of the legs and arms and the completion of the 50m breaststroke	Longitudinal	BM, H	AE, KFE	n.a.	50 Breast: 49.84 ± 5.51 s	50 Breast: 42.26 ± 2.73 s
Marinho et al. (2011)	To determine and analyze the anaerobic critical velocity comparing it with short distances performances in the four swimming techniques	Cross-sectional	BM, H	n.a.	AnCV	50 m Free: 1.45 ± 0.18 $m{\cdot}s^{-1}$ 100 m Free: 1.39 ± 0.17 $m{\cdot}s^{-1}$ 200 m Free: 1.29 ± 0.14 $m{\cdot}s^{-1}$ 50 m Fly: 1.36 ± 0.18 $m{\cdot}s^{-1}$ 100 m Fly: 1.23 ± 0.14 $m{\cdot}s^{-1}$ 200 m Fly: 1.08 ± 0.11 $m{\cdot}s^{-1}$ 50 m Back: 1.21 ± 0.09 $m{\cdot}s^{-1}$ 100 m Back: 1.17 ± 0.09 $m{\cdot}s^{-1}$ 200 m Back: 1.13 ± 0.09 $m{\cdot}s^{-1}$ 50 m Breast: 1.09 ± 0.16 $m{\cdot}s^{-1}$ 100 m Breast: 1.04 ± 0.13 $m{\cdot}s^{-1}$ 200 m Breast: 0.93 ± 0.11 $m{\cdot}s^{-1}$	
Marinho et al. (2020)	To understand the relationship between the coaches' demographics (academic degree, coaching level, training experience) in the applied training content and the swimmers' technical ability and performance.	Cross-sectional	BM, H, AS	v, dv, SL, R_e, F_r, C_{Da}	SI, η_F	100 m Free (Acad_level_1): 75.51 ± 10.02 s 100 m Free (Acad_level_2): 74.55 ± 9.56s 100 m Free (Acad_level_3): 73.62 ± 7.64s 100 m Free (Coach_level_1): 76.79 ± 11.27s 100 m Free (Coach_level_2): 75.06 ± 9.31s 100 m Free (Coach_level_3): 73.65 ± 8.43s 100 m Free (Exp_ ≤ 5): 75.44 ± 9.57 s 100 m Free (Exp_ > 5): 74.60 ± 9.54s	

(Continued)

TABLE 3 | Continued

Source	Purpose	Design	Anthropometrics	Biomechanics	Energetics/ Efficiency	Performance	
						Initial	Final
Mezzaroba and Machado (2014)	To determine the influence of age, anthropometry, and distance on stroke parameters and performance	Cross-sectional	BM, BF, H, TUEL, TLEL	V, SF, SL	SI	10–11 years 100 m Free: 1.10 ± 0.17 $m \cdot s^{-1}$ 10–11 years 200 m Free: 1.02 ± 0.15 $m \cdot s^{-1}$ 10–11 years 400 m Free: 0.95 ± 0.14 $m \cdot s^{-1}$ 12–13 years 100 m Free: 1.28 ± 0.12 $m \cdot s^{-1}$ 12–13 years 200 m Free: 1.14 ± 0.12 $m \cdot s^{-1}$ 12–13 years 400 m Free: 1.07 ± 0.14 $m \cdot s^{-1}$	
Morais et al. (2012)	To develop a structural equation model for performance in young swimmers based on selected kinematic, anthropometric and hydrodynamic variables	Cross-sectional	BM, H, AS, HSA	SL, dv, D_a	SI	Boys 100 Free: 78.33 ± 12.07 s Girls 100 Free: 85.25 ± 13.89 s Together 100 Free: 82.07 ± 12.96 s	
Morais et al. (2013a)	To analyze a gender and sports level effect, and sports level-gender interactions on anthropometrics, kinematics and energetics	Cross-sectional	BM, H, AS, TTSA, HSA, FSA	v, SL, SF, dv	SI, CV, η_F	Swimmers were faster in Tier and performance decreased until Tier 4 (for boys only and girls only)	
Morais et al. (2013b)	To follow-up the stability of performance and its determinant factors (i.e., anthropometrics, kinematics, hydrodynamics and efficiency)	Longitudinal (one competitive season)	BM, H, AS, TTSA, HSA, FSA, CP	D_a, C_{Da}, v, SL, SF, dv	SI, η_F	Performance improved significantly between the three evaluation moments (for boys and girls pooled together and individually)	
Morais et al. (2014a)	To model a latent growth curve of the performance and biomechanics	Longitudinal (one competitive season)	n.a.	D_a, C_{Da}, P_d, SF, dv	η_F	100 Free: 72.05 ± 5.33 s	100 Free: 66.13 ± 5.16 s
Morais et al. (2014b)	To assess the intra- and inter-individual variability of the performance and its determinant factors within and between seasons according to gender and skill level	Longitudinal (two competitive seasons)	BM, H, AS, TTSA, HSA, FSA, CP	D_a, C_{Da}, v, SL, SF, dv	SI, η_F	Boys (high skill) 100 Free: Δ =13.39% Boys (average skill) 100 Free: Δ =27.80% Girls (high skill) 100 Free: Δ =7.77% Girls (average skill) 100 Free: Δ =17.85%	
Morais et al. (2015)	To apply a new method to identify, classify, and follow up swimmers, based on their performance and its determinant factors, and to analyze the swimmers'stability over a competitive season with that method	Longitudinal (one competitive season)	AS, CP	C_{Da}, v, dv, SL	SI, η_F	High skill 100 Free: 71.17 ± 5.91 s Average skill 100 Free: 77.57 ± 4.44 s Low skill 100 Free: 83.67 ± 5.11 s	High skill 100 Free: 61.63 ± 2.90 s Average skill 100 Free: 68.64 ± 3.36 s Low skill 100 Free: 73.43 ± 3.92 s
Morais et al. (2016)	To compute a confirmatory model for swimming performance based on anthropometrics, strength, power output, kinematics, and efficiency.	Cross-sectional	BM, H, AS	BT, v, P_d,	η_F	100 Free: 74.25 ± 8.80 s	
Morais et al. (2017)	To test a performance-predictor model based on swimmers' biomechanical profile, relate the partial contribution of the main predictors with the training program over time, and analyze the time effect, sex effect, and time × sex interaction	Longitudinal (three competitive seasons)	BM, H, AS	SF, SL, v, dv	SI, η_F	Boys 100 Free: 76.26 ± 7.00 s Girls 100 Free: 79.06 ± 6.77 s	Boys 100 Free: 60.08 ± 3.22 s Girls 100 Free: 68.06 ± 4.40 s
Morais et al. (2020a)	To analyze the variations in performance, anthropometrics, and biomechanics break to gather insights on the detraining process	Longitudinal (11 weeks)	BM, H, AS, TTSA, HSA, FSA	D_a, C_{Da}, v, SL, SF, dv, P_d, P_k, P_{ext}, E_{tot}, F_r, v_h, R_e	SI, η_F	Boys 100 Free: 68.53 ± 6.81 s Girls 100 Free: 75.07 ± 7.84 s	Boys 100 Free: 70.05 ± 5.84 s Girls 100 Free: 76.53 ± 6.44 s
Morais et al. (2020b)	To classify, identify and follow-up swimmers into sub-groups (clusters), according to the performance and its biomechanical determinants, and analyze the individualvariations of each swimmer	Longitudinal (two competitive seasons)	BM, H, AS, TTSA, HSA, FSA, CP	D_a, C_{Da}, v, SL, SF, dv, P_d, P_k, P_{ext},	SI, η_F	High skill 100 Free: 68.07 ± 6.62 s Average skill 100 Free: 73.14 ± 4.87 s Low skill 100 Free: 82.60 ± 4.18 s	High skill 100 Free: 61.46 ± 3.43 s Average skill 100 Free: 65.33 ± 2.97 s Low skill 100 Free: 70.09 ± 3.48 s
Moreira et al. (2014)	To analyze the effects of growth on swimmers' biomechanical profile	Longitudinal (10 weeks)	BM, H, AS, HSA, FSA	D_a, C_{Da}, v, SL, SF	SI, η_F	Performance (swim speed) significantly increased	

(Continued)

TABLE 3 | Continued

Source	Purpose	Design	Anthropometrics	Biomechanics	Energetics/ Efficiency	Performance: Initial	Performance: Final
Nevill et al. (2020)	To explore which key somatic and demographic characteristics are common to all swimmers and identify further characteristics that benefit only specific strokes	Cross-sectional	BM, H, AS, BF, SH, ULL, UAL, LAL, HL, LLL, TL, LL, FL, ARG, FG, WG, TG, Calf G, AG, Biacr B, Biiliac B	v	n.a.	Boys 100 Breast: 97.70 ± 13.50 s Girls 100 Breast: 95.40 ± 9.50 s Girls 100 Back: 79.50 ± 5.00 s	
Ozeker et al. (2020)	To examine the effect of dry-land training in addition to swimming training on girl's strength and swimming performance	Longitudinal (8 weeks)	n.a.	v, SFlexion, SAbd, EExt, EFlex, HExt, HAbd, KFE, SAdd	CV	50 Free CG: 45.71 ± 7.44 s 50 Free EG: 35.24 ± 2.57 s 400 Free CG: 514.07 ± 92.58 s 400 Free EG: 352.57 ± 23.79 s	50 Free CG: 45.65 ± 7.42 s 50 Free EG: 34.25 ± 2.39 s 400 Free CG: 513.04 ± 92.98 s 400 Free EG: 343.98 ± 22.10 s
Poujade et al. (2003)	To define the determining factors 400 m performance	Cross-sectional	BM, BF, H, AS, BSA	v	C_s, VO_2	400 m Free: 335.00 ± 10.00 s	
Poujade et al. (2002)	To measure the Cs and to examine the relationship between Cs and velocity, morphology and stroking parameters	Cross-sectional	BM, BF, H, BSA, HLift	SF, SL, v	C_s, C_s/SA, C_s/SA, HL, VO_2	400 m Free: 335.77 ± 9.77 s	
Saavedra et al. (2013)	To determine the volume of training, how it evolves and its relationship with performance	Cross-sectional	BM, H, SH, AS	n.a.	n.a.	n.a.	
Saavedra et al. (2010)	To analyze swimming performance by developing multivariate predictive modelsbased on a wide variety of assessments from a multidimensional perspective	Cross-sectional	BM, BF, BMI, H, SH, AS, HL, HW, FL, FW, Biacr B,Biiliac B, Bitroch B, KB, EB, WB, CG, AFG, GG, TG, LG, AS/H,Biacr B/H, CG/H, GG/H, SSS	HJ, HG, AFlex, SFlex, Glide, SF, SL, v	SRE, FB, PT, SandR, SR, Abd, FAH, SI	n.a.	
Sammoud et al. (2018)	To use allometric models to estimate the optimal body size, limb segment length, and girth and breadth ratios associated with 100-m breaststroke speed performance	Cross-sectional	APHV, BM, H, AS, SH, BF, FM, FFM, BMI, ULL, UAL, LAL, HL, LLL, TL, LL, FL, ARG, FG, WG, TG, Calf G, AG, Biacr B, Biiliac B	v	n.a.	Boys 100 Breast: 97.70 ± 13.40 s Girls 100 Breast: 95.40 ± 9.50 s	
Sammoud et al. (2019)	To examine the effects of plyometric jump program in combination with swimming compared with swimming only on proxies of muscle power	Longitudinal (8 weeks)	APHV, BM, H	CMJ, SLJ, 25 m KWP, 25 m Free WP, v	n.a.	CG 15 Free: 9.53 ± 0.80 s CG 25 Free: 17.17 ± 1.20 s CG 50 Free: 37.50 ± 2.80 s EG 15 Free: 10.10 ± 0.50 s EG 25 Free: 18.20 ± 0.90 s EG 50 Free: 40.00 ± 1.70 s	CG 15 Free: 9.30 ± 0.80 s CG 25 Free:16.90 ± 1.40 s CG 50 Free: 37.60 ± 4.00 s EG 15 Free: 9.60 ± 0.40 s EG 25 Free: 17.52 ± 0.70 s EG 50 Free: 39.10 ± 1.50 s
Sammoud et al. (2021)	To examine the effects of an 8-week plyometric jump training program on jump and sport-specific performances inprepubertal femaleswimmers	Longitudinal (8 weeks)	APHV, BM, H, BMI	CMJ, SLJ	n.a.	CG 25 Free: 18.35 ± 1.19 s CG 50 Free: 40.51 ± 3.10 s EG 25 Free: 19.27 ± 1.13 s EG 50 Free: 42.79 ± 2.65 s	CG 25 Free: 18.50 ± 0.17 s CG 50 Free: 40.94 ± 0.59 s EG 25 Free: 18.05 ± 0.15 s EG 50 Free: 41.08 ± 0.52 s

(Continued)

TABLE 3 | Continued

Source	Purpose	Design	Anthropometrics	Biomechanics	Energetics/ Efficiency	Performance	
						Initial	Final
Seffrin et al. (2021)	To evaluate the characteristics of body, anthropometry, and neuromuscular fitness in young swimmers from 11 to 23 years old, and fit multiple regression models to verify which evaluated factors better explain performance in 100 and 400 m Freestyle	Cross-sectional	BM, LBM, H, AS, SH, ULL, LLL, FL, HL, TTSA, TW	CMJ, SJ, HG, AvgPext, AvgPflex, PText, PTflex, AvgPer, AvgPir, PTer, PTir	n.a.	Boys 100m Free: 84.73 ± 11.15 s Boys 400 m Free: 393.35 ± 62.93 s Girls 100m Free: 81.11 ± 8.45 s Girls 400 m Free: 376.65 ± 32.52 s	
Silva et al. (2012)	To characterize the backstroke swimming technique through the stroke parameters and the inter-arm coordination	Cross-sectional	BM, H, AS	v, SF, SL, SL/AS, IdC	SI	Boys 25 m Back: 1.18 ± 0.14 m·s^{-1} Girls 25 m Back: 1.06 ± 0.14 m·s^{-1}	
Silva et al. (2013)	To characterize the front crawl technique by assessing the general biomechanical parameters and the inter-arm coordination	Cross-sectional	BM, H, AS	v, SF, SL, SL/AS, IdC	SI	Boys 25 m Free: 1.46 ± 0.12 m·s^{-1} Girls 25 m Free: 1.37 ± 0.18 m·s^{-1}	
Staub et al. (2020b)	To explore how consistent career pathways develop among age group swimmers	Longitudinal (8 years)	n.a.	n.a.	n.a.	n.a.	
Staub et al. (2020a)	To investigate within-sport specialization and entry age in the careers of German age-group swimmers	Longitudinal (8 years)	n.a.	n.a.	n.a.	n.a.	
Tijani et al. (2019)	To investigate the relationship between anthropometrical and stroking parameters and their contribution to sprint swimming performance	Cross-sectional	BM, H, AS, AS/H, BMI, BF	v, SF, SL	SI	50 m Free: 31.27 ± 1.10s	
Tsalis et al. (2012)	To examine the physiological responses, the strokeparameter changes and the ability to sustain a velocity corresponding to critical velocity during interval swimming	Cross-sectional	BF, FM, LBM, S9	v, SF, SL	HR, CV, CSR, BI	Children 50 m: 37.70 ± 1.50 s Young 50 m: 32.40 ± 1.30 s Adult 50 m: 31.10 ± 2.20 s Children 100 m: 85.70 ± 4.80 s Young 100 m: 71.50 ± 2.90 s Adult 100 m: 68.20 ± 3.60 s Children 200 m: 191.80 ± 10.40 s Young 200 m:157.90 ± 9.20 s Adult 200 m: 151.30 ± 5.60 s Children 400 m: 400.40 ± 18.9 s Young 400 m: 332.30 ± 23.00 s Adult 400 m: 315.20 ± 14.60 s	
Zarzeczny et al. (2013)	To find out if critical swim speed estimated on the basis of two distances (50 and 400 m) corresponds to the results obtained during a standard 12-minute swim test	Cross-sectional	BM, H	v	CV, HR rest, RR sys, RR diast	12 min test Free: 0.85 ± 0.03 m·s^{-1} 12 min test Breast: 0.73 ± 0.02 m·s^{-1}	

n.a.—not applicable (i.e., not reported).

Free, freestyle; back, backstroke; breast, breaststroke; fly, butterfly; Acad_level, the academic level of coaches (1, bachelor; 2, master; 3, philosophy doctor); coach_level, the training level of coaches (1, level 1; 2, level 2; 3, level 3); Exp, training experience of coaches (≤ 5, equal or less than 5 years; > 5, more than 5 years); CG, control group; EG, experimental group; U13, under the 13-year level; U12, under the 12-year level.

of average age), including the freestyle and butterfly strokes (Nevill et al., 2020).

As young swimmers grow until reaching full maturity, the best way to gather deeper insights into the influence of anthropometrics on swimming performance is to design longitudinal studies (Lätt et al., 2009a,b; Abbott et al., 2021). When following up over a competitive season, swimmers who achieved better performances (in the 100-m freestyle) also had larger body sizes (Morais et al., 2020b). A similar trend was verified in the 400-m freestyle (Lätt et al., 2009a,b). Moreover, a 3-year study that recruited 91 swimmers from a TID program showed that the AS was a major cause of performance improvement (Morais et al., 2017). Nonetheless, it was argued that swimmers must "relearn" the stroke mechanics to better use the propelling limbs, whenever meaningful body changes happen, such as during growth spurts (Morais et al., 2017). This happens because, as mentioned earlier, anthropometry not only has a direct effect on the performance of swimmers but also holds a concurrent effect on other scientific domains related to swimming techniques (Tijani et al., 2019; Morais et al., 2020b). That is, longer lengths like H and AS are strongly related to longer stroke length (SL) (kinematics) (Silva et al., 2012; Morais et al., 2017); whereas, larger TTSA or BSA is strongly related to more drag (hydrodynamics) (Barbosa et al., 2014).

Young swimmers are prone to have several growth spurts within a competitive season (Abbott et al., 2021). Such spurts contribute to the improvement in several variables related to swimming technique (Morais et al., 2013b, 2015). It was shown that, even during detraining periods (i.e., training breaks) the performance impaired, but anthropometry was responsible for slowing down such impairment (Moreira et al., 2014; Morais et al., 2020a). That is, during an 11-week detraining period, the swimmers continued to grow up. Because they were taller at the end of the break, it allowed them to minimize the performance impairment (Morais et al., 2020a). This highlights the importance of a systematic and frequent assessment of the anthropometrics.

Biomechanics

Biomechanics is related to swimming techniques, such as SL, stroke frequency (SF), stroke index (SI), and intra-cyclic variation of the swim speed (dv), which are part of the "nurture" process and the ones that better explain performance (Lätt et al., 2009a; Barbosa et al., 2010; Morais et al., 2012). Top-tier swimmers are faster, because of better SL, SF, Reynolds number (R_e), Froude number (F_r), and hull speed (V_h) scores (Barbosa et al., 2019). Faster swimmers were also prone to have less dv (Barbosa et al., 2014; Figueiredo et al., 2016) and deliver more in-water mechanical power (Barbosa et al., 2015, 2019; Morais et al., 2020b). Thus, it seems that the fastest swimmers can promote smaller speed fluctuations (Barbosa et al., 2014) and produce more power concurrently (Barbosa et al., 2019; Morais et al., 2020b). It can be argued that in-water power is related to more dry-land strength. It has been shown that variables related to dry-land strength were correlated with sprint swimming (Garrido et al., 2010a; Seffrin et al., 2021) and middle-distance events (400-m freestyle—Seffrin et al., 2021). Moreover, the power to overcome drag can be explained by 94% of the dry-land strength (Morais et al., 2016). However, faster swimmers are also under more active drag (D_a) and coefficient of active drag (C_{Da}) (Barbosa et al., 2019). It should be noted that drag variables, such as D_a, passive drag (D_p), C_{Da}, and coefficient of passive drag (C_{Dp}), are highly dependent on velocity, TTSA, and BSA (Kjendlie and Stallman, 2008). Thus, bigger and faster swimmers are prone to be under more drag (Barbosa et al., 2014, 2019). Indeed, "matured" age-group swimmers performing freestyle (Silva et al., 2012) and backstroke (Silva et al., 2013) had higher stroke kinematics scores [namely swim speed (v) and SL]. Conversely, non-significant differences were found in the index of coordination (IdC) (i.e., motor control) between pre and postpubertal swimmers (Silva et al., 2012, 2013).

Longitudinal studies showed that variables related to biomechanics change significantly over time (Lätt et al., 2009a; Morais et al., 2015, 2020b). As aforementioned, young swimmers undergo growth and maturation processes that lead to changes in the swimming technique (Lätt et al., 2009a; Morais et al., 2017). They are prone to improve the kinematics and kinetics over long-term periods of time (Morais et al., 2017, 2020b). Nonetheless, in specific moments of a season, young swimmers may impair the stroke biomechanics (Morais et al., 2013b, 2014b). Despite the variations within the season, swimmers improved the stroke biomechanics when comparing the beginning and the end of the season. Longitudinal research also reported that swimmers cluster in groups with similar traits related to stroke biomechanics (Morais et al., 2015, 2020b). As far as the long term is concerned, i.e., during one or several competitive seasons, the variables that better characterize each group may change over time. Swimmers improve and impair the stroke biomechanics several times over one or more competitive seasons (Morais et al., 2015, 2020b). Notwithstanding, variations may not occur at the same time across all clusters (Morais et al., 2015, 2020b). Moreover, it has been shown that swimmers are also likely to change groups; that is, switching to another subgroup or performance level. A swimmer who is assigned to the top-tier subgroup may not remain in that subgroup. It is possible that, over the season, the swimmer may drop to a lower tier, and lower-tier swimmers can climb up to top-tier groups (Morais et al., 2020b). Performance levels are very dynamic over time, and swimmers can move to different tiers quite often. The shift is due to a concurrent change in the determinant factors underlying the performance, which, in turn, depend on the developmental training program they are under, as well as the rate of growth and maturation.

The relationship between the in-water training programs and swimming biomechanics can be better understood when internal and external training loads are monitored. However, few studies addressed this topic in developing programs for young swimmers (Garrido et al., 2010b; Saavedra et al., 2013; Morais et al., 2014a). High-training volumes during the first part of a season (with low intensity, including warm-up, recovery, and slow-pace drills) led to an improvement in performance (Morais et al., 2014a). The same authors (Morais et al., 2014a) evaluated a group of swimmers during a competitive season in four different moments. They achieved 59% of the final performance in the second evaluation moment and 99% in the third moment. Between the 3rd and 4th (final) moments, the swimmers improved by only 1%, with the SF as the main determinant (Morais et al., 2014a). Between the 3rd and 4th moments, the periodization included an increase in the aerobic power and aerobic capacity (Morais et al., 2014a). As their older counterparts, young swimmers increase SF whenever they want to reach faster speeds (Mezzaroba and Machado, 2014; Barbosa et al., 2019). The researchers noted that changes in performance are related to the type of training swimmers were undergoing at the time of each evaluation moment. Thus, coaches can use different training strategies for their periodization to reach previously outlined goals and avoid burnout.

Studies also aimed to understand the effect of dry-land strength on the performance of young swimmers (Sammoud et al., 2019, 2021; Ozeker et al., 2020). During an 8-week intervention (aerobic in-water training concurrently with dry-land strength), Garrido et al. (2010b) reported a trend in sprint performance improvement (25- and 50-m freestyle) due to strength training. This was confirmed in other sprint events (50- and 100-m freestyle and backstroke) (Alshdokhi et al., 2020). Swimmers assigned to the experimental group presented a larger increase in the selected variables compared with the control group (Alshdokhi et al., 2020). It was suggested that the improvement in dry-land strength resulted in better swimming performance. Others aimed to provide deeper insights into the effect of different types of dry-land strength and conditioning programs on sprint performance (50-m freestyle) (Amaro et al., 2017). It was noted that swimmers under explosiveness training (i.e., performing the repetition quickly) presented larger improvements in swimming speed compared with performing repetition/sets training (Amaro et al., 2017). The phenomenon of post-activation potentiation performance enhancement is defined as a voluntary dynamic force production after a short and acute bout of high-intensity voluntary exercise (Blazevich and Babault, 2019). A study used three 30-s post-activation potentiation protocols (10 min before competition) to understand its effect on the performance and stroke kinematics (Abbes et al., 2018). Authors verified that all protocols presented non-significant effects on the 50-m freestyle performance, SL, and SF. A follow-up study analyzed the effect of tethered swimming as post-activation potentiation in the 50-m freestyle performance and stroke kinematics (SL), and non-significant effects were observed (Abbes et al., 2020). Therefore, both studies suggest an unclear effect of post-activation potentiation performance enhancement on young swimmers.

Energetics and Efficiency

Energetics and efficiency also play a role in the performance of young swimmers. That said, the energetic spartial contribution to the performance increases with age (Zacca et al., 2020). It has been observed that VO_2 during submaximal swimming speeds is significantly lower in children than adults (Kjendlie et al., 2004a). A study that selected anthropometrics, kinematics, energetics, and efficiency as main outcomes demonstrated that the 100-m freestyle performance was predicted by anaerobic power (AnP), critical velocity (CV), and SI (as an efficiency proxy) (de Mello Vitor and Böhme, 2010).

The CV is a variable commonly used to assess the energetics of young swimmers (Denadai et al., 2000; Marinho et al., 2011; Zarzeczny et al., 2013). It is calculated based on the distance-time slope of several events or swimming distances (Dekerle et al., 2002). It is highly correlated with aerobic performance and, hence, used to control training intensities (Zarzeczny et al., 2013; Figueiredo et al., 2016). However, CV may underestimate swimming intensity corresponding to speed at a blood lactate concentration of 4 $\text{mmo}\cdot\text{l}^{-1}$ in swimmers aged 10 to 12 years old (Denadai et al., 2000). It was suggested that it relates, instead, to the intensity corresponding to the maximum steady state of lactate concentration (Denadai et al., 2000). The CV has a significantly direct effect on the 200-m freestyle (Barbosa et al., 2010) and can also provide a strong explanation in the shorter events performances, such as the 100-m freestyle (de Mello Vitor and Böhme, 2010). Swimmers with faster CV also delivered better performances in the 100-m freestyle (Morais et al., 2013a) and 25-m freestyle time trials (Figueiredo et al., 2016).

Besides the SI, researchers also selected the Froude efficiency (η_F) as another energetic proxy (e.g., de Mello Vitor and Böhme, 2010; Morais et al., 2014a). The SI measures the ability of the swimmer to complete a given distance with a particular speed in the fewest possible number of strokes (Costill et al., 1985). The η_F estimates the amount of work or power used to translate the body in water (Zamparo et al., 2020). Both variables are straightforward and less time-consuming to compute compared with a direct measurement of other energetics variables (Figueiredo et al., 2016; Barbosa et al., 2019; Morais et al., 2020b). Larger SI and η_F are associated with better performance in short distances, as the 100-m freestyle and 25-m freestyle time trial. Indeed, the fastest swimmers distinguish themselves from others because they have a better CV, SI, and ηF (Morais et al., 2013a; Figueiredo et al., 2016; Barbosa et al., 2019). Moreover, it should be highlighted that the increase in SI and η_F is related to the technical training that young swimmers undergo (Morais et al., 2017).

For longer events, such as the 400-m freestyle, the VO_{2max} (Duché et al., 1993; Poujade et al., 2003) and the VO_{2peak} (Jürimäe et al., 2007) were the best predictors of swimming performance within a set of energetic variables. Hue et al. (2013) showed that the fastest swimmers in the 400-m freestyle event also had better VO_{2max} than their slower counterparts. When tested by the 5 × 300-m protocol, young swimmers improved their swimming economy as they got older based on lower heart rate (HR) variability (Tsalis et al., 2012). In mid-distance events, another variable monitored very frequently was the energy cost of swimming (C_s), which increases with swimming speed (Poujade et al., 2002; Kjendlie et al., 2004a,b). Nonetheless, one study pointed out that kinematics (SL and SF), anthropometrics (body length—BL, BM, and BSA), and HL did not explain the C_S in young swimmers (Poujade et al., 2002). The authors suggested that underwater torque, technical ability, and maturation could be strong predictors. Another study reported that passive torque presented a significant linear relationship with absolute C_s in young swimmers (Kjendlie et al., 2004b). Overall, there is solid evidence that, for similar swimming speeds, young swimmers have more C_s than their older counterparts (Zamparo et al., 2000; Kjendlie et al., 2004a). Thus, the differences between young swimmers and their older counterparts in the economy are due to the less-technical ability of the former ones.

Longitudinal studies showed that an improvement in energetics (VO_2 and ΔLa) allowed an enhancement in performance (Lätt et al., 2009a,b). These studies were mostly focused on the 400-m freestyle (i.e., middle distance) (Lätt et al., 2009a,b; Ferreira et al., 2019). A research group followed boys (Lätt et al., 2009a) and girls (Lätt et al., 2009b) during two competitive seasons. It was observed that the VO_2 was among the best predictors of performances of both sexes. Others noted significant correlations between a set of energetic variables (i.e., Bl and Bg) in the 400-m freestyle performance (Ferreira et al., 2019). Nevertheless, SI (efficiency) was the best predictor of all the variables assessed (Lätt et al., 2009a,b), or the one that presented the highest correlation with performance (Ferreira et al., 2019). Additionally, it was suggested that the 400-m freestyle enhancement during a season was highly related to an increase in the SI, suggesting that, when swimmers are in this age group, coaches should prioritize technical development of the swimmers (Ferreira et al., 2021). That said, the authors indicated that, concurrently, with the technical enhancement, physiological variables are as important to optimize swimming performance in such middle-distance events (Ferreira et al., 2021). Thus, at early ages, training should focus on learning the proper swimming techniques (i.e., technical training).

Nonetheless, the same reasoning (i.e., importance of energetics/efficiency) can be claimed in shorter race events, at least based on research carried out in the 100-m freestyle (Morais et al., 2013b, 2014b). The η_F increased or at least was maintained over time (Morais et al., 2020b). Additionally, high skillful swimmers yielded larger efficiency over time compared with their slower counterparts (Morais et al., 2014b, 2015). The HR (as an energetic indicator) may also present an association with the energetics of swimmers in the 50-m, 100-m, (Alshdokhi et al., 2020), and 400-m freestyle (Ferreira et al., 2019). Both studies reported that training has a positive effect on HR of young swimmers. That is, swimmers decreased the HR, suggesting that, for the same task (50-m and 100-m—Alshdokhi et al., 2020; or 400-m freestyle—Ferreira et al., 2019), they required less effort, with improved performance. Therefore, it can be implied that, besides the middle-distance events (i.e., 400-m freestyle), energetics/efficiency also presents a strong contribution in shorter events (like the 50 and 100-m freestyle).

Performance in a Long-Term Athlete Development (LTAD) Perspective

Longitudinal studies can also help to understand the evolution of swimming performance from childhood to adulthood (Costa et al., 2011; Staub et al., 2020a,b). This research is paramount to better explain how the growth pace of each swimmer affects the performance and its determinant factors (Durand-Bush and Salmela, 2002). As previously noted, the performance level is highly dynamic and depends upon growth and maturation spurts, as well as the development program the swimmer is under. Stability assessment allows the prediction of the future success of young swimmers by the estimation of the performance progression. Based on the analysis of 242 young swimmers (from 12 to 18 years old), a study observed that swimmers should display a 14–19% improvement from childhood to adulthood in all freestyle events to become part of an elite group (Costa et al., 2011). The same authors also pointed out that the age of 16 is when the ability to predict the adult competitive level increases considerably. Thus, one cannot "neglect" a swimmer who, at a given moment, is slower than his/her peers, because, the following year, he/she can become one of the best in his/her age group (Morais et al., 2015, 2020b).

A study explored how consistent career pathways are among age-group swimmers (Staub et al., 2020b). Swimmers with better FINA points at 11 years old (including events, strokes, and distances) were more likely to be ranked during more years over the analyzed time frame (8 years), but the correlation showed a weak effect (Staub et al., 2020b). The authors argued that young swimmers should get the chance to yield from LTAD programs and should not be selected only by their age-group performance level (Staub et al., 2020b). It was claimed that LTAD programs should bring awareness about this phenomenon, which requires advanced understanding from coaches and other practitioners (Lang and Light, 2010).

It has been recently reported that both nature (i.e., anthropometrics) and nurture (i.e., training—namely sports technique) are important to excel in youth swimming (Barbosa et al., 2019). The best performers among three subgroups of swimmers (subgroup #1: age-group national champions, national record holders or enrolled in talent ID programs) scored very well in variables related to both nature and nurture parameters. Conversely, swimmers in the subgroup #3 (racing at local competitions) were weaker in both dimensions, and swimmers in the subgroup #2 (racing at national competitions) showed weaknesses in nature-related factors (i.e., anthropometrics) but were reasonably good in nurture factors (i.e., training). The subgroup #2 profile shows the potential of swimmers who may be seen as less genetically predisposed, as a result of an effective developmental program (Barbosa et al., 2019; Marinho et al., 2020).

As far as LTAD is concerned, there is also an ongoing dialog about the potential negative effects of large volumes of training in young swimmers (Nugent et al., 2017). Many coaches combine assumptions based on their experience with evidence-based practice. Recently, Marinho et al. (2020) have reported that an improvement in academic degree, coaching level, and coaching experience of the coaches presented a positive and significant contribution to swimming efficiency and performance of young athletes. Swimmers under the guidance of a coach with a higher academic degree, coaching level, or more years of coaching experience were more efficient and, concurrently, delivered better performances (Marinho et al., 2020). As youth swimming training should be focused on technical training (Morais et al., 2012), coaches should be able to provide their athletes with training in key skills and abilities based on such technique determinants. Therefore, age-group coaches are advised to design training programs that are underpinned on high-level and cutting-edge evidence.

Another major topic within LTAD is early specialization (Larson et al., 2019; Staub et al., 2020a). Early specialization refers to young athletes who limit their childhood to a single sport, deliberating their training and development on a singular sport (Baker, 2003). It was claimed that early specialization might promote far more risks than benefits (Wiersma, 2000). Youth athletes can suffer from social isolation, overdependence, burnout, manipulation, injury, and compromise their growth and maturation (Malina, 2010). Conversely, an athlete who practices a set of skills with increased frequency and duration becomes more proficient in those skills than one who practices them periodically (Wiersma, 2000). In competitive swimming, there are four competitive swim strokes and one event combining all (medley), as well as several race distances. Thus, in swimming, a within specialization may occur whenever a swimmer chooses and develops at an early age a single stroke or distance (or a combination of more than one stroke or distance, or both combined) (Staub et al., 2020a). A study showed that greater diversification within the same sport is positively correlated with success at the age of 18 (Staub et al., 2020a). Thus, the younger a swimmer enters the top 100, more likely he/she is to reach a top-tier at the age of 18 (Staub et al., 2020a). This suggests that early specialization may not be the best pathway to ensure higher performance in adulthood. Additionally, Larson et al. (2019) showed that a set of markers related to early specialization was related to burnout or a dropout in youth swimming. However, it was suggested that early specialization in one event, stroke or distance could be a way for coaches to accomplish qualification times and promote rapid adolescent success at the expense of long-term elite success as adults (Staub et al., 2020a). As such, developmental programs should expose young swimmers to a broad range of events (distances and swimming strokes) and even, at early stages, to other aquatic and non-aquatic sports.

CONCLUSIONS

Performance of young swimmers is characterized by a multifactorial, holistic, and dynamic phenomenon relying on several features from different scientific domains. Better performance has always been related to better swimming techniques. Concurrently, anthropometry (e.g., higher AS, H, and upper limbs) also plays an important role in performance. Swimmers with larger body dimensions are the fastest. This suggests that anthropometry (i.e., nature) and training (i.e., nurture) play key roles. The contribution of energetics and efficiency becomes more important as the swimmer gets older or whenever the swimming event becomes longer. Performance enhancement of young swimmers should rely on LTAD programs, always taking into consideration the growth spurt and the external training load of the swimmer. Coaches are advised to monitor the rate of growth of their athletes, since this can affect their performance. They should put more focus on improving swimming technique and less on the external training load.

DATA AVAILABILITY STATEMENT

The datasets presented in this article are not readily available because none. Requests to access the datasets should be directed to Jorge E. Morais, morais.jorgestrela@gmail.com.

AUTHOR CONTRIBUTIONS

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

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REFERENCES

Abbes, Z., Chamari, K., Mujika, I., Tabben, M., Bibi, K. W., Hussein, A. M., Martin, C., and Haddad, M. (2018). Do thirty-second post-activation potentiation exercises improve the 50-m freestyle sprint performance in adolescent swimmers? *Front Physiol.* 9:1464. doi: 10.3389/fphys.2018.01464

Abbes, Z., Haddad, M., Bibi, K. W., Mujika, I., Martin, C., and Chamari, K. (2020). Effect of tethered swimming as postactivation potentiation on swimming performance and technical, hemophysiological, and psychophysiological variables in adolescent swimmers. *Int. J. Sports Physiol. Perform.* 16, 311–315. doi: 10.1123/ijspp.2019-0669

Abbott, S., Yamauchi, G., Halaki, M., Castiglioni, M. T., Salter, J., and Cobley, S. (2021). Longitudinal relationships between maturation, technical efficiency, and performance in age-group swimmers: improving swimmer evaluation. *Int. J. Sports Physiol. Perform.* 03:77. doi: 10.1123/ijspp.2020-0377

Alshdokhi, K. A., Petersen, C. J., and Clarke, J. C. (2020). Effect of 8 weeks of grip strength training on adolescent sprint swimming: a randomized controlled trial. *Exerc. Med.* 4:1. doi: 10.26644/em.2020.001

Amaro, N. M., Marinho, D. A., Marques, M. C., Batalha, N. P., and Morouço, P. G. (2017). Effects of dry-land strength and conditioning programs in age group swimmers. *J. Strength Cond. Res.* 31, 2447–2454. doi: 10.1519/JSC.0000000000001709

Baker, J. (2003). Early specialization in youth sport: a requirement for adult expertise? *High. Abil. Stud.* 14, 85–94. doi: 10.1080/135981303 04091

Barbosa, T. M., Bartolomeu, R., Morais, J. E., and Costa, M. J. (2019). Skillful swimming in age-groups is determined by anthropometrics, biomechanics and energetics. *Front. Physiol.* 10:73. doi: 10.3389/fphys.2019.00073

Barbosa, T. M., Costa, M., Marinho, D. A., Coelho, J., Moreira, M., and Silva, A. J. (2010). Modeling the links between young swimmers' performance: energetic and biomechanic profiles. *Pediatr. Exerc. Sci.* 22, 379–391. doi: 10.1123/pes.22.3.379

Barbosa, T. M., Morais, J. E., Costa, M. J., Goncalves, J., Marinho, D. A., and Silva, A. J. (2014). Young swimmers' classification based on kinematics, hydrodynamics, and anthropometrics. *J. Appl. Biomech.* 30, 310–315. doi: 10.1123/jab.2013-0038

Barbosa, T. M., Morais, J. E., Marques, M. C., Costa, M. J., and Marinho, D. A. (2015). The power output and sprinting performance of young swimmers. *J. Strength Cond. Res.* 29, 440–450. doi: 10.1519/JSC.0000000000000626

Bielec, G., and Jurak, D. (2019). The relationship between selected anthropometric variables and the sports results of early pubescent swimmers. *Balt. J. Health Phys. Act.* 11, 124–130. doi: 10.29359/BJHPA.11.1.13

Blazevich, A. J., and Babault, N. (2019). Post-activation potentiation (PAP) vs. post-activation performance enhancement (PAPE) in humans: Historical perspective, underlying mechanisms, and current issues. *Front. Physiol.* 10:1359. doi: 10.3389/fphys.2019.01359

Blume, K., and Wolfarth, B. (2019). Identification of potential performance-related predictors in young competitive athletes. *Front. Physiol.* 10:1394. doi: 10.3389/fphys.2019.01394

Costa, M. J., Marinho, D. A., Bragada, J. A., Silva, A. J., Barbosa, T. M. (2011). Stability of elite freestyle performance from childhood to adulthood. *J. Sports Sci.* 29, 1183–1189. doi: 10.1080/02640414.2011.587196

Costill, D., Kovaleski, J., Porter, D., Kirwan, J., Fielding, R., and King, D. (1985). Energy expenditure during front crawl swimming: predicting success in middle-distance events. *Int. J. Sports Med.* 6:266–270. doi: 10.1055/s-2008-1025849

de Mello Vitor, F., and Böhme, M. T. S. (2010). Performance of young male swimmers in the 100-meters front crawl. *Pediatr. Exerc. Sci.* 22, 278–287. doi: 10.1123/pes.22.2.278

de Morton, N. A. (2009). The PEDro scale is a valid measure of the methodological quality of clinical trials: a demographic study. *Aust. J. Physiother.* 55, 129–133. doi: 10.1016/S0004-9514(09)70043-1

Dekerle, J., Sidney, M., Hespel, J. M., and Pelayo, P. (2002). Validity and reliability of critical speed, critical stroke rate, and anaerobic capacity in relation to front crawl swimming performances. *Int. J. Sports Med.* 23, 93–98. doi: 10.1055/s-2002-20125

Denadai, B. S., Greco, C. C., and Teixeira, M. (2000). Blood lactate response and critical speed in swimmers aged 10–12 years of different standards. *J. Sports Sci.* 18, 779–784. doi: 10.1080/026404100419838

Duché, P., Falgairette, G., Bedu, M., Lac, G., Robert, A., and Coudert, J. (1993). Analysis of performance of prepubertal swimmers assessed from anthropometric and bio-energetic characteristics. *Eur. J. Appl. Physiol. Occup. Physiol.* 66, 467–471. doi: 10.1007/BF00599623

Durand-Bush, N., and Salmela, J. H. (2002). The development and maintenance of expert athletic performance: Perceptions of world and Olympic champions. *J. Appl. Sport Psychol.* 14, 154–171. doi: 10.1080/10413200290103473

Ferraz, R., Branquinho, L., Loupo, R., Neiva, H., and Marinho, D. A. (2020). The relationship between anthropometric characteristics and sports performance in national-level young swimmers. *Eur. J. Hum. Mov.* 45:20. doi: 10.21134/eurjhm.2020.45.2

Ferreira, M. I., Barbosa, T. M., Costa, M. J., Neiva, H. P., and Marinho, D. A. (2016). Energetics, biomechanics, and performance in masters' swimmers: a systematic review. *J. Strength Cond. Res.* 30, 2069–2081. doi: 10.1519/JSC.0000000000001279

Ferreira, S., Carvalho, D., Monteiro, A. S., Abraldes, J. A. A., Vilas-Boas, J. P., Toubekis, A., et al. (2019). Physiological and biomechanical evaluation of a training macrocycle in children swimmers. *Sports* 7:57. doi: 10.3390/sports7030057

Ferreira, S., Carvalho, D. D., Cardoso, R., Rios, M., Soares, S., Toubekis, A., et al. (2021). Young swimmers' middle-distance performance variation within a training season. *Int. J. Environ. Res. Public Health.* 18:1010. doi: 10.3390/ijerph18031010

Figueiredo, P., Silva, A., Sampaio, A., Vilas-Boas, J. P., and Fernandes, R. J. (2016). Front crawl sprint performance: a cluster analysis of biomechanics, energetics, coordinative, and anthropometric determinants in young swimmers. *Mot. Control* 20, 209–221. doi: 10.1123/mc.2014-0050

Garrido, N., Marinho, D. A., Barbosa, T. M., Costa, A. M., Silva, A. J., Pérez-Turpin, J. A., et al. (2010a). Relationships between dry land strength, power variables and short sprint performance in young competitive swimmers. *J. Hum. Sport Exerc.* 5, 240–249. doi: 10.4100/jhse.2010.52.12

Garrido, N., Marinho, D. A., Reis, V. M., van den Tillaar, R., Costa, A. M., Silva, A. J., et al. (2010b). Does combined dry land strength and aerobic training inhibit performance of young competitive swimmers? *J. Sports Sci. Med.* 9, 300–310. Available online at: https://www.jssm.org/jssm-09-300.xml%3EFulltext

Geladas, N. D., Nassis, G. P., and Pavlicevic, S. (2005). Somatic and physical traits affecting sprint swimming performance in young swimmers. *Int. J. Sports Med.* 26, 139–144. doi: 10.1055/s-2004-817862

Hue, O., Antoine-Jonville, S., Galy, O., and Blonc, S. (2013). Anthropometric and physiological characteristics in young Afro-Caribbean swimmers: a preliminary study. *Int. J. Sports Physiol. Perform.*8, 271–278. doi: 10.1123/ijspp.8.3.271

Jürimäe, J., Haljaste, K., Cicchella, A., Lätt, E., Purge, P., Leppik, A., et al. (2007). Analysis of swimming performance from physical, physiological, and biomechanical parameters in young swimmers. *Pediatr. Exerc. Sci.* 19, 70–81. doi: 10.1123/pes.19.1.70

Kjendlie, P. L., Ingjer, F., Madsen, Ø., Stallman, R. K., and Stray-Gundersen, J. (2004a). Differences in the energy cost between children and adults during front crawl swimming. *Eur. J. Appl. Physiol.* 91, 473–480. doi: 10.1007/s00421-003-1022-0

Kjendlie, P. L., Ingjer, F., Stallman, R. K., and Stray-Gundersen, J. (2004b). Factors affecting swimming economy in children and adults. *Eur. J. Appl. Physiol.* 93, 65–74. doi: 10.1007/s00421-004-1164-8

Kjendlie, P. L., and Stallman, R. K. (2008). Drag characteristics of competitive swimming children and adults. *J. Appl. Biomech.* 24, 35–42. doi: 10.1123/jab.24.1.35

Koopmann, T., Faber, I., Baker, J., and Schorer, J. (2020). Assessing technical skills in talented youth athletes: a systematic review. *Sports Med.* 50, 1593–1611. doi: 10.1007/s40279-020-01299-4

Lang, M., and Light, R. (2010). Interpreting and implementing the long term athlete development model: English swimming coaches' views on the (swimming) LTAD in practice. *Int. J. Sports Sci. Coach.* 5, 389–402. doi: 10.1260/1747-9541.5.3.389

Larson, H. K., Young, B. W., McHugh, T. L. F., and Rodgers, W. M. (2019). Markers of early specialization and their relationships with burnout and dropout in swimming. *J. Sport Exerc. Psychol.* 41, 46–54. doi: 10.1123/jsep.2018-0305

Lätt, E., Jürimäe, J., Haljaste, K., Cicchella, A., Purge, P., and Jürimäe, T. (2009a). Longitudinal development of physical and performance parameters during biological maturation of young male swimmers. *Percept. Mot. Skills.* 108, 297–307. doi: 10.2466/pms.108.1.297-307

Lätt, E., Jürimäe, J., Haljaste, K., Cicchella, A., Purge, P., and Jürimäe, T. (2009b). Physical development and swimming performance during biological maturation in young female swimmers. *Coll. Antropol.* 33, 117–122.

Majid, W. K., Jari, H. S., and Noori, R. A. (2019). Performance training for the development of the harmonic ability and its impact on the rapid force and the achievement of (50) meters of breast for junior. *J. Glob. Pharma Technol.* 11, 71–76.

Malina, R. M. (2010). Early sport specialization: roots, effectiveness, risks. *Curr. Sports Med. Rep.* 9, 364–371. doi: 10.1249/JSR.0b013e3181fe3166

Marinho, D. A., Amorim, R. A., Costa, A. M., Marques, M. C., Pérez Turpin, J. A., and Neiva, H. P. (2011). "Anaerobic" critical velocity and swimming performance in young swimmers. *J. Hum. Sport Exerc.* 6, 80–86. doi: 10.4100/jhse.2011.61.09

Marinho, D. A., Barbosa, T. M., Lopes, V. P., Forte, P., Toubekis, A. G., and Morais, J. E. (2020). The influence of the coaches' demographics on young swimmers' performance and technical determinants. *Front. Psychol.* 11:1968. doi: 10.3389/fpsyg.2020.01968

Martindale, R. J., Collins, D., and Daubney, J. (2005). Talent development: a guide for practice and research within sport. *Question* 57, 353–375. doi: 10.1080/00336297.2005.10491862

Mezzaroba, P. V., and Machado, F. A. (2014). Effect of age, anthropometry, and distance in stroke parameters of young swimmers. *Int. J. Sports Physiol. Perform.* 9, 702–706. doi: 10.1123/ijspp.2013-0278

Mirwald, R. L., Baxter-Jones, A. D., Bailey, D. A., and Beunen, G. P. (2002). An assessment of maturity from anthropometric measurements. *Med. Sci. Sports Exerc.* 34, 689–694. doi: 10.1249/00005768-200204000-00020

Morais, J. E., Costa, M. J., Forte, P., Marques, M. C., Silva, A. J., Marinho, D. A., et al. (2014b). Longitudinal intra-and inter-individual variability in young swimmers' performance and determinant competition factors. *Motriz: Revista de Educação Física.* 20, 292–302. doi: 10.1590/S1980-65742014000300008

Morais, J. E., Forte, P., Silva, A. J., Barbosa, T. M., and Marinho, D. A. (2020b). Data modelling for inter- and intra-individual stability of young swimmers' performance: a longitudinal cluster analysis. *Res Quart Exerc Sport.* 92, 21–33. doi: 10.1080/02701367.2019.1708235

Morais, J. E., Garrido, N. D., Marques, M. C., Silva, A. J., Marinho, D. A., and Barbosa, T. M. (2013a). The influence of anthropometric, kinematic and energetic variables and gender on swimming performance in youth athletes. *J. Hum. Kinet.* 39, 203–211. doi: 10.2478/hukin-2013-0083

Morais, J. E., Jesus, S., Lopes, V., Garrido, N., Silva, A., Marinho, D., et al. (2012). Linking selected kinematic, anthropometric and hydrodynamic variables to young swimmer performance. *Pediatr. Exerc. Sci.* 24, 649–664. doi: 10.1123/pes.24.4.649

Morais, J. E., Lopes, V. P., Barbosa, T. M., Shin-ichiro, M., and Marinho, D. A. (2020a). How does 11-week detraining affect 11-12 years old swimmers' biomechanical determinants and its relationship with 100 m performance? *Sports Biomech.* 1–15. doi: 10.1080/14763141.2020.1726998

Morais, J. E., Marques, M. C., Marinho, D. A., Silva, A. J., and Barbosa, T. M. (2014a). Longitudinal modeling in sports: young swimmers' performance and biomechanics profile. *Hum. Mov. Sci.* 37, 111–122. doi: 10.1016/j.humov.2014.07.005

Morais, J. E., Saavedra, J. M., Costa, M. J., Silva, A. J., Marinho, D. A., and Barbosa, T. M. (2013b). Tracking young talented swimmers: follow-up of performance and its biomechanical determinant factors. *Acta Bioeng. Biomech.* 15, 129–138. doi: 10.5277/abb130316

Morais, J. E., Silva, A. J., Marinho, D. A., Lopes, V. P., and Barbosa, T. M. (2017). Determinant factors of long-term performance development in young swimmers. *Int. J. Sports Physiol. Perform.* 12, 198–205. doi: 10.1123/ijspp.2015-0420

Morais, J. E., Silva, A. J., Marinho, D. A., Marques, M. C., Batalha, N., and Barbosa, T. M. (2016). Modelling the relationship between biomechanics and performance of young sprinting swimmers. *Eur. J. Sport Sci.* 16, 661–668. doi: 10.1080/17461391.2016.1149227

Morais, J. E., Silva, A. J., Marinho, D. A., Seifert, L., and Barbosa, T. M. (2015). Cluster stability as a new method to assess changes in performance and its determinant factors over a season in young swimmers. *Int. J. Sports Physiol. Perform.* 10, 261–268. doi: 10.1123/ijspp.2013-0533

Moreira, M. F., Morais, J. E., Marinho, D. A., Silva, A. J., Barbosa, T. M., and Costa, M. J. (2014). Growth influences biomechanical profile of talented swimmers during the summer break. *Sports Biomech.* 13, 62–74. doi: 10.1080/14763141.2013.865139

Nevill, A. M., Negra, Y., Myers, T. D., Sammoud, S., and Chaabene, H. (2020). Key somatic variables associated with, and differences between the 4 swimming strokes. *J. Sports Sci.* 37, 787–794. doi: 10.1080/02640414.2020.1734311

Nugent, F. J., Comyns, T. M., and Warrington, G. D. (2017). Quality vs. quantity debate in swimming: perceptions and training practices of expert swimming coaches. *J. Hum. Kinet.* 57, 147–158. doi: 10.1515/hukin-2017-0056

Ozeker, K. Y., Bilge, M., and Kose, D. S. Y. (2020). The effect of dry-land training on functional strength and swimming performance of 10-12 years old swimmers. *Prog. Nutr.* 22:e2020028. doi: 10.23751/pn.v22i2-S.10615

Phillips, E., Davids, K., Renshaw, I., and Portus, M. (2010). Expert performance in sport and the dynamics of talent development. *Sports Med.* 40, 271–283. doi: 10.2165/11319430-000000000-00000

Poujade, B., Hautier, C., and Rouard, A. (2002). Determinants of the energy cost of front-crawl swimming in children. *Eur. J. Appl. Physiol.* 87, 1–6. doi: 10.1007/s00421-001-0564-2

Poujade, B., Hautier, C. A., and Rouard, A. (2003). Influence de la morphologie, de VO2max et du coût énergetique sur la performance en natation chez de jeunes nageurs. *Sci. Sports.* 18, 182–187. doi: 10.1016/S0765-1597(03)00164-3

Saavedra, J. M., Escalante, Y., Garcia-Hermoso, A., and Dominguez, A. M. (2013). Training volume and performance of young Spanish national and international level swimmers. *S. Afr. J. Res. Sport PH.* 35, 163–172.

Saavedra, J. M., Escalante, Y., and Rodríguez, F. A. (2010). A multivariate analysis of performance in young swimmers. *Pediatr. Exerc. Sci.* 22, 135–151. doi: 10.1123/pes.22.1.135

Sammoud, S., Negra, Y., Bouguezzi, R., Hachana, Y., Granacher, U., and Chaabene, H. (2021). The effects of plyometric jump training on jump and sport-specific performances in prepubertal female swimmers. *J. Exerc. Sci. Fit.* 19, 25–31. doi: 10.1016/j.jesf.2020.07.003

Sammoud, S., Negra, Y., Chaabene, H., Bouguezzi, R., Moran, J., and Granacher, U. (2019). The effects of plyometric jump training on jumping and swimming performances in prepubertal male swimmers. *J. Sports Sci. Med.* 18, 805–811. Available online at: https://www.jssm.org/jssm-18-805.xml%3EFulltext

Sammoud, S., Nevill, A. M., Negra, Y., Bouguezzi, R., Chaabene, H., and Hachana, Y. (2018). 100-m Breaststroke swimming performance in youth swimmers: the predictive value of anthropometrics. *Pediatr. Exerc. Sci.* 30, 393–401. doi: 10.1123/pes.2017-0220

Seffrin, A. D. E., Lira, C. A., Nikolaidis, P. T., Knechtle, B., and Andrade, M. S. (2021). Age-related performance determinants of young swimmers in 100-and 400-m events. *J. Sports Med. Phys. Fitness.* 1205:56. doi: 10.23736/S0022-4707.21.12045-6

Seifert, L., Button, C., and Davids, K. (2013). Key properties of expert movement systems in sport. *Sports Med.*43, 167–178. doi: 10.1007/s40279-012-0011-z

Silva, A., Figueiredo, P., Soares, S., Seifert, L., Vilas-Boas, J. P., and Fernandes, R. J. (2012). Front crawl technical characterization of 11-to 13-year-old swimmers. *Pediatr. Exerc. Sci.* 24, 409–419. doi: 10.1123/pes.24.3.409

Silva, A. F., Figueiredo, P., Seifert, L., Soares, S., Vilas-Boas, J. P., and Fernandes, R. J. (2013). Backstroke technical characterization of 11-13 year-old swimmers. *J. Sports Sci. Med.* 12:623. Available online at: https://www.jssm.org/jssm-12-623.xml%3EFulltext

Staub, I., Zinner, C., Bieder, A., and Vogt, T. (2020a). Within-sport specialisation and entry age as predictors of success among age group swimmers. *Eur. J. Sport Sci.* 20, 1160–1167. doi: 10.1080/17461391.2019.1702107

Staub, I., Zinner, C., Stallman, R. K., and Vogt, T. (2020b). The consistency of performance among age group swimmers over 8 consecutive years. *Ger. J. Exerc. Sport Res.* 50:123–129. doi: 10.1007/s12662-019-00628-8

Tijani, J. M., Zouhal, H., Rhibi, F., Hackney, A. C., Ben Ounis, O., Saidi, K., et al. (2019). Relationship between anthropometry and stroking parameters of front crawl sprint performance in young swimmers. *Medicina dello Sport.* 72, 355–365. doi: 10.23736/S0025-7826.19.03427-6

Toubekis, A. G., Tsami, A. P., and Tokmakidis, S. P. (2006). Critical velocity and lactate threshold in young swimmers. *Int. J. Sports Med.* 27, 117–123. doi: 10.1055/s-2005-837487

Tsalis, G., Toubekis, A. G., Michailidou, D., Gourgoulis, V., Douda, H., and Tokmakidis, S. P. (2012). Physiological responses and stroke-parameter changes during interval swimming in different age-group female swimmers. *J. Strength Cond. Res.* 26, 3312–3319. doi: 10.1519/JSC.0b013e31824e1724

Vaeyens, R., Gullich, A., Warr, C. R., and Philippaerts, R. (2009). Talent identification and promotion programmes of Olympic athletes. *J. Sports Sci.* 27, 1367–1380. doi: 10.1080/02640410903110974

Wiersma, L. D. (2000). Risks and benefits of youth sport specialization: perspectives and recommendations. *Pediatr. Exerc. Sci.* 12, 13–22. doi: 10.1123/pes.12.1.13

Zacca, R., Azevedo, R., Chainok, P., Vilas-Boas, J. P., Castro, F. A. D. S., Pyne, D. B., et al. (2020). Monitoring age-group swimmers over a training macrocycle: energetics, technique, and anthropometrics. *J. Strength Cond. Res.* 34, 818–827. doi: 10.1519/JSC.0000000000002762

Zamparo, P., Capelli, C., Cautero, M., and Di Nino, A. (2000). Energy cost of front-crawl swimming at supra-maximal speeds and underwater torque in young swimmers. *Eur. J. Appl. Physiol.* 83, 487–491. doi: 10.1007/s004210000318

Zamparo, P., Cortesi, M., and Gatta, G. (2020). The energy cost of swimming and its determinants. *Eur. J. Appl. Physiol.* 120, 41–66. doi: 10.1007/s00421-019-04270-y

Zarzeczny, R., Kuberski, M., Deska, A., Zarzeczna, D., and Rydz, K. (2013). The evaluation of critical swimming speed in 12-year-old boys. *Hum. Mov.* 14, 35–40. doi: 10.2478/humo-2013-0002

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ACRONYMS

Anthropometrics
AFG—arm flexed girth
AG—ankle girth
AL—arm length
APHV—age at peak height velocity
ARG—arm relaxed girth
AS—arm span
AS/H—arm span / height index
BA—body area
BF—body fat
Biacr B—biacromial breadth
Biacr B/Biiliac B—biacromial breadth/biiliac breadth index
Biiliac B—biiliac breadth
Bitroch B—bitrochanteric breadth
Biacr B/H—biacromial breadth/height index
BL—body length
BM—body mass
BMM—bone mineral mass
BMI—body mass index
BSA—body surface area
Calf G—calf girth
CC—chest circumference
CG—chest girth
CG/H—chest girth/height index
CP—chest perimeter
EB—elbow breath
FG—forearm girth
ForL—forearm length
FM—whole body fat
FFM—fat free mass
FL—foot length
FSA—frontal surface area
FW—foot width
GG—gluteal girth
GG/H—gluteal girth/height index
H—height
HL—hand length
Hlift—hydrostatic lift
HSA—hand surface area
HW—hand width
KB—knee breadth
LAL—lower arm length
LBM—lean body mass
LG—leg girth
LL—leg length
LLL—lower limb length
PS—propelling size
RH—reach height
SBMD—spine bone mineral density
SH—sitting height
SS—subscapular skinfold
SSS—sum of six skinfolds
S9—sum of nine skinfolds
TBMD—total bone mineral density
TG—thigh girth
TL—thigh length
TLEL—total lower extremity length
TS—triciptal skinfold
TSA—thoracic section area
TTSA—trunk transverse surface area
TUEL—total upper extremity length
TW—trunk width
ULL—upper limb length
UAL—upper arm length
WB—wrist breadth
WG—wrist girth

Biomechanics
AE—arm extension
AFlex—ankle flexibility
AvgPext—average power extension
AvgPflex—average power flexion
AvgPer—average power external shoulder rotation
AvgPir—average power internal shoulder rotation
BE—back extension
BJ—broad jump
BP—bench press
BR—ball range
BT—ball throwing
Bu—buoyancy
C_{DA}—coefficient of active drag
C_{Dp}—coefficient of passive drag
CMJ—countermovement jump
D_a—active drag
D_{aF}—drag factor
D_e—drag efficiency
D_p—passive drag
dv—intra-cyclic variation of the swim speed
dv/v—intra-cyclic variation of the swim speed/swim speed index
EExt—elbow extension
EFlex—elbow flexion
E_{tot}—total power input
F_r—Froude number
Glide—gliding variables
HG—hand grip
HExt—hip extension
HAbd—hip abduction
HJ—horizontal jump
HL—hydrostatic lift
HS—hand slip
IdC—index of coordination
KFE—knee flexion/extension
LE—leg extension
LF_{ext}—left forearm external rotation
LF_{int}—left forearm internal rotation
MF—mean force
MMI—mean mechanical impulse
PC—pronated chin-ups
P_d—power to overcome drag
P_k—mechanical power to transfer kinetic energy to water
P_{ext}—external mechanical power
PText—peak torque extension
PTflex—peak torque flexion

PTer—peak torque external shoulder rotation
PTir—peak torque internal shoulder rotation
R_e—Reynolds number
RF_{ext}—right forearm external rotation
RF_{int}—right forearm internal rotation
SAbd—shoulder abduction
SAdd—scapular adduction
SF—stroke frequency
SFlex—shoulder flexibility
SFlexion—shoulder flexion
SL—stroke length
$SL \cdot pSL^{-1}$—stroke length normalized for anatomical potential stroke length
SLJ—standing long jump
SL/AS—stroke length/arm span index
TDI—technique drag index
v—swim speed
v_h—hull speed
VJ—vertical jump
Vol—body volume
UT—underwater torque
25-m KWP—a 25-m kick without a push
25-m free WP—25-m freestyle without a push
ΔCM-CV—distance between the center of mass and the center of volume
α_{63}—body angle with the water line
Energetics/efficiency
Abd—abdominals test
AnCV—anaerobic critical velocity
AnP—anaerobic power
Bl—blood lactate
Bg—blood glucose
C_s—energy cost of swimming
C_s/SA—energy cost of swimming calculated per unit of surface area
C_s/SA.HL—energy cost of swimming calculated per unit of surface area and hydrostatic lift
CSR—critical stroke rate
CV—critical velocity
FAH—flexed arms hang
FB—flamingo balance
eVO_{2max}—estimated aerobic power
HR—heart rate
HR rest—resting heart rate
MP_{30}—mean power in 30 s
MAV—maximal aerobic velocity
η_F—Froude efficiency
PT—plate tapping
RR sys—resting systolic blood pressure
RR diast—resting diastolic blood pressure
RPE—rate of perceived exertion
SandR—sit and reach
SI—stroke index
SR—shuttle run
SRE—shuttle run endurance
V4—velocity corresponding to a blood lactate concentration of 4 $mmol \cdot l^{-1}$
VO_{2max}—maximal oxygen uptake
VO_{2peak}—peak oxygen uptake
VO_2—oxygen consumption
ΔLa—net increase of blood lactate

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Not Breathing During the Approach Phase Ameliorates Freestyle Turn Performance in Prepubertal Swimmers

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This study compared the effects of two breathing conditions during the freestyle turn approach phase in swimmers. Thirty-four prepubertal swimmers (mean ± SD: 10.59 ± 0.97 years) were divided into two groups: No Breath (NB), not breathing at the last stroke, and Breath Stroke (BS). Swimmers performed three turns with 5 min of rest between the repetitions. Kinematic parameters were recorded with two underwater and two surface cameras. Total turn time (NB: 9.31 ± 1.34 s; BS: 10.31 ± 1.80 s; $p = 0.049$), swim-in time (NB: 3.89 ± 0.63 s; BS 4.50 ± 0.79 s; $p = 0.02$) and rotation time (NB: 2.42 ± 0.29 s; BS: 3.03 ± 0.41 s; $p = 0.0001$) were significantly shorter and swim-in distance [NB: 0.70 (0.58,0.77) m; BS: 0.47 (0.34,0.55) m; $p = 0.0001$], glide distance (NB: 1.06 ± 0.21 m; BS: 0.70 ± 0.20 m; $p = 0.0001$) and surfacing distance [NB: 1.79 (1.19,2.24) m; BS: 1.18 (0.82,1.79) m; $p = 0.043$] were significantly longer in NB than in BS. Moreover, speed-in (NB: 1.04 ± 0.14 m/s; BS: 0.93 ± 0.14 m/s; $p = 0.031$) and push-off speed (NB: 2.52 ± 0.30 m/s; BS: 1.23 ± 0.20 m/s; $p = 0.001$) were significantly higher in NB than in BS. Swim-in time was positively and negatively correlated with rotation time and glide distance, respectively, whilst negative relationships between total turn time and swim-in distance, total turn time and surfacing distance and total turn time and speed-in were found. Our study showed that in prepubertal swimmers not breathing at the last stroke during the approach phase positively affected kinematic parameters of the turn, allowing to approach the wall faster, rotate the body quicker, increase push-off speed, reduce turn execution time, thus improving overall turn performance.

Keywords: swimming performance, freestyle turn, kinematic parameters, video analysis, prepubertal swimmers

INTRODUCTION

The swim race consists of start, clean swimming (or swim stroke), turns and finish. Previous studies showed that in freestyle races swimmers spend from ≈20 to ≈37% of total race time in executing swimming turns in 100 and 1,500 m races, respectively (Morais et al., 2019, 2020). The high relevance of turn outcome in swimming performances suggests that coaches and swimmers should dedicate a significant portion of the training to perfect this action.

During the turn, swimmers must reverse the direction of the body in the shortest time and regain the speed in the opposite direction (Blanksby et al., 1996). The tumble turn, also known as freestyle turn, involves different phases: the approach to the wall, the turn or rotation to reorient the body in preparation for swimming the next lap (tumble), the push-off or wall-contact, the glide, the underwater propulsion and the stroke resumption (Puel et al., 2012; Weimar et al., 2019).

A successful turn performance depends on a number of kinematic parameters within these different phases. Considering that the turn outcome significantly contributes to overall swimming performance (Morais et al., 2019, 2020), it is of great importance to identify what variables can enhance turning skill.

Scientific literature reported a number of studies examining the different phases of the turn and their most characterizing parameters, such as rotation time during the tumble (Rejman and Borowska, 2008), peak force and wall contact time during the push-off (Araujo et al., 2010; Nicol et al., 2019; Weimar et al., 2019) and velocity and displacement covered during the gliding phase (Zamparo et al., 2012; Marinho et al., 2020). However, to the best of our knowledge, most of these studies involved elite swimmers, whereas only limited information is available on turn performance in young swimmers. A previous study demonstrated that in young swimmers a greater head-wall distance at rotation was associated with fastest turns, showing a negative relationship during the approach phase between this parameter (defined the swim-in distance) and total turn time (Blanksby et al., 1996). The approach to the wall is the first phase of the freestyle turn and, during this phase, swimmers must proceed towards the wall at high speed, in order to have a strong push in the next wall-contact phase. More recently, Puel et al. (2012) confirmed, in elite swimmers, the importance of a longer head-wall distance at rotation during the approach to the wall.

In the early stages of training, coaches usually start the teaching the freestyle turn, learning the different phases separately and offering children more strategies and exercises to increase their motor skill level (Federazione Italiana Nuoto, 2014). For example, while learning the approach to the wall, coaches usually show prepubertal swimmers different breathing exercises to identify the most effective breathing technique to adopt before turning (Federazione Italiana Nuoto, 2014). Nevertheless, no studies investigated in young swimmers whether different breathing conditions significantly affect turn performance. This aspect could be particularly relevant during the developmental years, in which young swimmers must build and consolidate a specific and detailed motor pattern of the turn.

TABLE 1 | Participants' characteristics of No Breath (NB) and Breath Stroke (BS) groups.

	NB group ($n = 17$)	BS group ($n = 17$)
Age (years) (min, max)	10.60 ± 1.06 (9, 13)	10.59 ± 0.94 (9, 12)
Sex (M, F)	8 M, 9 F	9 M, 8 F
Swimming Experience (years)	5.67 ± 1.59	5.59 ± 2.03
Hours/ Week (h/wk)	8.40 ± 2.92	7.56 ± 2.65
Height (m)	1.43 ± 0.07	1.43 ± 0.08
Body Mass (kg)	34.17 ± 4.41	35.41 ± 5.69
BMI (kg/m^2)	16.78 ± 1.65	17.15 ± 1.64
Right arm (m)	0.48 ± 0.03	0.48 ± 0.04
Right arm+hand (m)	0.64 ± 0.04	0.64 ± 0.05
Left arm (m)	0.48 ± 0.03	0.48 ± 0.04
Left arm+hand (m)	0.64 ± 0.04	0.63 ± 0.05
Right leg (m)	0.81 ± 0.06	0.81 ± 0.06
Left leg (m)	0.81 ± 0.06	0.81 ± 0.06
Right foot (m)	0.22 ± 0.01	0.22 ± 0.02
Left foot (m)	0.22 ± 0.02	0.22 ± 0.03
50 m time (s)	41.5 (37.5, 47.6)	42.97 (39.4, 48.9)

Data are reported as mean ± SD values in case of normal distribution or median (interquartile interval) values in case of not-normal distribution.

Hence, to this aim, we examined in prepubertal swimmers with a similar swimming experience the effects induced by two different breathing techniques (not breathing at the last stroke vs. breathing at the last stroke) on selected kinematic features of freestyle turn phases and on turn performance. We hypothesized that not breathing at the last stroke during the approach to the wall could positively influence the turning performance, that in turn represents an important component in overall swimming performance.

MATERIALS AND METHODS

Participants

Thirty-four prepubertal swimmers (17 males and 17 females), with at least 6 h/week of training volume and 5 years of swimming experience, were recruited. Participants were divided into two groups, on the basis of the preferred breathing technique at the last stroke before turning: No Breath (NB) and Breath Stroke (BS). In the NB group ($n = 17$), prepubertal swimmers did not breathe at the last stroke during the approach phase, while in the BS group ($n = 17$) participants breathed. Two out 17 of participants of the NB group did not complete the experimental protocol. No significant differences between groups concerning age, gender, years of swimming practice, anthropometric measures and 50 m swim time were found (**Table 1**).

Before entering the study, prepubertal swimmers' parents were fully informed about the study aims and procedures. Participants and their legal guardians provided written informed consent. The experimental protocol was conformed to the code of Ethics of the World Medical Association (Declaration of Helsinki). The local ethics committee of the University of Genoa approved the study (Comitato Etico per la Ricerca di Ateneo, Genoa, Italy, No. 2020/21).

Sample Size

Estimation of sample size was performed using the GPower software (3.1 software Düsseldorf, Germany) applying an a-priori two-sided power analysis. This calculation generated a desired sample size of at least 15 subjects for each group. However, we recruited 34 participants, 17 in the NB group and 17 in the BS group, to allow for drop-out during the intervention period (Faul et al., 2007).

Experimental Design

Before the experimental protocol, tape markers, allowing the tracking of relocation of different segments of the body, were applied to the participants. Markers were located on both sides of the body on the head, shoulders, elbows, wrists, hips, knees and ankles of each swimmer. The experimental protocol was performed in a 25 m pool. Prior to the testing trials, swimmers warmed up with a 600 m swim including preparatory exercises for the experimental test, then they performed three freestyle turns as fast as possible, with 5 min of rest between the repetitions.

Video Analysis Setting

A 2D video analysis was performed using Kinovea software 0.8.15 (Copyright © 2006–2011, Joan Charmant & Contrib). Each trial was recorded by four cameras (two underwater and two surface-fixed) (GoPro® HERO5, 60Hz) at 120 fps and with a resolution of 720 pixel. The two underwater cameras were positioned with the suction cup on a Plexiglas panel fixed to the lateral wall of the swimming pool. Both cameras were located at a depth of 0.36 m, at a distance of 0.6 m and 2.10 m from the turning wall, respectively (**Figure 1A**).

In order to obtain a frontal view of the swimmer, a third surface camera was placed on the board of the swimming pool, to a height of 0.30 m from the edge and with a downward inclination of 45°. The fourth surface camera was positioned above the lateral wall of the pool, on a ladder situated at a distance of 1.31 m from the turning wall and at a height of 1.87 m from the floor (**Figure 1B**). A distance of 5 m from the swimming pool wall was assumed as the turn distance (Blanksby et al., 1996; Rejman and Borowska, 2008). Moreover, a black rubber band on the rope in the pool lane, 5 m away from the turning wall, was fixed in water, as a reference point for the video analysis of the selected kinematic variables.

Outcome Measures

The video analysis was carried out by a researcher blinded to the aim of the study.

Temporal, distance and speed parameters of the freestyle turn phases were chosen for the performance analysis (**Figure 1C**). Parameters' specification and description (Rejman and Borowska, 2008; Puel et al., 2012) are reported in **Table 2**. Data used in the statistical analysis correspond to the average data over the three turn repetitions and to their coefficient of variability (CV).

Statistical Analysis

The distribution of the outcome parameters was tested by means of Shapiro-Wilk test. Total turn time (s), swim-in time (s), rotation time (s), wall-contact time (s), glide distance (m), speed-in ($m\cdot s^{-1}$), speed-out ($m\cdot s^{-1}$), push-off speed ($m\cdot s^{-1}$) and push-off angle (°) were normally distributed, whilst swim-in distance (m) and surfacing distance (m) were not normally distributed. All CV values were not normally distributed.

The comparison between NB and BS groups was performed by means of independent *t*-tests in case of normally-distributed data, and Mann-Whitney test in case of not normally-distributed data. The analyses were performed using IBM SPSS STATISTIC, version 20 for Windows. The level of significance was set at $p = 0.05$. In this study, kinematic parameters are reported as mean value ± standard error associated with Hedges's index (*g*)—a measure of effect size (Tomczak and Tomczak, 2014), in case of normal distribution, and median value (interquartile interval) associated with the eta squareη^2–a measure of effect size (Tomczak and Tomczak, 2014), when not normally distributed. CV values, computed for each variable as standard deviation/mean*100, are reported as means values and 95% CI.

Pearson's correlations were applied to evaluate the relationship between swim-in time and rotation time, swim-in time and glide distance, and speed-in and total turn time. Spearman's correlation was used to check for relationships between the total turn time and the swim-in distance, and the total turn time and the surfacing distance. Correlations were evaluated considering data from both groups pooled together, and considering data from the two groups separately. Bonferroni's correction for multiple comparisons was applied. For this reason, the significance level was set at $p = 0.05/2 = 0.025$.

RESULTS

Kinematic Parameters

The statistical analyses showed that total turn time was significantly lower in NB group (9.31 ± 1.34 s) than in BS group (10.31 ± 1.80 s) [$t_{(30)} = 29.89$, $p = 0.049$, $g = 0.58$], as well as the swim-in time [NB group 3.89 ± 0.63 s; BS group 4.50 ± 0.79 s; $t_{(30)} = -2.41$, $p = 0.02$, $g = 0.85$], whereas the swim-in distance was significantly higher in the NB group [0.70 (0.58, 0.77) m] than in the BS group [(0.47 (0.34, 0.55) m] ($Z = -3.69$, $p = 0.0001$, $\eta^2 = 0.424$). Rotation time was found to be significantly lower in NB (2.42 ± 0.29 s) than in BS (3.03 ± 0.41 s) group [$t_{(30)} = -4.76$, $p = 0.0001$, $g = 1.69$]. No difference appeared between the two groups in wall-contact time [NB group 0.57 ± 0.26 s; BS group 0.70 ± 0.25 s; $t_{(30)} = -1.38$, $p = 0.18$, $g = 0.49$]. Glide distance was significantly higher in NB group (1.06 ± 0.21 m) than in BS group (0.70 ± 0.20 m) [$t_{(30)} = 4.06$, $p = 0.0001$, $g = 1.44$] as well as the surfacing distance [NB group 1.79 (1.19, 2.24) m; BS group 1.18 (0.82, 1.79); $Z = -2.02$, $p = 0.043$, $\eta^2 = 0.128$]. Speed-in was significantly higher in NB (1.04 ± 0.14 m/s) than in BS group (0.93 ± 0.14 m/s) [$t_{(30)} = 2.26$, $p = 0.031$, $g = 0.80$], whilst no significant difference was found in speed-out [NB group 1.30 ± 0.19 m/s; BS group 1.23 ± 0.20 m/s; $t_{(30)} = 1.07$, $p = 0.3$, $g = 0.38$]. Finally, push-off speed was significantly higher in NB (2.52 ± 0.30 m/s) than in BS (2.14 ± 0.30 m/s) group [$t_{(30)}$

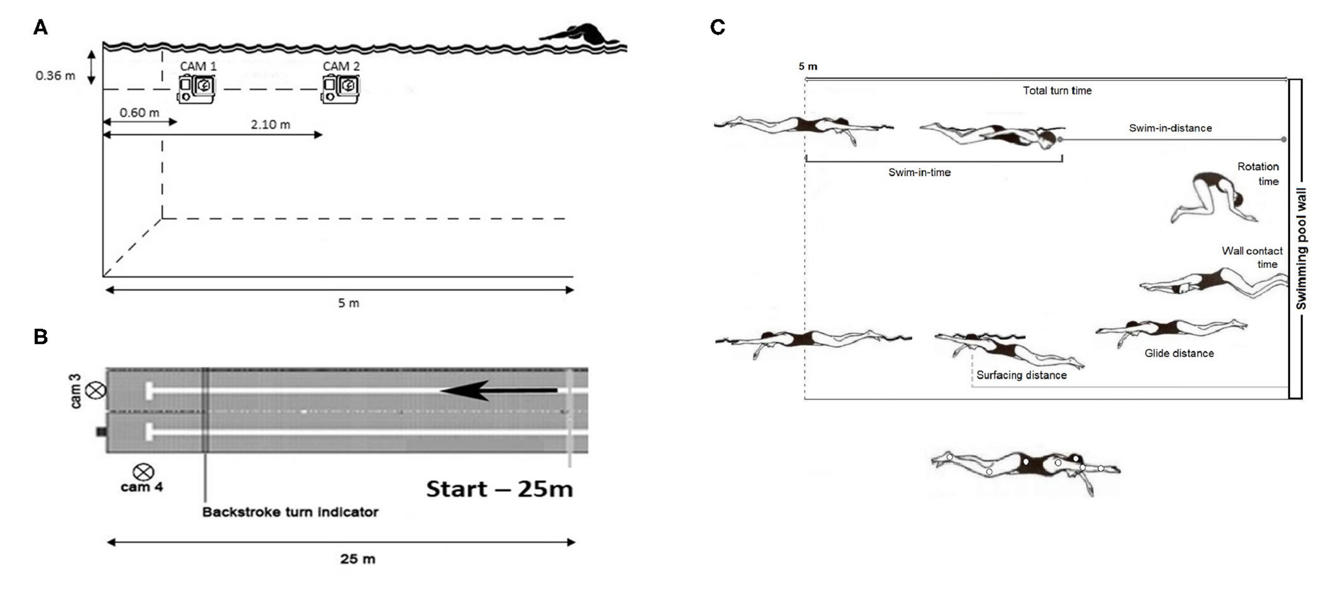

FIGURE 1 | Position of the two underwater cameras **(A)** and of the two surface cameras **(B)**; outcome variables and markers position **(C)** for video analysis.

TABLE 2 | Parameters' specification and description and reference markers.

Parameters		Definitions
Time	Total turn time (s)	Time period from the moment when the hip joints pass through the point placed 5 m from the wall before turning, till the moment when the hip joints pass through the point placed 5 m from the wall after turning. Reference marker: hip.
	Swim-in time (s)	Time period from the moment when the hip joints pass through the point placed 5 m from the wall before turning, till the moment of the turning initiation (downward movement of the head). Reference markers: hip, head.
	Rotation time (s)	Time period from the moment of the turning initiation, till the moment when the turning is finished (first moment of the feet contact with the wall). Reference markers: wrist and ankle.
	Wall contact time (s)	Time period from the first feet contact with the wall, till the moment when the feet lost contact with the wall. Reference marker: ankle.
Distance	Swim-in distance (m)	Head to wall distance at the start of the rotation. Reference marker: head.
	Glide distance (m)	Distance of the hip joints displacement between the moment when the feet lost contact with the wall and the moment of the first propulsive movement initiation. Reference marker: hip.
	Surfacing distance (m)	Distance of the hip joints displacement between the moment when feet lost contact with the wall, and the moment of the surfacing. Reference marker: hip.
Speed	Speed-in (m·s^{-1})	Average speed from when the hip is 5 m from the wall to the first contact of the feet to the wall. Reference marker: hip.
	Speed-out (m·s^{-1})	Average speed since the last contact of the feet to the wall up to 5 m. Reference marker: hip.
	Push-off speed (m·s^{-1})	Speed at the end of push-off calculated at hip joints. Reference marker: hip.
Angle	Push-off angle (°)	Angle described by the markers positioned on the head, hip and ankle at the instant of push-off.

$= 3.53$, $p = 0.001$, $g = 1.25$], whilst no significant difference was present between groups in push-off angles, although the values of NB groups were closer to 180° than those of BS group [NB group 176 ± 7.27°; BS group 170 ± 12.56°; $t_{(30)} = 1.51$, $p = 0.13$, $g = 0.62$].

The analyses on CV values of all the previously mentioned parameters did not find any significant differences among groups. CV values are reported afterwards. CV Total turn time: NB 1.67 (1.21, 2.12) and BS 1.35 (0.87, 1.83) ($Z = -1.21$, $p = 0.23$,$\eta^2 = 0.046$); CV Swim-in time: NB 3.53 (2.49, 4.58) and BS 3.29 (2.37, 4.22) ($Z = -0.31$, $p = 0.76$,$\eta^2 = 0.003$); CV Rotation time NB: 5.87 (4.29, 7.45) and BS 4.82 (3.20, 6.45) ($Z = -1.33$, $p = 0.18$,$\eta^2 = 0.056$); CV Wall-contact time: NB 10.07 (6.83, 13.30) and BS 9.88 (6.17, 13.60) ($Z = -0.53$, $p = 0.60$,$\eta^2 = 0.009$); CV Swim-in distance: NB 12.67 (9.00, 16.33) and BS 16.06 (11.11, 21.021) ($Z = -0.78$, $p = 0.44$,$\eta^2 = 0.019$); CV Glide distance: NB 12.00 (8.94, 15.06) and BS 13.59 (8.64, 18.54) ($Z = 0.00$, $p = 1$,$\eta^2 = 0.00$); CV Surfacing distance: NB 6.53 (4.59, 8.47) and BS 7.00 (4.29, 9.71) ($Z = -0.11$, $p = 0.91$,$\eta^2 = 0.00$); CV Speed-in: NB 6.60 (5.28, 7.92) and BS 0.06 (0.04, 0.09) ($Z = -0.48$, $p = 0.63$,$\eta^2 = 0.007$);

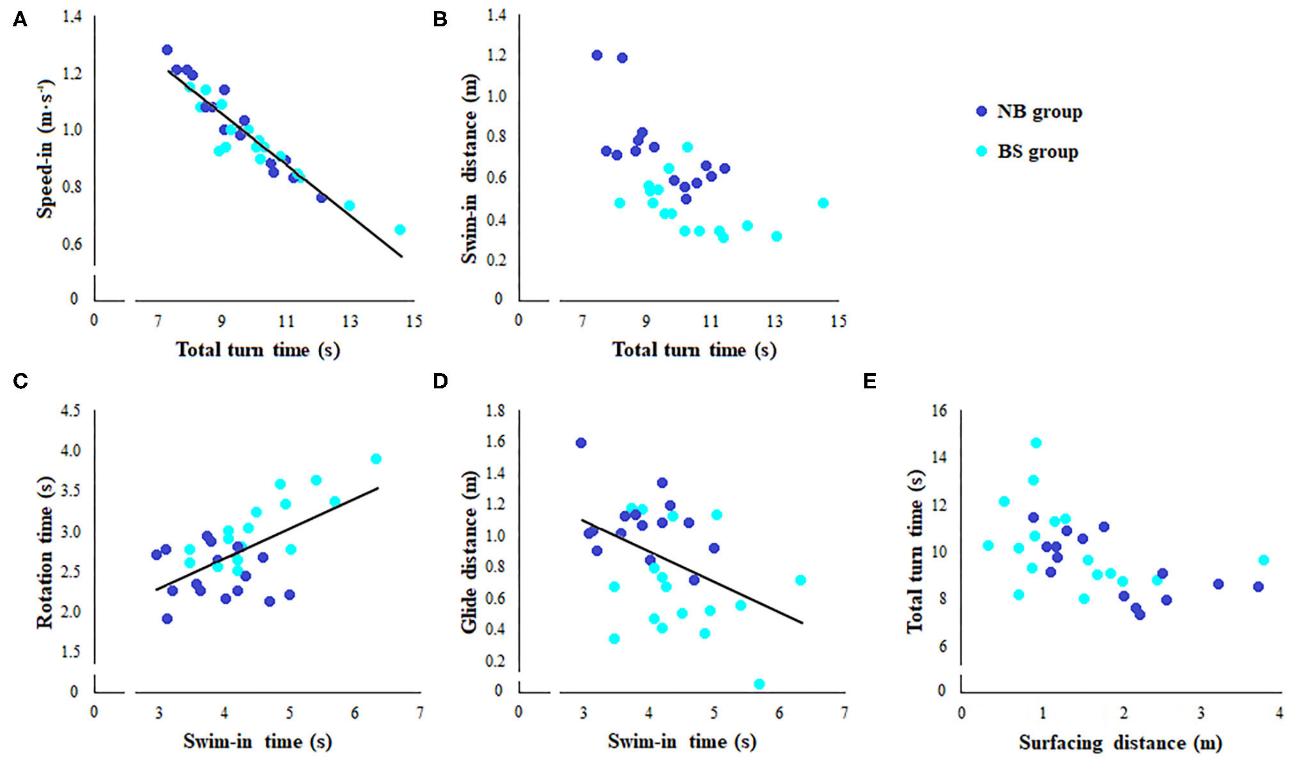

FIGURE 2 | Relationships between kinematic parameters of the different turn phases for No Breath (NB—dark blue circles) and Breath Stroke (BS—light blue circles) groups' data. Each circle represents a single subject. When present, the line refers to linear regression analysis computed on the data of the two groups pooled together. **(A)** Speed-in vs. total turn time; **(B)** swim-in distance vs. total turn time; **(C)** rotation time vs. swim-in time; **(D)** glide distance vs. swim-in time; **(E)** surfacing distance vs. total turn time.

CV Speed-out: NB 5.07 (3.82, 6.31) and BS 6.35 (4.96, 7.75) ($Z = -0.28$, $p = 0.78, \eta^2 = 0.003$); CV Push-off speed: NB 4.13 (3.17, 5.09) and BS 5.29 (4.21, 6.38) ($Z = -1.72$, $p = 0.09, \eta^2 = 0.092$).

Correlation Analysis

When considering the data from the two groups pooled together, significant negative relationships appeared between total turn time and surfacing distance ($R = -0.66$, $p = 0.0003$), and total turn time and swim-in distance ($R = -0.59$, $p = 0.0006$). Furthermore, a significant positive relationship was found between swim-in time and rotation time ($R = 0.62$, $p = 0.0002$). At last, significant negative relationships were observed between swim-in time and glide distance ($R = -0.44$, $p = 0.01$), and between speed-in and total turn time ($R = -0.94$, $p = 0.0002$) (**Figure 2**).

The correlation analysis performed separately on each group showed that the significant negative relationship between surfacing distance and total turn time was present in NB ($R = -0.73$, $p = 0.002$), whilst a trend towards the significance appeared in BS ($R = -0.46$, $p = 0.07$). The significant negative relationship between the total turn time and swim-in distance was observed for both groups (NB: $R = -0.69$, $p = 0.004$, BS: $R = -0.60$, $p = 0.012$). The significant positive relationship between swim-in time and rotation time was present only in BS group ($R = 0.81$, $p = 0.0003$). No significant relationship appeared between swim-in time and glide distance when considering the two groups separately. Finally, significant negative relationships were found in both groups between speed-in and total turn time (NB: $R = -0.98$, $p = 0.0004$, BS: $R = -0.92$, $p = 0.0005$).

DISCUSSION

The present study compared, for the first time, in prepubertal swimmers two breathing techniques (not breathing vs. breathing at the last stroke) during the freestyle turn approach phase, to investigate their possible effects both on kinematic parameters of the next turn phases and on overall turn performance.

According to a previous study (Blanksby et al., 1996), we adopted the total turn time over 5 m as turn performance test, since we considered that using the 50 m time could have masked some aspects of the turn technique, as 50 m swimming time includes some advantages from the first few meters at the start but also some negative effects related to fatigue over the final few meters (Blanksby et al., 1996).

In this study we demonstrated that in prepubertal swimmers not breathing at the last stroke during the approach phase induced positive effects on the kinematic parameters of the subsequent turn phases, thus improving the freestyle turn execution time. Freestyle turn involves a complex turning action that includes a main rotation around the transverse axis and on the sagittal plane, combined or not with a rotation around the other axis, especially the longitudinal one (Vilas-Boas and Fernandez, 2003), and it is typically divided into several phases. During the initial learning stages, young swimmers must achieve a motor competence for turn techniques (Federazione Italiana Nuoto, 2014), and errors within a single phase could affect kinematic parameters of the other turn phases, thus impairing turn performance (Hines, 2008).

Effects on Kinematic Parameters of the Approach Phase

During the approach phase, the NB group showed a significantly higher speed-in value compared with the BS group, suggesting that not breathing at the last stroke allowed swimmers to maintain the head and the whole body in a hydrodynamic position without breaking the approach to the wall and therefore not losing speed during this phase.

In addition, the NB group showed a significantly higher swim-in distance with a significantly shorter rotation time and a swim-in time compared with the BS group, demonstrating that not breathing at the last stroke allows prepubertal swimmers to start the rotation farther away from the wall, thus reducing the turn time, as previously observed in young (Blanksby et al., 1996) and elite swimmers (Puel et al., 2012). This probably happened since all body segments turned simultaneously: the head did not move in advance with respect to the body, and feet, hips, shoulders and head were aligned during the contact of the feet with the wall, resulting in an advantageous position for the subsequent push-off phase. Indeed, the mean value of the push-off angle of the NB group was closer to 180° than that of the BS group, suggesting that head, hips and feet of swimmers not breathing at the last stroke were more aligned than the others. However, the analysis on the push-off angle did not reveal a significant difference between groups, but this aspect could be probably linked to the high variability of the BS group.

Moreover, the time needed to rotate the head and breathe would explain the higher distance covered by the athletes of the BS group and, therefore, their shorter swim-in distance.

Effects on Kinematic Parameters of the Push-Off Phase

The push-off speed value of the NB group was significantly higher than in the BS group, showing that swimmers who did not breathe at the last stroke were able to maintain high speed values not only in the approach phase but also in the subsequent phases.

Effects on Kinematic Parameters of the Underwater Phase

Our results suggest that not breathing at the last stroke during the approach phase can positively influence the kinematic variables of the underwater phase. In fact, under our experimental condition, the NB group showed significantly higher glide distance and surfacing distance values compared to the BS group, thus proving both a better sliding immediately after the push from the wall and a longer underwater displacement to the resurfacing point.

Mean glide and surfacing distances were shorter than those found by Blanksby et al. (1996) in prepubertal swimmers. These differences can be attributed partially to the different anthropometric characteristics of the subjects recruited in each study, to measurement techniques and to skill level of the swimmers, from which the conscious decision of choosing the point at which to resume stroking depends (Blanksby et al., 1996).

Previous literature supported the importance of the underwater phase demonstrating how the lengthening of this phase is crucial in reducing total turn time (Blanksby et al., 1996, 1998; Cossor and BR, 2001). Underwater distance has also been shown to be affected by the athlete's ability to maintain a streamlined position during the underwater phase, proving inexperienced swimmers less proficient at streamlining than elite ones (Blanksby et al., 1996; Nicol et al., 2019). Our data indicate that an increased speed off the wall enabled NB to hold the glide further and to resume swimming later than BS. However, the speed-out between the two groups was not statistically different. It has been shown that a significant negative correlation exists between the surfacing distance and the swim resumption speed, i.e., the speed-off (Blanksby et al., 1996). Swimmers who glide too long after push-off will decelerate to less than their average swimming speed. On the whole, this observation suggests that prepubertal swimmers might have less experience in feeling the best point at which to resume swimming after the turn, thus failing to maximise the propulsive force from the wall, losing some of the push-off benefits.

Effects on Total Turn Time

As a result of all these significant changes shown in kinematic parameters of the different phases of the turn, total turn execution time in the NB group was reduced. Successful performance in short-course races has been shown to depend on the effectiveness of the turn execution time (Slawson et al., 2010; Webster et al., 2011; Chakravorti et al., 2012). In the present work, the total turn time over 5 m was chosen as a benchmark for analysing turn performance, as all fundamental aspects of the turn technique are incorporated within this distance (Blanksby et al., 1996). Our results showed that the decrease in execution times and the higher speeds during the approach and tumble phases, together with the longer underwater displacement following the non-breathing condition, reduced the total turn time.

It is noteworthy that, as the subjects recruited in this study had similar swimming skills and experience, the improvement in turn execution time can be attributed to the specific breathing feature adopted during the approach phase.

Correlation Analysis

The correlation analysis showed a negative relationship between total turn time and either speed-in or swim-in distance. This suggests that a faster approach to the wall and a rotation of the body farther away from the wall, reduced turn execution time. At the same time, the significant positive relationship between swim-in time and rotation time, and the negative relationship between swim-in time and glide distance suggest that a shorter time of approach to the wall allows a quicker rotation and a longer slide during the underwater phase. Finally, surfacing distance showed a negative correlation with total turn time. This observation is in agreement with a recent study that showed that longer underwater distances were associated with faster turns, confirming the importance of this variable as one of the best predictors of turn performance (Nicol et al., 2019).

In conclusion, in prepubertal swimmers not breathing at the last stroke during the approach phase positively affected the kinematic parameters of the turn, allowing a faster approach to the wall, a quicker rotation of the body, an increased push-off speed, and a shorter turn time, thus improving overall turn performance.

Nevertheless, some limitations are worth noting. First of all, future studies could adopt a crossover design, to confirm results while changing experimental conditions for each participant. Moreover, each subject performed experimental tests on the same day. Future works should repeat tests for each subject on different days, to rule out the possibility that day-to-day variation in physical fitness and performance influences the results. Moreover, further studies are needed to investigate what race distances can benefit the most from this breathing condition during the freestyle turn.

The results of the present study offer useful information and important practical applications for coaches in order to analyse turn kinematic parameters that most characterized turn performance in prepubertal swimmers. In particular, coaches should take into account that not breathing at the last stroke during the approach phase before turning allows their prepubertal swimmers to reduce the turn execution time. This aspect could be particularly relevant in short-course races (i.e., 50–100 m), where turn technique is crucial for the success of the competition. Another important practical application deriving from this study is the low-cost equipment used in the experimental design, easily applicable to all swimming pool contexts. It would be advisable, in the future, to encourage the implement of video analysis as a monitoring tool during training to give coaches detailed information on their swimmers' skill 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 Comitato Etico per la Ricerca di Ateneo, Genoa, Italy, No. 2020/21. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

AUTHOR CONTRIBUTIONS

EF and MB contributed conception and design of the study and critically discussed the results. LS, SO, and LP performed the experimental study. AB, MP, and CL organized the database and performed the data analysis. EF and AB wrote the first draft of the manuscript. VF and PR wrote sections of the manuscript. All authors contributed to manuscript revision, read, and approved the submitted version.

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REFERENCES

Araujo, L., Pereira, S., Gatti, R., Freitas, E., Jacomel, G., Roesler, H., et al. (2010). Analysis of the lateral push-off in the freestyle flip turn. *J. Sports Sci.* 18, 1175–1181. doi: 10.1080/02640414.2010.485207

Blanksby, B., Gathercole, D., and Marshall, R. (1996). Force plate and video analysis of the tumble turn by age group swimmers. *J. Swim. Res.* 11, 40–45.

Blanksby, B., Simpson, J., Elliott, B., and McElroy, K. (1998). Biomechanical factors influencing breaststroke turns by age-group swimmers. *J. Appl. Biomech.* 14, 180–189. doi: 10.1123/jab.14.2.180

Chakravorti, N., Slawson, S. E., Cossor, J., Conway, P. P., and West, A. A. (2012). Swimming turn technique optimisation by real-time measurement of foot pressure and position. *Proc. Eng.* 34, 586–591. doi: 10.1016/j.proeng.2012.04.100

Cossor, J., and BR, M. (2001). "Swim start performances at the Sydney 2000 Olympic games," in *Biomechanics Symposia/University of San Francisco*, 70–74.

Faul, F., Erdfelder, E., Lang, A. G., and Buchner, A. (2007). A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behav. Res. Methods* 39, 175–191. doi: 10.3758/BF03193146

Federazione Italiana Nuoto (2014). *Dispense corsi, allievi istruttori, istruttore base.* ed. F. I. Nuoto.

Hines, E. (2008). *Fitness Swimming. 2nd ed.*, eds B. Volckening and G. Mills Champaign, IL: Human Kinetics.

Marinho, D. A., Barbosa, T. M., Neiva, H. P., Silva, A. J., and Morais, J. E. (2020). Comparison of the start, turn and finish performance of elite swimmers in 100 m and 200 m races. *J. Sport. Sci. Med.* 19, 397–407.

Morais, J. E., Barbosa, T. M., Forte, P., Bragada, J. A., Castro, F. A. D. S., and Marinho, D. A (2020). Stability analysis and prediction of pacing in elite 1500 m freestyle male swimmers. *Sport. Biomech.* 2020, 1–18. doi: 10.1080/14763141.2020.1810749

Morais, J. E., Marinho, D. A., Arellano, R., and Barbosa, T. M. (2019). Start and turn performances of elite sprinters at the 2016 European Championships in swimming. *Sport. Biomech.* 18, 100–114. doi: 10.1080/14763141.2018.1435713

Nicol, E., Ball, K., and Tor, E. (2019). The biomechanics of freestyle and butterfly turn technique in elite swimmers. *Sport. Biomech.* 20, 444–457. doi: 10.1080/14763141.2018.1561930

Puel, F., Morlier, J., Avalos, M., Mesnard, M., Cid, M., and Hellard, P. (2012). 3D kinematic and dynamic analysis of the front crawl tumble turn in elite male swimmers. *J. Biomech.* 45, 510–515. doi: 10.1016/j.jbiomech.2011.11.043

Rejman, R., and Borowska, G. (2008). Searching for criteria in evaluating the monofin swimming turn from the perspective of coaching and improving technique. *J. Sport. Sci. Med.* 7, 67–77.

Slawson, S., Conway, P., Justham, L., Le Sage, T., and West, A. (2010). Dynamic signature for tumble turn performance in swimming. *Proc. Eng.* 2, 3391–3396. doi: 10.1016/j.proeng.2010.04.163

Tomczak, M., and Tomczak, E. (2014). The need to report effect size estimates revisited. An overview of some recommended measures of effect size Language and cognition: L2 influence on conceptualization of motion and event construal. View project. *TRENDS Sport Sci.* 1, 19–25.

Vilas-Boas, J., and Fernandez, R. (2003). "Swimming starts and turns: Determinant factors of swimming performance," in *Actes des 3èmes Journées Spécialisées de Natation.*, eds. P. Pelayo and M. Sidney (Lille: Univeristé de Lille), 84–95.

Webster, J., West, A., Conway, P., and Cain, M. (2011). Development of a pressure sensor for swimming turns. *Proc. Eng.* 13, 126–132. doi: 10.1016/j.proeng.2011.05.062

Weimar, W., Sumner, A., Romer, B., Fox, J., Rehm, J., Decoux, B., et al. (2019). Kinetic analysis of swimming flip-turn push-off techniques. *Sports* 7:32. doi: 10.3390/sports7020032

Zamparo, P., Vicentini, M., Scattolini, A., Rigamonti, M., and Bonifazi, M. (2012). The contribution of underwater kicking efficiency in determining "turning performance" in front crawl swimming. *J. Sports Med. Phys. Fitness* 52, 457–464.

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Swimming Phase-Based Performance Evaluation Using a Single IMU in Main Swimming Techniques

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Comprehensive monitoring of performance is essential for swimmers and swimming coaches to optimize the training. Regardless of the swimming technique, the swimmer passes various swimming phases from wall to wall, including a dive into the water or wall push-off, then glide and strokes preparation and finally, swimming up to the turn. The coach focuses on improving the performance of the swimmer in each of these phases. The purpose of this study was to assess the potential of using a sacrum-worn inertial measurement unit (IMU) for performance evaluation in each swimming phase (wall push-off, glide, stroke preparation and swimming) of elite swimmers in four main swimming techniques (i.e. front crawl, breaststroke, butterfly and backstroke). Nineteen swimmers were asked to wear a sacrum IMU and swim four one-way 25 m trials in each technique, attached to a tethered speedometer and filmed by cameras in the whole lap as reference systems. Based on the literature, several goal metrics were extracted from the instantaneous velocity (e.g. average velocity per stroke cycle) and displacement (e.g. time to reach 15 m from the wall) data from a tethered speedometer for the swimming phases, each one representing the goodness of swimmer's performance. Following a novel approach, that starts from swimming bout detection and continues until detecting the swimming phases, the IMU kinematic variables in each swimming phase were extracted. The highly associated variables with the corresponding goal metrics were detected by LASSO (least absolute shrinkage and selection operator) variable selection and used for estimating the goal metrics with a linear regression model. The selected kinematic variables were relevant to the motion characteristics of each phase (e.g. selection of propulsion-related variables in wall push-off phase), providing more interpretability to the model. The estimation reached a determination coefficient (R^2) value more than 0.75 and a relative RMSE less than 10% for most goal metrics in all swimming techniques. The results show that a single sacrum IMU can provide a wide range of performance-related swimming kinematic variables, useful for performance evaluation in four main swimming techniques.

Keywords: sports biomechanics, wearable sensor, swimming, performance evaluation, variable selection

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INTRODUCTION

Swimming coaches seek comprehensive monitoring of performance to develop and refine a competition model for their top athletes. During a competition, the swimmer goes through several swimming phases from wall to wall, including a dive into the water or wall push-off, then glide and strokes preparation and finally swimming up to the turn at the end of the lap and repeating the same sequence in the next lap. Therefore, to have a comprehensive performance evaluation, studies have focused on various swimming phases, since the swimmers aim to master all of them (Mooney et al., 2016). As the principal goal of a swimmer is to reduce the swimming time by increasing the velocity, performance evaluation goal metrics in different phases are based on time records and velocity. Flight distance (Ruschel et al., 2007), time to 15 m (Vantorre et al., 2010), average velocity per stroke (Dadashi et al., 2015), swimming phase average velocity (Mason and Cossor, 2000), turn time (5 m before to 10 m after the wall) (Mooney et al., 2016) or lap time are examples of common goal metrics.

Recently, wearable IMUs (inertial measurement unit) have been used more for swimming motion analysis in all competitive swimming techniques (Guignard et al., 2017b), because of the challenges of video-based systems application in aquatic environments (Callaway et al., 2010). They are used in a multitude of studies for variable extraction in various swimming phases, such as start (Vantorre et al., 2014), swimming (Davey et al., 2008), and turn (Slawson et al., 2012). Novel orientation analysis algorithms made it possible to estimate the 3-dimensional orientation of IMU with high accuracy by fusing accelerometer, gyroscope and magnetometer data (Madgwick et al., 2011). This approach is implemented in swimming for inter-segmental coordination assessment (Guignard et al., 2017a), posture recognition (Wang et al., 2019) and intra-stroke velocity (Worsey et al., 2018). In another study, a new analysis approach is proposed and trunk elevation, body balance, and body rotation are used as new indices for swimming analysis (Félix et al., 2019; Morouço et al., 2020). Considering the significance of phase related kinematic variables, we have recently proposed a macro-micro approach for swimming analysis using IMUs (Hamidi Rad et al., 2021). In our approach, swimming bouts, laps and swimming technique are detected in macro analysis. Afterwards in micro level, each lap is segmented into swimming phases of wall push-off (*Push*), glide (*Glid*), strokes preparation (*StPr*), swimming (*Swim*) and turn (*Turn*) from wall to wall. In the next level of micro analysis, the kinematic variables within each swimming phase (micro variables) are extracted from IMU data.

These studies show there is still a substantial undiscovered potential for kinematic variable extraction with IMUs in swimming analysis. However, the association between the swimming kinematic variables extracted by IMU and the above-mentioned goal metrics is still unclear. Furthermore, as the variables provided by the IMU are claimed to be associated with the swimmers' performance, they can be used for estimating the goal metrics of performance evaluation. As a result, the relationship between IMU kinematic variables and goal metrics is yet to be studied to prove IMU potential not only for swimming kinematic variable extraction, but also for performance evaluation and training optimization.

The main objective of this study is to find the association between swimming kinematics extracted using a sacrum-worn IMU and goal metrics in different swimming phases. We hypothesized that the micro variables extracted from IMU data are associated with the goal metrics used for performance evaluation, regardless of the swimming technique. Following the macro-micro approach for swimming analysis (Hamidi Rad et al., 2021), within each swimming phase (*Push*, *Glid*, *StPr* and *Swim*), we selected the kinematic variables that are highly associated with goal metrics. We then used the selected kinematics to estimate the goal metrics. Using the underlying model we can explains how kinematics determine the performance.

MATERIALS AND METHODS

Measurement Setup and Protocol

Nineteen elite swimmers took part in this study, whose attributes are shown in **Table 1**. They were informed of the procedure and gave their written consent prior to participation. This study was approved by the EPFL human research ethics committee (HREC, No: 050/2018). One IMU (Physilog® IV, GaitUp, CH.) was attached to swimmer's sacrum, using waterproof band (Tegaderm, 3M Co., USA). The sensor contained a 3D gyroscope (±2000 °/s) and 3D accelerometer (±16 g), with a sampling rate of 500 Hz (**Figure 1**). A functional calibration was performed after sensor installation with simple movements in land (upright standing and squats) before the measurement to make the data independent of sensor placement on swimmer's body (Dadashi et al., 2013). During the measurements, the swimmers were asked to perform four one-way trials in each swimming technique (i.e. front crawl, breaststroke, butterfly, backstroke) with a progressive velocity (70–100%) in a 25 m indoor pool, starting with wall push-off inside water. The trials were separated with 1-min rests, and the total duration of the measurement was around 1 hour per swimmer.

Two systems were used as references in our study to validate the goal metrics estimated by the IMU. The first one was a set of four 2-D cameras (GoPro Hero 7 Black, GoPro Inc., US) used for detecting the swimming phases. The cameras synchronized with the IMU, using the LED light of a push-button (Hamidi Rad et al., 2021) were attached to the pool wall (distributed along the length of the pool) to videotape all the lap from wall to wall underwater with a 60 Hz rate (**Figure 1**). The second reference system was a tethered speedometer (SpeedRT®, ApLab, Rome, Italy), attached with a belt to the waist of the swimmer. The speedometer calculated the displacement and velocity of the swimmer at a rate of 100 Hz and was used for finding the reference values of goal metrics in different swimming phases. As the speedometer was installed on the starting block above the swimmer's level, it caused a parallax problem (Le Sage et al., 2011). Since the device level difference with respect to the still pool water was known (62 ± 1 cm), the velocity projection along the swimming direction was separated as the forward velocity of the swimmer.

TABLE 1 | Statistics of the study participants. All variables are presented as mean ± standard deviation. $Record_{50m}$ is the average and standard deviation of 50 m record of the swimmers separately for each swimming technique.

Male	Female	Age (yrs)	Height (cm)	Weight (kg)	$Record_{50m}$ (s)	
9	10	19.5 ± 2.7	177.5 ± 7.5	67.9 ± 8.3	Front crawl	25.85 ± 1.65
					Breaststroke	34.76 ± 3.87
					Butterfly	28.55 ± 2.47
					Backstroke	30.19 ± 1.88

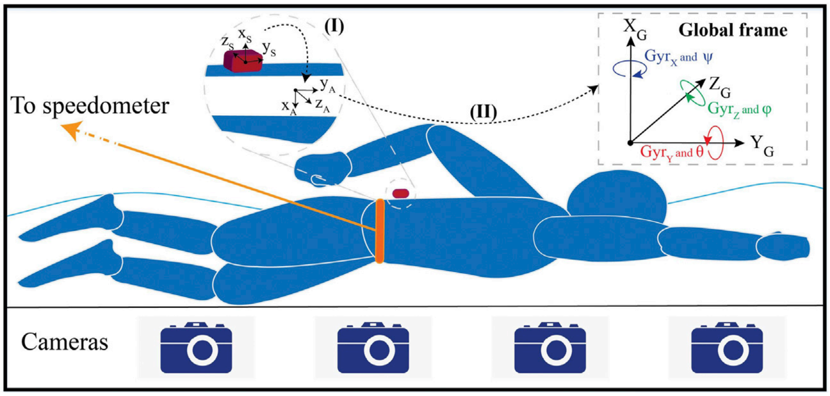

FIGURE 1 | Measurement setup including one IMU attached to the sacrum, four cameras to capture the whole lap and tethered speedometer to record swimmer's displacement and velocity. IMU data is transferred from sensor frame $(x,y,z)_S$, first to anatomical frame $(x,y,z)_A$ using functional calibration (I), and then to the global frame $(X,Y,Z)_G$ using the gradient-descend based optimization algorithm (II). The global axes of acceleration, angular velocity and angles are displayed in the figure.

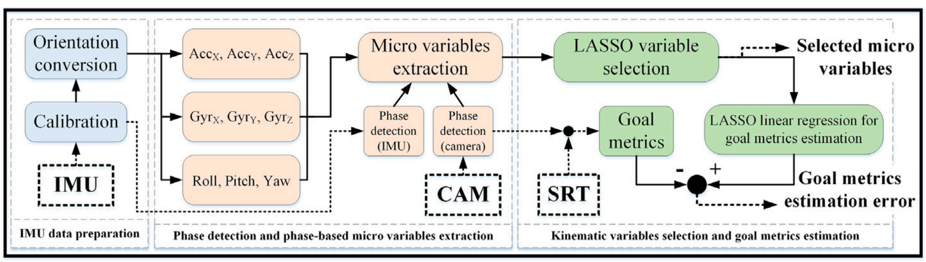

FIGURE 2 | Flowchart of the performance evaluation algorithm. IMU data preparation including IMU calibration and expressing data in the global frame **(left),** phase detection by cameras (CAM) or IMU calibrated data and micro variable extraction from IMU data in global frame **(middle)** and variable selection from micro variables and the goal metrics estimation **(right).** The actual goal metrics are defined and extracted from the velocity and displacement data by tethered speedometer (SRT) during swimming phases separated by the cameras (CAM).

Performance Evaluation

The general flowchart for performance evaluation is outlined in **Figure 2**. The algorithm includes three parts: 1) IMU data preparation 2) phase detection and phase-based micro variables extraction, 3) kinematic variable selection and goal metrics estimation. IMU data preparation aims to transfer the data to the global frame to achieve the true motion data of swimmer's sacrum. Then we divided each lap into four phases of *Push*, *Glid*, *StPr* and *Swim* by camera or IMU (Hamidi Rad et al., 2021). In order to observe the error induced by IMU-based phase detection, the rest of the analysis was done once with swimming phases detected by cameras and once by the IMU for comparison, the results of which are illustrated in supplementary materials. Using the data in global frame (acceleration (Acc_X, Acc_Y, Acc_Z), angular velocity (Gyr_X, Gyr_Y, Gyr_Z) and orientation (Roll, Pitch, Yaw)) within the detected phases, we extracted the micro variables of each phase.

In the third part of this approach, we used the extracted phase-based micro variables to estimate the goal metrics. First, LASSO (least absolute shrinkage and selection operator) variable selection is used to rank and select the micro variables with higher importance (Fonti and Belitser, 2017). Using the speedometer and camera data, several goal metrics are extracted on the velocity and displacement of the swimmer in different swimming phases. These goal metrics are representatives of how well the swimmer performed in the corresponding phase. Finally, we used the selected micro variables to estimate the goal metrics. The principal outputs of this analysis are the selected variables and the error of using them for goal metrics estimation.

IMU Data Preparation

First, the data was calibrated for offset, scale and non-orthogonality (Ferraris et al., 1995). As explained in *Measurement Setup and Protocol*, a functional calibration is also performed before each measurement trial. The goal of this calibration is to transform the data from sensor frame $(x, y, z)_S$ to anatomical frame $(x, y, z)_A$ (**Figure 1-I**). Following that, the data is ready to be expressed in the global frame. The swimmers were asked to hold an upright posture in water before lap start for 5 seconds to find the initial orientation of the sacrum with respect to the pool. The changes from the initial orientation are estimated by angular velocity integration from gyroscope data and corrected with acceleration using a gradient-descend based optimization algorithm (Madgwick et al., 2011). The algorithm provides the orientation changes in quaternion q [represented by four elements (q_1, q_2, q_3, q_4)] and use them to convert the accelerometer and gyroscope data from anatomical frame $[(x, y, z)_A]$ to global frame $[(X, Y, Z)_G]$ (**Figure 1-II**), expressed in **Eqs 1**, **2**.

$$Acc_G = q \otimes [0\, Acc_A] \otimes q^T \tag{1}$$

$$Gyr_G = q \otimes [0\, Gyr_A] \otimes q^T \tag{2}$$

Where Acc_A and Acc_G are the acceleration in anatomical and global frame respectively, $\otimes$ represents quaternion multiplication and q^T is the transpose of the quaternion q. The same notation holds true for gyroscope data in **Eq. 2**. Moreover, by changing quaternions into Euler angles, roll (θ), pitch (φ) and yaw (ψ) angles could be found (**Eq. 3**). The angles θ, φ and ψ are defined respectively around the longitudinal, mediolateral, and anterior-posterior axes of swimmer's sacrum.

$$\begin{cases} \psi = \text{Atan2}\left(2q_2q_3 - 2q_1q_4, 2q_1^2 + 2q_2^2 - 1\right) \\ \theta = -\sin^{-1}\left(2q_2q_4 + 2q_1q_3\right) \\ \varphi = \text{Atan2}\left(2q_3q_4 - 2q_1q_2, 2q_1^2 + 2q_4^2 - 1\right) \end{cases} \tag{3}$$

Phase-Based Micro Variables

For IMU-based detection of swimming phases, we used a macro-micro approach in our previous study, started from swimming bouts detection down to lap segmentation into swimming phases (Hamidi Rad et al., 2021). Using the acceleration, angular velocity and orientation data in global frame, various kinematic variables based on motion biomechanics in every swimming phase are defined. As frequently discussed in the literature, fast swimming depends on 1) the ability to generate high propulsive forces, 2) the ability to keep the correct posture for reducing the drag, while 3) swimming with the highest efficiency (Toussaint and Truijens, 2005). Therefore, knowledge of the propulsion, posture and efficiency is relevant to optimize swimming performance. We related the extracted micro variables to one of these three categories (**Table 2**). We also added a fourth group for the variables related to the durations and rates of motion, which did not fit into the previous three categories. For example stroke rate in *Swim* phase which is not necessarily a sign of high or low propulsion, good or bad posture and high or low efficiency but it is widely used for performance evaluation (Siirtola et al., 2011; Beanland et al., 2014).

We extracted the micro variables by extremum detection, integration or calculation of the average, range and standard deviation of the signal. The variables defined per stroke in *Swim* phase need a cycle separation algorithm. For front crawl and backstroke, the duration between the two successive positive peaks on the longitudinal angular velocity in anatomical frame (Gyr_y) is one cycle (Dadashi et al., 2013). The same method is used with mediolateral angular velocity in anatomical frame (Gyr_z) for cycle separation of breaststroke and butterfly techniques.

Goal Metrics

We extracted eight goal metrics from the tethered speedometer data i.e. the velocity and displacement of the swimmer, from wall to wall within the swimming phases detected on the cameras (**Figure 3**).

1. *Push* maximum velocity: the highest velocity during the lap is generated at start, as the swimmer can reach a velocity much greater than other swimming phases (Shimadzu et al., 2008). During *Push* phase, the maximum velocity reached is used to assess wall push-off (Stamm et al., 2013). We use this value as the goal metric for *Push* phase.
2. *Glid* end velocity: the velocity decreases during *Glid* phase because of water drag. The swimmer should keep the streamlined horizontal posture and start *StPr* phase at the right time before losing too much velocity (Vantorre et al., 2014). So we considered the velocity of the swimmer at the end of *Glid* phase as the goal metric for this phase.
3. *StPr* average velocity: the average velocity of the swimmer during *StPr* lower limbs actions is shown to have a negative correlation with 15-m time of the swimmer (Cossor and Mason, 2001). We used it as the goal metric for *StPr* phase.

During *Swim* phase, the performance of the swimmer can be studied per cycle or in the whole phase. Thus two goal metrics are defined in this phase:

4. *Swim*—average velocity per cycle: the average velocity of the swimmer per cycle provides valuable information of swimmer's performance in every cycle (Dadashi et al., 2015).
5. *Swim*—average velocity of *Swim* phase: for looking at all the cycles together, the average velocity of the whole *Swim* phase is used as the second goal metric for this phase.

We also used three more goal metrics based on the literature, which include more than one phase.

TABLE 2 | Categories and description of the phase-based micro variable defined on IMU data in global frame. The name of the functions used for micro variables extraction are abbreviated in parentheses.

Category	Description	Micro variables
Propulsion	Variables related to the amount of propulsion generated by the swimmer	Mean (*Mean*), range (*Range*) and standard deviation (*SD*) of Acc_X, Acc_Y and Acc_Z. Maximum (*Max*), integral (*Int*), and momentum change (*Momentum*) of Acc_Y
Posture	Variables related to the body posture and drag effects on swimmer' body	*Mean*, *Range* and *SD* of θ and φ
Efficiency	Variables related to the efficiency of motion which can reflect in acceleration	Ratio of positive Acc_Y to $\|Acc\|$ (*Eff_dir*) or to negative Acc_Y (*Eff*), distance per stroke (*DPS*) in *Swim* phase
Duration/ rate	Variables related to the duration of a phase or the rate of movement	*Mean*, *Range* and *SD* of Gyr_X, Gyr_Y and Gyr_Z. phases and cycles duration. Kick rate and count in *StPr* phase. Stroke rate and count in *Swim* phase

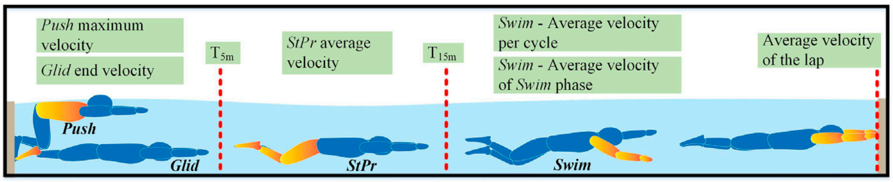

FIGURE 3 | The defined goal metrics for different swimming phases from wall to wall.

6. T_{5m}: normally *Glid* phase finishes before reaching 5 m from the wall when the swimmer starts by wall push-off in all swimming techniques. The time it takes the swimmer to reach 5 m from the wall is a goal metric (Zatsiorsky et al., 1979), which shows the combination of swimmer's performance during *Push* and *Glid* phases.
7. T_{15m}: 15 m is the limit for the swimmer to re-surface (except for breaststroke technique) according to FINA (Federation International de Natation) rules. So the time it takes to reach 15 m from the wall is a goal metric referring to underwater phases (*Push*, *Glid* and *StPr*) (Vantorre et al., 2010).
8. Lap average velocity: considering all the phases together, average velocity of the lap (determined by lap time) is the final goal metric, displaying the overall performance of the swimmer in all phases (Davey et al., 2008; Mooney et al., 2016).

Among the defined goal metrics, *Push* maximum velocity is calculated with a peak detection algorithm in *Push* phase. The rest of the goal metrics only rely on the beginning or end of swimming phases, which are already obtained by phase detection.

Association Between Micro Variables and Goal Metrics

After extracting the micro variables from IMU and goal metrics from speedometer and camera data, we look for association between every goal metric with the micro variables of its corresponding phase or phases. For example, *Push* maximum velocity is associated with *Push* phase micro variables. For goal metrics involving more than one phase, such as T_{5m}, T_{15m} and lap average velocity related to *Push/Glid*, *Push/Glid/StPr* and all phases respectively, the micro variables from the relevant phases were used.

To identify the variables with higher significance, we ran a variable selection algorithm. In the first step, we normalized each variable and removed the multicollinearity between them using variance inflation factors (VIF) (Mansfield and Helms, 1982). LASSO variable selection is then applied over the variables related to each goal metric, to select the ones of higher importance. LASSO is a forward-looking variable selectin method for regression, which improves both the estimation accuracy and the interpretability of the model (Muthukrishnan and Rohini, 2017). It ranks the variables and allocates a wight to each one based on their significance in the regression model. Among the selected variables, we neglected the ones with a relative weight less than 5% because of their less important role. Moreover, to quantify the contribution of each category to the regression model, we summed the relative weights of variables from each category (propulsion, posture, efficiency and duration/rate).

Once the significant variables were identified, we utilized them to estimate the goal metrics by a LASSO regression model with leave-one-out cross-validation to avoid overfitting (Berrar, 2018). The cross validated determination coefficient (R^2) is reported as a metric of association between true values (reference values from speedometer) and the estimated value (output of the models). The error between the true and estimated values of goal metrics is analyzed using the root mean square of error (*RMSE*) and its relative value in percent.

RESULTS

A sample size analysis based on a previous study (Dadashi et al., 2012) that used the same speedometer and measurement protocol for velocity estimation is performed. Considering a power of 80% (β = 0.2) and 95% (α = 0.05) confidence interval, we reached a sample size of 64 for this study. Since the models are generated

TABLE 3 | The results of evaluating LASSO regression for goal metrics estimation. The determination coefficient (R^2) and root mean square of error (RMSE) and the relative RMSE (in %) of regression are reported for each swimming technique.

Goal metric	Front crawl		Breaststroke	
	R^2	RMSE (%)	R^2	RMSE (%)
Push maximum velocity (m/s)	0.74	0.140 (5.7)	0.75	0.131 (5.3)
Glid end velocity (m/s)	0.76	0.123 (10.1)	0.64	0.139 (11.1)
StPr average velocity (m/s)	0.72	0.075 (4.4)	0.58	0.058 (5.9)
Swim—average velocity per cycle (m/s)	0.89	0.050 (8.3)	0.84	0.044 (5.7)
Average velocity of *Swim* phase (m/s)	0.90	0.044 (2.7)	0.71	0.061 (5.3)
T_{5m} (s)	0.64	0.158 (7.6)	0.74	0.209 (6.9)
T_{15m} (s)	0.75	0.369 (4.3)	0.81	0.430 (6.7)
Lap average velocity (m/s)	0.95	0.032 (2.4)	0.85	0.038 (3.4)
	Butterfly		Backstroke	
Push maximum velocity (m/s)	0.71	0.149 (5.9)	0.72	0.107 (4.9)
Glid end velocity (m/s)	0.80	0.111 (9.1)	0.84	0.104 (6.4)
StPr average velocity (m/s)	0.75	0.152 (6.7)	0.75	0.079 (5.3)
Swim—average velocity per cycle (m/s)	0.88	0.067 (4.9)	0.89	0.076 (5.7)
Average velocity of *Swim* phase (m/s)	0.79	0.049 (3.3)	0.73	0.056 (4.3)
T_{5m} (s)	0.63	0.209 (7.0)	0.71	0.202 (6.4)
T_{15m} (s)	0.79	0.344 (4.6)	0.77	0.521 (5.0)
Lap average velocity (m/s)	0.86	0.049 (3.3)	0.80	0.063 (4.6)

TABLE 4 | The selected variables for estimating each goal metric for front crawl technique, written in the order of relative weights. The variables are written in the order of their relative weights. For the abbreviated name of functions, see **Table 2**.

Goal metric	Selected variables
Push maximum velocity	*Range* (φ), *SD* (φ), *Int* (Acc_Y), *Momentum* (Acc_Y), *Range* (Acc_Y), *Max* (Acc_Y), *Mean* (Gyr_Z), *Eff* (Acc_Y)
Glid end velocity	*Glid* duration, *Momentum* (Acc_Y), *Int* (Acc_Y), *Range* (Acc_Y), *Range* (φ), *Mean* (φ)
StPr average velocity	*Mean* (Acc_Y), *Eff* (Acc_Y), *Eff_dir* (Acc_Y), *SD* (Acc_Y) , number of kicks, *StPr* duration
Swim—average velocity per cycle	Cycle duration, DPS, *Mean* (φ) per cycle
Average velocity of *Swim* phase	Stroke rate, Mean (φ), number of strokes, *SD* (Acc_Y), *Range* (θ)
T_{5m}	*Momentum* (Acc_Y) in *Glid*, *Max* (Gyr_Z) in *Push*, *SD* (φ) in *Glid*, *Range* (φ) in *Push, Max* (Gyr_Z) in *Glid*
T_{15m}	*Glid* duration, *Range* (φ) in *StPr*, *SD* (Gyr_Z) in *StPr*, *SD* (Acc_Y) in *Push*, *StPr* kick rate, *Momentum* (Acc_Y) in *Push*
Lap average velocity	Stroke rate, number of strokes, *Max* (Acc_Y) in *Push*, *Mean* (Acc_Y) in *Glid*, *Mean* (φ) in *Swim*, number of kicks in *StPr*

using the data from all swimmers pooled together, the number of observations used to estimate all goal metrics, except for average velocity of the cycle in *Swim* phase was 76 samples. The overall number of cycles used for estimating the average velocity per cycle in *Swim* phase was 1,166, 627, 695 and 1,052 for front crawl, breaststroke, butterfly and backstroke respectively.

Goal Metrics Estimation

The cross-validated values (R^2, RMSE and the relative RMSE in percent) of LASSO regression model used for estimating the corresponding goal metric are reported in **Table 3** for each goal metric. **Table 3** shows that LASSO regression model fits the data with an R^2 value more than 0.75 for most goal metrics in all swimming techniques. The RMSE of the regression are less than 0.15 $m/_s$ (11%) for all goal metrics defined over velocity and less than 0.21 s (7%) and 0.52 s (5%) for T_{5m} and T_{15m} respectively. The highest value of relative RMSE belongs to *Glid* end velocity with 11.1%, while the relative error is less than 10% in all other cases. The results are also calculated with swimming phases found by cameras for comparison in supplementary materials (**Supplementary Table SA1**).

Micro-Variables Selection

The selected variables for each goal metric estimation during front crawl technique are listed in **Table 4**. Same tables for other swimming techniques are brought in supplementary materials (**Supplementary Tables A2–A4**). Among acceleration axes, Acc_Y and its related variables [e.g. *Mean* (Acc_Y), *Max* (Acc_Y), *Int* (Acc_Y)] are more selected for different goal metrics. Gyr_Z and φ related variables seem to be more associated with the defined goal metrics than other axes of orientation in front crawl technique. For $T_{5m,}$ T_{15m} and lap average velocity, a mixture of variables from corresponding phases are selected, some of which were already selected for the specific goal metric of these phases.

The overall contribution of each category in estimating the goal metrics is illustrated in **Figure 4** for all four swimming techniques. It is observable that propulsion category plays an important role in *Push* phase, while posture-related variables are more selected in *Glid* phase. *StPr* phase is less affected by efficiency compared to other categories. Efficiency and propulsion categories are both significant in determining the average velocity per cycle in *Swim* phase. Duration/rate category

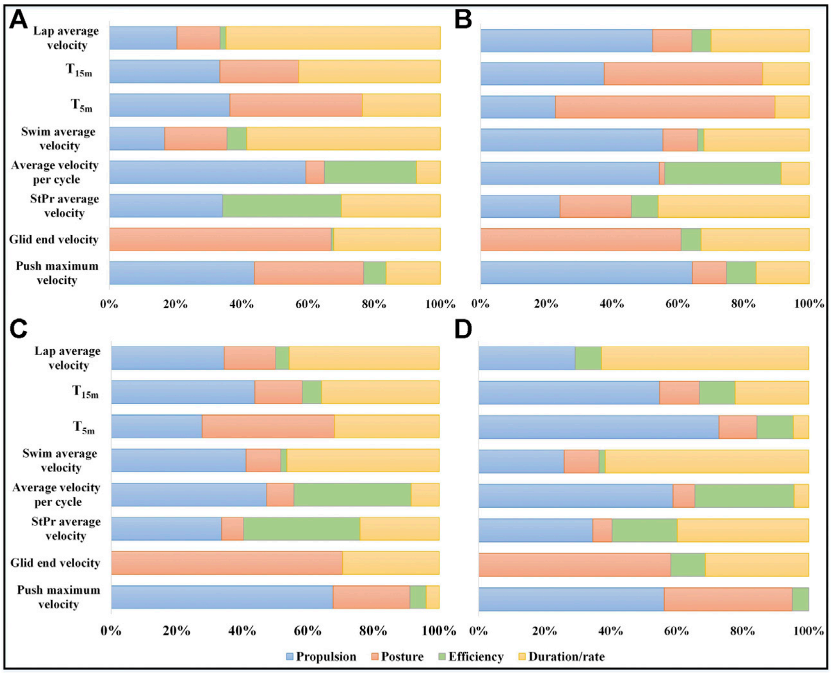

FIGURE 4 | Variable categories contribution to goal metrics estimation for front crawl **(A)**, breaststroke **(B)**, butterfly **(C)** and backstroke **(D)**. The contribution of each category (propulsion: blue, posture: orange, efficiency: green, duration/rate: yellow) is represented in percent for estimating the corresponding goal metric. The results are based on the variables with higher than 5% relative weight in LASSO variable selection.

is dominant in estimating average velocity of *Swim* phase and lap average velocity. T_{5m} and T_{15m} are affected mainly by a mixture of propulsion, posture and duration/rate categories depending on the swimming technique.

DISCUSSION

In this research, we studied the association between IMU micro variables and the performance evaluation goal metrics found by camera and speedometer during the swimming phases from wall to wall in four main swimming techniques. The obtained results confirmed our hypothesis that micro variables extracted from a single IMU placed at sacrum within each phase are associated with the corresponding goal metrics used generally for performance evaluation. As a result, using a single IMU would be enough for performance evaluation in main swimming techniques. Micro variables, showing strong association with the goal metrics, were identified thanks to LASSO variable selection and used for predicting the goal metrics.

Goal Metrics Estimation

The selected kinematic variables within each swimming phase were used for estimating the corresponding goal metrics (**Table 3**). Estimating the *Push* maximum velocity and *Glid* end velocity showed similar results in different swimming techniques, as the two initial phases are the same for them (only for backstroke, the swimmer has a supine posture). The relative RMSE is the highest for *Glid* end velocity estimation (11%) because this goal metric has the lowest value in the whole lap. In the *StPr* phase, the average velocity shows a high amount of variability among the swimmers, and determination coefficient (i.e. the proportion of the variance of the true goal metric value explained by the regression model) is relatively lower for it (less than 0.8 in all techniques) compared to other goal metrics in all techniques, because a linear model is not efficient enough in reflecting the variation of this goal metric, and a non-linear model might estimate it better.

Average velocity per cycle is estimated in all techniques with a determination coefficient more than 0.84 and an RMSE less than 0.076 m/s and relative error less than 6%. However, estimating the average velocity of the whole *Swim* phase achieved poorer results (R^2 of 0.71–0.90 in different techniques). As estimating each cycle average velocity is more accurate in all techniques, the average value of all cycles in *Swim* phase can also be used for estimating *Swim* phase average velocity. The regression models for estimating T_{5m} show less accuracy (R^2 less than 0.80 in different techniques), making it difficult to trust the estimation results. Depending on swimming technique and swimmers' pace, they might start *StPr* phase earlier than 5 m from the wall. So T_{5m} is partly affected by *StPr* phase and using only *Push* and *Glid* phases might not be enough for estimation. On the contrary, the first three phases (*Push*, *Glid* and *StPr*) finish before 15 m from the wall and using them for estimating the T_{15m} results in more accurate regression models (R^2 more than 0.75 in different techniques). Finally, the lap average velocity is estimated using a selection of the kinematic variables from all phases with a relatively small error (RMSE less than 0.063 m/s for all techniques). The results have been only slightly improved when using cameras for phase detection (section 1 of **Supplementary Materials**).

Micro Variables Selection

As shown in **Table 4** and **Figure 4** during the *Push* phase, the kinematic variables related to φ and Acc_Y are ranked as more important, which shows the significance of keeping the right posture and generating high propulsion in *Push* phase. The *Mean* (Gyr_Z) and *Eff* (Acc_Y) are selected at last. The weight contribution of *Push* kinematic variables can be categorized more in propulsion and posture groups, which is the same for all techniques (**Figures 4A–D**), as the *Push* movement is the same. During *Glid* phase, phase duration is chosen the first, since the longer the *Glid* phase is, the more velocity will be lost. *Momentum* (Acc_Y) and *Int* (Acc_Y) are also considered important since they represent the effect of water drag on swimmer's body. High *Range* (φ) and *Mean* (φ) during *Glid* are a sign of bad posture, which causes more drag. In terms of categories, none of the micro variables can be categorized in propulsion because *Glid* phase does not include any propulsive motion. As a result, the categories of posture and duration/rate are the dominant groups in this phase, regardless of the technique.

StPr phase has the highest amount of velocity variation on speedometer data and the average velocity during this phase is related to a combination of forward acceleration, accelerating efficiency, number of kicks and phase duration. Two types of efficiency-related variables are selected for this phase. *Eff* (Acc_Y) represents the ratio of positive to all forward acceleration and *Eff_dir* (Acc_Y) is the ratio of forward acceleration to the acceleration norm. Since this phase includes strong kicking, generating the highest amount of acceleration in forward direction (Acc_Y) with respect to other axes is selected as an important variable. *StPr* phase is the same for front crawl, butterfly and backstroke as it includes butterfly kicks in all of them. **Figures 4A,C,D** also shows similar categories of propulsion, efficiency and duration/rate for the variables selected in this phase. For breaststroke technique, *StPr* phase includes one upper limbs cycle followed by a lower limb action and the posture related variables are also important compared to other categories (**Figure 4B**).

For *Swim* phase goal metrics, the average velocity per stroke is mainly associated with the duration of each cycle and the DPS. The *Mean* (φ) is also selected which relates to the swimmer's posture. This selection is the same in all swimming techniques (**Figures 4B–D**) as the average velocity per stroke can be estimated by dividing the DPS by the cycle duration. The second goal metric of *Swim* phase is the average velocity of the whole phase. The variables related to the rate and number of strokes are more dominant as the swimmers increase the stroke rate for fast swimming. The *SD* (Acc_Y), *Mean* (φ) and *Range* (θ) are other kinematic variables selected for estimating this goal metric, highlighting the significance of consistent propulsion and body posture in *Swim* phase. As a result, the three categories of duration/rate, posture and propulsion are more pronounced for estimating *Swim* phase average velocity in all techniques.

T_{5m}, T_{15m} and lap average velocity are dependent on more than one phase, and the variable selection algorithm picks a number of variables from each phase. Most of the selected variables for these goal metrics were already selected for relevant phases such as selecting *Momentum* (Acc_Y) of *Glid* for T_{5m}, *Glid* duration for T_{15m} or stroke rate for lap average velocity, proving the significance of such variables even in a larger scale. Moreover, this shows the dependence of overall swimmer's performance on their local performance in each phase. Among the techniques, T_{5m} and T_{15m} are estimated with a mixture of propulsion, posture and duration/rate categories in front crawl, breaststroke and butterfly, whereas during backstroke, the propulsion is dominant for both goal metrics. This emphasises on the tendency of the swimmers to longer underwater phases in backstroke (De Jesus et al., 2011), that asks for highly propulsive butterfly kicks.

With an overall observation on **Figure 4**, it is noted that the dominant categories in swimming phases are in line with the swimming phase biomechanics. *Push* phase asks for high propulsion, and *Glid* phase is more about keeping the right posture to avoid the drag. *StPr* phase is a combination of propulsion, posture and efficiency. Since the variable selection algorithm chooses the best variables for goal metric estimation, the variables which have the strongest relationship with the goal metrics are selected. As a result, we cannot assert that the rest of the variables are of no importance in swimming. For example, the *DPS* and cycle duration were dominant in estimating the average velocity per cycle in *Swim* phase, while no one can ignore the importance of orientation-related variables (e.g. θ angle) (Psycharakis and Sanders, 2010) or propulsion (Toussaint, 2002) in this phase. However, having a longer *DPS* in a shorter cycle duration is the result of correct orientation and high propulsion so the selected variables include other variable categories implicitly.

This study shows that a single sacrum IMU can provide kinematic variables relevant to the performance of the swimmer, in different techniques and phases for performance evaluation without using complex instrumentation such as speedometers or cameras. This offers new tools for training, where for example output of the IMU can be transferred to a mobile application for coaches and swimmers to easily follow the progress of the swimmers. Although using wearables induces more drag on swimmer body (Magalhaes et al., 2015), it needs extremely less effort than cameras for preparation and use, and it overcomes many of the limits of video-based systems (Callaway et al., 2010). The kinematic variables that were found dominant in our study were already analyzed using IMU of video-based methods but their relationship with the goal metrics were not studied. Swimmer's posture during *Push* and *Glid* (Pereira et al., 2015), *Glid* duration (Guimaraes and Hay, 1985), *StPr* kicking rate (Shimojo et al., 2014), *Swim* stroke rate (Beanland et al., 2014) or DPS (Bächlin et al., 2008) are examples of the micro variables that were found relevant to performance, and we also found them significant in this study.

Both male and female swimmers were included for generating the results of this study to have a larger, more variant dataset. Comparing the swimmers due to their individual differences is out of the scope of our study. The estimations are done over all swimming velocities so the results are valid for 70–100 percent of swimmers' paces. The synchronization error between the three systems of IMU, cameras and speedometer is a source of error in this study. Since tethered speedometer was used as reference in this study, the measurements were done over one-way trials without turn and turn motion is not evaluated. In this study, we used linear regression to have interpretable models highlighting the main variables correlated to the goal metrics. More complex non-linear models could be used if the goal is more accurate prediction of goal metrics.

CONCLUSION

Using the IMU data, we extracted numerous kinematic variables related to propulsion, posture, efficiency and duration/rate of motion in four main swimming phases, associated with the goal metrics defined over velocity and time of swimming in each swimming phase. These kinematic variables were biomechanically interpretable and were able to predict the goal metrics using LASSO linear regression. The generated models fit the data with an R^2 value more than 0.75 for most goal metrics. The RMSE of the regression were less than 0.15 m/s and 11% for goal metrics defined over velocity and 0.52 s and 7.6% for goal metrics defined over time. Our study shows that a single sacrum-worn IMU has the potential to evaluate the swimmer performance in different swimming phases in line with standard goal metrics. Practically, our proposed method can be useful for coaches to identify the weakness and strength of their swimmers and track their progress during training sessions with a single IMU. This study can be continued with implementation of the regression models on new dataset for validation, using more complex models (e.g. non-linear regression) for better goal metric estimation, completing the analysis for diving start and turn and using other sensor locations for estimation accuracy comparison.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusion of this article will be made available to qualified researcher, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the EPFL human research ethics committee (HREC, No: 050/2018). The patients/participants provided their written informed consent to participate in this study.

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. FD supervised the study and KA co-advised it. 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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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fbioe.2021.793302/full#supplementary-material

REFERENCES

Bächlin, M., Förster, K., Schumm, J., Breu, D., Germann, J., and Tröster, G. (2008). "An Automatic Parameter Extraction Method for the 7×50 m Stroke Efficiency," in 2008 Third International Conference on Pervasive Computing and Applications ICPCA08, Alexandria, Egypt, 442–447. doi:10.1109/ICPCA.2008.4783628

Beanland, E., Main, L. C., Aisbett, B., Gastin, P., and Netto, K. (2014). Validation of GPS and Accelerometer Technology in Swimming. *J. Sci. Med. Sport* 17, 234–238. doi:10.1016/j.jsams.2013.04.007

Berrar, D. (2019). "Cross-validation," in *Encyclopedia of Bioinformatics and Computational Biology: ABC of Bioinformatics* (Academic Pres), 1–3, 542–545. doi:10.1016/B978-0-12-809633-8.20349-X

Callaway, A. J., Cobb, J. E., and Jones, I. (2009). A Comparison of Video and Accelerometer Based Approaches Applied to Performance Monitoring in Swimming. *Int. J. Sports Sci. Coach.* 4, 139–153. doi:10.1260/1747-9541.4.1.139

Cossor, J. M., and Mason, B. R. (2001). "Swim Start Performances at the Sydney 2000 Olympic Games," in International Society of Biomechanics in Sports: XIX International Symposium (University of San Francisco), 70–74.

Dadashi, F., Crettenand, F., Millet, G. P., and Aminian, K. (2012). Front-Crawl Instantaneous Velocity Estimation Using a Wearable Inertial Measurement Unit. *Sensors* 12, 12927–12939. doi:10.3390/s121012927

Dadashi, F., Crettenand, F., Millet, G. P., Seifert, L., Komar, J., and Aminian, K. (2013). Automatic Front-Crawl Temporal Phase Detection Using Adaptive Filtering of Inertial Signals. *J. Sports Sci.* 31, 1251–1260. doi:10.1080/02640414.2013.778420

Dadashi, F., Millet, G. P., and Aminian, K. (2015). A Bayesian Approach for Pervasive Estimation of Breaststroke Velocity Using a Wearable IMU. *Pervasive Mobile Comput.* 19, 37–46. doi:10.1016/j.pmcj.2014.03.001

Davey, N., Anderson, M., and James, D. A. (2008). Validation Trial of an Accelerometer-based Sensor Platform for Swimming. *Sports Techn.* 1, 202–207. doi:10.1080/19346182.2008.9648474

De Jesus, K., De Jesus, K., Figueiredo, P., Gonçalves, P., Pereira, S., Vilas-Boas, J. P., et al. (2011). Biomechanical Analysis of Backstroke Swimming Starts. *Int. J. Sports Med.* 32, 546–551. doi:10.1055/s-0031-1273688

Félix, E. R., Silva, B. H., Olstad, P. L., Cabri, J., and Correia, P. L. (2019). SwimBIT: A Novel Approach to Stroke Analysis during Swim Training Based on Attitude and Heading Reference System (AHRS). *Sports* 7, 238. doi:10.3390/sports7110238

Ferraris, F., Grimaldi, U., and Parvis, M. (1995). Procedure for Effortless In-Field Calibration of Three-axis Rate Gyros and Accelerometers. *Sensors Mater.* 311.

Fonti, V., and Belitser, E. (2017). Feature Selection Using LASSO. *VU Amsterdam Res. Pap. Bus. Anal.*, 1–25.

Guignard, B., Rouard, A., Chollet, D., Ayad, O., Bonifazi, M., Dalla Vedova, D., et al. (2017a). Perception and Action in Swimming: Effects of Aquatic Environment on Upper Limb Inter-segmental Coordination. *Hum. Move. Sci.* 55, 240–254. doi:10.1016/j.humov.2017.08.003

Guignard, B., Rouard, A., Chollet, D., and Seifert, L. (2017b). Behavioral Dynamics in Swimming: The Appropriate Use of Inertial Measurement Units. *Front. Psychol.* 8, 383. doi:10.3389/fpsyg.2017.00383

Guimaraes, A. C. S., and Hay, J. G. (1985). A Mechanical Analysis of the Grab Starting Technique in Swimming. *J. Appl. Biomech.* 1, 25–35. doi:10.1123/ijsb.1.1.25

Hamidi Rad, M., Gremeaux, V., Dadashi, F., and Aminian, K. (2021). A Novel Macro-Micro Approach for Swimming Analysis in Main Swimming Techniques Using IMU Sensors. *Front. Bioeng. Biotechnol.* 8, 1–16. doi:10.3389/fbioe.2020.597738

Le Sage, T., Bindel, A., Conway, P. P., Justham, L. M., Slawson, S. E., and West, A. A. (2011). Embedded Programming and Real-Time Signal Processing of Swimming Strokes. *Sports Eng.* 14, 1–14. doi:10.1007/s12283-011-0070-7

Madgwick, S. O. H., Harrison, A. J. L., and Vaidyanathan, R. (2011). "Estimation of IMU and MARG Orientation Using a Gradient Descent Algorithm," in 2011 IEEE International Conference on Rehabilitation Robotics, Zurich, Switzerland. doi:10.1109/ICORR.2011.5975346

Magalhaes, F. A. d., Vannozzi, G., Gatta, G., and Fantozzi, S. (2015). Wearable Inertial Sensors in Swimming Motion Analysis: a Systematic Review. *J. Sports Sci.* 33, 732–745. doi:10.1080/02640414.2014.962574

Mansfield, E. R., and Helms, B. P. (1982). Detecting Multicollinearity. *Am. Statistician* 36, 158–160. doi:10.1080/00031305.1982.10482818

Mason, B., and Cossor, J. (2000). "What Can We Learn from Competition Analysis at the 1999 Pan Pacific Swimming Championships," in International Symposium on Biomechanics in Sports Applied programme, Canberra, Australia, 75–82.

Mooney, R., Corley, G., Godfrey, A., Quinlan, L., and ÓLaighin, G. (2016). Inertial Sensor Technology for Elite Swimming Performance Analysis: A Systematic Review. *Sensors* 16, 18. doi:10.3390/s16010018

Morouço, P., Pinto, J., Félix, E., Correia, P. L., Humana, F. D. M., Lisboa, U. D., et al. (2020). "Development of a Low- Cost Imu for Swimmers' Evaluation," in International Conference of Biomechanics in Sports, 952–955.

Muthukrishnan, R., and Rohini, R. (2016). "LASSO: A Feature Selection Technique," in 2016 IEEE International Conference on Advances in Computer Applications (ICACA), Coimbatore, India, 18–20. doi:10.1109/ICACA.2016.7887916

Pereira, S. M., Ruschel, C., Hubert, M., Machado, L., Roesler, H., Fernandes, R. J., et al. (2015). Kinematic, Kinetic and Emg Analysis of Four Front Crawl Flip Turn Techniques. *J. Sports Sci.* 33, 2006–2015. doi:10.1080/02640414.2015.1026374

Psycharakis, S. G., and Sanders, R. H. (2010). Body Roll in Swimming: A Review. *J. Sports Sci.* 28, 229–236. doi:10.1080/02640410903508847

Ruschel, C., Araujo, L., Pereira, S. M., and Roesler, H. (2007). "Kinematical Analysis of the Swimming Start : Block, Flight and Underwater Phases," in XXV ISBS Symp, Ouro Preto, Brazil, 385–388.

Shimadzu, H., Shibata, R., and Ohgi, Y. (2008). Modelling Swimmers' Speeds over the Course of a Race. *J. Biomech.* 41, 549–555. doi:10.1016/j.jbiomech.2007.10.007

Shimojo, H., Sengoku, Y., Miyoshi, T., Tsubakimoto, S., and Takagi, H. (2014). Effect of Imposing Changes in Kick Frequency on Kinematics during Undulatory Underwater Swimming at Maximal Effort in Male Swimmers. *Hum. Move. Sci.* 38, 94–105. doi:10.1016/j.humov.2014.09.001

Siirtola, P., Laurinen, P., Roning, J., and Kinnunen, H. (2011). "Efficient Accelerometer-Based Swimming Exercise Tracking," in 2011 IEEE Symposium on Computational Intelligence and Data Mining (CIDM), Paris, France, 156–161. doi:10.1109/CIDM.2011.5949430

Slawson, S. E., Justham, L. M., Conway, P. P., Le-Sage, T., and West, A. A. (2012). Characterizing the Swimming Tumble Turn Using Acceleration Data. *Proc. Inst. Mech. Eng. P: J. Sports Eng. Techn.* 226, 3–15. doi:10.1177/1754337111428395

Stamm, A., James, D. A., Burkett, B. B., Hagem, R. M., and Thiel, D. V. (2013). Determining Maximum Push-Off Velocity in Swimming Using Accelerometers. *Proced. Eng.* 60, 201–207. doi:10.1016/j.proeng.2013.07.067

Truijens, M., and Toussaint, H. (2005). Biomechanical Aspects of Peak Performance in Human Swimming. *Anim. Biol.* 55, 17–40. doi:10.1163/1570756053276907

Toussaint, H. M. (2002). "Biomechanics of Propulsion and Drag in Front Crawl Swimming," in 20 International Symposium on Biomechanics in Sports, 2002, Cáceres, Spain, 13–22. Available at: https://ojs.ub.uni-konstanz.de/cpa/article/viewFile/613/538%0Ahttp://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Biomechanics+of+propulsion+and+drag+in+front+crawl+swimming#5.

Vantorre, J., Seifert, L., Fernandes, R. J., Boas, J. P. V., and Chollet, D. (2010). Kinematical Profiling of the Front Crawl Start. *Int. J. Sports Med.* 31, 16–21. doi:10.1055/s-0029-1241208

Vantorre, J., Chollet, D., and Seifert, L. (2014). Biomechanical Analysis of the Swim-Start: A Review. *J. Sports Sci. Med.* 13, 223–231.

Wang, Z., Shi, X., Wang, J., Gao, F., Li, J., Guo, M., et al. (2019). "Swimming Motion Analysis and Posture Recognition Based on Wearable Inertial Sensors," in 2019 IEEE International Conference on Systems, Man and Cybernetics (SMC), Bari, Italy, 3371–3376. doi:10.1109/smc.2019.8913847

Worsey, M. T. O., Pahl, R., Thiel, D. V., and Milburn, P. D. (2018). A Comparison of Computational Methods to Determine Intrastroke Velocity in Swimming Using IMUs. *IEEE Sens. Lett.* 2, 1–4. doi:10.1109/lsens.2018.2804893

Zatsiorsky, V. M., Bulgakova, N. Z., and Chaplinsky, N. M. (1979). Biomechanical Analysis of Starting Techniques in Swimming. *Swim* III, 199–206.

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BRIEF RESEARCH REPORT
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Muscle Oxygenation, Heart Rate, and Blood Lactate Concentration During Submaximal and Maximal Interval Swimming

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This study aimed to determine the relationship between three testing procedures during different intensity interval efforts in swimming. Twelve national-level swimmers of both genders executed, on different occasions and after a standardized warm-up, a swimming protocol consisting of either a submaximal (Submax: 8 efforts of 50 m) or a maximal interval (Max: 4 efforts of 15 m), followed by two series of four maximal 25 m efforts. Near-infrared spectroscopy in terms of muscle oxygen saturation (SmO_2), heart rate (HR), and blood lactate concentration (BLa) were analyzed at three testing points: after the Submax or the Max protocol (TP_1), after the 1st 4 × 25-m (TP_2), and after the 2nd maximal 4 × 25-m set (TP_3). BLa and HR showed significant changes during all testing points in both protocols ($P \leq 0.01$; *ES range*: 0.45–1.40). SmO_2 was different only between TP_1 and TP_3 in both protocols ($P \leq 0.05$–0.01; *ES* range: 0.36–1.20). A large correlation during the Max protocol between SmO_2 and HR (r: 0.931; $P \leq 0.01$), and also between SmO_2 and BLa was obtained at TP_1 (r: 0.722; $P \leq 0.05$). A range of moderate-to-large correlations was revealed for SmO_2/HR, and BLa/HR for TP_2 and TP_3 after both protocols (r range: 0.595–0.728; $P \leq 0.05$) were executed. SmO_2 is a novel parameter that can be used when aiming for a comprehensive evaluation of competitive swimmers' acute responses to sprint interval swimming, in conjunction with HR and BLa.

Keywords: physiological testing procedures, near-infrared spectroscopy (NIRS), interrelationship, different intensity protocols, interval swimming

INTRODUCTION

Monitoring training intensity is essential for evaluating athletes' response to an exercise program. A testing tool often utilized in sports environments as an intensity marker is blood lactate (BLa) concentration due to its sensitivity to detect training-induced changes (Beneke et al., 2011). Despite several potential limitations, including its invasive nature (Swart and Jennings, 2004), BLa testing has been extensively used in swimming to evaluate current performance status, and potentially predict future performance outcomes (Smith et al., 2002). Complementary to BLa testing, the percentage of maximum heart rate (HR) also makes an important contribution to assess training intensity (Borresen and Lambert, 2008), although characterized as not very informative regarding an athlete's training status (Buchheit, 2014). Moreover, the critical velocity may be used as a feasible and practical approach for monitoring swimming training intensity (Tijani et al., 2021).

Near-infrared spectroscopy (NIRS) is a relatively new technique with increasing popularity due to the fact that it non-invasively and directly enables measurements of changes in tissue oxygenation and hemodynamics as a response to dynamic exercise (Bhambhani, 2004). Recently, this technology has been applied in swimming as a complementary method to monitor peripheral training adaptations, to examine acute training responses to athletes of different competitive levels, and to evaluate different active recovery protocols (Jones et al., 2018; Dalamitros et al., 2019; Pratama and Yimlamai, 2020). In addition, NIRS has been examined as a potential alternative to BLa measurement in swimmers of different training levels (Wu et al., 2015). However, in this latter case, the testing procedure included an incremental dry-land test.

In swimming training, interval sets of various intensities are daily incorporated to activate either aerobic or anaerobic processes. As such, exploring the potential relationship of different testing procedures used to assess training intensity, namely, muscle oxygenation, HR, and BLa during submaximal and maximal efforts, could be important for both swim coaches and for sports scientists. Moreover, since it has been reported that warm-up protocols of different intensities induce different BLa but not HR responses on a subsequent maximal 100 m time-trial (Neiva et al., 2017), it would be interesting if such results were examined using muscle oxygenation testing. Thus, the purpose of this study was to evaluate and compare the interrelationship between muscle oxygenation (SmO_2), HR, and BLa after a submaximal (Submax) or a maximal (Max) swimming interval protocol, and a main subsequent maximal interval set.

MATERIALS AND METHODS

Subjects

A total of twelve national-level swimmers, nine male ($n = 9$; age: 21.9 ± 2.0 years; body mass: 78.8 ± 9.8 kg; body height: 182.7 ± 8.1 cm; FINA 2019 scoring points: 578.4 ± 89.0) and three female ($n = 3$; age: 20.2 ± 1.5 years; weight: 64.5 ± 6.7 kg; height: 174.3 ± 3.5 cm; FINA 2019 scoring points: 638.7 ± 23.0), from two different swimming clubs participated in this study. Swimmers were specialized in various race distances and swimming techniques. Fédération Internationale de Natation (FINA) scoring calculation was based on each athlete's specialty event according to short course's 2019 world records. Written informed consent was obtained from each participant. All procedures were in accordance with the Helsinki declaration and were approved by the Institutional Review Board.

Methodology

Participants were engaged in two testing sessions. During the first session, anthropometric (body height and body mass) and training characteristics (distance specialty, preferred swimming technique, and best swimming times) were recorded. After completing a standardized in-water warm-up consisting of 1,200 m (continuous swimming/arm and kick drills/short sprints/cool down) following a 2 min passive rest, participants randomly performed either the Submax or the Max interval swimming protocol, in a counter-balanced order. Three days later, the second protocol was applied. Submax interval set consisted of 8 × 50 m intercepted with a 30 s passive rest, at an intensity corresponding to the critical velocity, which was calculated by 92% of the best performance during a maximal 400 m test (Zacca et al., 2016) conducted the week before the initiation of the study. During the Max interval protocol, swimmers performed a 4 × 15 m set starting at 1 min. Following both Submax and Max interval protocols, participants executed the main interval set consisting of 2 × 4 × 25 m at maximal intensity with a 30 s passive rest between each 25 m and 4 min between sets.

Muscle oxygen saturation (SmO_2) measurement was conducted with a portable near-infrared spectroscopy (NIRS) device (MOXY, Fortiori Design LLC, Hutchinson, Minnesota, USA). The SmO_2 of the deltoid muscle of the dominant arm of each participant was measured in a sitting position, with the swimmer's arms hanging freely to the side and fully relaxed. The device was placed in the middle of the muscle belly, while the exact position was pointed with a permanent marker to place the monitor in the same spot for each measurement. All athletes presented skinfold thickness less than the accepted limit of 12 mm at the measurement point (Barstow, 2019). SmO_2 of the relaxed muscle was recorded for 1 min at rest and the average values were analyzed. Subsequent recordings for SmO_2 measurements took place during the 1st post-exercise minute, giving adequate time for athletes to exit the water at three specific testing points: following the Submax or Max protocols, (TP_1), following the first 4 × 25 set, (TP_2), and following the second 4 × 25 set (TP_3). Simultaneously, during all tests, HR was recorded using chest belt telemetry (Polar S810 Electro, Kempele, Finland). To measure BLa, a portable analyzer (Lactate Scout 4, EKF Diagnostics, Germany) was used. BLa was collected at the second post-exercise min. SmO_2 and BLa measurements were conducted by two experienced examiners under the same conditions. The testing procedure is summarized in **Figure 1**.

All swim tests were performed using a push-off start from within the water with the front-crawl technique. Swimmers were instructed to avoid underwater gliding. All procedures were conducted during the same training period (December) and in the daytime (8:00:00–9.30:00 h), under the same water temperature (26–27°C) in an indoor 25 m swimming pool. Swimmers were advised to follow the same training routine as well as diet, hydration, and sleeping habits the day before testing.

Statistical Analysis

Kolmogorov-Smirnov test for normality, Pearson's correlation analysis, and analysis of variance (ANOVA) with repeated measures were conducted. SmO_2, BLa, and HR data were analyzed using two-way ANOVA (*protocol*: Submax and Max × *time*: TP_1, TP_2, and TP_3) with repeated measures on *time* factor. *Post-hoc* analyses were conducted using the Scheffé test. Correlation thresholds were classified as: <0.1 = *trivial*, <0.3 = *small*, <0.5 = *moderate*, <0.7 = *large*, <0.9 = *very large*, and ≤1.0 = *near perfect* (Hopkins et al., 2009). Effect size

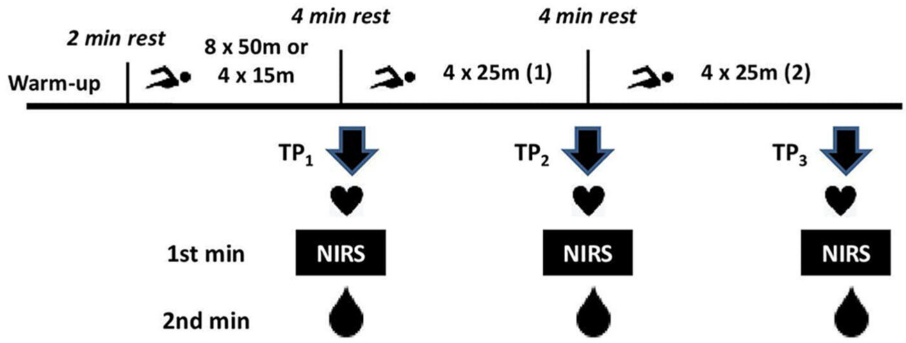

FIGURE 1 | Schematic representations of the testing procedure. TP_1 = testing point 1; TP_2 = testing point 2; TP_3 testing point 3.

(*ES*) values of $\leq$0.2, between 0.21, and 0.8, and >0.8 were considered as small, moderate, and large, respectively (Cohen, 1988). The statistical significance level was set at $p \leq 0.05$. All statistical analyses were conducted using SPSS 25.0 software (IBM, NY, USA). Data are presented as mean ± standard deviation (*SD*).

RESULTS

No effect of *protocol* was found ($p = 0.198$) in any of the measured parameters. In contrast, a significant main effect of *time* was revealed ($p < 0.001$). HR and BLa were increased between all three testing points at both protocols ($p < 0.05$; $p < 0.001$, *ES* range: 0.36–1.40). SmO_2 values were only different between TP_1 and TP_3 ($p < 0.05$ and 0.001; *ES*: 1.09 and 1.20, for the Submax and Max protocols, respectively), but not either TP_1 and TP_2 or TP_2 and TP3 after both protocols ($p > 0.05$) (**Table 1**).

Muscle oxygen saturation (SmO_2) and BLa values were *highly* correlated at TP_1 during the Max protocol ($r = 0.722$; $p < 0.05$), while *moderate* correlations were found at TP_2 and TP_3 ($r = 0.488$ and 0.498; $p > 0.05$). HR and SmO_2 showed a range of *moderate*-to-*high* correlation magnitudes during the three testing points at both protocols (*r* range: 0.645–0.728; $p < 0.01$), while a *very high* correlation was obtained at TP_1 after the Max protocol ($r = 0.931$; $p < 0.01$). Similarly, BLa and HR correlation coefficient were also *moderate*-to-*high* at all testing points in both protocols (*r* range: 0.595–0.694; $p < 0.05$). Finally, *small* correlations were observed between SmO_2 and BLa during the Submax protocol at all testing points (*r* range: 0.147–0.285; $p > 0.05$) (**Table 2**).

DISCUSSION

The application of portable near-infrared spectroscopy technology in the sport performance area is progressively increasing. The present study demonstrated that the muscle oxygenation variable evaluated (SmO_2) was mainly correlated with BLa and HR values after the Max protocol. That is, immediately after the completion of a very low volume sprint interval set (4 × 15 m, duration of 7–8 s).

A significant correlation between SmO_2 and BLa values has been previously described in swimmers during incremental testing performed on dry land. In this case, the application of NIRS technology was suggested as a non-invasive alternative to BLa testing (Wu et al., 2015). The novelty of our study is that, for the first time, this interrelationship was examined during interval efforts based on anaerobic and aerobic metabolism that are regularly applied in swimming training.

Understanding muscle physiology during dynamic exercise is essential for evaluating exercise intensity. SmO_2 values of the deltoid muscle during front-crawl swimming provided a clear representation of the balance between O_2 delivery and extraction of the body's part which mostly functions during horizontal propulsion (Morouço et al., 2015). BLa, on its part, is sensitive to changes in exercise intensity and duration (Beneke et al., 2011). On the other hand, real-time data accumulation through NIRS is a useful evaluation tool during training efforts (Jones et al., 2018). Thus, the conjunction of the two testing procedures may prove beneficial for accurately and thoroughly evaluating intensity during swimming. In the present study, muscle oxygenation was reduced progressively regardless of the intensity of the "priming" exercise (Submax or Max protocols). However, a limitation of the present study may be recognized by the post-swimming NIRS measurement. This was applied to avoid any movement of the apparatus on the muscle during fast arm movements. One-minute post-swim values are expected to be higher compared to the values during swimming. In this case, swimming and recovery rate values may be different between protocols, but this was not detected with a single recovery sampling, thus affecting the correlation between SmO_2 with BLa and HR. On the other hand, collecting recovery values makes the measurement more practical and feasible to use during training.

Swimming coaches and sports scientists usually apply field tests during both training and competition. In this sense, BLa and HR measurements serve as "standard" physiological testing procedures. Acknowledging that different responses, especially in

TABLE 1 | Statistical significance, effect size, muscle oxygen saturation, heart rate, and blood lactate values at all testing points during both protocols.

Protocol	Variables	TP_1	TP_2	TP_3	*P*	*ES*
Submax	SmO_2 (%)	59.4 ± 9.1	52.2 ± 10.6	48.3 ± 11.2	0.046[a]	0.36–1.09
	HR ($b \cdot min^{-1}$)	154 ± 19.7	170 ± 8.8	174 ± 8.9	0.003[a,b]	0.45–1.40
	BLa ($mmol \cdot L^{-1}$)	3.5 ± 1.4	8.4 ± 2.5	11.8 ± 3.0	0.000[c,d,e]	0.52–1.24
Max	SmO_2 (%)	57.0 ± 6.4	47.8 ± 9.0	37.8 ± 11.4	0.001[c]	1.19–1.20
	HR ($b \cdot min^{-1}$)	145 ± 14.2	167 ± 11.0	172 ± 6.4	0.000[c,d,e]	0.57–0.22
	BLa ($mmol \cdot L^{-1}$)	4.4 ± 1.5	9.5 ± 2.6	12.7 ± 2.9	0.000[c,d,e]	0.49–1.16

Submax protocol: 8 × 50 m; Max protocol: 4 × 15 m; TP_1, Testing point after the 8 × 50 m or the 4 x 15 m; TP_2, Testing point after the 1st 4 × 25 m; TP_3, Testing point after the 2nd 4 × 25 m; SmO_2, muscle oxygenation; BLa, blood lactate concentration; HR, heart rate; [a]TP_1 significantly different from TP_3 ($p < 0.05$), [b]TP_1 significantly different from TP_2 ($p < 0.05$); [c]TP_1 significantly different from TP3 ($p < 0.001$); [d]TP_1 significantly different from TP_2 ($p < 0.001$); [e]TP_2 significantly different from TP_3 ($p < 0.001$).

TABLE 2 | Pearson's correlation magnitudes between the different testing procedures at all testing points during both protocols.

Submax protocol								
	TP_1			TP_2			TP_3	
	BLa	HR		BLa	HR		BLa	HR
SmO_2	0.147	0.683*	SmO_2	0.202	0.695*	SmO_2	0.285	0.645*
BLa		0.595*	BLa		0.660*	BLa		0.679*
Max protocol								
	TP_1			TP_2			TP_3	
	BLa	HR		BLa	HR		BLa	HR
SmO_2	0.722*	0.931**	SmO_2	0.488	0.723*	SmO_2	0.498	0.728*
BLa		0.694*	BLa		0.694*	BLa		0.622*

*Submax protocol: 8 × 50 m; Max protocol: 4 × 15 m; TP_1: Testing point after the 8 × 50 m or the 4 x 15 m; TP_2, Testing point after the 1st 4 × 25 m; TP_3, Testing point after the 2nd 4 × 25 m; SmO_2, muscle oxygenation; BLa, blood lactate concentration; HR, heart rate. *$p < 0.05$; **$p < 0.01$.*

high training efforts, have been shown during BLa and HR testing in swimming (Skorski et al., 2012), their usage in combination with near-infrared spectroscopy measurement can be realized as a form of alternative or complementary method, depending on the performed exercise intensity. Moreover, it may potentially offer a non-invasive analysis of dynamic changes in oxygenation and blood volume, detect the relative muscles contribution, and assess training-induced adaptations after endurance training (Jones and Cooper, 2016; Jones et al., 2018). Future studies should consider this relationship in swimming distances of longer duration.

The interpretation and practical translation of the data collected from the NIRS portable device is probably the biggest challenge when this type of technology is applied. Information on skeletal muscle oxygen levels can increase the understanding regarding the internal load of both active and less active muscles as evident in the case of two or more monitors being involved during training and recovery periods (Manchado-Gobatto et al., 2020). Moreover, high muscle deoxygenation values, like those obtained during sprint interval sets, may be linked to greater peripheral adaptations (Paquette et al., 2019) or may even characterize the training status among individuals (Ding et al., 2001). Overall, NIRS method is presented as an appropriate solution for quick and continuous field-based evaluation in a variety of sports, thus, assessing both acute and chronic adaptations, while characterized by high sensitivity in different exercise demands and good reproducibility values (Perrey and Ferrari, 2018). Still, protocol standardization is vital considering the existing limitations, such as the impact of adipose tissue thickness and the need for suitable physiological calibration (McManus et al., 2018; Barstow, 2019).

The application of the NIRS technology to monitor muscle oxygenation responses in this study (MOXY monitor) has been recently used in different sport activities, including sprint kayaking, sport climbing, and cross-country skiing. In general, these studies highlighted the potential of this research tool to provide information regarding peripheral adaptations following high-intensity interval training (Paquette et al., 2019, 2021), SmO_2 availability in different exercise intensities (Feldmann et al., 2020), and muscle activation of upper and lower muscle groups during a long distance race (Stöggl and Born, 2021). In this study, the implementation of a low volume maximal intensity set (2 × 4 × 25 m) was driven by previous findings indicating significant BLa increases with a similar training stimulus (Kabasakalis et al., 2020), while the rest of the intervals were guided by the need to perform the measurements. The specific Submax and Max protocols applied were chosen based on stimulating different metabolic energy systems. In accordance with a previous swimming study that analyzed the responses of different warm-up intensities on BLa and HR levels (Neiva et al., 2017), both Submax and Max protocols concluded no significant variations on the respective values in any of the three testing points. Therefore, it can be suggested that physiological testing during maximal short interval performance is not affected by previous "pre-activation" protocols.

In conclusion, after maximal swimming protocols consisted of very short (i.e., 15 m) and short interval efforts (i.e., 25 m), a high interrelationship between values of muscle oxygenation as expressed by muscle oxygen saturation, heart rate, and blood lactate testing were revealed as compared to those obtained after an identical protocol where lower intensity interval efforts were initially applied.

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/s.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Vasilis Mougios, Aristotle University of Thessaloniki, Department of Physical Education & Sport Science, Evangelia Kouidi, Aristotle University of Thessaloniki, Department of Physical Education & Sport Science Giorgos Grouios, Aristotle University of Thessaloniki, Department of Physical Education & Sport Science. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

AD, ES, and AK collected the data. ES and AK analyzed the data. AD, ES, and AK wrote the manuscript. AT revised the manuscript. All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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REFERENCES

Barstow, T. J. (2019). Understanding near infrared spectroscopy and its application to skeletal muscle research. *J. Appl. Physiol*. 126, 1360–1376. doi: 10.1152/japplphysiol.00166.2018

Beneke, R., Leithauser, R. M., and Ochentel, O. (2011). Blood lactate diagnostics in exercise testing and training. *Int. J. Sports. Physiol. Perform.* 6, 8–24. doi: 10.1123/ijspp.6.1.8

Bhambhani, Y. N. (2004). Muscle oxygenation trends during dynamic exercise measured by near infrared spectroscopy. *Can. J. Appl. Physiol*. 29, 504–523. doi: 10.1139/h04-033

Borresen, J., and Lambert, M. I. (2008). Quantifying training load: a comparison of subjective and objective methods. *Int. J. Sports Physiol. Perform*. 3, 16–30. doi: 10.1123/ijspp.3.1.16

Buchheit, M. (2014). Monitoring training status with HR measures: do all roads lead to Rome? *Front. Physiol*. 5:73. doi: 10.3389/fphys.2014.00073

Cohen, J. (1988). *Statistical Power Analysis for the Behavioral Sciences.* 2nd edn. New York, NY: Lawrence Erlbaum Associates.

Dalamitros, A. A., Mavridis, G., Semaltianou, E., Loupos, D., and Manou, V. (2019). Psychophysiological and performance-related responses of a potentiation activity in swimmers of different competitive levels. *Physiol. Behav*. 204, 106–111. doi: 10.1016/j.physbeh.2019.02.018

Ding, H., Wang, G., Lei, W., Wang, R., Huang, L., Xia, Q., et al. (2001). Non-invasive quantitative assessment of oxidative metabolism in quadriceps muscles by near infrared spectroscopy. *Br. J. Sports Med*. 35, 441–444. doi: 10.1136/bjsm.35.6.441

Feldmann, A. M., Erlacher, D., Pfister, S., and Lehmann, R. (2020). Muscle oxygen dynamics in elite climbers during finger-hang tests at varying intensities. *Sci. Rep*. 10:3040. doi: 10.1038/s41598-020-60029-y

Hopkins, W. G., Marshall, S. W., Batterham, A. M., and Hanin, J. (2009). Progressive statistics for studies in sports medicine and exercise science. *Med. Sci. Sports Exerc.* 41, 3–12. doi: 10.1249/MSS.0b013e31818cb278

Jones, B., and Cooper, C. E. (2016). Underwater near-infrared spectroscopy: muscle oxygen changes in the upper and lower extremities in club level swimmers and triathletes. *Adv. Exp. Med. Biol*. 876, 35–40. doi: 10.1007/978-1-4939-3023-4_4

Jones, B., Parry, D., and Cooper, C. E. (2018). Underwater near-infrared spectroscopy can measure training adaptations in adolescent swimmers. *PeerJ* 6:e4393. doi: 10.7717/peerj.4393

Kabasakalis, A., Nikolaidis, S., Tsalis, G., and Mougios, V. (2020). Response of blood biomarkers to sprint interval swimming. *Int. J. Sports Physiol. Perform*. 22, 1442–1447. doi: 10.1123/ijspp.2019-0747

Manchado-Gobatto, F. B., Marostegan, A. B., Rasteiro, F. M., Cirino, C., Cruz, J. P., Moreno, M. A., et al. (2020). New insights into mechanical, metabolic and muscle oxygenation signals during and after high-intensity tethered running. *Sci. Rep*. 10:6336. doi: 10.1038/s41598-020-63297-w

McManus, C. J., Collison, J., and Cooper, C. E. (2018). Performance comparison of the MOXY and PortaMon near-infrared spectroscopy muscle oximeters at rest and during exercise. *J. Biomed. Opt*. 23, 1–14. doi: 10.1117/1.JBO.23.1.015007

Morouço, P. G., Marinho, D. A., Izquierdo, M., Neiva, H., and Marques, M. C. (2015). Relative contribution of arms and legs in 30 s fully tethered front crawl swimming. *J. Biomed. Biotechnol*. 563206, 1–6. doi: 10.1155/2015/563206

Neiva, H. P., Marques, M. C., Barbosa, T. M., Izquierdo, M., Viana, J. L., Teixeira, A. M., et al. (2017). Warm-up for sprint swimming: race-pace or aerobic stimulation? A randomized study. *J. Strength Cond. Res*. 31, 2423–2431. doi: 10.1519/JSC.0000000000001701

Paquette, M., Bieuzen, F., and Billaut, F. (2019). Sustained muscle deoxygenation vs. sustained high VO2 during high-intensity interval training in sprint canoe-kayak. *Front. Sports Act. Living*. 1:6. doi: 10.3389/fspor.2019.00006

Paquette, M., Bieuzen, F., and Billaut, F. (2021). The effect of HIIT vs. SIT on muscle oxygenation in trained sprint kayakers. *Eur. J. Appl. Physiol*. 121, 2743–2759. doi: 10.1007/s00421-021-04743-z

Perrey, S., and Ferrari, M. (2018). Muscle oximetry in sports science: a systematic review. *Sports Med*. 48, 597–616. doi: 10.1007/s40279-017-0820-1

Pratama, A. B., and Yimlamai, T. (2020). Effects of active and passive recovery on muscle oxygenation and swimming performance. *Int J. Sports Physiol. Perform.* 15, 1289–1296. doi: 10.1123/ijspp.2019-0537

Skorski, S., Faude, O., Urhausen, A., Kindermann, W., and Meyer, T. (2012). Intensity control in swim training by means of the individual anaerobic threshold. *J. Strength Cond. Res*. 26, 3304–3311. doi: 10.1519/JSC.0b013e31824b6014

Smith, D. J., Norris, S. R., and Hogg, J. M. (2002). Performance evaluation of swimmers: scientific tools. *Sports Med*. 32, 539–554. doi: 10.2165/00007256-200232090-00001

Stöggl, T., and Born, D.-P. (2021). Near infrared spectroscopy for muscle specific analysis of intensity and fatigue during cross-country skiing competition—a case report. *Sensors* 21:2535. doi: 10.3390/s21072535

Swart, J., and Jennings, C. L. (2004). Use of blood lactate concentration as a marker of training status. *S. Afr. J. Sports. Med*. 16, 1–5.

Tijani, J. M., Rhibi, F., Zouhal, H., Dalamitros, A. A., and Ben Abderrahman, A. (2021). Effect of training at intensities around critical velocity on 400 meters front crawl performance in young swimmers. *J. Sports Med. Phys. Fitness*. doi: 10.23736/S0022-4707.21.12314-X. [Epub ahead of print].

Wu, Y., Song, T., and Xu, G. (2015). Changes of muscle oxygenation and blood lactate concentration of swimming athletes during graded incremental exercise. *Front. Optoelectron*. 8, 451–455. doi: 10.1007/s12200-015-0532-9

Zacca, R., Fernandes, R. J., Pyne, D. B., and Castro, F. A. (2016). Swimming training assessment: the critical velocity and the 400-m test for age-group swimmers. *J. Strength Cond. Res*. 30, 1365–1372. doi: 10.1519/JSC.0000000000001239

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Are Young Swimmers Short and Middle Distances Energy Cost Sex-Specific?

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This study assessed the energy cost in swimming (C) during short and middle distances to analyze the sex-specific responses of C during supramaximal velocity and whether body composition account to the expected differences. Twenty-six swimmers (13 men and 13 women: 16.7 ± 1.9 vs. 15.5 ± 2.8 years old and 70.8 ± 10.6 vs. 55.9 ± 7.0 kg of weight) performed maximal front crawl swimming trials in 50, 100, and 200 m. The oxygen uptake ($\dot{V}O_2$) was analyzed along with the tests (and post-exercise) through a portable gas analyser connected to a respiratory snorkel. Blood samples were collected before and after exercise (at the 1st, 3rd, 5th, and 7th min) to determine blood lactate concentration [La$^-$]. The lean mass of the trunk (LM_{Trunk}), upper limb (LM_{UL}), and lower limb (LM_{LL}) was assessed using dual X-ray energy absorptiometry. Anaerobic energy demand was calculated from the phosphagen and glycolytic components, with the first corresponding to the fast component of the $\dot{V}O_2$ bi-exponential recovery phase and the second from the 2.72 ml × kg^{-1} equivalent for each 1.0 mmol × L^{-1} [La$^-$] variation above the baseline value. The aerobic demand was obtained from the integral value of the $\dot{V}O_2$ vs. swimming time curve. The C was estimated by the rate between total energy releasing (in Joules) and swimming velocity. The sex effect on C for each swimming trial was verified by the two-way ANOVA (Bonferroni *post hoc* test) and the relationships between LM_{Trunk}, LM_{UL}, and LM_{LL} to C were tested by Pearson coefficient. The C was higher for men than women in 50 (1.8 ± 0.3 vs. 1.3 ± 0.3 kJ × m^{-1}), 100 (1.4 ± 0.1 vs. 1.0 ± 0.2 kJ × m^{-1}), and 200 m (1.0 ± 0.2 vs. 0.8 ± 0.1 kJ × m^{-1}) with $p < 0.01$ for all comparisons. In addition, C differed between distances for each sex ($p < 0.01$). The regional LM_{Trunk} (26.5 ± 3.6 vs. 20.1 ± 2.6 kg), LM_{UL} (6.8 ± 1.0 vs. 4.3 ± 0.8 kg), and LM_{LL} (20.4 ± 2.6 vs. 13.6 ± 2.5 kg) for men vs. women were significantly correlated to C in 50 (R^2_{adj} = 0.73), 100 (R^2_{adj} = 0.61), and 200 m (R^2_{adj} = 0.60, $p < 0.01$). Therefore, the increase in C with distance is higher for men than women and is determined by the lean mass in trunk and upper and lower limbs independent of the differences in body composition between sexes.

Keywords: oxygen uptake, energy demand, swimming performance, body composition, sex

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INTRODUCTION

Swimming energy cost (C) expresses the effectiveness of a motor task, allowing the analysis of the motor ability to save or enhance energy production and reflect skilled performance level and muscular work capacity (respectively) from low to high swimming intensities (Fernandes et al., 2006; Zamparo et al., 2008, 2011; Gonjo et al., 2018). In a front crawl, C increases from 0.70 to 1.23 kJ × m^{-1} at 1.0 and 1.5 m × s^{-1}, reaching 2.20 kJ × m^{-1} at 2 m × s^{-1} among elite male swimmers (Capelli et al., 1998). The alteration from low to high velocities in swimming requires both muscle power output and energy release to be increased proportionally. Therefore, C defines how mechanical and metabolic capabilities interact to enhance swimming velocity and tolerance according to swimmer sex-group, training status (Toussaint and Hollander, 1994; Capelli et al., 1998; Fernandes et al., 2005, 2006), technical level, and swimming stroke technique (di Prampero et al., 2008; Gonjo et al., 2018).

In elite male swimmers, the energy requirements reach ∼3.33, ∼2.72, and ∼1.94 kW at 45.7, 91.4, and 182.9 m in a front crawl performed at ∼1.97, ∼1.75, and ∼1.62 m × s^{-1} (Capelli et al., 1998). However, the energy requirements attained ∼3.16, ∼1.86, and ∼1.25 kW for young swimmers from both sexes performing 50, 100, and 200 m in a front crawl at ∼1.67, ∼1.46, and ∼1.29 m × s^{-1} (Almeida et al., 2020). These differences in energy contributions and swimming performances would probably rely on the swimmers' technical and conditioning levels (Fernandes et al., 2006). Muscle mass and fiber composition can also account to those differences, since muscle strength, anaerobic power, and reliance on glycolytic motor units are age group performance influencing factors in short distance swimming races (Hellard et al., 2018).

It is reasonable to consider the amount of muscle mass involved in an exercise with a reliable index of the energetic contribution during a high intensity performance. This is due to how the potential of metabolic resources to the energy releasing can be scaled in body size units, e.g., 0.418 kJ × kg^{-1} for phosphocreatine, 0.0689 kJ × $mmol^{-1}$ × kg^{-1} for blood lactate accumulation, and 0.125 kJ × kg^{-1} for O_2 stored in arterial blood, i.e., ∼6 ml × kg^{-1} (Medbo et al., 1988). Nevertheless, other key attributes beyond larger muscle mass to anaerobic releasing are greater fast-type muscle fiber composition (enhancing enzymatic lactate dehydrogenase inhibition/activation rulers and redox potential) and glycogen source, which differ between sexes (Esbjörnsson et al., 1993; Esbjörnsson-Liljedahl et al., 1999).

These differences can reflect the advantage in power production by the body region wherein lean mass is larger, e.g., for upper limbs, when comparing men to women (Weber et al., 2006). In swimming, studies corroborating the role of lean mass on high intensity exercise performance have demonstrated that lean mass in upper-limbs correlates with the maximal aerobic velocity, the velocity at 200 m races, and anaerobic reserve estimates among young men (Pessôa Filho et al., 2016). In addition, the highest muscle mass in upper and lower limbs is associated with higher aerobic and anaerobic release during performances lasting 2–3 min among swimmers of both sexes (Ogita et al., 1996). Furthermore, the 400 m front crawl swimming performance peak $\dot{V}O_2$ and C differed between prepubertal and pubertal male swimmers, which was a result that can be explained considering the differences in anthropometrical variables, including lean mass (Jürimäe et al., 2007).

However, while adenosine triphosphate turnover requirements of short to middle swimming distances (e.g., 50, 100, and 200 m) are preconized to rely on large anaerobic metabolism demand, with aerobic contribution rising in proportionality to distance-trial length (Almeida et al., 2020), the assumptions for the sex-specific response regarding C and the role of lean mass is lacking. C values for both sexes have been reported for maximal and supramaximal velocities (Zamparo et al., 2000) but the values of C were measured at 1.2, 1.4, and 1.6 m × s^{-1}, which were not necessarily velocities corresponding to 50, 100, and 200 m trial performances for all tested swimmers. In addition, the reasons explaining the C differences between sexes at these swimming intensities remain elusive.

Therefore, the association between velocity and energy supply, having sex-based factors as a rule, would evidence a limited rate of energy release for a specific metabolic pathway due to muscle mass difference, even when technical and conditioning levels remain constant. The lack of studies comparing male and female swimmers underappreciated the role of regional and whole-body composition on race performance and swimming training specificity for men and women. Moreover, considering the specific C values during short (50 and 100 m) and middle distances swimming efforts (200 m), the sex differences regarding regional and whole-body lean mass would expect to have an important role. The current study aimed to analyze the C sex-specific responses during supramaximal velocity and if body composition account to the expected differences.

MATERIALS AND METHODS

Twenty-six swimmers participated in the current study (13 men and 13 women with 16.7 ± 1.9 vs. 15.5 ± 2.8 years of age, 178.4 ± 8.4 vs. 162.9 ± 7.6 cm of height, 70.8 ± 10.6 vs. 55.9 ± 7.0 kg of weight). All swimmers were regularly engaged in competitive training programs for at least three annual seasons, with a volume of 25 km × $week^{-1}$ during the testing application. Their best front crawl performances at the 50, 100, and 200 m represented 575 ± 95 vs. 534 ± 63, 599 ± 100 vs. 529 ± 78, and 588 ± 94 vs. 552 ± 83 FINA points for male and female swimmers, respectively. Participants were informed about all the study procedures and experimental risks and signed a written informed consent (or their legal guardians when under 18 years old) prior to the experiments. The current research was conducted according to the Declaration of Helsinki and was approved by the Ethics Committee of the São Paulo State University (Protocol 54372516.3.0000.5398).

The participants performed five tests, all in front crawl and separated by, at least, 24 h: (i) a 200 m maximal test to establish the velocities during the incremental step test; (ii) an incremental step test performed in six progressive steps

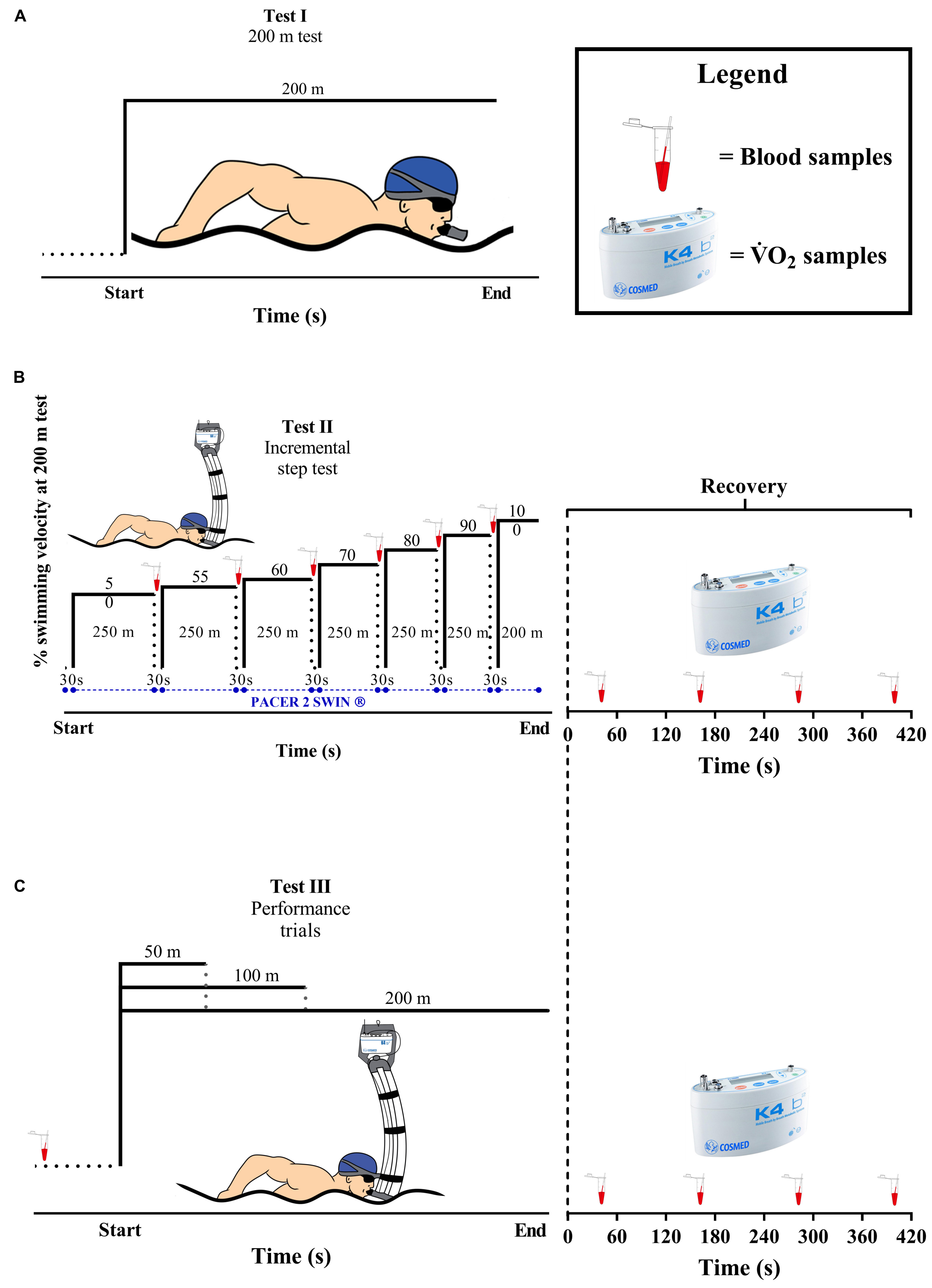

FIGURE 1 | An overview of the experimental protocol. **(A)** The 200 m maximal test. **(B)** The incremental step test. **(C)** 50, 100, and 200 m maximal trials.

TABLE 1 | Performance and physiological profiles during short and middle distance races.

	Distances (m)		
	50	100	200
Time (s)			
Men	30.0 ± 2.9	67.5 ± 5.3‡‡	159.3 ± 12.3‡‡§§
Women	33.0 ± 0.5**	71.0 ± 3.3‡‡	164.1 ± 8.1‡‡§§
Velocity ($m \times s^{-1}$)			
Men	1.68 ± 0.17	1.49 ± 0.12‡‡	1.26 ± 0.09‡‡§§
Women	1.52 ± 0.07**	1.41 ± 0.07*‡‡	1.22 ± 0.06‡‡§§
$[La\text{-}]_{peak}$ ($mmol \times L^{-1}$)			
Men	9.2 ± 1.9	11.4 ± 2.1‡‡	10.2 ± 1.8
Women	9.8 ± 1.4	11.6 ± 1.8‡‡	10.9 ± 1.4
Energy, EqO_2 (L)			
Men	4.13 ± 0.67	6.38 ± 0.77‡‡	9.85 ± 1.59‡‡§§
Women	3.08 ± 0.66**	4.77 ± 0.97**‡‡	7.94 ± 1.22**‡‡§§
Power ($kJ \times s^{-1}$)			
Men	2.92 ± 0.64	1.99 ± 0.33‡‡	1.30 ± 0.21‡‡§§
Women	1.96 ± 0.41**	1.41 ± 0.32**‡‡	1.01 ± 0.16**‡‡§§

*Significantly different from men at $p \leq 0.01$** in 50, 100, and 200 m.*
Significantly different from 50 m at $p \leq 0.01$‡‡.
Significantly different from 100 m at $p \leq 0.01$§§.

of 250 m at 50, 55, 60, 70, 80, and 90% plus a single set at 100% of 200 m test, or until voluntary exhaustion (i.e., when swimmers were unable to follow the pacing or stop the exercise (Almeida et al., 2021); and (iii) 50, 100, and 200 m maximal trials (see **Figure 1**). The control of the swimming velocity during the incremental step test was provided by an underwater LED circuit (Pacer2 Swim®, KulzerTEC, Aveiro, Portugal). At the end of each step, a passive rest (30 s) was performed for blood lactate sampling. All procedures were performed in a 25 m indoor pool and, to minimize the differences of prior exercise and the circadian rhythms effects, the same environmental conditions were applied (~50 of relative humidity, ~28°C of water temperature, and ±2 h of time of day). The tests were performed during the preparatory period of the training season, and all swimmers went through a familiarization process with the gas collection instruments in the week before the experiments.

Pulmonary gas exchange was analyzed breath-by-breath during and in the 420 s after the incremental step test and the 50, 100, and 200 m maximal trials were analyzed using a portable gas analyzer ($K4b^2$, Cosmed, Rome, Italy) connected to the swimmer by a respiratory snorkel (new-AquaTrainer®, Cosmed, Rome, Italy; Baldari et al., 2013). The $K4b^2$ unit was calibrated before each test according to the manufacturer's instructions, and the snorkel was connected to the swimmer before each test for assessing the $\dot{V}O_2$ baseline (e.g., last 30 s averaged values sampled with swimmer resting for 10 min seated on the pool wall). Blood samples (25 μl) were collected before each test, during the intervals of the incremental step test, and at the 1st, 3rd, 5th, and 7th min after all tests for peak blood lactate concentration determination ($[La^-]_{peak}$) (YSI, 2300 STAT, Yellow Springs, OH, United States).

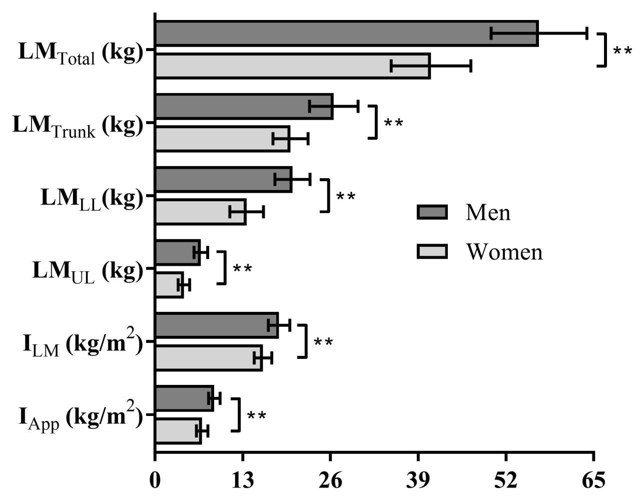

FIGURE 2 | Body composition variables for men and women. Obs.: Significantly different at $\rho \leq 0.01$**.

Dual-energy x-ray absorptiometry (DXA; Hologic®,QDR Discovery Wi®) was used for obtaining regional and whole-body composition, with the software Hologic APEX® displaying values for body mass, bone mass, body lean mass (LM_{Total}), trunk lean mass (LM_{Trunk}), upper limb lean mass (LM_{UL}), lower limb lean mass (LM_{LL}), lean mass index ($I_{LM} = LM \times H^{1/2}$), and appendicular muscle index ($I_{App} = LM_{App} \times H^{1/2}$). The measurements for upper and lower limbs are the results from the sum of the left and right upper and lower limbs values, respectively, the trunk measurements corresponded to the central body region (from neck to pelvis), and the lean mass measurements result from fat free mass minus bone mineral content (Sala et al., 2007). The equipment was calibrated following the manufacturer's recommendations, and all the analysis were operated by an experienced technician. Participants wore light clothing and were positioned in the supine position on a flat table with the feet close together and the upper limbs placed parallel to the trunk.

The $\dot{V}O_2$ data obtained during incremental step test were smoothed (3 s filter and 15 s moving mean) and peak $\dot{V}O_2$ ($\dot{V}O_{2peak}$) considered the highest value observed, while the velocity at the stage where the $\dot{V}O_{2peak}$ was attained and was corresponded to the $v\dot{V}O_{2peak}$, despite the swimmer being able to initiate another step and the $\dot{V}O_2$ rise was not larger than ~2 ml × min^{-1} × kg^{-1} (Reis et al., 2012). From the performance of 50, 100, and 200 m, the breath-by-breath $\dot{V}O_2$ was continuously sampled during each trial with a recovery for 420 s. The data were time aligned, followed by noise exclusion (coughing, sighing, and sneezing), which were defined as three standard-deviation from the local mean of five breaths and, finally, the data were interpolated second-by-second (Pessoa Filho et al., 2012). $\dot{V}O_2$ off-kinetics was adjusted by a biexponential equation according to Scheuermann et al. (2001) (Eq. 1):

$$VO_2\,(t) = EEVO_2 - A_{1\,off}\left\{1 - e^{-\left[\left(t_f - TD_1\right)/\tau_1\right]}\right\} - A_{2\,off}\left\{1 - e^{-\left[\left(t_f - TD_2\right)/\tau 2\right]}\right\} \quad (1)$$

where $EE\dot{V}O_2$ is the end-exercise $\dot{V}O_2$ (the last 15 s moving averaged value), representing the baseline at the very onset of the recovery phase. The physiologically relevant exponential $\dot{V}O_2$ response is the primary phase (A_{1off}) of the recovery curve and the amplitude of the second phase (A_{2off}) corresponds to the slow component of $\dot{V}O_2$ recovery ($SC\dot{V}O_2$). The time delay (TD_1 and TD_2) and time constants (τ_1 and τ_2) describe the onset and the velocity of $\dot{V}O_2$ recovery in each phase and t_f is the total recovery time. The cardiodynamic phase at the beginning of the recovery was excluded by removing the first 15–20 s of $\dot{V}O_2$ response (Özyener et al., 2001).

During each swimming test, the aerobic energy demand (E_{Aer}) was obtained from the net $\dot{V}O_2$ curve time integral (Eq. 2), and the anaerobic energy demand (E_{An}), in O_2 equivalents (EqO_2), was obtained by the phosphagen (E_{PCr}) and glycolytic ($E_{[La-]}$) components (Margaria et al., 1933; di Prampero and Ferretti, 1999). The E_{PCr} was determined from the recovery phase fast component ($\dot{V}O_{2Fast}$) using data from the off-kinetic primary phase considering the $\dot{V}O_2$ magnitude from the TD_1 limited to the total recovery time (Stirling et al., 2005; Eq. 3). The amount of 9% corresponding to O_2 body reserves was subtracted from $\dot{V}O_{2Fast}$ to strictly reflect the E_{PCr} debt after exercise (Medbo et al., 1988; di Prampero and Ferretti, 1999; Weber and Schneider, 2002). $E_{[La-]}$ was determined according to Eq. 4 (di Prampero and Ferretti, 1999).

$$E_{\mathrm{Aer}} = \int_{t_0}^{t_{Lim}} \dot{V}O_2 \times \mathrm{d}t \quad (2)$$

$$\dot{V}O_{2Fast} = A_{1_{Off}} \times \tau_1 \left\{1 - \mathrm{e}^{\left[\left(t_f - TD_1\right)/\tau_1\right]}\right\} + A_{1_{Off}}\left\{\left(TD_1 - t_f\right)\mathrm{e}^{\left[\left(t_f - TD_1\right)/\tau_1\right]}\right\} \quad (3)$$

$$E_{[\mathrm{La}^-]} = \left[\left(\beta \times \Delta[\mathrm{La}^{-1}] \times \mathrm{BM}\right)\right] \quad (4)$$

where β is the O_2 equivalent for each 1.0 mmol × L^{-1} [La$^-$] of variation above the baseline value corresponding to 2.72 ml × kg^{-1} in swimming, Δ[La$^-$] is the variation of the [La$^-$] above the resting value (Δ[La$^-$] = $[La^-]_{peak}$ - $[La^-]_{rest}$), and BM is the whole-body mass in kg.

The estimated absolute values of each of the above-referred energetic components provide total energetic demand (E_{Total}) and were converted into J, assuming an energy equivalent of 20.9 kJ × LO_2^{-1}. Subsequently, this energy demand was normalized by the performance time, providing a value in kJ × s^{-1}, i.e., the absolute power equivalent. Finally, this power unit was rated by the swimming velocity for each swimming distance providing the C (kJ × m^{-1}). The value of the anaerobic C (C_{An}) was determined by the sum of C_{PCr} and $C_{[La-]}$, and the total cost (C_{Total}) was obtained from the sum of the C_{An} and aerobic C (C_{Aer}).

Normality of the data was checked with Shapiro-Wilk test ($n < 50$), the sphericity by the Mauchly test, and using the Greenhouse-Geisser correction when violated. Independent *t*-student test analyzed the effect of sex on body composition variables and on swimming velocity, time performance, $[La^-]_{peak}$, and estimated absolute values in EqO_2, P, and E_{Total} for each of the studied test distances. The differences in energetics and C values between sexes (men vs. women) by distances (i.e., 50, 100, and 200 m) and for each distance by sex were tested by the two-way ANOVA, with Bonferroni as *post hoc* test for pairwise comparison. The effect size for the *t*-student test was calculated using Hedges' *g* and interpreted as follows: <0.19 (insignificant), 0.20–0.49 (small), 0.50–0.79 (moderate), 0.80–1.29 (large), and >1.30 (very large) (Rosenthal, 1996). For ANOVA, the partial square eta ($\eta^2{}_p$) was used and interpreted as follows: 0.0099 (small), 0.0588 (medium), and 0.1379 (large; Cohen, 1988).

The relationships between C and body composition variables were assessed by Pearson's coefficient and classified as follows: 0.00–0.29 (small), 0.30–0.49 (low), 0.50–0.69 (moderate), 0.70–0.89 (high), and 0.90–1.00 (very high; Mukaka, 2012). The regression coefficient that was adjusted to the sample ($R^2{}_{adj}$) analyzed the similarity of variance between C and body composition variables during each 50, 100, and 200 m distance and was considered as <0.04 (trivial), 0.04–0.24 (small), 0.25–0.63 (medium), and >0.64 (strong; Ferguson, 2009). Pearson and

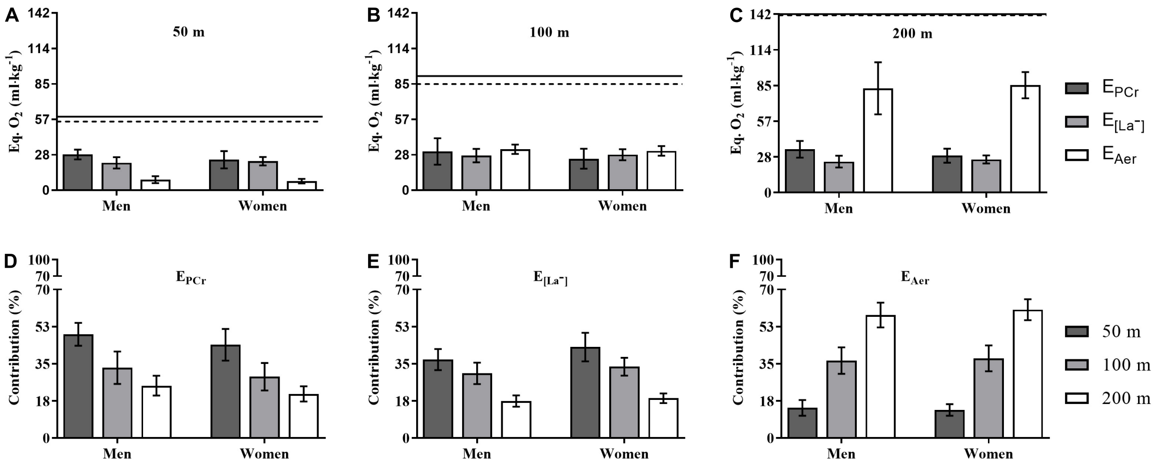

FIGURE 3 | The energetic demand **(A–C)** contribution **(D–F)** to the performance in 50, 100, and 200 m for men and women. Obs.: Horizontal continuous and traced lines at the top of Panels **(A–C)** refer to E_{Total} for men and women, respectively. The acronyms E_{PCr}, $E_{[La-]}$, and E_{Aer} represent the phosphagenic, glycolytic, and aerobic components of E_{Total}. See text for statistical analysis.

regression analysis were controlled for the sex-specific variance of the values. The sample power for the coefficient of correlation, considering the sample size, was the corresponding value of $Z\alpha = 1.96$ for a security index of $\alpha = 0.05$. The level of significance was set at $\rho \leq 0.05$ for all analysis, with all statistical analyzes performed with the Statistical Package for the Social Sciences (SPSS, version 26.0, Chicago, IL, United States).

RESULTS

The $\dot{V}O_{2peak}$ values associated to the incremental test was 4.05 ± 0.46 and 3.09 ± 0.36 LO_2, and $v\dot{V}O_{2peak}$ corresponded to 1.30 ± 0.07 and 1.20 ± 0.06 $m \times s^{-1}$, respectively, for men and women. During the v50m, v100m, and v200m, the performances corresponded to 129.8 ± 13.7, 114.8 ± 9.0, and 97.4 ± 7.9% of $v\dot{V}O_{2peak}$ for men and 126.7 ± 8.6, 117.7 ± 6.9, and 101.9 ± 5.7% of $v\dot{V}O_{2peak}$ for women with no differences between sexes for each distance (all at $\rho > 0.05$). The data related to performances and physiological responses are shown in **Table 1**. Swimming velocity and *p* were higher for short compared to long swimming distances (i.e., 50 > 100 > 200 m), while total energy measurements in EqO_2 increased with swimming distance (i.e., 50 < 100 < 200 m). Males demanded higher EqO_2 and *p* than female swimmers for the 50, 100, and 200 m, but the swimming velocity differed only during 50 and 100 m swimming bouts. **Figure 2** highlights the differences between sexes regarding body composition variables. The comparisons between sexes for $LM_{Total,}$ LM_{Trunk}, LM_{LL}, LM_{UL}, I_{LM}, and I_{App} indicated higher values for men than women (all at $\rho < 0.01$), with the effect size "*g*" ranging from 1.43 to 2.60 and, therefore, were all considered very large.

The E_{Total} demand for men and women during 50 (58.8 ± 8.4 *vs*. 54.9 ± 8.2 $ml \times kg^{-1}$), 100 (91.5 ± 14.2 *vs*. 85.0 ± 12.2 $ml \times kg^{-1}$), and 200 m (141.9 ± 24.6 *vs*. 141.0 ± 10.4 $ml \times kg^{-1}$) did not differ (ρ = 0.24, 0.23, and 0.91) between sexes for each distance. **Figure 3** depicts the energetics during the performances of the 50, 100, and 200 m with regards to the demands (Panels A–C, in EqO_2 per BM) and contributions [Panels D–F, in relative terms (%)] attained by the energetics components (E_{PCr}, $E_{[La-]}$, and E_{Aer}). The E_{PCr} contribution was higher for men than women only for the 200 m ($\rho = 0.04$, $\eta^2p = 0.247$), with no differences for the 50 ($\rho = 0.75$) and 100 m ($\rho = 0.13$) distances, while the $E_{[La-]}$ and E_{Aer} components showed no differences between sexes for the 50 (ρ = 0.40 and 0.22), 100 (ρ = 0.73 and 0.37), and 200 m (ρ = 0.30 and 0.70) distances. The contributions of E_{PCr}, $E_{[La-]}$, and E_{Aer} components to the E_{Total} demand in the 50, 100, and 200 m differed between all distances for men and women at $\rho < 0.01$ level, i.e., $\%E_{PCr}$ 50 > 100 > 200 m ($\eta^2p = 0.815$); $\%E_{[La-]}$ 50 > 100 > 200 m ($\eta^2p = 0.890$); and $\%E_{Aer}$ 50 < 100 < 200 m ($\eta^2p = 0.954$), whatever the sex. Moreover, men had higher $\%E_{PCr}$ in the 200 m than women ($\rho = 0.03$), while women had higher $\%E_{[La-]}$ in the 50 m than men ($\rho = 0.02$), with no other differences.

For the performances in the 50, 100, and 200 m tests, the values obtained for C_{An}, C_{Aer}, and C_{Total} are presented in **Figure 4**. The Panels A–C (**Figure 2**) demonstrate the sex-effect on C_{An}, C_{Aer}, and C_{Total}, with higher values for men than women in the 50, 100, and 200 m tests ($\rho < 0.01$, and $\eta^2{}_p$ = 0.456, = 0.487, and = 0.519). Also, the reduction of C_{An} and C_{Total} values with the increase of the swimming distance was observed for both sexes (Panels A and C), i.e., C_{An} and C_{Total} in 50 > 100 > 200 m ($\rho < 0.01$, and $\eta^2{}_p$ = 0.919 and = 0.778). However, the C_{Aer} values were higher with the increase of the swimming distance for both sexes (Panel B), i.e., C_{Aer} in 50 < 100 < 200 m ($\rho < 0.01$, and $\eta^2{}_p = 0.838$). When expressed per unit of body mass (i.e., $J \times kg^{-1} \times m^{-1}$), the C_{Total} values did not differ for men vs. women in 50 (24.6 vs. 23.0, $\rho = 0.24$), 100 (19.1 vs. 17.8, $\rho = 0.22$), and 200 m (14.8 vs. 14.7, $\rho = 0.91$).

Table 2 shows the Pearson's coefficients for the correlations of whole-body and regional lean mass variables with the

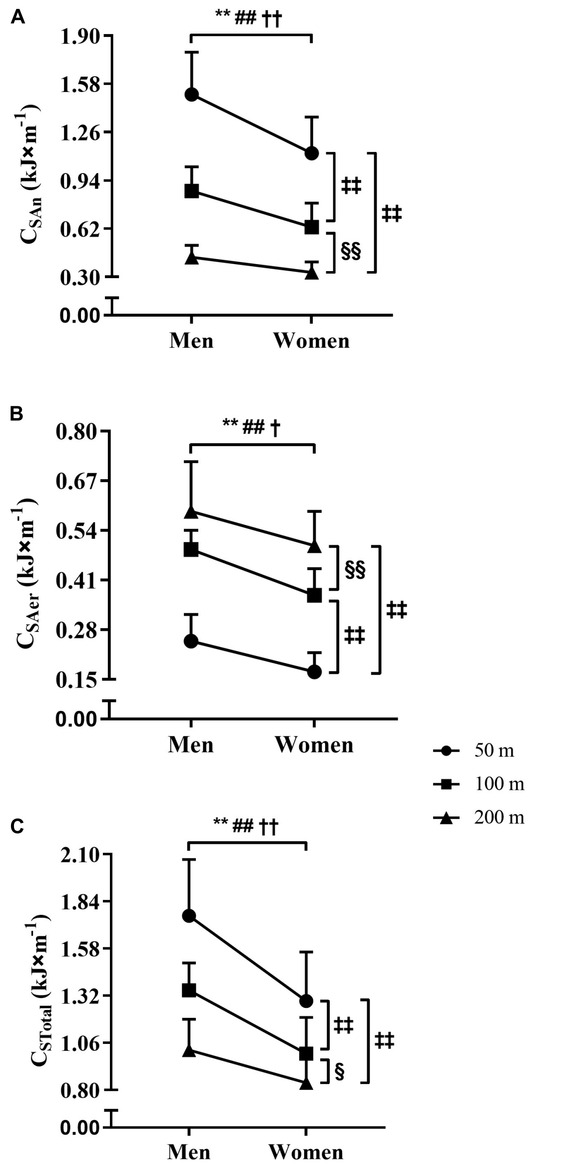

FIGURE 4 | The comparisons of C_{An}, C_{Aer}, and C_{Total} values **(A–C)** between the sexes and distances. Obs.: The acronyms C_{An}, C_{Aer}, and C_{Total} represent the anaerobic, aerobic, and total costs. Significantly different from men at $\rho \leq 0.05^{\dagger}$ in 200 m, and at $\rho \leq 0.01$ in 50**, 100$^{\#\#}$, and 200 m††. Significantly different from 50 m at $\rho \leq 0.01^{\ddagger\ddagger}$. Significantly different from 100 m at $\rho \leq 0.05$ § and ≤ 0.01 §§.

measurements of C_{An}, C_{Aer}, and C_{Total} in 50, 100, and 200 m. The correlations were considered significant, classified as moderate or high, and attaining SP ≥ 95% for all analysis, with exception to the LM_{UL}, I_{LM}, and I_{App} with C_{Total} in the 200 m, which were low and SP < 80%. The variables LM_{Trunk}, LM_{UL}, and LM_{LL} showed medium to strong influence on C_{An}, C_{Aer}, and C_{Total} values in the 50, 100, and 200 m (**Figure 5**, Panels A–I), with LM_{Trunk} and LM_{UL} attaining high rates to explain the C_{An} values during these distances (Panels A–C), and LM_{LL} as the variable explaining the C_{Aer} values for all distances (Panels D–F). Finally, the results at Panels G–I highlight the rates of 72, 61, and 60% for the variables LM_{Trunk}, LM_{UL}, and LM_{LL}, explaining C_{Total} values in 50, 100, and 200 m, respectively.

DISCUSSION

This study addressed the C during short and middle distances performances in swimming, finding a sex-specific response regarding the energetics contribution to the performances, to C during each swimming distance, and to the role of regional lean mass on C values. The findings indicated no differences between sexes for the E_{Total} and for the components E_{PCr}, $E_{[La-]}$, and E_{Aer}, suggesting similar capacity between young men and women to meet the energy requirements per unit of body mass in a front crawl. However, the C_{Total} was higher in men than women for all swimming distances performed, despite how both sexes presented similar C components regarding the reliance on C_{Ana} and C_{Aer} expenditure, respectively, during short distances (50 and 100 m) and middle distances (200 m). For the current study, these differences in C_{An}, C_{Aer}, and C_{Total} can be attributed to the increased production of metabolic power in men, which was observed to relate to lean mass in the trunk and upper and lower limbs.

The similarities for E_{PCr}, $E_{[La-]}$, and E_{Aer} in the 50, 100, and 200 m (with E_{PCr} at the 200 m being the only exception) support the evidence that fast-energy pathways (i.e., phosphagens and glycolysis), level of activation, and contribution, while the oxidative supply is rising from short to middle distances performances, have no constraints related to sex-specific energy metabolism. In addition, similarities were also noted to the interplay (% of contribution) between E_{PCr}, $E_{[La-]}$, and E_{Aer} as trial time increases from the 50 to 200 m, evidencing that sex has no influence on given metabolism requirements neither on the balance between the metabolism components as the demand changes according to the swimming intensity and duration over the distances.

These findings are aligned with the evidence toward similarities in energetics rely on fiber type distribution in biceps brachialis and vastus lateralis, with no differences between young men and women, and on the reports relating fiber firing to exercise intensity as sex-independent (Esbjörnsson et al., 1993; Miller et al., 1993; Hunter, 2016). In addition, other reports evidencing larger fiber areas (I, IIa, and IIb) of the biceps brachialis and vastus lateralis in men than women (Esbjörnsson et al., 1993; Miller et al., 1993) probably account for the differences in total muscle PCr content between sexes (Esbjörnsson et al., 1993; Esbjörnsson-Liljedahl et al., 1999). Therefore, the PCr content might explain the small differences between sexes observed in the current study and account for the higher reliance on E_{PCr} in men compared to women as the distance increases from 50 to 200 m, and for the women reliance on larger $E_{[La-]}$ than men during the performance of short distance, i.e., 50 m.

However, the finding in which no differences between men and women, regarding anaerobic glycolytic contribution, is not in agreement with the well-reported reduced glycolytic activity

TABLE 2 | Relationship between body composition variables and values of C_{An}, C_{Aer}, and C_{Total} for the 50, 100, and 200 m.

		LM_{Total}	LM_{Trunk}	LM_{LL}	LM_{UL}	I_{LM}	I_{App}
C_{An}	50 m	0.85**	0.86**	0.82**	0.81**	0.76**	0.74**
		(100%)	(100%)	(100%)	(100%)	(100%)	(99%)
	100 m	0.68**	0.68**	0.64**	0.70**	0.65**	0.64**
		(97%)	(97%)	(95%)	(98%)	(95%)	(95%)
	200 m	0.85**	0.86**	0.83**	0.82**	0.77**	0.75**
		(100%)	(100%)	(100%)	(100%)	(100%)	(100%)
C_{Aer}	50 m	0.56**	0.54**	0.56**	0.57**	0.47*	0.52**
		(84%)	(82%)	(84%)	(86%)	(67%)	(76%)
	100 m	0.75**	0.71**	0.73**	0.73**	0.65**	0.71**
		(100%)	(99%)	(100%)	(99%)	(95%)	(99%)
	200 m	0.56**	0.54**	0.59**	0.46*	0.41*	0.45*
		(84%)	(82%)	(88%)	(66%)	(53%)	(63%)
C_{Total}	50 m	0.85**	0.86**	0.83**	0.82**	0.75**	0.75**
		(100%)	(100%)	(100%)	(100%)	(100%)	(100%)
	100 m	0.78**	0.77**	0.76**	0.79**	0.73**	0.74**
		(100%)	(100%)	(100%)	(100%)	(99%)	(99%)
	200 m	0.78**	0.78**	0.79**	0.71**	0.65**	0.66**
		(100%)	(100%)	(100%)	(98%)	(95%)	(96%)

Obs.: Data are showing the coefficient (r) and sample power in percentage.
Significantly different at $\rho \leq 0.05$ and ≤ 0.01**.*
LM_{Total}, LM_{Trunk}, LM_{LL}, and LM_{UL} are lean mass in whole-body, trunk and lower and upper limbs, and I_{LM} and I_{App} are lean mass index and appendicular lean mass index.

for women when compared to men during Wingate and MAOD tests in cycling and running (Esbjörnsson et al., 1993; Gratas-Delamarche et al., 1994; Naughton et al., 1997; Hill and Vingren, 2011). These studies attributed the differences upon glycolytic demand to the higher absolute exercise intensity reached by men (i.e., peak power) since no significant differences between sexes in power (Maud and Shultz, 1986; Nindl et al., 1995; Hegge et al., 2015) or anaerobic demand (Weber and Schneider, 2002) were found when whole-body and regional mass or lean mass were considered.

In addition, the $[La^{-}]_{peak}$ values for the current study are aligned with the values reported for the 50, 100, and 200 m maximal swimming performances (Chatard et al., 1988; Troup et al., 1992; Capelli et al., 1998) and, therefore, the acidosis level is compatible to the other results exploring the energetics requirements during short and middle distances swimming performance. Furthermore, the observed similarities between men vs. women in $[La^{-}]_{peak}$ and $E_{[La-]}$ responses cannot be attributed to the trial differences in $\%v\dot{V}O_{2peak}$ and duration during each performance since these parameters were not significantly different between sexes. The only exception was the duration of 50 m, which was smaller in men than women. However, the differences seem to not be large enough to modify glycolytic contribution according to sex-specific performances.

The lack of differences between sexes was also observed for E_{Aer} responses in 50, 100, and 200 m, which was an expected result considering the limited capacity to uptake and deliver oxygen to the working muscles at exercise rates higher than or close to $\dot{V}O_{2peak}$ for women is associated to the body size differences to men and, therefore, relating energetics to a scaling issue (Weber and Schneider, 2002). Indeed, the absolute differences in cardiac, circulatory, and respiratory determinants of O_2 availability to muscle while exercising near or at 100% $\dot{V}O_{2peak}$ are not significant when comparing sexes per unit of lean mass (Peltonen et al., 2013), which are further supported to the evidence that fiber type I functions and distribution, pulmonary diffusive capacity, blood volume, and hemoglobin content are not different when comparing between sexes accounting to the effect of body size or lean mass (Esbjörnsson-Liljedahl et al., 1999; Russ et al., 2005; Haizlip et al., 2015; Bouwsema et al., 2017; Koons et al., 2019).

Analogous to the evidence of "size" effect on energetics between sexes (Chatard et al., 1991), the results from the current study also observed higher absolute energy demand in EqO_2 for men compared to women in the 50, 100, and 200 m tests, either considering the total (i.e., E_{Total}) or the components of the energetics (i.e., E_{PCr}, $E_{[La-]}$ and E_{Aer}). These results remain unchanged even when considering the performance variable time or velocity to normalize energy demand, giving important insights into the relevance of body morphology for the sex-specific energetics response per unit of time or distance while swimming at high intensity rates. The remarkable finding is the predominance of anaerobic energy releasing per unit of distance in the 50 and 100 m, whereas aerobic energy predominated along the 200 m. Furthermore, aerobic and anaerobic C differed between sexes, with lean mass in the trunk and upper and lower limbs explaining 60–73% of C_{Total} for 50–200 m.

In swimming, the energy contribution from phosphagen, glycolytic, and aerobic components during 50, 100, and 200 m has been reported to differ between sexes only in 200 m and with regards the phosphagen (men > women) and glycolytic (men < women) contributions (Almeida et al., 2020). When

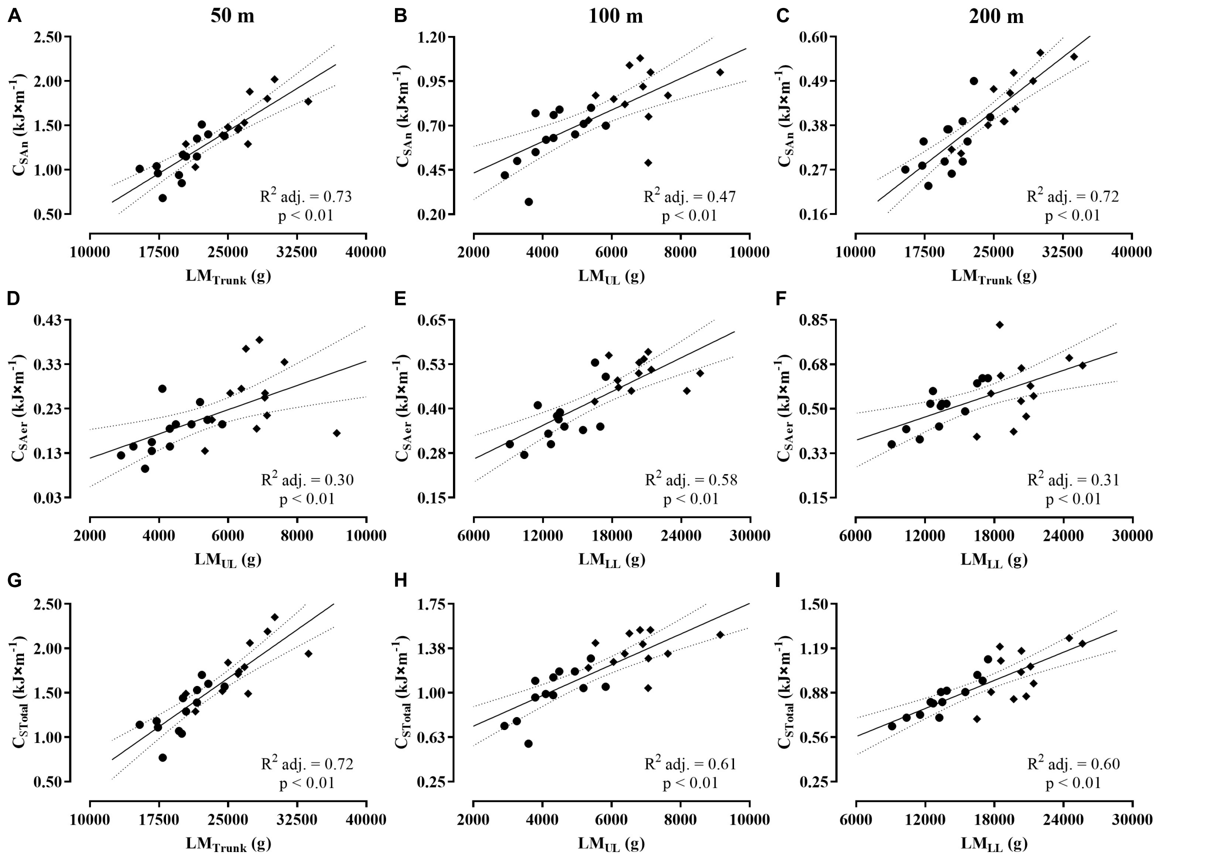

FIGURE 5 | Dispersion plots between body composition variables and values of C_{An}, C_{Aer}, and C_{Total} for the 50 m **(A,D,G)**, 100 m **(B,E,H)**, and 200 m **(C,F,I)**. Obs.: The symbols (♦) and (●) represent the dispersion for men and women, respectively. The acronyms CAn, CAer, and CTotal represent the anaerobic, aerobic, and total costs.

comparing the current data from the energy released with the aforementioned reports, there are slight differences with regards to anaerobic energetics, which are probably due to the methodological assumptions for the estimation of phosphagen and glycolytic components (i.e., the subtracted amount of hemoglobin O_2 content and the stoichiometric coefficient for blood lactate net accumulation – Medbo et al., 1988; di Prampero and Ferretti, 1999) since swimmers are similar with regards to age group, conditioning index ($\dot{V}O_{2peak}$ and $v\dot{V}O_{2peak}$), and performance pacing (v and $\%v\dot{V}O_{2peak}$). However, the differences between the studies are also large for aerobic contribution, which just reinforce the concerns on the data processing strategies influence on $\dot{V}O_2$ analysis (Robergs et al., 2010). However, the interpretation from Almeida et al. (2020) that energetics during short and middle distances performance did not differ between sexes per unit of body mass is aligned with the current results.

Indeed, the reports for aerobic and anaerobic percentage of contribution to total energy released by elite male swimmers in 50 (∼15/85%), 100 (∼33/77%), and 200 yards (∼62/38%) (Capelli et al., 1998) are quite aligned to the current findings and therefore supports the reliance on anaerobic sources during performances around 60 s, which has already been demonstrated for swimming (Capelli et al., 1998; Ogita et al., 2003) and cycling exercise (Bangsbo et al., 1990; Spencer and Gastin, 2001). The current results indicated a larger phosphagen than glycolytic contribution for the anaerobic releasing during 50 and 200 m in men, and similar contributions for these two components in women during 50, 100, and 200 m, which are not aligned to previous reports. In fact, highest glycolytic reliance during short and middle distances performances have been observed in elite male swimmers [i.e.: $E_{PCr}/E_{[La^-]}$ (%) ∼26/54, 19/43, 13/24 in 50, 100 and 200 yards, Capelli et al., 1998; and $E_{PCr}/E_{[La^-]}$ (%) ∼11/15 in 200 m, Sousa et al., 2013] and for junior and senior male swimmers [i.e., $E_{PCr}/E_{[La^-]}$ (%) ∼20/27 and 18/37 in 100 m, Hellard et al., 2018], but exceptionally, Figueiredo et al. (2011) reported $E_{PCr}/E_{[La^-]}$ (%) ∼20/14% in 200 m, which is close to the proportionality in the current study.

The aforementioned estimates of E_{PCr}, supposing a maximal depletion of PCr store (i.e., 18.5 mmol/kg of wet muscle at 23.4 s time constant for substrate splitting), have been suggested as reasonable (Capelli et al., 1998; Hellard et al., 2018) and expected to give similar results when compared to the analyzes of the fast component of $\dot{V}O_2$ recovery curve (at least for the 200 m swimming performance; Sousa et al., 2013). However, in the current study, the values observed for the time constant of the $\dot{V}O_2$ recovery fast component ranged from 44 to 46 s for 50, 100, and 200 m, which are in the range reported for severe exercise in cycling (35 ± 11 s), high intensity lower limbs extension (51 ± 6 s) (Özyener et al., 2001; Rossiter et al., 2002), and short distance swimming trial (Almeida et al., 2020) but diverge with that reported for 200 m in swimming (27 ± 5 s, Sousa et al., 2013). Despite the differences of parameters selection (i.e., $EE\dot{V}O_2$ *vs.* $\dot{V}O_{2baseline}$) for the equation model that can account for the differences of the time constant response, the evidence of similarities or discrepancies between methods for phosphagen component estimation needed to be further investigated.

Nevertheless, considering that the release of ~3.33, ~2.72, and ~1.94 kW in elite male college swimmers during short and middle distances performances at ~139, ~123, and ~114% $v\dot{V}O_{2max}$ (Capelli et al., 1998), and that the maximal anaerobic supply during high-intensity performances can reach 1,452 J × kg^{-1} (or ~69.5 ml × kg^{-1}) in well-trained swimmers (Toussaint and Hollander, 1994), we suppose that the swimmers in the current study are still in the development training stage therefore requiring metabolic power output and anaerobic capacity improvements. Despite how the women have shown lower values, the average anaerobic release (i.e., E_{PCr} + $E_{[La^-]}$) reached the highest values during the 100 and 200 m (e.g., ~57 ml × kg^{-1}) which is lower than values for the 200 m (~68 ml × kg^{-1}) reported in international level male swimmers (Fernandes et al., 2006), corroborating the range for improvements in the aforementioned variables for young swimmers. However, the current values are also revealed to be higher than anaerobic release during 100 m (e.g., ~48 and 54 ml × kg^{-1}) as reported for male swimmers with 18–22 years old and low to high FINA points (Hellard et al., 2018), and higher than the estimated anaerobic capacity (e.g., ~50–52 ml × kg^{-1}) for college swimmers (Ogita et al., 1996, 2003; Capelli et al., 1998).

From these comparisons, there is considerable support to consider no sex-constraints among young swimmers to reach the expecting anaerobic conditioning to compete at a high level despite the transference for elite performance being limited to the fact that current swimmers are well-trained but not top-level athletes. However, the energy releasing sources do not seem to be the only determinant to the performance level during short and middle distances (Figueiredo et al., 2013; Ribeiro et al., 2017; Zacca et al., 2020), although the variables power and cost have been considered determinants of swimming performance, exercise tolerance, total energy requirement, and aerobic/anaerobic metabolism balance during high-intensity bouts (Toussaint, 1990; Chatard et al., 1991; Fernandes et al., 2006; di Prampero et al., 2008).

For example, as swimming velocity increases, the metabolic power should raise proportionality to afford mechanical adjustments with no technical impairments (i.e., accommodating higher stroke rate with minimal disturbance in stroke length), allowing to differentiate swimmers according to the conditioning and technical levels (Toussaint, 1990; Wakayoshi et al., 1995; Ribeiro et al., 2017). This explains the lower race pace, energy power, and cost when comparing men from the current study with college male swimmers performing short and middle distances, or even the economical pacing of these later swimmers when compared to the ones from the current study by estimating C from front crawl equation (=$0.228[10^{.488v}]$, Capelli et al., 1998) at the same average velocity in 50, 100, and 200 m (e.g., ~1.5 vs. ~1.7; ~1.2 vs. ~1.3; and ~.9 vs. ~1.0 kJ × m^{-1}). Despite that the economy is a feature of the skilled technique, other variables like age, anthropometry, training level, and engaged muscle mass can account for C difference among male swimmers (Chatard et al., 1990, 1991; Fernandes et al., 2006; Morris et al., 2016; Hellard et al., 2018), which seems to be the case for the comparisons with values from the current study.

However, the current findings are aligned with the statements on the C augmentation with swimming front crawl velocity increment at supramaximal velocities (Capelli et al., 1998), which was observed for both sexes. The increase in C with velocity has been demonstrated for young female swimmers with a different level of performance in 400 m, while performing a common range of velocities below each group level from v400m (Chatard et al., 1991), for teenage women during the performance of 50, 100, 200, and 400 m (Zamparo et al., 2000), and between young competitive female swimmers performing 200 m with different stroke rate values (Morris et al., 2016). Although the C values for female swimmers are scarce for performances at supramaximal velocities, a single study demonstrated that young women spent 19, 15, and 10% less energy when compared to young men at 1.2, 1.4, and 1.6 m × s^{-1} (Zamparo et al., 2000), which were not, necessarily, the actual velocities for 400, 200, 100, and 50 m. Therefore, the current findings can be useful to compare C measurement methods and analyze performance levels while swimming at actual 50, 100, and 200 m events.

For example, the average C values reported for high ranked young female swimmers at 1.4 m × s^{-1} (or ~103% $v\dot{V}O_{2peak}$) was 27.3 ml × m^{-1} (Unnithan et al., 2009), which is 31% lower than the C estimated in the current study at the correspondent swimming intensity (~102% $v\dot{V}O_{2peak}$ at 200 m) or 43% lower than C at the same pacing (~1.41 m × s^{-1} at 100 m). Taking into account that these authors assessed only $\dot{V}O_2$ response to estimate C, and that anaerobic contribution to 200 and 100 m can reach ~29 and ~46%, respectively, for women (Almeida et al., 2020), these C values can be considered equivalent. Indeed, the C values for women observed in the current study for 200 m are only ~8% higher than the C for low trained level female swimmers (~13.6 J × kg^{-1} × m^{-1}) performing at 1.2 m × s^{-1} (or ~103% $v\dot{V}O_{2peak}$), but are 25% higher than C of high-trained level female swimmers (~11.7 J × kg^{-1} × m^{-1}) performing at the same absolute pacing (1.2 m × s^{-1}) but at lower relative intensity (~86% $v\dot{V}O_{2peak}$) (Fernandes et al., 2006). While the comparison with low-trained swimmers did not differ, since the E_{PCr} was not considered to the energetics measurements, which usually account for more than ~10% at exercise rate (Sousa et al., 2013), the comparison to the high-trained woman highlights the importance of swimming economy to the athlete consolidation.

Moreover, the current findings also observed that the differences in C_{Total} between sexes during each distance were eliminated when expressed in body mass units, which is aligned to the reports for both sexes at the same absolute submaximal pacing (i.e., 1.3 m × s^{-1}) but different exercise rate for men *vs*. women: ∼90 *vs*. ∼98% $v\dot{V}O_{2peak}$ (Fernandes et al., 2006). However, previous studies comparing both sexes at 100% $v\dot{V}O_{2peak}$ (Fernandes et al., 2005) or at different stroke rates and velocities (Morris et al., 2016) found higher C for men than women, which was considered an effect of high velocity or stroke rate achieved at $\dot{V}O_{2peak}$ in men and, therefore, different energy requirement compared to women. The current findings support that the higher C for young men than young women while performing 50 to 200 m can be attributed to the highest velocity performed by men, which is probably accounted to the larger hydrodynamic resistance (Zamparo et al., 2000, 2008).

The current study did not observe differences in C when scaled to the body mass, which may be occurred due to the paired supramaximal exercise rate where hydrodynamics compromises both sexes maximally and hence accounting less to explain the C values variation with velocity (Zamparo et al., 2000, 2008). Also, differences between sexes of C values at swimming circumstance >100%$v\dot{V}O_{2peak}$, lasting 30–150 s, would be supported to the differences in $\dot{V}O_2$ adjustments to its maximum and the rate of anaerobic stores depletion, which have been theoretically demonstrated by comparing swimmers while swimming with different stroke technique or having no similar $\dot{V}O_{2peak}$ level (di Prampero et al., 2008). In absence of this case, the technical proficiency (favoring women) and the energetic releasing (favoring men) would be balanced by a given similar C between sexes. However, this still remains in a theoretical scenery and could be explored in the future studies by analyzing swimmers with similar C.

Finally, this is the first study demonstrating that swimmers with the largest lean mass in the trunk and upper limb are less economical while performing 50 and 100 m because lean mass is related to high anaerobic C, and swimmers with the largest lean mass in the lower limb should present more aerobic C, whatever the sex. On the other hand, if C increases with swimming velocity demanding high metabolic energy (Zamparo et al., 2000, 2008; di Prampero et al., 2008), then lean mass content between swimmers is crucial to the improvement of short and middle distance performances, which is a sex-specific C statement complementing that reporting body mass and composition as explanatory variables for energy metabolism and performance differences between athletes from different maturation level (Hellard et al., 2018).

Inasmuch as the biological level of maturation for each sex-group was not determined in the current study, we are unable to refute the fact that maturation level has an effect on energetics and C, and on the relation of these variables with lean mass. Thus, this is a limitation of the current findings, indicating that the interplay between lean mass and energy releasing could be an effect of maturation and not related to sex differences (Jürimäe et al., 2007) or, at least, suggesting limited transference to other age-groups. Although, swimmers were supposed to have similar status respective to each sexual developmental stage, as suggested to the low variability of lean mass, height, and body weight values in each sex-group (Zemel, 2013).

Furthermore, as traditional or specific resistance training can modify force-velocity relationship in muscle and neuromuscular coordination affecting swimming performance positively along with increasing lean mass (Crowley et al., 2017), it should therefore be highly recommended to explore in future studies the potential of muscle hypertrophy to improve swimming performance during supramaximal exercise rates. Taking all of these in consideration, the findings suggest young male and female swimmers can improve their actual conditioning level, and, therefore, their short and middle distances performances by following exercises planning to improve trunk and upper and lower limbs lean mass, enabling limbs muscles to attend for high C demands.

CONCLUSION

The current study observed sex independence on the profile of contribution and reliance of the energetics components during high intensity swimming performance. This evidence is favoring no constraints for the energetics capability of women to match men's energy balance and releasing during high intensity swimming performance. Moreover, current results about C are aligned to the notion that differences between sexes on energetics are related to body mass and composition, and therefore eliminated when scaled to body size dimensions. However, this finding refers to an analysis not encompassing top-level athletes, but concern to swimmers in-preparation and with similar training experience and conditioning levels for which the differences in hydrodynamics and supramaximal exercise rates are minor. Finally, the specificities of each sex regarding the energetics and lean mass responses to training should be further explored in future studies engaging top-level swimmers from different age-groups.

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 Ethics Committee of the São Paulo State University (Protocol 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, TA, JR, FA, and DP conceived and designed the study. DM, TA, CV, ME, AM, JR, and DP conducted the experiments and analyzed the data. DM, TA, ME, AM, JR, FA, RF, and DP wrote the manuscript. All authors contributed to the article, read, and approved the manuscript.

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REFERENCES

Almeida, T. A. F., Pessôa Filho, D. M., Espada, M. A. C., Reis, J. F., Sancassani, A., Massini, D. A., et al. (2021). Physiological responses during high-intensity interval training in young swimmers. *Front. Physiol.* 12:662029. doi: 10.3389/fphys.2021.662029

Almeida, T. A. F., Pessôa Filho, D. M., Espada, M. A. C., Reis, J. F., Simionato, A. R., Siqueira, L. O. C., et al. (2020). V̇O2 kinetics and energy contribution in simulated maximal performance during short and middle distance-trials in swimming. *Eur. J. Appl. Physiol.* 120, 1097–1109. doi: 10.1007/s00421-020-04348-y

Baldari, C., Fernandes, R. J., Meucci, M., Ribeiro, J., Vilas-Boas, J. P., and Guidetti, L. (2013). Is the new aquatrainer® snorkel valid for V̇O2 assessment in swimming? *Int. J. Sports Med.* 34, 336–344. doi: 10.1055/s-0032-1321804

Bangsbo, J., Gollnick, P. D., Graham, T. E., Juel, C., Kiens, B., Mizuno, M., et al. (1990). Anaerobic energy production and O2 deficit-debt relationship during exhaustive exercise in humans. *J. Physiol.* 422, 539–559. doi: 10.1113/jphysiol.1990.sp018000

Bouwsema, M. M., Tedjasaputra, V., and Stickland, M. K. (2017). Are there sex differences in the capillary blood volume and diffusing capacity response to exercise? *J. Appl. Physiol.* 122, 460–469. doi: 10.1152/japplphysiol.00389.2016

Capelli, C., Pendergast, D. R., and Termin, B. (1998). Energetics of swimming at maximal speeds in humans. *J. Appl. Physiol.* 78, 385–393. doi: 10.1007/s004210050435

Chatard, J. C., Lavoie, J. M., and Lacour, J. R. (1991). Energy cost of front crawl swimming in women. *Eur. J. Appl. Physiol.* 63, 12–16. doi: 10.1007/BF00760794

Chatard, J. C., Lavoie, J. M., and Lacourl, J. R. (1990). Analysis of determinants of swimming economy in front crawl. *Eur. J. Appl. Physiol.* 61, 88–92. doi: 10.1007/BF00236699

Chatard, J. C., Paulin, M., and Lacour, J. R. (1988). "Postcompetition blood lactate measurements and swimming performance: illustrated by data from a 400 m olympic record holder," in *Swimming Science V*, eds B. E. Ungerechts, K. Wilke, and K. Reischle (Champaign, IL: Human Kinetics), 311–316.

Cohen, J. (ed.) (1988). *Statistical Power Analysis for the Behavioral Sciences*. Hillsdale, NJ: L. Erlbaum Associates, doi: 10.4324/9780203771587

Crowley, E., Harrison, A. J., and Lyons, M. (2017). The impact of resistance training on swimming performance: a systematic review. *Sports Med.* 47, 2285–2307. doi: 10.1007/s40279-017-0730-2

di Prampero, P. E., Dekerle, J., Capelli, C., and Zamparo, P. (2008). The critical velocity in swimming. *Eur. J. Appl. Physiol.* 102, 165–171. doi: 10.1007/s00421-007-0569-6

di Prampero, P. E., and Ferretti, G. (1999). The energetics of anaerobic muscle metabolism: a reappraisal of older and recent concept. *Respir. Physiol.* 118, 103–115. doi: 10.1016/s0034-5687(99)00083-3

Esbjörnsson, M., Sylven, C., Holm, I., and Jansson, E. (1993). Fast twitch fibres may predict anaerobic performance in both females and males. *Int. J. Sports Med.* 14, 257–263. doi: 10.1055/s-2007-1021174

Esbjörnsson-Liljedahl, M., Sundberg, C. J., Norman, B., and Jansson, E. (1999). Metabolic response in type I and type II muscle fibers during a 30-s cycle sprint in men and women. *J. Appl. Physiol.* 87, 1326–1332. doi: 10.1152/jappl.1999.87.4.1326

Ferguson, C. J. (2009). An Effect size primer: a guide for clinicians and researchers. *Prof. Psychol. Res. Pract.* 40, 532–538. doi: 10.1037/a0015808

Fernandes, R., Billat, V., Cruz, A., Colaço, P., Cardoso, C., and Vilas-Boas, J. P. (2005). Has gender any effect on the relationship between time limit at VO2max velocity and swimming economy? *J. Hum. Mov. Stud.* 49, 127–148.

Fernandes, R. J., Billat, V. L., Cruz, A. C., Colaço, P. J., Cardoso, C. S., and Vilas-Boas, J. P. (2006). Does net energy cost of swimming affect time to exhaustion at the individual's maximal oxygen consumption velocity? *J. Sports Med. Phys. Fitness* 46, 373–380.

Figueiredo, P., Pendergast, D. R., Vilas-Boas, J. P., and Fernandes, R. J. (2013). Interplay of biomechanical, energetic, coordinative, and muscular factors in a 200 m front crawl swim. *Biomed. Res. Int.* 2013:897232. doi: 10.1155/2013/897232

Figueiredo, P., Zamparo, P., Sousa, A., Vilas-Boas, J. P., and Fernandes, R. J. (2011). An energy balance of the 200 m front crawl race. *Eur. J. Appl. Physiol.* 111, 767–777. doi: 10.1007/s00421-010-1696-z

Gonjo, T., McCabe, C., Sousa, A., Ribeiro, J., Fernandes, R. J., Vilas-Boas, J. P., et al. (2018). Differences in kinematics and energy cost between front crawl and backstroke below the anaerobic threshold. *Eur. J. Appl. Physiol.* 118, 1107–1118. doi: 10.1007/s00421-018-3841-z

Gratas-Delamarche, A., Le Cam, R., Delamarche, P., Monnier, M., and Koubi, H. (1994). Lactate and catecholamine responses in male and female sprinters during a Wingate test. *Eur. J. Appl. Physiol. Occup. Physiol.* 68, 362–366. doi: 10.1007/BF00571458

Haizlip, K. M., Harrison, B. C., and Leinwand, L. A. (2015). Sex-based differences in skeletal muscle kinetics and fiber-type composition. *Physiol* 30, 30–39. doi: 10.1152/physiol.00024.2014

Hegge, A. M., Myhre, K., Welde, B., Holmberg, H. C., and SandbakK, O. (2015). Are gender differences in upper-body power generated by elite cross-country skiers augmented by increasing the intensity of exercise? *PLoS One.* 10:e0127509. doi: 10.1371/journal.pone.0127509

Hellard, P., Pla, R., Rodríguez, F. A., Simbana, D., and Pyne, D. B. (2018). Dynamics of the metabolic response during a competitive 100 m freestyle in elite male swimmers. *Int. J. Sports. Physiol. Perform.* 13, 1011–1020. doi: 10.1123/ijspp.2017-0597

Hill, D. W., and Vingren, J. L. (2011). Maximal accumulated oxygen deficit in running and cycling. *Appl. Physiol. Nutr. Metab.* 36, 831–838. doi: 10.1139/h11-108

Hunter, S. K. (2016). The relevance of sex differences in performance fatigability. *Med. Sci. Sports Exerc.* 48, 2247–2256. doi: 10.1249/MSS.0000000000000928

Jürimäe, J., Haljaste, K., Cicchella, A., Lätt, E., Purge, P., Leppik, A., et al. (2007). Analysis of swimming performance from physical, physiological, and biomechanical parameters in young swimmers. *Pediatr. Exerc. Sci.* 19, 70–81. doi: 10.1123/pes.19.1.70

Koons, N. J., Suresh, M. R., Schlotman, T. E., and Convertino, V. A. (2019). Interrelationship between sex, age, blood volume, and V̇O2max. *Aerosp. Med. Hum. Perform.* 90, 362–368. doi: 10.3357/AMHP.5255.2019

Margaria, R., Edwards, H. T., and Dill, D. B. (1933). The possible mechanisms of contracting and paying the oxygen debt and the role of lactic acid in muscular contraction. *Am. J. Physiol.* 106, 689–714. doi: 10.1152/ajplegacy.1933.106.3.689

Maud, P. J., and Shultz, B. B. (1986). Gender comparisons in anaerobic power and anaerobic capacity tests. *Br. J. Sports Med.* 20, 51–54. doi: 10.1136/bjsm.20.2.51

Medbo, J. I., Mohn, A. C., Tabata, I., Bahr, R., Vaage, O., and Sejersted, O. M. (1988). Anaerobic capacity determined by maximal accumulated O2 deficit. *J. Appl. Physiol.* 64, 50–60. doi: 10.1152/jappl.1988.64.1.50

Miller, A. E. J., Macdougall, J. D., Tarnopolsky, M. A., and Sale, D. G. (1993). Gender differences in strength and muscle fiber characteristics. *Eur. J. Appl. Physiol. Occup. Physiol.* 66, 254–262. doi: 10.1007/bf00235103

Morris, K. S., Osborne, M. A., Shephard, M. E., Skinner, T. L., and Jenkins, D. G. (2016). Velocity, aerobic power and metabolic cost of whole body and arms only front crawl swimming at various stroke rates. *Eur. J. Appl. Physiol.* 116, 1075–1085. doi: 10.1007/s00421-016-3372-4

Mukaka, M. M. (2012). Statistics corner: a guide to appropriate use of correlation coefficient in medical research. *Malawi Med. J.* 24, 69–71.

Naughton, G. A., Carlson, J. S., Buttifant, D. C., Selig, S. E., Meldrum, K., Mckenna, M. J., et al. (1997). Accumulated oxygen deficit measurements during and after high-intensity exercise in trained male and female adolescents. *Eur. J. Appl. Physiol. Occup. Physiol.* 76, 525–531. doi: 10.1007/s004210050285

Nindl, B. C., Mahar, M. T., Harman, E. A., and Patton, J. F. (1995). Lower and upper body anaerobic performance in male and female adolescent athletes. *Med. Sci. Sports Exerc.* 27, 235–241.

Ogita, F., Hara, M., and Tabata, I. (1996). Anaerobic capacity and maximal oxygen uptake during arm stroke, leg kicking and whole-body swimming. *Acta. Physiol. Scand.* 157, 435–441. doi: 10.1046/j.1365-201X.1996.490237000.x

Ogita, F., Onodera, T., Tamaki, H., Toussaint, H. M., Hollander, A. P., and Wakayoshi, K. (2003). "Metabolic profile during exhaustive arm stroke, leg kick, and whole-body swimming lasting 15s to 10 min," in *Biomechanics and Medicine in Swimming IX*, ed. J. C. Chatard (Saint-Etienne: University of Saint-Etienne), 361–366.

Özyener, F., Rossiter, H. B., Ward, S. A., and Whipp, B. J. (2001). Influence of exercise intensity on the on-and off-transient kinetics of pulmonary oxygen uptake in humans. *J. Physiol.* 533, 891–902.

Peltonen, J. E., Hägglund, H., Koskela-Koivisto, T., Koponen, A. S., Aho, J. M., Rissanen, A. P. E., et al. (2013). Alveolar gas exchange, oxygen delivery and tissue deoxygenation in men and women during incremental exercise. *Respir. Physiol. Neurobiol.* 188, 102–112. doi: 10.1016/j.resp.2013.05.014

Pessoa Filho, D. M., Alves, F. B., Reis, J. F., Greco, C. C., and Denadai, B. S. (2012). V̇O2 kinetics during heavy and severe exercise in swimming. *Int. J. Sports Med.* 33, 744–748. doi: 10.1055/s-0031-1299753

Pessôa Filho, D. M., Simionato, A. R., Siqueira, L. O. D. C., Espada, M. A., and Pestana, D. (2016). Influence of regional and whole-body composition on swimming performance and aerobic indices. *Braz J of Sports Med* 22, 195–199. doi: 10.1590/1517-869220162203151766

Reis, J. F., Alves, F. B., Bruno, P. M., Vleck, V., and Millet, G. P. (2012). Oxygen uptake kinetics and middle-distance swimming performance. *J. Sci. Med. Sport.* 15, 58–63. doi: 10.1016/j.jsams.2011.05.012

Ribeiro, J., Toubekis, A. G., Figueiredo, P., de Jesus, K., Toussaint, H. M., Alves, F., et al. (2017). Biophysical determinants of front crawl swimming at moderate and severe intensities. *Int. J. Sports Physiol. Perform.* 12, 241–246. doi: 10.1123/ijspp.2015-0766

Robergs, R. A., Dwyer, D., and Astorino, T. (2010). Recommendations for improved data processing from expired gas analysis indirect calorimetry. *Sports Med.* 40, 95–111. doi: 10.2165/11319670-000000000-00000

Rosenthal, J. A. (1996). Qualitative descriptors of strength of association and effect size. *J. Soc. Service Res.* 21, 37–59. doi: 10.1300/J079V21N04_02

Rossiter, H. B., Ward, S. A., Kowalchuk, J. M., Howe, F. A., Griffiths, J. R., and Whipp, B. J. (2002). Dynamic asymmetry of phosphocreatine concentration and O2 uptake between the on-and off-transients of moderate-and high-intensity exercise in humans. *J. Physiol.* 541, 991–1002. doi: 10.1113/jphysiol.2001.012910

Russ, D. W., Lanza, I. R., Rothman, D., and Kent-Braun, J. A. (2005). Sex differences in glycolysis during brief, intense isometric contractions. *Muscle Nerve* 32, 647–655. doi: 10.1002/mus.20396

Sala, A., Webber, C. E., Morrison, J., Beaumont, L. F., and Barr, R. D. (2007). Whole-body bone mineral content, lean body mass, and fat mass measured by dual-energy X ray absorptiometry in a population of normal Canadian children and adolescents. *Can. Assoc. Radiol. J.* 58, 46–52.

Scheuermann, B. W., Hoelting, B. D., Noble, M. L., and Barstow, T. J. (2001). The slow component of O2 uptake is not accompanied by changes in muscle EMG during repeated bouts of heavy exercise in humans. *J. Physiol.* 531, 245–256. doi: 10.1111/j.1469-7793.2001.0245j.x

Sousa, A., Figueiredo, P., Zamparo, P., Vilas-Boas, J. P., and Fernandes, R. J. (2013). Anaerobic alactic energy assessment in middle distance swimming. *Eur. J. Appl. Physiol.* 113, 2153–2158. doi: 10.1007/s00421-013-2646-3

Spencer, M. R., and Gastin, P. B. (2001). Energy system contribution during 200-to 1500 m running in highly trained athletes. *Med. Sci. Sports Exerc.* 33, 157–162. doi: 10.1097/00005768-200101000-00024

Stirling, J. R., Zakynthinaki, M. S., and Saltin, B. (2005). A model of oxygen uptake kinetics in response to exercise: including a means of calculating oxygen demand/deficit/debt. *Bull. Math. Biol.* 67, 989–1015. doi: 10.1016/j.bulm.2004.12.005

Toussaint, H. M. (1990). Differences in propelling efficiency between competitive and triathlon swimmers. *Med. Sci. Sports Exerc.* 22, 409–415.

Toussaint, H. M., and Hollander, A. P. (1994). Energetics of competitive swimming: implications for training programs. *Exerc. Sports Sci. Rev.* 18, 384–405. doi: 10.2165/00007256-199418060-00004

Troup, J., Hollander, A., Bone, M., Trappe, S., and Barzdukas, A. (1992). "Performance-related differenced in the anaerobic contribution of competitive freestyle swimmers," in *Biomechanics and Medicine in Swimming VI*, eds D. MacLaren, T. Reilly, and A. Lees (London: E & FN SPON), 271–278.

Unnithan, V., Holohan, J., Fernhall, B., Wylegala, J., Rowland, T., and Pendergast, D. R. (2009). Aerobic cost in elite female adolescent swimmers. *Int. J. Sports Med.* 30, 194–199. doi: 10.1055/s-0028-1104583

Wakayoshi, K., D'Acquisto, L., Cappaert, J., and Troup, J. (1995). Relationship between oxygen uptake, stroke rate and swimming velocity in competitive swimming. *Int. J. Sports Med.* 16, 19–23. doi: 10.1055/s-2007-972957

Weber, C. L., Chia, M., and Inbar, O. (2006). Gender differences in anaerobic power of the arms and legs–a scaling issue. *Med. Sci. Sports Exerc.* 38, 129–137. doi: 10.1249/01.mss.0000179902.31527.2c

Weber, C. L., and Schneider, D. A. (2002). Increases in maximal accumulated oxygen deficit after high-intensity interval training are not gender dependent. *J. Appl. Physiol.* 92, 1795–1801. doi: 10.1152/japplphysiol.00546.2001

Zacca, R., Azevedo, R., Ramos, V. R. Jr., Abraldes, J. A., Vilas-Boas, J. P., de Souza Castro, F. A., et al. (2020). Biophysical follow-up of age-group swimmers during a traditional three-peak preparation program. *J. Strength Cond. Res.* 34, 2585–2595. doi: 10.1519/JSC.0000000000002964

Zamparo, P., Capelli, C., Cautero, M., and Di Nino, A. (2000). Energy cost of front crawl swimming at supramaximal speeds and underwater torque in young swimmers. *Eur. J. Appl. Physiol.* 83, 487–491. doi: 10.1007/s004210000318

Zamparo, P., Capelli, C., and Pendergast, D. (2011). Energetics of swimming: a historical perspective. *Eur. J. Appl. Physiol.* 111, 367–378. doi: 10.1007/s00421-010-1433-7

Zamparo, P., Lazzer, S., Antoniazzi, C., Cedolin, S., Avon, R., and Lesa, C. (2008). The interplay between propelling efficiency, hydrodynamic position and energy cost of front crawl in 8 to 19-year-old swimmers. *Eur. J. Appl. Physiol.* 104, 689–699. doi: 10.1007/s00421-008-0822-7

Zemel, B. (2013). Bone mineral accretion and its relationship to growth, sexual maturation and body composition during childhood and adolescence. *World Rev. Nutr. Diet.* 106, 39–45. doi: 10.1159/000342601

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Relationship Between Hand Kinematics, Hand Hydrodynamic Pressure Distribution and Hand Propulsive Force in Sprint Front Crawl Swimming

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Purpose: This study investigated the relationship between hand kinematics, hand hydrodynamic pressure distribution and hand propulsive force when swimming the front crawl with maximum effort.

Methods: Twenty-four male swimmers participated in the study, and the competition levels ranged from regional to national finals. The trials consisted of three 20 m front crawl swims with apnea and maximal effort, one of which was selected for analysis. Six small pressure sensors were attached to each hand to measure the hydrodynamic pressure distribution in the hands, 15 motion capture cameras were placed in the water to obtain the actual coordinates of the hands.

Results: Mean swimming velocity was positively correlated with hand speed ($r = 0.881$), propulsive force ($r = 0.751$) and pressure force ($r = 0.687$). Pressure on the dorsum of the hand showed very high and high negative correlations with hand speed ($r = -0.720$), propulsive force ($r = -0.656$) and mean swimming velocity ($r = -0.676$). On the contrary, palm pressure did not correlate with hand speed and mean swimming velocity. Still, it showed positive correlations with propulsive force ($r = 0.512$), pressure force ($r = 0.736$) and angle of attack ($r = 0.471$). Comparing the absolute values of the mean pressure on the palm and the dorsum of the hand, the mean pressure on the dorsum was significantly higher and had a larger effect size ($d = 3.71$).

Conclusion: It is suggested that higher hand speed resulted in a more significant decrease in dorsum pressure (absolute value greater than palm pressure), increasing the hand propulsive force and improving mean swimming velocity.

Keywords: hand propulsive force, swimming velocity, hydrodynamic pressure, dorsum pressure, stroke frequency

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INTRODUCTION

Mainly two factors determine the swimming velocity: propulsion and drag force. When the swimming velocity is constant, the mean propulsion and the mean drag are the same (van der Vaart et al., 1987). Increasing the swimming velocity requires increasing the propulsion or decreasing the drag. However, due to the complexity of unsteady flow mechanics in human swimming, it is currently impossible to measure propulsion and drag directly. Thus, researchers have established indirect methods to estimate these forces, such as the MAD-system (Hollander et al., 1986), velocity perturbation method (Kolmogorov and Duplishcheva, 1992), assisted towing method (Formosa et al., 2012), MRT (measured values of residual thrust) method (Narita et al., 2017). These methods enable researchers to estimate drag (and consequently propulsion, assuming the swimmer maintains a constant velocity ignoring force and velocity fluctuations within a stroke cycle) acting on the whole body but do not provide information on the sources of the total forces.

On the other hand, pressure sensors have been used to estimate the propulsion exerted by the hand in recent years (Kudo et al., 2012; Tsunokawa et al., 2019a; Koga et al., 2020, 2021). The measurement method using pressure sensors has a limitation: it can only measure the fluid force exerted by a part of the swimmer's body. On the other hand, it can directly identify the magnitude of the force and the direction of force acting in real-time. Because of the above, it is more realistic to use propulsion rather than drag as a cue to obtain empirical data for improving swimming velocity.

It has been suggested that the arms exert more propulsion than the legs in front crawl swimming (Cohen et al., 2017) and that the hands contribute the most propulsion among the upper arm, forearm and hand (Toussaint et al., 2002; Samson et al., 2017; Takagi et al., 2021). Hence, the magnitude of propulsion in hand is related to swimming velocity (Tsunokawa et al., 2019b). Kudo et al. (2016) compared the hand propulsive force in the Insweep and Upsweep phases during 25 m front crawl swimming with a maximum effort by advanced and intermediate level swimmers. The results showed that advanced swimmers exhibited more significant hand propulsive force, and a higher competitive level was associated with more substantial hand propulsive force.

The forces acting on the body surface underwater include pressure and friction. Since pressure is the major contributor to hand propulsive force (Samson et al., 2017), the hand propulsive force is calculated as the force in the propulsive direction by measuring the pressure on the hand surface (Tsunokawa et al., 2018a,b). The pressure force of the hand is calculated by multiplying the (so called) hydrodynamic pressure difference between hydrodynamic pressure on the palm side and dorsum side of the hand by the hand's area. The hydrodynamic pressure difference is related to the magnitude of the hand pressure force because the hydrodynamic pressure acts from the higher pressure to the lower pressure. In front crawl swimming, hydrodynamic pressure on the palm side shows a positive value, while the hydrodynamic pressure on the dorsum side shows a negative value (Takagi et al., 2014). In a study investigating the change in hand pressure force with increasing stroke frequency in front crawl swimming, the hand pressure force increased with increasing stroke frequency. The increase in hand pressure force was due to the more significant contribution from the increase in absolute hydrodynamic pressure on the dorsum side than on the palm side (Koga et al., 2021). However, this study reported hydrodynamic pressure distributions within individuals and cycles. Still, the relationship between the magnitude of the propulsive force and the value of hydrodynamic pressure distribution between individuals was not clarified.

In addition, it has been reported that the magnitude of hand propulsive force varied with some kinematic variables. A study that subjectively and gradually increased swimming velocity reported an increase in hand propulsive force, as well as an increase in stroke frequency and hand speed (Tsunokawa et al., 2019a). In a study in which stroke frequency was increased to over self-selected stroke frequency, both hand propulsive force and angle of attack decreased (Koga et al., 2020). This decrease of attack angle has been suggested to be related to the value of hydrodynamic pressure on the palm side. Thus, it is inferred that some kinematics of the hand affect the magnitude of hand propulsive force.

However, previous studies have not clarified the relationship between the kinematic variables of the hand, the hand's pressure distribution, and the fluid force exerted by the hand when swimming the front crawl. Therefore, this study aimed to determine the interrelationships between the hand kinematic variables, hydrodynamic pressure, and fluid forces exerted by trained swimmers when swimming the front crawl with maximum effort. The results obtained are expected to provide coaches and swimmers with new insights into the mechanisms of what they should keep in mind to swim faster.

MATERIALS AND METHODS

Participant

Twenty-four male swimmers participated in this study, and their competition level ranged from the regional to the national final. The personal characteristics of the swimmers are shown in **Table 1**. The swimmers were informed purpose and content of this study and the risks involved, and their written consent to participate was obtained. The Ethics Committee approved the study of the University of Tsukuba.

Experimental Setup

The experiment was conducted in the indoor 50 m pool. After a self-selected warm-up, the swimmers were asked to perform three 20 m front crawl swimming trials with no breathing and maximum effort. The trial area was between 5 and 25 m from the wall, and the swimmers started in a floating position to avoid the effect of the wall kicking on their swimming velocity. One stroke cycle in front crawl swimming was defined as the duration of entry of one hand into the water to the entry of the same hand again. Due to the limitations of the measurement area, the motion capture system could not capture all markers during a complete stroke, depending on when the swimmer entered

TABLE 1 | Participants' physical characteristics, speciality and performance level.

Swimmer	Age (years)	Height (m)	Weight (kg)	Speciality	Best Record of 50 m front crawl (s")	FINA point
A	19	176.0	72.0	Front crawl	22.61	791.0
B	26	174.0	72.0	Front crawl	22.79	772.4
C	26	184.0	81.0	Front crawl	22.96	755.3
D	25	181.0	76.0	Front crawl	22.98	753.4
E	22	177.0	80.0	Front crawl	23.22	730.3
F	22	187.0	80.0	Front crawl	23.27	725.6
G	24	186.0	78.0	Front crawl	23.50	704.5
H	21	169.0	69.0	Front crawl	23.52	702.7
I	21	175.0	70.0	Back stroke	23.86	673.1
J	22	174.6	79.0	Front crawl	23.93	667.2
K	20	181.0	71.5	Front crawl	24.06	656.4
L	19	175.5	70.0	Breast stroke	24.20	645.1
M	21	183.0	77.0	Front crawl	24.26	640.3
N	21	175.0	75.0	Individual medley	24.31	636.4
O	22	169.0	63.0	Back stroke	24.87	594.3
P	23	176.0	72.5	Breast stroke	24.89	592.9
Q	21	179.0	70.0	Front crawl	24.91	591.5
R	20	168.0	62.0	Butterfly	24.99	585.8
S	20	172.5	68.0	Back stroke	25.00	585.1
T	20	175.0	69.0	Front crawl	25.18	572.7
U	20	175.0	74.0	Individual medley	25.28	565.9
V	19	176.0	78.0	Back stroke	25.42	556.6
W	20	171.0	68.0	Breast stroke	25.55	548.1
X	20	164.0	66.0	Front crawl	26.24	506.0
Mean	21.4	176.0	72.5		24.24	648.0
SD	2.0	5.6	5.2		0.97	78.2

the measurement area. Therefore, the trial with an entire one-stroke cycle within the measurement area was considered the appropriate trial for analysis among the three trials.

Data Acquisition

Three-dimensional motion analysis was conducted using a three-dimensional real-time motion measurement system, VENUS 3D (Nobby Tech. Ltd., Japan), to obtain absolute coordinates of markers. The measurement area was 5 m between 17 and 22 m from the pool wall, and 15 cameras were placed underwater surrounding the measurement area (**Figure 1**). The water depth of the measurement area was 2 m. We used the dynamic calibration system provided with the VENUS 3D to acquire more than 2,000 samples by swinging the wand to calibrate the measurement area. The standard error of the underwater motion capture in calibration was < 0.3 mm. LED markers were attached to 10 points on the left and right great trochanter, the left and right second and fifth metacarpophalangeal joints, the left and right radial styloid process, and the left and right ulnar styloid process (**Figure 2A**). The trials were recorded with 100 Hz. This study used a fixed right-hand coordinate system with the swimmer's propulsive direction as the Y-axis, the lateral directions as the X-axis, and the vertical direction as the Z-axis.

Waterproofed small pressure sensors (Round, diameter: 6 mm, thickness: 0.6 mm, PS-05KC, Kyowa Electronic Instruments Co. Ltd., Japan, **Figure 2A**) were attached to the swimmer's hand to measure the pressure distribution on the hands during the trial, following the method described by Tsunokawa et al. (2018b). At 12 locations, the sensors were attached to the palm and dorsum sides of the second, third and fifth metacarpophalangeal joints. The hand plane was divided into three segments (A_{1}-$_{3}$) by the second and fourth interphalangeal spaces (Area: $A_1 = 54.8 \pm 11.0$ cm^2, $A_2 = 73.4 \pm 8.3$ cm^2, $A_3 = 39.5 \pm 6.8$ cm^2, **Figure 2A**). Pressure was assumed to act uniformly in a segment, and the value of each pressure sensor was defined the representative pressure value acted to the each segment. The signals output from the pressure sensors were recorded on a laptop with 100 Hz by using a universal recorder (EDX-100A, Kyowa Electronic Instruments Co. Ltd., Japan). All signals from the motion capture system and the pressure sensors were synchronized and stored on a laptop. Since the pressure sensors were wired, a cart carrying the equipment was moved with the swimmer (**Figure 1**). Because the motion capture cameras were placed only underwater, only the stroke motion underwater was analyzed.

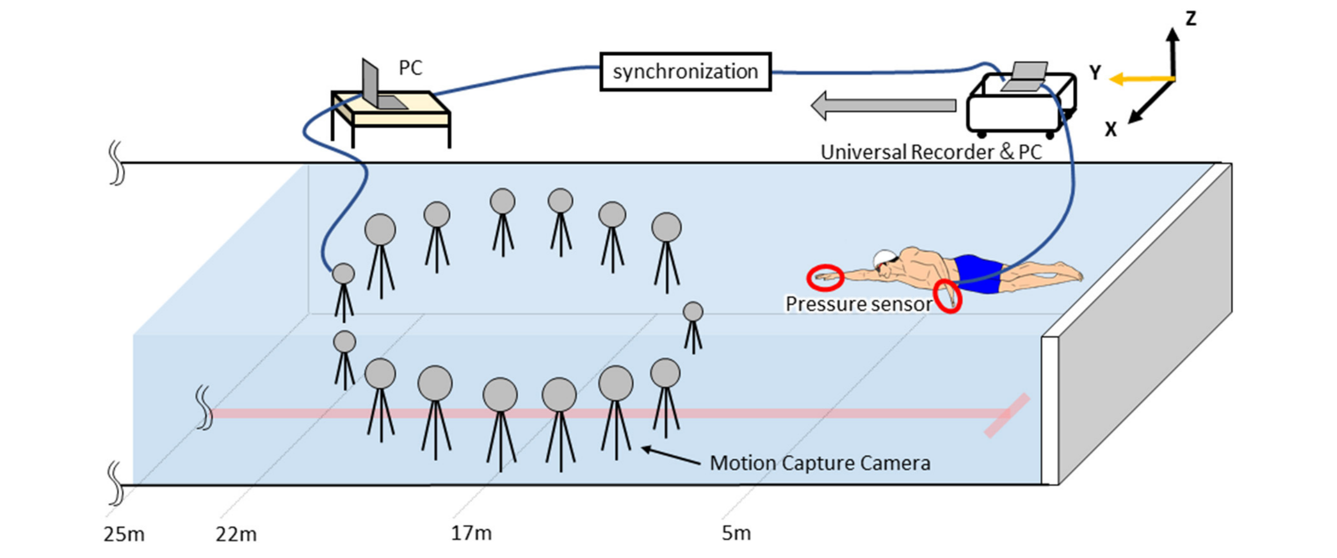

FIGURE 1 | Experimental setting. Placement of motion capture cameras and measurement area.

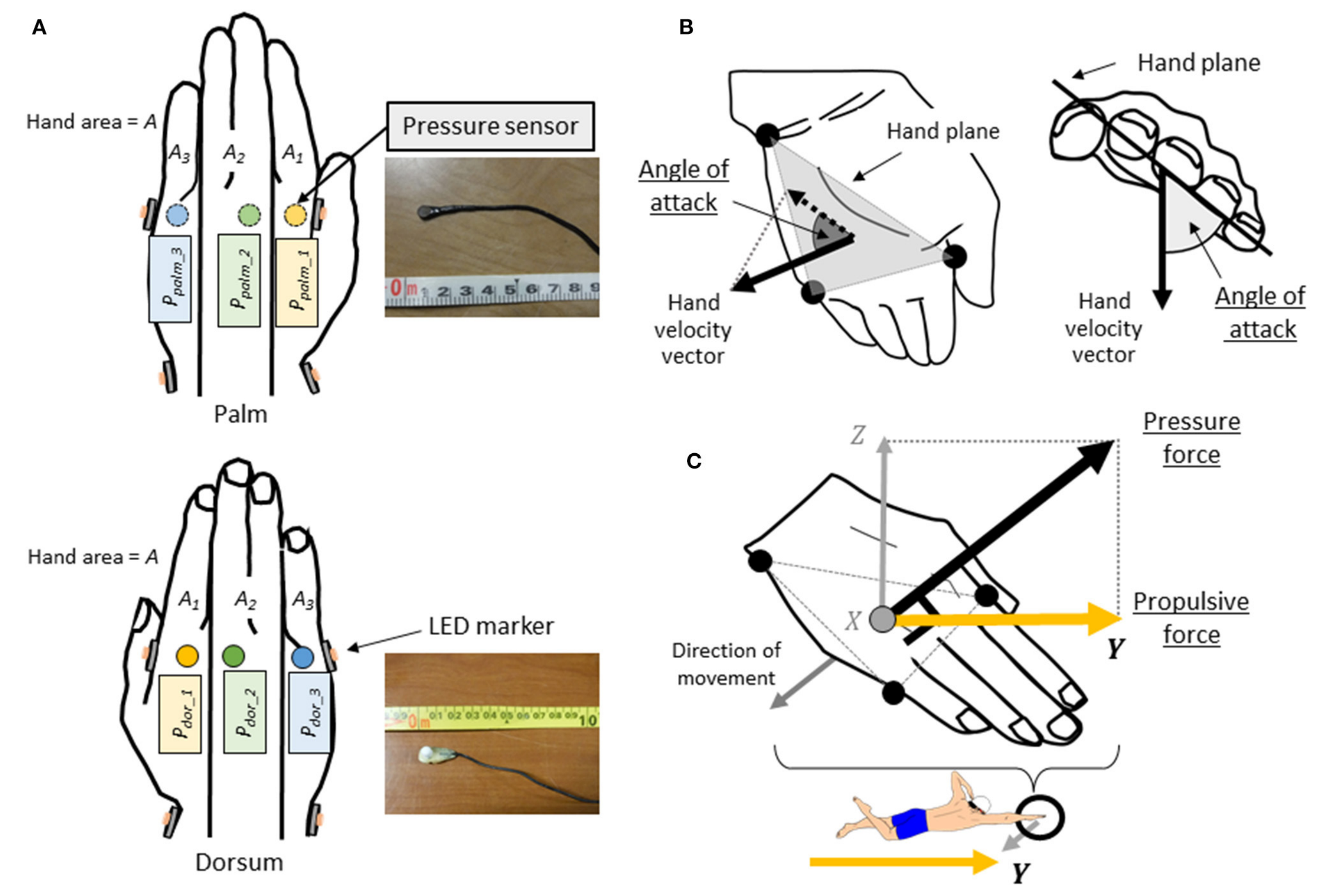

FIGURE 2 | (A) The location of the pressure sensors and the LED markers attached to the hands. **(B)** Definition of angle of attack. **(C)** Definition of hand plane, hand pressure force acting perpendicular to the hand plane, and hand propulsive force.

Data Analysis

Kinematic Parameters

The average swimming velocity per stroke cycle was calculated by time-differentiating the displacement that the midpoint of the left and right great trochanter moved in the Y-axis direction, calculated using motion capture analysis software (VESUS 3D 4.3, Nobby Tech. Ltd., Japan). The stroke frequency was calculated from the reciprocal of the time taken per cycle, and the stroke length was calculated by dividing swimming velocity by stroke frequency. The hand speed was calculated by time-differentiating the 3D displacement traveled at the midpoint of each coordinate of the hand (second and fifth metacarpophalangeal joints, ulnar styloid process). The distance traveled by the hand in the water was calculated by multiplying the speed of the hand by the time taken for one stroke in the water. The angle of attack was calculated as the angle of projection of the hand velocity vector onto the plane of the hand composed of two vectors pointing from the ulnar styloid process to the fifth and second metacarpophalangeal joints (**Figure 2B**). The hand speed, angle of attack, distance traveled by the hand in water and stroke time in water were averaged only during the period of movement through the water in the measurement space.

Hydrodynamic Pressure

The pressure value measured at sensors ($P_{measured}$) combined hydrodynamic pressure of P_{effect} and $P_{potential}$ (Equation 1, **Figure 3A**). The effective pressure (P_{effect}) is the pressure acting perpendicular to the surface of the sensor, reflecting the change in energy in the fluid due to the swimming motion. The $P_{potential}$ is the pressure due to the change in the potential, i.e. water depth ($P_{potential}$, Equation 2).

$$P_{measured} = P_{effect} + P_{potential} \tag{1}$$

$$P_{potential} = \rho g z \tag{2}$$

where ρ indicates the water density (997 kg/m^3), relative flow velocity (v), g indicates the acceleration of gravity (9.80665 m/s^2), and z indicates the depth of the pressure sensor. z is set to zero at the water surface, and becomes positive as it gets deeper (**Figure 3B**). The position of each pressure sensor attached to the hand was calculated from the coordinates of the second and fifth metacarpophalangeal joints and the midpoint of both joints, assuming that the six sensors are located at approximately the same depth of water.

For the pressure distribution measurement, atmospheric pressure was set to zero. The pressure data at each hand's segment was smoothed using a low-pass Butterworth digital filter at a cut-off frequency of 15 Hz by reference to the previous study (Tsunokawa et al., 2018b). Since the magnitude of pressure force is the pressure difference between the palm and the dorsum of the hand multiplied by the hand area, it is important to show the P_{effect} for the palm and the dorsum of the hand respectively. When determining the P_{effect} on the palm side (p_{palm}) and dorsum side (p_{dor}), instead of averaging the $P_{measured}$, the area of each of the three segments (**Figure 2A**) and the pressure due to the change in water depth ($P_{potential}$, **Figure 3B**) were considered and the p_{palm} and p_{dor} were calculated according to the Equations 3 and 4 (**Figures 3C,D**).

$$p_{palm} = \frac{\sum_{i=1}^{3} \left(p_{palm\_i} - P_{potential\_i}\right) \times A_i}{A} \tag{3}$$

$$p_{dor} = \frac{\sum_{i=1}^{3} \left(p_{dor_i} - P_{potential\_i}\right) \times A_i}{A} \tag{4}$$

where A_i indicates the hand's area of i-th segment ($i = 1$–3), p_{palm_i} and p_{dor_i} indicate the measured pressure on the i-th segment of the palm and dorsum respectively, $P_{potential\_i}$ indicate the pressure due to water depth on the i-th segment. A indicates the entire hand's area. Mean p_{palm} and p_{dor} were calculated only when the hand was in the underwater phase.

Hand Pressure Force and Propulsive Force

The hand pressure force was calculated by multiplying the difference between the pressures measured on the palm and dorsum side of the hand in each segment by the area of the segment and summing the forces in the three segments, as shown in Equation 5 (**Figures 4A–C**)

$$Hand\ pressure\ force = \sum\nolimits_{i=1}^{3} (p_{palm\_i} - p_{dor\_i}) \times A_i \tag{5}$$

where A_i indicates the hand's area of i-th segment ($i = 1$–3), p_{palm_i} and p_{dor_i} indicate the measured pressure on the i-th segment of the palm and dorsum, respectively. In the calculation of the difference between pressure on the palm and the dorsum of the hand, it is not necessary to consider the depth and the hand area, because the sensors depth and area of the hand where the pressure acts are approximately the same on the palm and the dorsum of the hand. Therefore, the pressure difference between the palm and dorsum of the hand is calculated by directly calculating the difference using the values measured by pressure sensors on the palm and dorsum, and the difference between pressure on the palm and the dorsum of the hand was calculated.

This hand pressure force refers to the hydrodynamic force acting perpendicular to the plane of the hand. Therefore, the pressure force's vector of the hand was assumed to be the same as the normal vector perpendicular to the plane of the hand (**Figure 2C**). The hand propulsive force is defined as the hand pressure force acting in the direction of the Y-axis, which is the propulsive direction of the swimmer. Therefore, the unit vector of each directional component of the normal vector to the hand plane was obtained, and the hand propulsive force was calculated by multiplying the hand pressure force by the unit vector in the Y-axis direction, as shown in **Figure 2C**.

Since the hand pressure force and propulsive force were measured with the left and right hands, the sum of the left- and right-hand values at each time point were calculated (**Figure 4D**). Then the average value of the hand's pressure force and propulsive force for one stroke cycle were calculated. In addition, the propulsion ratio, which indicates how much of the hand pressure force was used to propel the hand, was calculated. The propulsion ratio was calculated by dividing the propulsive

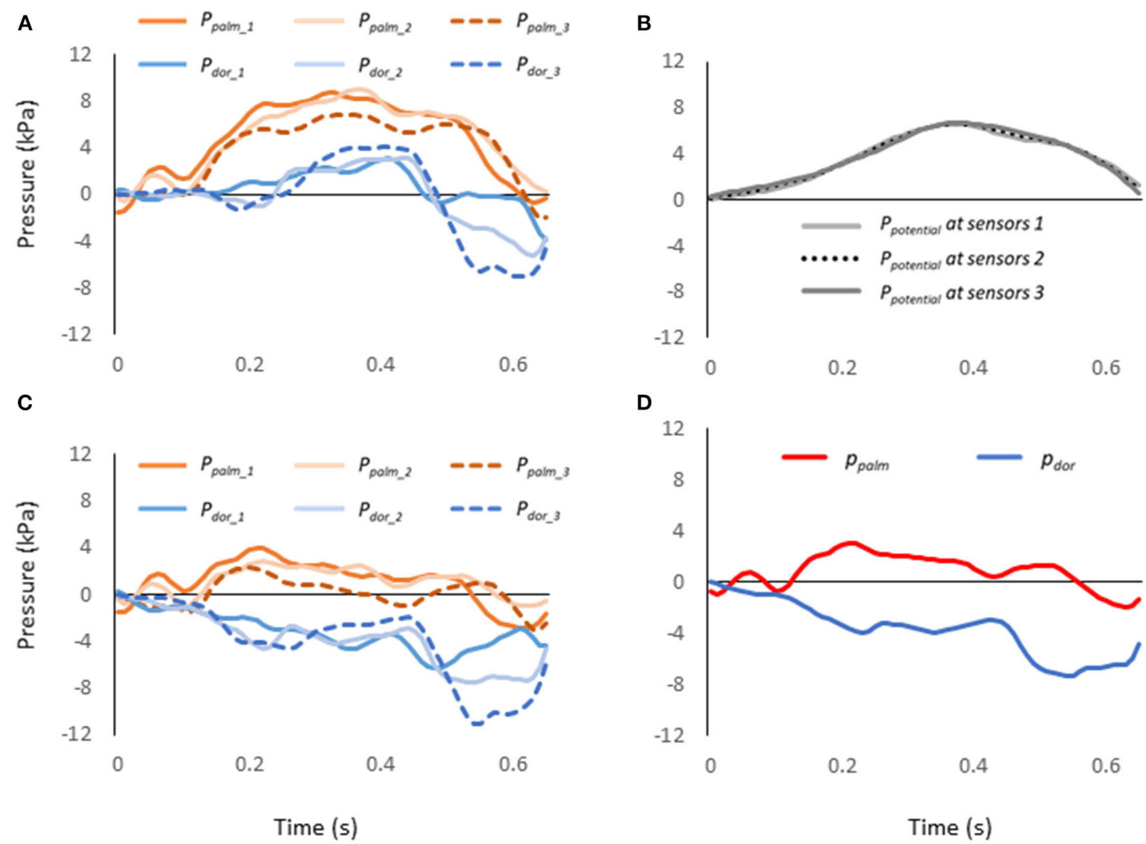

FIGURE 3 | (A) Pressure value measured by each pressure sensor. **(B)** $P_{potential}$ at each pressure sensor. **(C)** P_{effect} at each pressure sensor calculated by subtracting $P_{potential}$ from the value of each pressure sensor. **(D)** The representative values of the pressure calculated considering the differences between the three segments of the hand.

force of the hand by the pressure force of the hand (Tsunokawa et al., 2018a).

Statistical Analysis

Data for all variables were analyzed using time averages as representative values. Data were analyzed using SPSS Statistics 25.0. The normality of the samples was verified using the Shapiro-Wilk test, and the results showed that all data were normally distributed. The Pearson correlation coefficient was calculated to test the relationship between each variable. The coefficient of correlation < 0.30 indicated a low correlation, between 0.31 and 0.49 indicated a moderate correlation, between 0.50 and 0.69 indicated high correlation, between 0.70 and 0.89 indicated a very high correlation, and higher than 0.90 indicate extremely high correlation (Hopkins et al., 2009). In addition, a unpaired t-test was used to compare the mean absolute value of the p_{palm} and p_{dor}. Cohen's d was used to calculate the effect size. Cohen's d value < 0.60 indicated a small effect size, between 0.61 and 1.20 indicated a moderate effect size, between 1.21 and 2.00 indicated a large effect size, between 2.01 and 4.00 indicated a very large effect size, and higher than 4.01 indicated a extremely large effect size (Hopkins et al., 2009; Barbosa et al., 2021). The statistical significance level was set at $\alpha = 0.05$.

RESULTS

Correlation coefficients between the variables are shown in **Table 2**, and variables with a statistical significance level of <5% were highlighted in gray. In addition, **Figure 5** shows a schematic representation of the mutual correlation coefficients for each variable.

Figure 6 shows the results of comparing the mean absolute values of p_{palm} and p_{dor}. The absolute values of the p_{dor} were significantly higher than the p_{palm} (p_{palm}: 1.17 ± 0.50 kPa, p_{dor}: 2.83 ± 0.39 kPa, $p < 0.001$, effect size 3.71).

Figure 7 shows the changes in the right-hand overtime variables for the fastest swimmer A and the slowest swimmer X as a typical example. Compared to swimmer X, swimmer A had greater hand propulsive force and hand pressure force, the higher absolute value of p_{dor}, and higher hand speed.

DISCUSSION

This study aimed to identify the factors responsible for high hand propulsive force in swimmers who can reach high swimming velocity and assess the influence of hand hydrodynamic pressure and hand kinematics. Swimming velocity was significantly

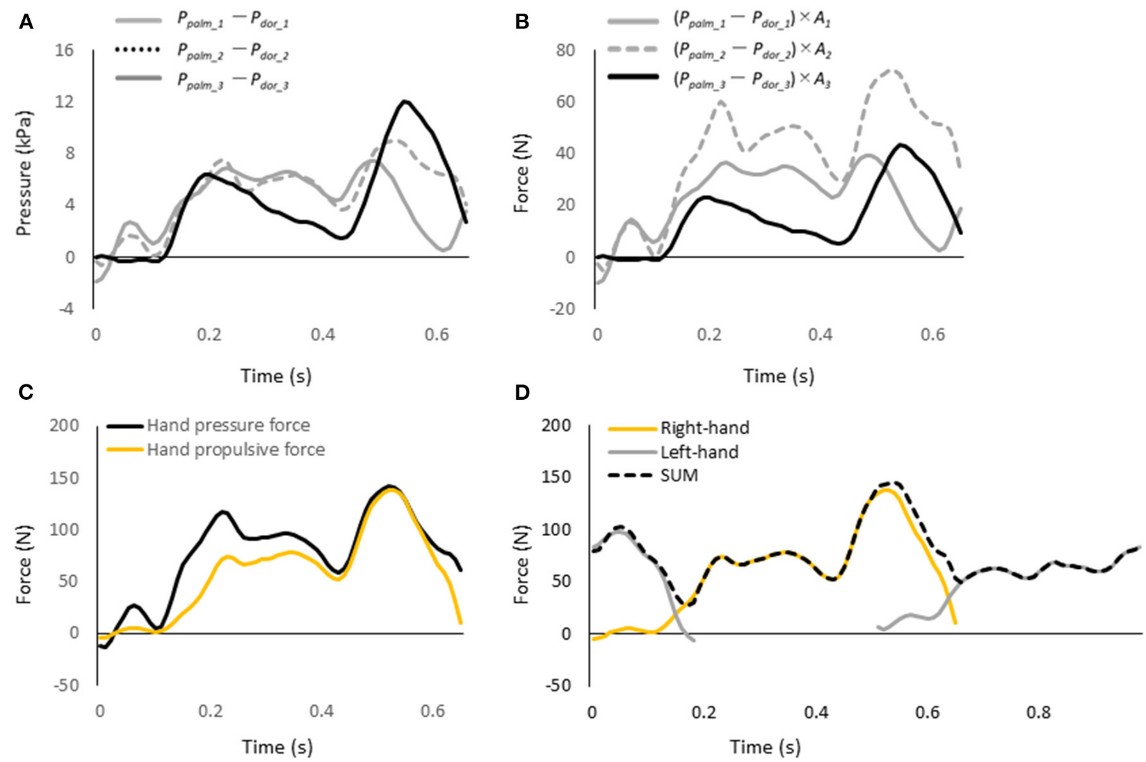

FIGURE 4 | (A) Pressure difference in each hand segment. **(B)** Pressure force in each hand segment. **(C)** Pressure force and propulsive force exerted by the entire hand. **(D)** Hand propulsive force of the sum of the left and right values at each time point (dash line).

positively correlated with hand speed, propulsive force and pressure force, with correlation coefficients of $r = 0.881$, 0.751 and 0.687, respectively. Understandably, the swimming velocity showed a high or very high correlation with the above variables. In other words, the faster the hand moves in the water, the greater the hydrodynamic force exerted by the hand is. Therefore, the greater the propulsive force acting in the propulsive direction greater the swimming velocity, a very straightforward mechanism. However, although this mechanism is based on the interpretation of the quasi-steady theory, recent studies (Toussaint et al., 2002; Takagi et al., 2014) have shown that the quasi-steady assumption does not necessarily hold because the flow field around the hand is unsteady. Therefore, based on the results of this study, we will discuss the mechanism of improving propulsion and swimming velocity.

The pressure force was calculated by multiplying the difference between the pressures measured on the palm and dorsum side of the hand by the hand's area. Thus, the greater the pressure difference, the greater the pressure force exerted. Therefore, the p_{palm} and p_{dor} were considered separately. Firstly, the p_{dor} showed a very high and high negative correlation with the hand speed ($r = -0.720$), the propulsive force ($r = -0.656$) and the swimming velocity ($r = -0.676$) (**Table 2**). In other words, it can be interpreted that as the hand speed increased, the p_{dor} decreased, and the propulsive force increased, which led to an increase in swimming velocity. On the other hand, p_{palm} was not correlated with hand speed but showed a positive correlation with propulsive force ($r = 0.512$) and angle of attack ($r = 0.471$) (**Table 2**). Furthermore, a comparison of the absolute values of p_{palm} and p_{dor} shows that the absolute value on the P_{dor} was more than twice as large as it on the p_{palm}, as shown in **Figure 6**.

Integrating the above results assumes that the swimmer with high hand speed generates a strong vortex on the dorsum side of the hand, which reduces the p_{dor} (Takagi et al., 2014), resulting in a negative pressure, and the absolute value of which is considerably greater than the p_{palm}. This significant decrease in p_{dor} increases the hydrodynamic pressure difference between the palm and dorsum of the hand. It is main contributer to the increase in hydrodynamic force. This phenomenon was also confirmed in the work of Takagi et al. (2013, 2014), who analyzed the flow around the hand using PIV (Particle Image Velocimetry) with a robotic arm. They reported that vortices were generated on the dorsum side of the hand, especially at the point where the direction of movement of the hand changed, resulting in an unsteady lift force were reported. A study that observed the behavior of water around the hand through simple demonstrations also suggest that the force generation at the hand is primarily due to the acceleration of water on the dorsum of the hand, rather than "pushing" water on the palm of the hand (Soh and Sanders, 2021). In addition, Fuchiwaki et al. (2007) investigated the vortex structure of the wake of a wing undergoing heaving motion at different motion speeds. They

TABLE 2 | Correlation coefficient of each variable.

	Mean swimming velocity	Stroke frequency	Stroke length	Mean hand pressure force	Mean hand propulsive force	Propulsion ratio	Mean hand speed	Mean angle of attack	Mean p_{palm}	Mean p_{dor}	Stroke time underwater	Travel distance underwater
Mean swimming velocity		0.135	0.509*	0.687**	0.751**	0.15	0.881**	0.142	0.269	−0.676**	−0.328	0.282
Stroke frequency			−0.780**	0.054	0.182	0.292	0.395	0.03	0.137	−0.416*	−0.857**	−0.737**
Stroke length				0.371	0.294	−0.168	0.213	0.059	0.047	−0.053	0.522**	0.800**
Mean hand pressure force					0.873**	−0.228	0.676**	0.355	0.736**	−0.566**	−0.22	0.269
Mean hand propulsive force						0.269	0.696**	0.444*	0.512*	−0.656**	−0.287	0.202
Propulsion ratio							0.08	0.216	−0.395	−0.179	−0.199	−0.184
Mean hand speed								0.19	0.324	−0.720**	−0.569**	0.097
Mean angle of attack									0.471*	0.149	−0.044	0.098
Mean p_{palm}										−0.129	−0.311	−0.118
Mean p_{dor}											0.486*	0.023
Stroke time underwater												0.760**
Travel distance underwater												

**p* < 0.05, ***p* < 0.01. Gray shades indicate that the correlation is significant.

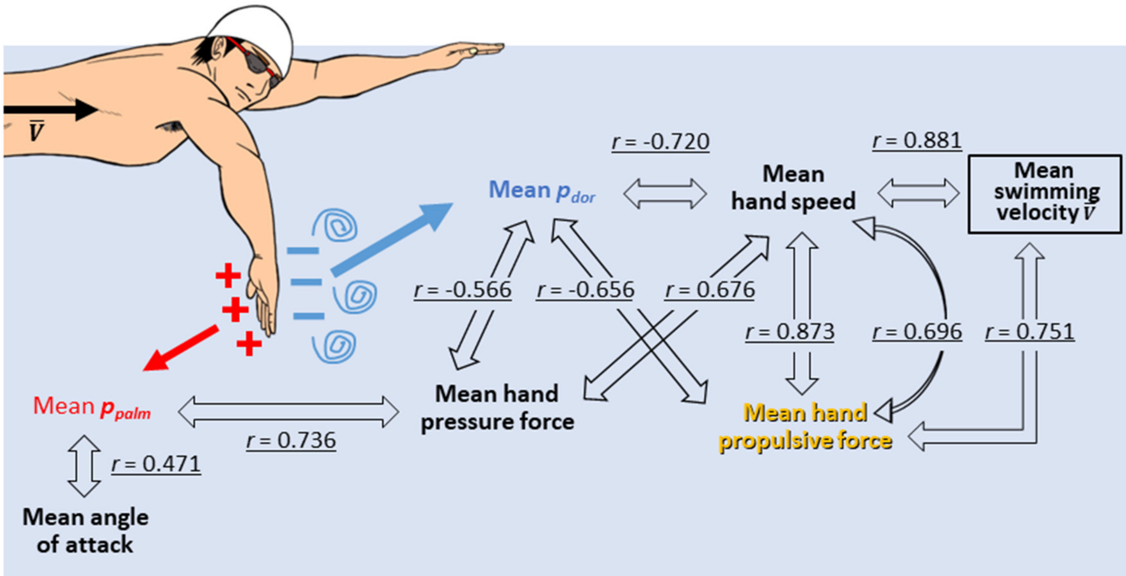

FIGURE 5 | Schematic representation of the mutual correlation coefficients for each variable.

reported that the higher the motion speed, the higher the vorticity of the wake and the higher the propulsive force. A reduction in the p_{dor} is more critical than p_{palm}, but this does not mean the p_{palm} is not involved in the increase in propulsive force. The p_{palm} is also related to pressure force and propulsive force but is less involved than the p_{dor}, suggesting that the p_{dor} is more important for faster swimmers. This suggestion is shared by the results obtained in the Koga et al. (2021) experiment, which analyzed p_{palm} and p_{dor} changes in well-trained swimmers by gradually increasing the stroke frequency within individuals. This study reported that as the stroke frequency was increased, the swimming velocity also increased, but the p_{palm} did not increase significantly, whereas the p_{dor} decreased significantly and the hydrodynamic pressure difference increased. This phenomenon is consistent with the report of Tsunokawa et al. (2015) that the absolute value of the p_{dor} of the foot was higher than the p_{palm} of the foot during the breaststroke kicking without upper limb movement. Moreover, it is consistent with Kawai et al. (2020) report investigating the foot propulsive force and hydrodynamic pressure distribution during the eggbeater kicking with maximum effort in water polo players. They reported that the variation of the magnitude of the foot pressure force was more in tune with the value of p_{dor} of the foot than the p_{palm} of the foot.

However, this fact may be hard to believe for swimmers who have always thought to push the water to move forward. Therefore, we would like to suggest some hints for improving swimming velocity by comparing the raw data of swimmer A, who had the highest average swimming velocity, and swimmer X, who had the slowest average swimming velocity, among the 24 swimmers who participated in this experiment (**Figure 7**). In the upper part of **Figure 7**, the pressure force (black) and the propulsive force (yellow) during one stroke are shown. It is clear from the figure that the pressure force and propulsive force of swimmer A were larger than those of swimmer X from the middle to the end of the stroke. Next, focusing on the p_{palm} (red) and the p_{dor} (blue) in the middle row, the p_{dor} of swimmer A was much lower than that of swimmer X, although the p_{palm} were similar. This gap between the p_{palm} and p_{dor} is directly related to the pressure force and the propulsive force, so it can be inferred that the propulsive force of swimmer X is lower as a result. Finally,

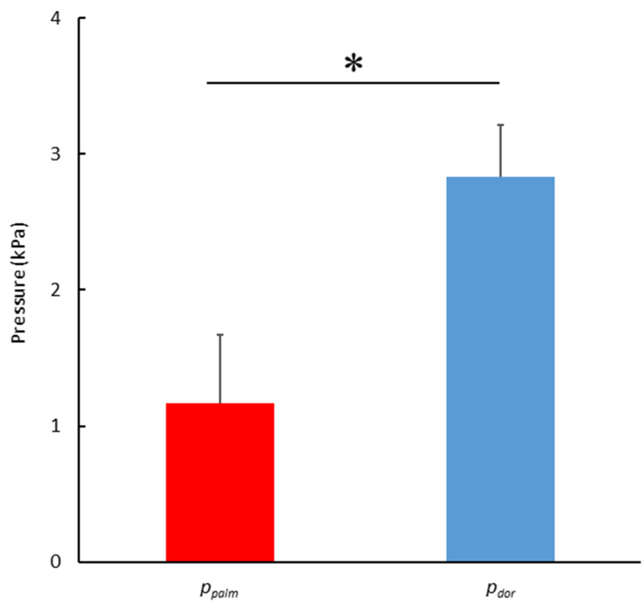

FIGURE 6 | Comparison of the mean pressure in the absolute value between the p_{palm} and the p_{dor}. (*$p < 0.05$).

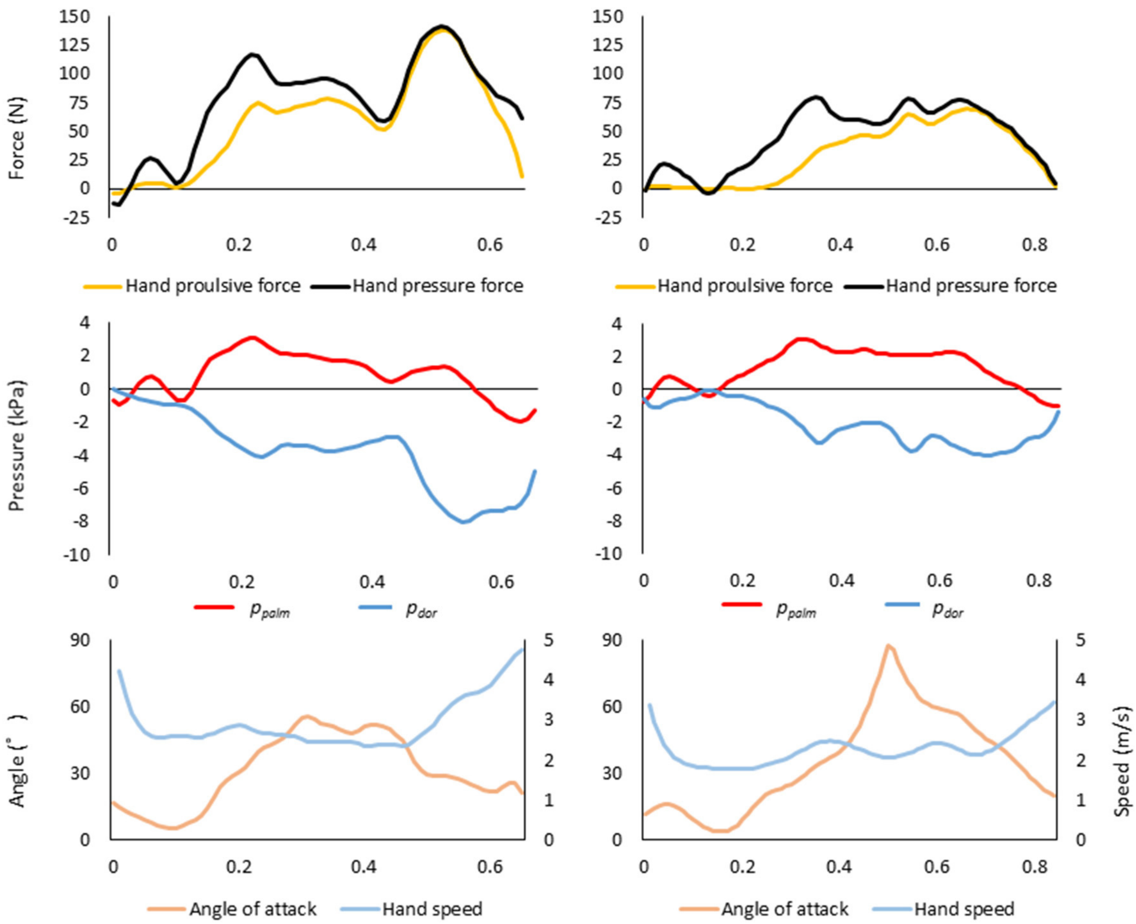

FIGURE 7 | Variation over time of each variable (top, fluid force; middle, effective pressure; bottom, angle of attack and hand speed) in the right hand of the fastest swimmer A (left column) and the slowest swimmer X (right column).

comparing the hand speed (light blue) and the angle of attack (orange), the hand speed of swimmer A increased significantly in the second half of the stroke, whereas the speed of swimmer X did not increase much. Swimmer A's angle of attack ranged from 20° to 50°, whereas Swimmer X's angle of attack varied considerably from 10° to 90°. Since the attack angle is correlated with the pressure on the palm, it should be kept to a certain degree. However, the CFD (Computer Fluid Dynamics) flow visualization experiment by Samson et al. (2018) showed that either too large or too small an angle of attack might not cause a decrease in pressure on the dorsum of the hand effectively. Therefore, it may be advisable to maintain an optimal angle of attack.

Next, we discuss the relationship between the swimming velocity and hand kinematics and stroke indices. As mentioned earlier, the swimming velocity was highly correlated with the hand speed. However, the hand speed did not correlate with stroke frequency (**Table 2**). The result above mentioned is an essential point. If a swimmer blindly increases the number of strokes to increase hand speed, the time and distance that the hand moves in the water will be shortened, and the hand may leave the water without increasing hand speed sufficiently. Stroke length was also correlated with swimming velocity ($r = 0.509$). In other words, if the swimmer swam faster, the distance traveled in one stroke would be longer, but stroke length is only a result, and a longer stroke length did not imply a faster swim speed. Instead, it should be understood that the distance traveled per stroke was longer due to moving the hand as fast and long as possible in the water. So how can swimmers increase the speed of their hands? Although we cannot draw any conclusions based on the results of this study alone, a possible inference is that swimmers need to consider the following factors to increase hand speed. For example, a combination of left and right upper limbs, rolling movements, and coordination of upper limb stroking movements with lower limb kicking movements. Because, unlike on land, there is no fulcrum in the water, so simply trying to increase hand speed may not result in the desired increase in speed.

For the relationship between the swimming velocity and hand forces, the swimming velocity was highly correlated with the hand's pressure and propulsive force. The hand pressure force was also highly correlated ($r = 0.873$) with the hand propulsive force. However, there was no relationship between the swimming velocity and propulsive ratio. In other words, swimmers with high swimming velocity do not necessarily have a higher propulsion ratio. In front crawl swimming, the force exerted by the hand acts not only in the propulsive direction but also in the vertical and lateral directions. These back and forth, vertical and horizontal fluid forces are thought to have different roles. For example, the force acting vertically upward lifts the body near or above the water's surface (Nakashima, 2007) and may reduce the area that receives drag from the water. Therefore, to swim faster, the hand pressure force should act not only in the propulsive direction but also in the vertical and lateral directions. Because the forces acting vertical and lateral direction might contribute to lifting the body, reducing resistance and promoting a rolling motion of the upper trunk would increase the speed of the backward movement of the hand.

Limitation and Future Tasks

This study has some limitations. The pressure sensor used in the hydrodynamic pressure distribution measurement can only measure the hydrodynamic pressure acting perpendicular to the hand plane. It has been suggested that the negative hydrodynamic pressure increases in the latter half of the underwater stroke due to the effect of frictional forces caused by the generation of axial flow from the shoulder to the hand (Toussaint et al., 2002). Therefore, it is necessary to measure the friction component to measure the propulsive force accurately. However, considering that the main cause of hand propulsive force is the pressure component (Samson et al., 2017), estimating the propulsive force by measuring the hand's hydrodynamic pressure distribution seems reasonable.

In this study, the pressure was assumed to act uniformly on the each hand segments, and the value of each pressure sensor was defined as the representative pressure value acting on each segment. In reality, the value varies depending on the part of the hand surface. Hence, more sensors need to be used to subdivide the hand segments and improve the accuracy of the measurement. However, at present, the sensors are wired, and affixing many sensors to both hands may interfere with the swimming motion. Therefore, there is a need to develop a measurement method that provides both high measurement accuracy and less burden to the swimmer.

In front crawl swimming, the arms exert greater propulsive force than the legs (Cohen et al., 2017), and of the upper arms, forearms and hands, it has been suggested that the hands exert the largest propulsive force (Toussaint et al., 2002; Samson et al., 2017; Takagi et al., 2021). Therefore, the present experiment was conducted based on the assumption that the force exerted by the segments other than the hand would be negligible. However, the results of this experiment showed that the rolling and kicking movements are also essential factors in increasing hand speed. Silveira et al. (2017) also reported that the kicking motion by the lower lims increases stroke length, which in turn affects swimming velocity. The next step is to take a more macroscopic view of the swimming motion and elucidate how hand speed is increased to obtain significant hand propulsive force.

CONCLUSION

Swimmers with faster swimming velocity had higher hand speed and greater hand propulsive force. Pressure on the dorsum of the hand had a significant negative correlation with swimming velocity, hand speed and hand propulsive force. In contrast, palm pressure was not significantly correlated with swimming velocity and hand speed but was significantly correlated with hand propulsive force and angle of attack. Comparing the values of palm and dorsum pressure in absolute value, dorsum pressure was more than twice as high as palm pressure, suggesting that it significantly influences the force acting on the hand. Therefore, it can be inferred that swimmers who swim faster have a greater decrease in hand dorsum pressure due to their faster hand speed, which exerts a more significant hand propulsive force.

DATA AVAILABILITY STATEMENT

The datasets 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 University of Tsukuba. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

DK, TT, YS, KH, and HT contributed to the conception and design of this study. DK, KH, and YN made data acquisition. DK wrote the manuscript draft. TT, YS, KH, and HT contributed to the manuscript revisions. All authors approved the submission of this final draft.

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REFERENCES

Barbosa, A. C., Barroso, R., Gonjo, T., Rossi, M. M., Paolucci, L. A., Olstad, B. H., et al. (2021). 50 m freestyle in 21, 22 and 23 s: what differentiates the speed curve of world-class and elite male swimmers? *Int. J. Perform. Anal. Sport* 21, 1055–1066. doi: 10.1080/24748668.2021.1971509

Cohen, R. C. Z., Cleary, P. W., Mason, B. R., and Pease, D. L. (2017). Forces during front crawl swimming at different stroke rates. *Sports Eng*. 21, 63–73. doi: 10.1007/s12283-017-0246-x

Formosa, D. P., Toussaint, H., Mason, B. R., and Burkett, B. (2012). Comparative analysis of active drag using the MAD system and an assisted towing method in front crawl swimming. *J. Appl. Biomech*. 28, 746–750. doi: 10.1123/jab.28.6.746

Fuchiwaki, M., Tanaka, K., and Nagayama, K. (2007). Vortex flow and dynamic thrust of an unsteady airfoil. *Trans. JSME B* 73, 922–929. doi: 10.1299/kikaib.73.922

Hollander, A., De Groot, G., van Ingen Schenau, G., Toussaint, H., De Best, H., Peeters, W., et al. (1986). Measurement of active drag during crawl arm stroke swimming. *J. Sports Sci*. 4, 21–30. doi: 10.1080/02640418608732094

Hopkins, W., Marshall, S., Batterham, A., and Hanin, J. (2009). Progressive statistics for studies in sports medicine and exercise science. *Med. Sci. Sports Exerc*. 41, 3. doi: 10.1249/MSS.0b013e31818cb278

Kawai, E., Tsunokawa, T., Sakaue, H., and Takagi, H. (2020). Propulsive forces on water polo players' feet from eggbeater kicking estimated by pressure distribution analysis. *Sports Biomech.* doi: 10.1080/14763141.2020.1797152. [Epub ahead of print].

Koga, D., Gonjo, T., Kawai, E., Tsunokawa, T., Sakai, S., Sengoku, Y., et al. (2020). Effects of exceeding stroke frequency of maximal effort on hand kinematics and hand propulsive force in front crawl. *Sports Biomech*. doi: 10.1080/14763141.2020.1814852. [Epub ahead of print].

Koga, D., Tsunokawa, T., Sengoku, Y., Homma, M., and Takagi, H. (2021). Relationship between stroke frequency and hand propulsive force in the front crawl. *Japan J. Phys. Educ. Health Sport Sci*. 66, 207–218. doi: 10.5432/jjpehss.20123

Kolmogorov, S. V., and Duplishcheva, O. A. (1992). Active drag, useful mechanical power output and hydrodynamic force coefficient in different swimming strokes at maximal velocity. *J. Biomech*. 25, 311–318. doi: 10.1016/0021-9290(92)90028-Y

Kudo, S., Mastuda, Y., Sakurai, Y., Ichikawa, H., and Ikuta, Y. (2016). Differences in stroke technique to exert hand propulsion between advanced and intermediate swimmers. *ISBS Proc. Arch*. 34, 707–710.

Kudo, S., Sujae, I. H., and Jabbar, K. (2012). Application of pressure measures to predict propulsive forces exerted by the hand during swimming. *ISBS Proc. Arch*. 30,192–195.

Nakashima, M. (2007). Mechanical study of standard six-beat front crawl swimming by using swimming human simulation model. *J. Fluid Sci. Technol*. 2, 290–301. doi: 10.1299/jfst.2.290

Narita, K., Nakashima, M., and Takagi, H. (2017). Developing a methodology for estimating the drag in front-crawl swimming at various velocities. *J. Biomech*. 54, 123–128. doi: 10.1016/j.jbiomech.2017.01.037

Samson, M., Bernard, A., Monnet, T., Lacouture, P., and David, L. (2017). Unsteady computational fluid dynamics in front crawl swimming. *Comput. Methods Biomech. Biomed. Eng*. 20, 783–793. doi: 10.1080/10255842.2017.1302434

Samson, M., Monnet, T., Bernard, A., Lacouture, P., and David, L. (2018). Analysis of a swimmer's hand and forearm in impulsive start from rest using computational fluid dynamics in unsteady flow conditions. *J. Biomech*. 67, 157–165. doi: 10.1016/j.jbiomech.2017.12.003

Silveira, R. P., de Souza Castro, F. A., Figueiredo, P., Vilas-Boas, J. P., and Zamparo, P. (2017). The effects of leg kick on swimming speed and arm-stroke efficiency in the front crawl. *Int. J. Sports Physiol*. 12, 728–735. doi: 10.1123/ijspp.2016-0232

Soh, J., and Sanders, R. (2021). The clues are in the flow: how swim propulsion should be interpreted. *Sports Biomech*. 20, 798–814. doi: 10.1080/14763141.2019.1602162

Takagi, H., Nakashima, M., Ozaki, T., and Matsuuchi, K. (2013). Unsteady hydrodynamic forces acting on a robotic hand and its flow field. *J. Biomech*. 46, 1825–1832. doi: 10.1016/j.jbiomech.2013.05.006

Takagi, H., Nakashima, M., Ozaki, T., and Matsuchi, K. (2014). Unsteady hydrodynamic forces acting on a robotic arm and its flow field: application to the crawl stroke. *J. Biomech*. 47, 1401–1408. doi: 10.1016/j.jbiomech.2014.01.046

Takagi, H., Nakashima, M., Sengoku, Y., Tsunokawa, T., Koga, D., Narita, K., et al. (2021). How do swimmers control their front crawl swimming velocity? Current knowledge and gaps from hydrodynamic perspectives. *Sports Biomech*. doi: 10.1080/14763141.2021.1959946. [Epub ahead of print].

Toussaint, H. M., Van den Berg, C., and Beek, W. J. (2002). "Pumped-up propulsion" during front crawl swimming. *Med. Sci. Sports Exerc*. 34, 314–319. doi: 10.1097/00005768-200202000-00020

Tsunokawa, T., Mankyu, H., and Ogita, F. (2019a). Relationship between swimming velocity and stroke parameters during the front-crawl: analysis using pressure measurement and underwater motion capture. *Japan J. Phys. Educ. Health Sport Sci*. 64, 385–400. doi: 10.5432/jjpehss.18053

Tsunokawa, T., Mankyu, H., Takagi, H., and Ogita, F. (2019b). The effect of using paddles on hand propulsive forces and Froude efficiency in arm-stroke-only front-crawl swimming at various velocities. *Hum. Mov. Sci*. 64, 378–388. doi: 10.1016/j.humov.2019.03.007

Tsunokawa, T., Narita, K., Mankyu, H., Ogita, F., and Takagi, H. (2018a). "Estimation of propulsive forces acting on a hand using pressure measurement and underwater motion capture during front crawl swimming," in *XIII th International Symposium on Biomechanics and Medicine in Swimming Proceedings* (Tsukuba).

Tsunokawa, T., Sengoku, Y., Tsubakimoto, S., and Takagi, H. (2015). The relationship between the unsteady fluid force and the pressure distribution around the foot during breaststroke kicking. *Japan J. Phys. Educ. Health Sport Sci*. 60, 165–175. doi: 10.5432/jjpehss.14098

Tsunokawa, T., Tsuno, T., Mankyu, H., Takagi, H., and Ogita, F. (2018b). The effect of paddles on pressure and force generation at the hand during front crawl. *Hum. Mov. Sci*. 57, 409–416. doi: 10.1016/j.humov.2017.10.002

van der Vaart, A. J., Savelberg, H. H., de Groot, G., Hollander, A. P., Toussaint, H. M., and van Ingen Schenau, G. J. (1987). An estimation of drag in front crawl swimming. *J. Biomech*. 20, 543–546. doi: 10.1016/0021-9290(87)90254-5

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The Impact of a Swimming Training Season on Anthropometrics, Maturation, and Kinematics in 12-Year-Old and Under Age-Group Swimmers: A Network Analysis

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Understanding fluctuations and associations between swimming performance-related variables provide strategic insights into a swimmer's preparation program. Through network analysis, we verified the relationships between anthropometrics, maturation, and kinematics changes (Δ) in 25-m breaststroke (BREAST) and butterfly (FLY) swimming performance, before and after a 47-week swimming training season. Twenty age-group swimmers (n =11 girls: 10.0 ± 1.3 years and n = 9 boys: 10.5 ± 0.9 years) performed a 25-m all-out swim test (T25) in BREAST and FLY techniques, before and after 47 weeks. Three measures of centrality, transformed into a z-score, were generated: betweenness, closeness, and strength. Data were compared (t-test) and effect sizes were identified with Hedges' g. Large effect sizes were observed for swimming performance improvements in BREAST (32.0 ± 7.5 to 24.5 ± 3.8 s; g = 1.26; Δ = −21.9 %) and FLY (30.3 ± 7.0 to 21.8 ± 3.6 s; g = 1.52; Δ = −26.5 %). Small to moderate effect sizes were observed for anthropometric changes. Moderate effect size was observed for maturity offset changes (−2.0 ± 0.9 to −1.3 ± 1.0; g = 0.73; Δ = 50.9 ± 281 %). Changes in maturity offset, stroke rate (SR), and stroke length for both BREAST and FLY swimming speeds were highlighted by the weight matrix. For betweenness, closeness, and strength, changes in arm span (AS) (BREAST) and stroke length (FLY) were remarkable. The dynamic process of athletic development and the perception of complexity of fluctuations and associations between performance-related variables were underpinned, particularly for simultaneous swimming techniques in age-group swimmers.

Keywords: analysis, digital technology, long-term athletic development, biomechanics, technique, anthropometrics, exercise physiology, maturation

INTRODUCTION

The performance of age-group swimmers improves based on the relationships among technical, physical and anthropometric factors, which are characterized by a complex adaptive system (CAS). Whereas there is body growth, drag and propulsion change, i.e., the swimming performance related factors may be deeply influenced by the anthropometric characteristics. Not conceptualizing swimming performance as a CAS phenomenon is a limitation that should be avoided (Morais et al., 2014; Ferreira et al., 2019; Zacca et al., 2020b). To complement the traditional statistical approaches, a multivariate model (as global as possible) could bring new insights on changes in swimming performance, particularly during a training season. Network analyses can provide a global view of this multivariate phenomenon, that is, accessing both linear and nonlinear relationships between swimming performance-related variables (Holland, 2006; Schmittmann et al., 2013; Goethel et al., 2020; Guido, 2020; Pol et al., 2020).

There is a scientific and practical interest in individual maturation and the ideal period to start working on individual physical skills in long-term athletic development (LTAD; Lätt et al., 2009; Dias et al., 2012; Collins et al., 2019). Longitudinal studies can provide relevant insights (Mitchell et al., 2020; Zacca et al., 2020a), but there are few longitudinal studies based on 12-year-old and under age-group swimmers (Morais et al., 2014, 2020; Ferreira et al., 2019). It is well reported that anthropometrics and maturation can affect athletic development in age-group swimmers (Dias et al., 2012; Moreira et al., 2014; Morais et al., 2020), with enhanced swimming performance being observed even after detraining periods (Meylan et al., 2014; Moreira et al., 2014). The interplay between maturation and training response should be considered by coaches (Muller et al., 2017; Pichardo et al., 2018), but most previous analyses are fragmented instead of considering the interdependence among the selected variables (Goethel et al., 2020). Monitoring maturity status through age at peak height velocity (PHV) can be an effective, practical, and noninvasive approach (Beunen and Malina, 1988; Mirwald et al., 2002; Philippaerts et al., 2006; Malina, 2016).

The human body consists of several interdependent systems, and multiple factors can affect the ability to swim fast. Identifying which factors are important for fast swimming and how to maximize these factors for performance improvements requires understanding the existing network relationships. Interventions and/or phenomena in a specific system can trigger responses in another apparently unrelated system (Goethel et al., 2020). By applying network analysis, it is possible to identify the effects and interactions of each variable in a global approach, especially when considering the effects of changes in variables over time and their possible effects on changes in other variables. We therefore performed a global analysis using the changes in representative variables to assess which variables, in relation to their changes, could be more important for swimming performance. So, the aim of this study is to identify the relationships between changes in anthropometrics, maturation, and swimming kinematics on breaststroke (BREAST) and butterfly (FLY), before and after a 47-week swimming training season in 12-year-old and under age-group swimmers.

METHODS

Participants

Twenty age-group swimmers participated in this study. Age for girls ($n = 11$) and boys ($n = 9$) were, respectively, 10.0 ± 1.3 (4.0) and 10.5 ± 0.9 (2.5) years (mean ± SD, and range), respectively. The participants were engaged in swimming training for at least 12 months, swimming 3 to 5 times per week, 1.000 to 2.000 m per session and had been engaged in a swimming training program for at least for 6 months. During the 47 weeks, the best performance in the 50-m front crawl was, for girls and boys, respectively, 40.2 ± 5.4 (min–max: 36.6–43.8) and 36.8 ± 6.5 (31.8–41.9) s.

Procedures

All swimmers were evaluated during two identical testing sessions: (i) before the training season, that is, during the first week of training after the summer vacation; and (ii) after 47 weeks, at the end of the last macrocycle of the season. First, the anthropometric profile was obtained, which was consisted by height (HE), arm span (AS), total body mass (BM), and sitting height (SH). After an approximately 400-m moderate-intensity warmup, swimmers performed two 25-m all-out swim tests (T25; randomized order), one in breaststroke (BREAST), and one in butterfly (FLY), whereas kinematic variables were collected manually by one trained and experienced evaluator (Hay and Guimarães, 1983) using a stopwatch (CASIO HS-70w, Japan). We used manual data collection to assess technical variables (kinematic) since it is feasible for swimming coaches in their daily training. The performance of 25 m (s), time (s) to swim intermediate 10 m, and time (s) to perform three consecutive stroke cycles along the intermediate 10 m were collected manually (Hay and Guimarães, 1983), with kinematic variables being calculated according to Equations 1–4:

$$\text{Swimming speed } (\text{m.s}^{-1}): \text{v} = 10 \text{ m.time of } 10 \text{ m}^{-1} \quad (1)$$

$$\text{Stroke rate } (\text{cycles.s}^{-1}): \text{SR} = 3 \text{ stroke cycles.time of 3 stroke cycles}^{-1} \quad (2)$$

$$\text{Stroke length (m): SL} = \text{v.SR}^{-1} \quad (3)$$

$$\text{Stroke index } (\text{m}^2.\text{s}^{-1}): \text{SI} = \text{v.SL} \quad (4)$$

Then, stroke rate (SR) was multiplied by 60 to obtain SR in cycles·min^{-1}.

Anthropometrics

Height, AS, BM, and SH were measured (Heyward and Stolarczyk, 1996), and leg length (LL) was estimated as stature minus sitting height (Mirwald et al., 2002). For BM, a weighting scale (TECHLINE®, Brazil) was used. For HE, AS, SH, and LL, a 250-cm tape (VONDER®, Brazil) was used.

Maturation

Maturity offset equations (Mirwald et al., 2002) were applied with anthropometrics and age data. The equations for boys and girls are, respectively (Equations 5 and 6):

$$BMO = -9.236 + \left[0.0002708^{*}\left(LL^{*}SH\right)\right] - \left[0.001663^{*}\left(A^{*}LL\right)\right] + [0.007216^{*}(A^{*}SH)] + \{0.02292^{*}[\left(\frac{\text{BM}}{\text{height}}\right)^{*}100]\} \quad (5)$$

$$GMO = -9.376 + \left[0.0001882^{*}\left(LL^{*}SH\right)\right] + \left[0.0022^{*}\left(A^{*}LL\right)\right] + \left[0.005847^{*}\left(A^{*}SH\right)\right] - [0.002658^{*}\left(A^{*}BM\right)] + \{0.07693^{*}[\left(\frac{\text{BM}}{\text{height}}\right)^{*} 100]\} \quad (6)$$

where BMO and GMO are, respectively, boys and girl's maturity offset; LL is leg length; SH is sitting height; A is age, and BM is body mass. With BMO and GMO data, any negative result is before PHV (maturity offset < 0, i.e., time left to reach the peak), and any positive results are after PHV (maturity offset $=$ or > 0, i.e., indicating whether the participant is exactly at the beginning moment of PHV or how much this has passed). These equations are gender-specific, considering biological significance and statistics to predict maturity. Maturity offset indicates how far, in years, an age-group swimmer is approaching or moving away from PHV.

Statistical Analysis

Mean, SD and 95% confidence intervals were obtained and reported for all studied variables. Shapiro–Wilk test was applied to verify the data distribution, and comparisons were performed with paired-samples *t*-tests. In fact, gender as an independent variable was initially considered, but no significant effect was identified for any of the studied variables, possibly due to a similar maturation level of the participants. Therefore, we performed *t*-test comparisons instead of factorial ANOVA. Effect sizes were calculated from Hedges' g (Lakens, 2013) and interpreted with the following criteria: 0–0.19 trivial, 0.2–0.59 small, 0.6–1.19 moderate, 1.2–1.99 large, 2.0–3.99 very large, and $\geq$ 4.0 nearly perfect (Hopkins, 2002). Changes in % [Δ = (value after – value before)·100] were calculated for all variables.

To verify the associations among anthropometric, kinematics, and maturation variables changes, for both, BREAST and FLY, a machine learning technique (Network Analysis) was used (Epskamp et al., 2012). Gender was inserted in the network as a dichotomous variable (1 = girls and 2 = boys). In the network, variables were separated in Group 1, with gender and Δ of age, height, arm span, body mass; group 2 with Δ of T25, v, SR, SL, SI; and group 3 with just the Δ of the MO. Measures of centrality were generated to understand the role of each variable's change in the system, that is, the values are transformed into a z-score. We used three measures in our study (Epskamp et al., 2012):

(i) *Betweenness centrality*: estimated from the number of times that a node is part of the shortest path among all other pairs of nodes connected to the network.
(ii) *Closeness centrality*: determined from the inverse of the distances from one node to all others.
(iii) *Strength centrality:* the sum of all the weights of the paths that connect a node to the others.

We used the pairwise Markov random field model to improve the accuracy of the partial correlation network. The estimation algorithm used assumes the highest-order interaction of the true graph. The algorithm includes an L1 (regularized neighborhood regression) penalty. Regularization is achieved by a "less absolute contraction and selection operator" (LASSO) that controls the model's sparsity (Friedman et al., 2008). The Bayesian extended information criterion (EBIC) was used due to its conservative method for selecting the Lambda from the regularization parameter. The EBIC uses a hyperparameter (y) that determines how much the EBIC selects sparse models (Chen and Chen, 2008; Foygel and Drton, 2010). The y value is usually set between zero and 0.5; higher values indicate more parsimonious models with fewer edges, whereas a value closer to zero indicates an estimate with more edges. A y value of 0.25 is potentially useful for exploratory networks, and this value was adopted in our study (Foygel and Drton, 2010). The adjustment function returns the estimated parameters and a weighted and unweighted adjacency matrix. The positive relationships in the network are expressed in green and the negative in red. The thickness and intensity of the colors represent the magnitude of the associations. The "*graph*" package in the Rstudio software (*http://www.rstudio.com/)*, and the "*qgraph*" package was used to construct the graphs (Epskamp et al., 2012).

RESULTS

Table 1 shows the results for anthropometrics and kinematics changes, effect sizes, and Δ. Small to moderate effect sizes were observed for changes on anthropometrical variables. Large effect sizes were observed for changes in nearly all kinematic variables, both in BREAST and in FLY. Performance of T25 in BREAST and FLY showed large improvements after 47 weeks. Only BREAST (trivial) and FLY (small) SL did not present at least moderate changes.

For BREAST, **Figure 1** shows the network of association among changes in anthropometrics, maturation, and kinematics. Specifically in relation to the changes in T25 BREAST, the followings stand out: the strong and negative association with Δv, the negative association with ΔSR, and the positive association with ΔAS. Positive and strong associations were identified between changes in height and AS, and between changes in AS and body mass. The relationship between changes in SL and SR was strong. Changes in SR showed more central associations inside the network.

The weight matrix for the BREAST is presented in **Table 2**. The results found for ΔMO and Δv (−0.93), ΔMO and ΔSR (−0.59), and for ΔSR and ΔSL (0.49) are highlighted.

For FLY, **Figure 2** shows the network of association among changes in anthropometrics, maturation, and kinematics. Specifically in relation to the changes in T25 FLY, the followings stand out: the strong and negative association with Δv, the

TABLE 1 | BEFORE and AFTER 47 weeks (47w) mean ± SD values (95% confidence intervals), *p*-values, effects sizes (Hedges' g), and Δ% for anthropometric and performance/kinematics ($n = 20$).

	Before 47 weeks		After 47 weeks		*p*-value; Effect size Δ% (before vs. after)	
Anthropometrics						
Age (years)	10.2 ± 1.2 (9.6 to 10.8)		11.1 ± 1.2 (10.5 to 11.7)		<0.001; 0.75 (moderate) 8.9 ± 1.3	
Height (cm)	142.3 ± 9.7 (137.7 to 146.6)		147.8 ± 9.5 (143.1 to 151.9)		<0.001; 0.57 (small) 3.8 ± 1.4	
AS (cm)	143.6 ± 10.4 (138.5 to 148.1)		150.8 ± 11.3 (145.1 to 155.6)		<0.001; 0.41 (small) 4.9 ± 1.8	
BM (kg)	36.7 ± 8.2 (32.9 to 36.4)		41.4 ± 8.5 (37.0 to 45.0)		<0.001; 0.56 (small) 12.1 ± 6.7	
MO (years)	−2.0 ± 0.9 (−2.4 to −1.5)		−1.3 ± 1.0 (−1.8 to −0.8)		<0.001; 0.73 (moderate) 50.9 ± 281	
Performance/ kinematics	**BREAST**	**FLY**	**BREAST**	**FLY**	**BREAST**	**FLY**
T25 (s)	32.0 ± 7.5 (28.4 to 35.7)	30.3 ± 7.0 (27.0 to 33.6)	24.5 ± 3.8 (22.7 to 26.4)	21.8 ± 3.6 (20.1 to 23.5)	<0.001; 1.26 (large) −21.9 ± 9.5	<0.001; 1.52 (large) −26.5 ± 11.0
v ($m{\cdot}s^{-1}$)	0.71 ± 0.12 (0.65 to 0.77)	0.76 ± 0.18 (0.68 to 0.85)	0.90 ± 0.12 (0.84 to 0.96)	1.05 ± 0.16 (0.97 to 1.12)	<0.001; 1.58 (large) 28.5 ± 19.7	<0.001; 1.70 (large) 41.0 ± 25.3
SR (cycles·min^{-1})	45.9 ± 11.9 (40.4 to 51.5)	37.1 ± 9.7 (32.5 to 41.6)	58.6 ± 8.6 (54.4 to 62.8)	45.6 ± 11.8 (40.0 to 51.1)	0.001; 1.22 (large) 26.7± 44.1	0.002; 0.78 (moderate) 16.3 ± 23
SL (m)	0.96 ± 0.23 (0.84 to 1.07)	1.30 ± 0.38 (1.13 to 1.48)	0.93 ± 0.13 (0.84 to 1.07)	1.43 ± 0.25 (1.31 to 1.55)	0.63; 0.16 (trivial) 2.2 ± 26.1	0.11; 0.40 (small) 16.7 ± 32.5
SI ($m^2 \cdot s^{-1}$)	0.69 ± 0.24 (0.58 to 0.81)	1.04 ± 0.41 (0.84 to 1.23)	0.84 ± 0.20 (0.75 to 0.94)	1.50 ± 0.35 (1.33 to 1.66)	0.005; 0.67 (moderate) 31.9 ± 49.2	0.001; 1.20 (large) 66.8 ± 77.4

AS, arm span; BM, body mass; MO, maturity offset; T25, performance in 25-m; v, swimming speed; SR, stroke rate; SL, stroke length; SI, stroke index.

negative association with ΔSR and ΔSL. Positive and strong associations were identified between changes in HE and AS, and between changes in AS and BM. The relationship between changes in SL and SR was strong. Changes in SR showed more central associations inside the network.

The weight matrix for the FLY is presented in **Table 3**. The results found for ΔMS and ΔSR (−0.92) are highlighted.

Table 4 shows the centrality measurements for BREAST and FLY. We highlight for betweenness, closeness, and strength ΔAS in BREAST and ΔSL in FLY. As gender is a dichotomous variable and does not suffer changes, those centrality measures will not be accounted.

DISCUSSION

We performed a global analysis to identify the relationships between changes in anthropometrics, maturation, and kinematics in 12-year-old and under age-group swimmers when swimming BREAST and FLY during a typical training season (47 weeks). The main finding of this study was that changes in performance and kinematics were higher than anthropometrics after 47 weeks, that is, improvements in swimming performance (T25) do not seem to be so dependent on growth, even though AS has stood out in the analysis of centrality measures.

Changes in technique (kinematics) may be related to motor coordination development in swimming (Guignard et al., 2017). Young swimmers are susceptible to change in their swimming

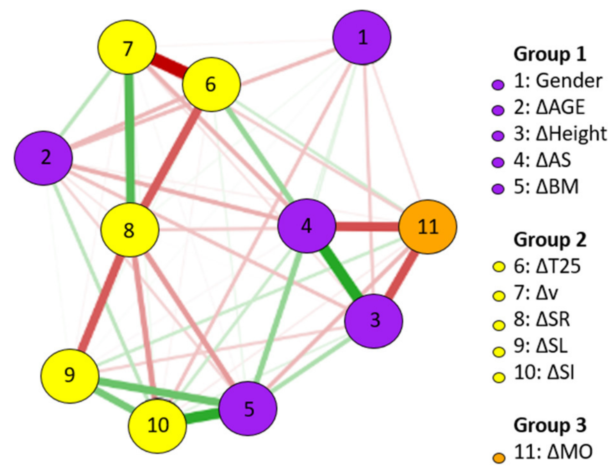

FIGURE 1 | BREAST network of association between changes (Δ) in anthropometrics, maturation, and kinematics (using gender as a dichotomous variable); $n = 20$.

mechanics at least three times in each competitive season (Morais et al., 2020). Typically, front crawl is the first swimming technique during swimming lessons in North America, whereas BREAST is the first in Europe, Asia, and Japan (Langerdorfer, 2013). However, Brazilian age-group swimmers composed our sample, where North America's learning sequence is normally followed.

TABLE 2 | The weight matrix for the BREAST with the Δ% (gender as a dichotomous variable) ($n = 20$).

	BREAST										
	Gender	**ΔAge**	**ΔHeight**	**ΔAS**	**ΔBM**	**ΔMO**	**ΔT25**	**Δv**	**ΔSR**	**ΔSL**	**ΔSI**
Gender	0										
ΔAge	−0.24	0									
ΔHeight	−0.19	−0.22	0								
ΔAS	0.10	−0.28	0.79	0							
ΔBM	0.09	−0.15	0.29	0.38	0						
ΔT25	0.01	−0.26	0.23	0.37	0.07	0					
Δ*v*	−0.03	0.24	−0.10	−0.27	−0.02	**−0.93**	0				
ΔSR	0.04	−0.08	−0.00	−0.07	−0.36	**−0.59**	0.63	0			
ΔSL	0.02	0.02	−0.17	−0.02	0.54	0.05	−0.03	**−0.60**	0		
ΔSI	−0.21	0.23	0.11	0.18	0.77	−0.04	0.05	−0.38	**0.49**	0	
ΔMO	−0.12	−0.05	−0.63	−0.64	−0.26	0.17	−0.18	−0.18	0.18	−0.07	0

Δ, delta%; age; height; AS, arm span; BM, body mass; T25, performance in 25-m; v, swimming speed; SR, stroke rate; SL, stroke length; SI, stroke index; MO, maturity offset. Bold values that stand out in the analyzes.

Thus, swimmers from our study were probably still in the process of learning simultaneous swimming techniques.

Simultaneous swimming techniques involve more coordinative skills and are less economic than alternate ones (Zamparo et al., 2020). BREAST is characterized by underwater recovery of both arms and legs (Leblanc et al., 2009), which produces resistive forces and consequently more energy expenditure (Zamparo et al., 2009). Other aspects that can influence poor glide and more exhausting action in BREAST are the head position combined with the breathing phase (Kapus et al., 2018) and the poor effectiveness of leg propulsion (Strzała et al., 2012). Similar events occur in FLY, in which both hands move to the surface from the water simultaneously (Thomas, 1990), something that tends to destabilize the positioning of the body (Sanders et al., 1995), turning the FLY into an "undulating stroke" (Riewald and Rodeo, 2015), characterized by the up- and downmovements of the body. Based on the motor coordination development, there are constraints in the motor learning process in the aquatic environment, which are visualized with the Newell (1986) model. Environmental, task, and organism factors may restrict the dynamic of the response, which could follow the reasoning about the process for improving simultaneous stroke performance.

The network analyses using changes in anthropometrics, maturation, and kinematics for both, BREAST and FLY, revealed the complexity of the systems. In swimming (Guignard et al., 2017), every action of a swimmer somehow disturbs the aquatic environment. This disturbance leads to new patterns of movement and so on. Likewise, a network analysis using data from a longitudinal approach that somehow can influence performance showed the multiple associations between changes after 47 weeks on anthropometric and kinematic variables. Even that, changes in T25 were mainly linked to Δ*v*, ΔSR, and ΔAS for BREAST, and Δ*v*, ΔSR, and ΔSL for FLY. The notion of complexity on changes in swimming performance was reinforced, especially for simultaneous techniques in age-group swimmers.

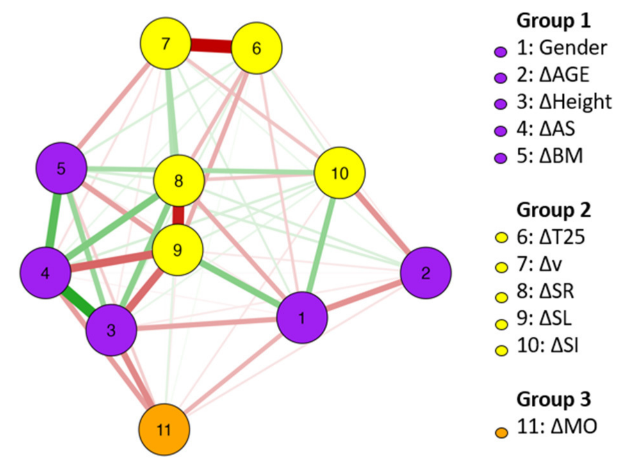

FIGURE 2 | FLY network of association between changes (Δ) in anthropometrics, maturation, and kinematics (using gender as a dichotomous variable); $n = 20$.

Regarding centrality, the betweenness indicates which variables are closer to others and could be the easiest path for changes. In the BREAST, changes in AS and SR (both 1.34) and SI (0.94) were highlighted. Clearly, AS changes are beyond intervention possibilities. However, the focus on SR and stroke index (SI, an indirect measure swimming efficiency) to a given v (Costill et al., 1985) seems to be important in BREAST performance development. Regarding FLY, changes in the SL (2.02) are probably related to the variation in the distance covered per cycle, but in a specific way; that is, the complex coordination between one arm stroke, one undulation, and two kicks could be executed in an easier way by young swimmers (Tosta et al., 2019), which implies an improved performance.

The closeness measure can indicate which variables could be more quickly affected by interventions. Regarding BREAST,

TABLE 3 | The weight matrix for the FLY with the Δ% (gender (gender as a dichotomous variable) (*n* = 20).

	FLY										
	Gender	**Δ Age**	**Δ Height**	**Δ AS**	**Δ BM**	**Δ T25**	**Δv**	**Δ SR**	**Δ SL**	**Δ SI**	**Δ MO**
Gender	0.00										
Δ Age	−0.39	0.00									
Δ Height	−0.33	−0.08	0.00								
ΔAS	−0.04	−0.03	0.78	0.00							
ΔBM	−0.07	0.13	0.36	0.59	0.00						
ΔT25	−0.16	−0.07	0.10	0.08	0.13						
Δ*v*	0.11	0.07	−0.07	−0.11	−0.32	0.00					
ΔSR	−0.30	0.13	0.41	0.46	0.14	**−0.92**	0.00	0.00			
ΔSL	**0.43**	−0.08	**−0.53**	**−0.55**	−0.34	−0.24	0.30	−0.82	0.00		
ΔSI	0.39	−0.38	0.08	0.13	0.31	−0.30	0.27	−0.21	0.12	0.00	
ΔMO	−0.27	−0.10	−0.43	−0.35	−0.17	0.11	−0.21	0.10	−0.07	−0.09	0.00

Δ, delta%; age; height; AS, arm span; BM, body mass; T25, performance in 25-m; v, swimming speed; SR, stroke rate; SL, stroke length; SI, stroke index; MO, maturity offset. Bold values that stand out in the analyzes.

TABLE 4 | BREAST and FLY centrality measures (gender as dichotomous variable) (*n* = 20).

	Betweenness		Closeness		Strength	
	BREAST	**FLY**	**BREAST**	**FLY**	**BREAST**	**FLY**
Gender	−1.05	1.73	−2.39	0.31	−2.33	−0.01
ΔAge	−0.25	−0.83	−0.88	−1.44	−1.10	−1.56
ΔHeight	−0.25	0.02	−0.18	0.77	0.46	0.98
ΔAS	**1.34**	0.02	**1.19**	0.82	**1.11**	0.91
ΔBM	0.94	0.02	0.72	0.47	0.82	0.08
ΔT25	0.14	−0.83	0.67	−1.09	0.45	−0.53
Δ*v*	−1.05	−0.25	0.02	−0.74	0.08	−0.19
ΔSR	1.34	−0.83	0.30	0.71	0.82	0.89
ΔSL	−1.05	**2.02**	0.14	**1.67**	−0.52	**1.50**
ΔSI	0.94	−0.25	0.85	−0.49	0.14	−0.72
ΔMO	−1.05	−0.83	−0.46	−0.99	0.05	−1.34

z-scored centrality metrics; Δ, delta%; age; height; AS, arm span; BM, body mass; T25, performance in 25-m; v, swimming speed; SR, stroke rate; SL, stroke length; SI, stroke index; MO, maturity offset. Bold values that stand out in the analyzes.

changes in AS and SR (both 1.34) and SI (0.94) were highlighted. Since AS is an anthropometric variable, the focus for faster changes in performance in BREAST should be on changes in SR and SI (a variable that incorporates both SL and v) (Costill et al., 1985). Regarding FLY, as in the betweenness measure, changes in SL are dominant in performance changes. The strength measure indicates which variables (in the current pattern of the network) have the strongest relationships. For both BREAST and FLY, changes in AS showed high values of strength. However, changes in SR (for BREAST) and SL (for FLY) were also highlighted. All these centrality measures must be analyzed under the environment constraint theory (Newell, 1986).

According to Newell (1986), environment constraints refer to the environmental conditions surrounding the subject and can be physical or social, such as the aquatic milieu, water and air temperature, and audience, among others. Establishing oneself as an independent individual in the aquatic milieu is a long and necessary process to become a swimmer. This skill mastery requires repetitive exercise for a certain time before actually mastering it (Gani et al., 2019). The individual thus acquires "water sensitivity" and can properly use his or her body dimensions and propulsive force to advance. This relationship was evident for FLY, mainly due to changes in SL. Perhaps, changes in SL were related to the undulation, that is, the FLY leg kick. This movement is not a "natural" movement for humans, that is, it involves an individual adaptation with the environment combined with a development in motor skills. Over time, children replace the "pedaling" movement of the legs by oscillation of the flippered foot (Collard et al., 2013), which leads to the issue of task constraints.

Task constraints describe the activity to be performed by the subject and whether individual objectives, rules or instructions, and possible implements are included. Task constraints can generate changes in movement patterns, and these changes trigger changes in the system, which leads individuals to a new organizational state (Newell, 1986). Synchronization between specific motor points of arm and leg actions are the key factor for fast FLY swimming (Strzała et al., 2017). Technical development provides a more economic technique, using less force for a determinant movement. Previous data by Havriluk (2010) indicated that the advantage of faster swimmers derives more from technique than force capacity.

Typically, beginner swimmers spend more time with the head out of water during breathing time when swimming BREAST. It has been well reported that head position influences technique (Kapus et al., 2018), and leg glide is significantly smaller among nonexperienced swimmers (Leblanc et al., 2009). The authors observed that recreational swimmers perform BREAST arm recovery while doing their leg kick, which shows a simultaneous extension of their two pairs of limbs. In addition, novice swimmers are prone to not pull with their arms while recovering their legs (Taguchi, 1975). These actions are related to changes in motor skills which are developed during training sessions (**Table 1**). Moreover, impaired SL combined with increased SR when comparing before and after may be related to less time spent during breathing time when swimmers are more experienced, making the stroke more cyclic and adjusted to the T25 pace.

Organism constraints refer to the characteristics of the subject (Newell, 1986), such as anthropometric, physiological, and psychological factors. Changes in AS for both BREAST and FLY presented a high strength value (**Table 4**) and was one of the variables with the strongest associations inside the network. A previous study (Sammoud et al., 2018) indicated that fat mass is the most important whole-body size characteristic for 100-m BREAST (∼12 years old) and was one of the variables with the strongest associations inside the network. Sammoud et al. (2017) suggested that anthropometric measurements are strongly associated with the 100-m butterfly speed performance of age-group swimmers (∼13 years old). High-level swimmers present a wider AS, imposing higher v and SI, and therefore, faster performance (Sammoud et al., 2017) than those with shorter AS. These findings highlight that anthropometric factors are somehow related to the performance changes during a training season in age-group swimmers.

Maturity offset can play a role in the organism constraints for stroke coordination. For BREAST and FLY, changes in MO showed a high relationship with the development process, with high values for betweenness (**Table 4**), that is, puberty affects swimming technique development. Likewise, in FLY, changes in MO showed higher values of closeness and strength. Swimmers with a more advanced maturation status presented better coordination when swimming FLY than others (Tosta et al., 2019). However, although maturation of prepubertal swimmers seems to be an important factor for consideration in FLY stroke coordination, it does not affect the maximum performance for short distances (Tosta et al., 2019). Despite some correlation between changes in AS and changes performance of T25, kinematics (SR and SI) better explained swimming performance.

The swimming athletic development process is multifactorial (Zacca et al., 2020a). Coaches should be aware of their athletes' maturation processes, understand the impact of growth on changes in performance, and seek the best swimming technique (Zacca et al., 2020b). However, looking at all factors, as a global model, is fundamental to understanding swimmer's development (Goethel et al., 2020). Knowing how to handle changes in SR and SL and considering body growth and maturation can help in LTAD strategies for swimming and related aquatic sports.

The use of network analysis to understand a phenomenon in sports and health sciences is quite new, but its basic ideas have been noted since the 1960s (Grusky, 1963). The digital technology development has contributed to an exponential increase in network analysis studies in health and sport sciences (Wäsche et al., 2017; Goethel et al., 2020; Lord et al., 2020). Although network analysis offers advantages compared to traditional statistical procedures, it is important to acknowledge some shortcomings and potential limitations. Network analysis, a set of integrated techniques, was applied in this study trying to describe relations among variables, by analyzing the structures that emerge from the recurrence of these relations. When performing a network analysis, it is assumed that better interpretations of phenomena are yielded. Despite that, causal relationships between networks and a specific phenomenon normally involve a theoretically informed decision that identifies the independent and dependent variables. Whereas deterministic methods usually highlight that network analysis enables to study how the structure of relationships affectsthe phenomena, "structurally bounded purposive actions may affect the social structure and vice versa (Chiesi, 2001). The sample size can be a problem for estimating networks with many parameters and consequently for interpretation. To increase reliability and limit the number of possibly spurious relationships in the network, we use statistical regularization techniques that consider the complexity of the model to minimize the small sample. First, we used a LASSO (Friedman et al., 2008) applied to the estimation of partial correlation networks. LASSO performs well in estimating partial correlation networks (Fan et al., 2009), and this results in some small weak edge estimates being reduced to exactly zero, resulting in a sparse network (Tibshirani, 1996). LASSO generates a tighter graph (fewer connections between nodes), reflecting merely the most important empirical relationships in the data. Simulation studies suggest that LASSO has a low probability of false positives, which provides some confidence that an observed edge is indeed present in the network in small samples (Krämer et al., 2009). Besides, LASSO requires the definition of a tuning parameter. The sparsity of the produced network by LASSO depends on the value that the researcher sets the fitting parameter (λ), that is, the higher the selected λ value, the more edges are removed from the network, Thus, its value directly influences the structure of the output (i.e., the network). Thus, the fitting parameter "λ" needs to be carefully selected to generate a network structure that minimizes the number of spurious edges while maximizing the number of true edges (Foygel and Drton, 2010). To ensure an optimal fitting selected parameter, a typical method includes estimating multiple networks under different λ values. These different networks range from a completely connected network (where each node is connected to each other) to an empty network (where no nodes are connected).

LASSO estimations generate a collection of networks rather than a single network, that is, it is important to select the ideal network model, which is usually achieved by minimizing the "extended Bayesian information criterion" (EBIC) (Chen and Chen, 2008), which works well in identifying the true network structure (Foygel and Drton, 2010; van Borkulo et al., 2014), especially when the true network is scarce. EBIC has been extensively used in psychology networks (e.g., Beard et al., 2016; Isvoranu et al., 2016), preschoolers (Bandeira et al., 2020; Martins et al., 2021) by increasing the accuracy and interpretability of generated networks (Tibshirani, 1996). Thus, although network models can be reliable and robust with small samples, this aspect may be a limitation in our study. Finally, studies with older swimmers and/or adding physiological related variables (e.g., metabolic power and energy cost; di Prampero, 1986; Zamparo et al., 2020; Zacca et al., 2020b) will be welcomed in the next related experiments.

Twelve-year-old and under age-group swimmers regularly change their technique when swimming BREAST and FLY. Maturation, HE, AS, and SL showed a great impact on BREAST development, whereas age, SR, and HE had a strong impact for FLY. The SI represents an indirect measure of swimming efficiency and should be monitored in both BREAST and FLY to connect growth with the other technique variables. The dynamic process of athletic development and the perception of complexity of changes and relationships between swimming performance-related variables were underpinned, particularly for simultaneous techniques in age-group swimmers.

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 Universidade Federal do Rio Grande do Sul. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

AUTHOR CONTRIBUTIONS

JF, PB, RZ, and FC developed the original research inquiry and analyzed data, collaborated in data interpretation, writing, and reviewing the manuscript. JF and FC recruited participants and collected data. All authors approved the final version of this manuscript.

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REFERENCES

Bandeira, P., Duncan, M., Pessoa, M. L., Soares, I., Da Silva, L., Mota, J., et al. (2020). TGMD-2 short version: Evidence of validity and associations with sex, age and BMI in preschool children. *J. Motor Learn. Development* 8, 528–543. doi: 10.1123/jmld.2019-0040

Beard, C., Millner, A. J., Forgeard, M. J., Fried, E. I., Hsu, K. J., Treadway, M. T., et al. (2016). Network analysis of depression and anxiety symptom relationships in a psychiatric sample. *Psychol. Med.* 46, 3359–3369. doi: 10.1017/S0033291716002300

Beunen, G., and Malina, R. M. (1988). Growth and physical performance relative to the timing of the adolescent spurt. *Exer. Sport Sci. Rev.* 16, 503–540. doi: 10.1249/00003677-198800160-00018

Chen, J., and Chen, Z. (2008). Extended bayesian information criterion for model selection with large model space. *Biometrika*. 94, 759–771. doi: 10.1093/biomet/asn034

Chiesi, A. M. (2001). Network Analysis. *Int. Encyclopedia Soc. Behav. Sci.* 12, 10499–10502. doi: 10.1016/B0-08-043076-7/04211-X

Collard, L., Gourmelin, E., and Schwob, V. (2013). The fifth stroke: the effect of learning the dolphin kick technique on swimming speed in 22 novice swimmers. *J. Swimm. Res.* 21, 1—15.

Collins, A., Ward, K., Mcclanahan, B., Slawson, D. L., Vukadinovich, C., Mays, K. E., et al. (2019). Bone accrual in children and adolescent nonelite swimmers: a 2-Year Longitudinal Study. *Clinic. J. Sport Med.* 29, 43–48. doi: 10.1097/JSM.0000000000000484

Costill, D., L., Kovaleski, J., Porter, D., Kirwan, J., Fielding, R., and King, D. (1985). Energy expenditure during front crawl swimming: predicting success in middle-distance events. *Int. J. Sports Med.* 6, 266–270. doi: 10.1055/s-2008-1025849

di Prampero, P. E. (1986). The energy cost of human locomotion on land and in water. *Int. J. Sports Med.* 7, 55–72 doi: 10.1055/s-2008-1025736

Dias, P., Marques, M., and Marinho, D. (2012). Performance evaluation in young swimmers during 28 weeks of training. *J. Physic. Educ. Sport*. 12, 30—38.

Epskamp, S., Cramer, A., Waldorp, L., Schmittmann, V., and Borsboom, D. (2012). qgraph: Network visualizations of relationships in psychometric data. *J. Statistic. Softw*. 48, 1–18. doi: 10.18637/jss.v048.i04

Fan, J., Feng, Y., and Wu, Y. (2009). Network exploration via the adaptive LASSO and SCAD penalties. *Annal Appl. Statistic.* 3, 521–541. doi: 10.1214/08-AOAS215

Ferreira, S., Carvalho, D., Monteiro, A. S., Abraldes, J. A., Vilas-Boas, J. P., Toubekis, A., et al. (2019). Physiological and biomechanical evaluation of a training macrocycle in children swimmers. *MDPI Sports J.* 7:1–9. doi: 10.3390/sports7030057

Foygel, R., and Drton, M. (2010). Extended bayesian information criterira for gaussian graphical models. *Adv. Neural Inform. Process. Syst.* 23, 1—14.

Friedman, J., Hastie, T., and Tibshirani, R. (2008). Sparse inverse covariance estimation with the graphical lasso. *Biostatistics*. 9:432–441. doi: 10.1093/biostatistics/kxm045

Gani, R., Tangkudung, J., and Dlis, F. (2019). Development exercise model in butterfly swimming for athletes in the age group 11-13 years based on drill through android app. *J. Educ. Health Sport*. 9, 376–387.

Goethel, M., Gonçalves, M., Brietzke, C., Cardozo, A. C., Vilas-Boas, J. P., and Ervilha, U. F. (2020). A global view on how local muscular fatigue affects human performance. *Proc. Natl. Acad. Sci. U S A*. 117, 19866–19872. doi: 10.1073/pnas.2007579117

Grusky, O. (1963). The effects of formal structure on managerial recruitment: A study of baseball organization. *Sociometry* 26, 345–353. doi: 10.2307/2786074

Guido, C. (2020). A Perspective on complexity and networks science. *J. Physics: Complexity*. 1, 1–5. doi: 10.1088/2632-072X/ab9a24

Guignard, B., Rouard, A., Chollet, D., Hart, J., Davids, K., and Seifert, L. (2017). Individual-Environment interactions in swimming: the smallest unit for analysing the emergence of coordination dynamics in performance? *Sports Med*. 47, 1543–1554. doi: 10.1007/s40279-017-0684-4

Havriluk, R. (2010). "Performance level differences in swimming: Relative contributions of strength and technique," in *XIth International Symposium for Biomechanics and Medicine Swimming; Oslo: Biomechanics and Medicine Swimming XI*, pp. 321–323.

Hay, J., and Guimarães, A. C. S. (1983). A quantitative look at swimming biomechanics. *Swimm. Tech*. 20, 11–17.

Heyward, V. H., and Stolarczyk, L. M. (1996). *Applied Body Composition Assessment*. Champaign: Human Kinetics.

Holland, J. H. (2006). Studying complex adaptive systems. *J. Syst. Sci. Complex*. 19, 1–8. doi: 10.1007/s11424-006-0001-z

Hopkins, W. G. (2002). *A Scale of Magnitudes for Effect Statistics. A New View of Statistics*. Available online at: http://sportsci.org/resource/stats/effectmag.html

Isvoranu, A. M., Borsboom, D., van Os, J., and Guloksuz, S. (2016). A network approach to environmental impact in psychotic disorders: brief theoretical framework. *Schizophrenia Bull.* 42, 870–873 doi: 10.1093/schbul/sbw049

Kapus, J., Moravec, T., and Lomax, M. (2018). Effects of head position on the duration of breaststroke swimming in preschool swimming beginners. *Kinesiologia Slovenica*. 24, 17–27.

Krämer, N., Schäfer, J., and Boulesteix, A. L. (2009). Regularized estimation of large-scale gene association networks using *graphical Gaussian models. BMC Bioinform.* 10, 384. doi: 10.1186/1471-2105-10-384

Lakens, D. (2013). Calculating and reporting effect sizes to facilitate cumulative science: a practical primer for t-tests and ANOVAs. *Front. Psychol*. 26; 863. doi: 10.3389/fpsyg.2013.00863

Langerdorfer, S. (2013). Which Stroke First? *Int. J. Aquatic Res. Educ*. 7, 5–8. doi: 10.25035/ijare.07.04.02

Lätt, E., Jurimae, J., Haljaste, K., Cicchella, A., Purge, P., and Jurimae, T. (2009). Physical development and swimming performance during biological maturation in young female swimmers. *Collegium Antropolo*. 33, 117–122.

Leblanc, H., Seifert, L., and Chollet, D. (2009). Arm-leg coordination in recreational and competitive breaststroke swimmers. *J. Sci. Med*. 12, 352–356. doi: 10.1016/j.jsams.2008.01.001

Lord, F., Pyne, D. B., Welvaert, M., and Mara, J. K. (2020). Methods of performance analysis in team invasion sports: a systematic review. *J. Sports Sci.* 38, 2338–2349. doi: 10.1080/02640414.2020.1785185

Malina, R. (2016). Validation of maturity offset in the Fels longitudinal study. *Pediatric Exer. Sci*. 28, 439–455. doi: 10.1123/pes.2015-0090

Martins, C., Webster, E. K., Bandeira, P. F. R., and Staiano, A. E. (2021). Identifying fundamental motor skills building blocks in preschool children from Brazil and the United States: a network analysis. *J. Motor Learn. Develop*. 21, 1–20. doi: 10.1123/jmld.2021-0022

Meylan, C. M. P., Cronin, J. B., Oliver, J. L., Hopkins, W. G., and Contreras, B. (2014). The effect of maturation on adaptations to strength training and detraining in 11–15-year-olds. *Scand. J. Med. Sci. Sports*. 24, 156–164. doi: 10.1111/sms.12128

Mirwald, R., Baxter-Jones, A., Bailey, D., and Beunen, G. (2002). An assessment of maturity from anthropometric measurements. *J. Am. Coll. Sports Med*. 34, 689–694. doi: 10.1249/00005768-200204000-00020

Mitchell, L., Rattray, B., Fowlie, J., Saunders, P., and Pyne, D. (2020). The impact of different training load quantification and modelling methodologies on performance predictions in elite swimmers. *Euro. J. Sports Sci*. 20, 1–10. doi: 10.1080/17461391.2020.1719211

Morais, J., Forte, P., Silva, A., Barbosa, T., and Marinho, D. (2020). Data modeling for inter- and intra-individual stability of young swimmers' performance: a longitudinal cluster analysis. *Res. Q. Exer. Sport*. 92, 1–13. doi: 10.1080/02701367.2019.1708235

Morais, J. E., Marques, M. C., Marinho, D. A., Silva, A. J., and Barbosa, T. M. (2014). Longitudinal modeling in sports: young swimmers' performance and biomechanics profile. *Hum. Move. Sci*. 37:111–122. doi: 10.1016/j.humov.2014.07.005

Moreira, M., Morais, J., Marinho, D., Silva, A., Barbosa, T., and Costa, M. (2014). Growth influences biomechanical profile of talented swimmers during the summer break. *Sports Biomechanics*. 13, 62–74. doi: 10.1080/14763141.2013.865139

Muller, L., Hildebrandt, C., Muller, E., Fink, C., and Raschner, C. (2017). Long-term athletic development in youth alpine ski racing: the effect of physical fitness, ski racing technique, anthropometrics and biological maturity status on injuries. *Front. Physiol.* 8, 1–11. doi: 10.3389/fphys.2017.00656

Newell, K. M. (1986). "Constraints on the development of coordination", in *Motor Development in Children: Aspect of Coordination and Control*, ed Wade MG and Whiting HTA, Dordrecht: Nijhoff; 341–360.

Philippaerts, R. M., Vaeyens, R., Janssens, M., Renterghem, B. V., Matthys, D., Craen, R., et al. (2006). The relationship between peak height velocity and physical performance in youth soccer players. *J. Sports Sci*. 24, 221–230. doi: 10.1080/02640410500189371

Pichardo, A. W., Oliver, J. L., Harrison, C. B., Maulder, P. S., and Lloyd, R. S. (2018). Integrating models of long-term athletic development to maximize the physical development of youth. *Int. J. Sports Sci. Coach*. 13, 1189–1199. doi: 10.1177/1747954118785503

Pol, R., Balagu,é, N., Ric, A., Torrents, C., Kiely, J., and Hristovski, R. (2020). Training or synergizing? complex systems principles change the understanding of sport processes. *Sports Med. Open*. 6, 1–13. doi: 10.1186/s40798-020-00256-9

Riewald, S., and Rodeo, S. (2015). Science of swimming faster. *Hum. Kinetics*. 15:854. doi: 10.5040/9781492595854

Sammoud, S., Nevill, A. M., Negra, Y., Bouguezzi, R., Chaabene, H., and Hachana, Y. (2017). Allometric associations between body size, shape, and 100-m butterfly speed performance. *J. Sports Med. Physic. Fitness*. 58, 630–637. doi: 10.23736/S0022-4707.17.07480-1

Sammoud, S., Nevill, A. M., Negra, Y., Chaabene, H., and Hachana, Y. (2018). 100-m breaststroke swimming performance in youth swimmers: the predictive value of anthropometrics. *Pediatric Exer. Sci*. 30, 393–401. doi: 10.1123/pes.2017-0220

Sanders, R. H., Cappaert, J. M., and Devlin, R. K. (1995). Wave characteristics of butterfly swimming. *J. Biomechan*. 28, 9–16. doi: 10.1016/0021-9290(95)80002-6

Schmittmann, V. D., Cramer, A., Waldorp, L., Epskamp, S., Kievit, R., and Borsboom, D. (2013). Deconstructing the construct: A network perspective on psychological phenomena. *New Ideas Psychol*. 31, 43–53. doi: 10.1016/j.newideapsych.2011.02.007

Strzała, M., Krezałek, P., Kaca, M., Głab, G., Ostrowski, A., Stanula, A., et al. (2012). Swimming speed of the breaststroke kick. *J. Hum. Kinetics*. 35, 133–139. doi: 10.2478/v10078-012-0087-4

Strzała, M., Stanula, A., Krezałek, P., Ostrowski, A., Kaca, M., and Głab, G. (2017). Butterfly sprint swimming technique, analysis of somatic and spatial-temporal coordination variables. *J. Hum. Kinetics*. 60, 51–62. doi: 10.1515/hukin-2017-0089

Taguchi, M. (1975). Biomechanical analysis of arms and legs coordination in the breaststroke. *Fukuoka Univ Rev Phys Educ*. 5, 181–192.

Thomas, D. G. (1990). *Advanced Swimming: Steps to Success (Steps to Success Activity Series)*. Human Kinetics. ISBN: 0880113898

Tibshirani, R. (1996). Regression shrinkage and selection via the lasso. *J. Roy. Statistic. Soc. Series B* 58, 267–288. doi: 10.1111/j.2517-6161.1996.tb02080.x

Tosta, J., Ribeiro, A., Silveira, R., Franken, M., Barroso, R., Portella, D. L., et al. (2019). Butterfly coordination and maturational stage of young swimmers. *Brazil. J. Physic. Educ. Sport*. 33, 479–485. doi: 10.11606/issn.1981-4690.v33i3p479-485

van Borkulo, C., Borsboom, D., and Epskamp, S., et al. (2014). A new method for constructing networks from binary data. *Sci. Rep.* 4, 5918. doi: 10.1038/srep05918

Wäsche, H., Dickson, G., Woll, A., and Brandes, U. (2017). Social network analysis in sport research: an emerging paradigm. *Euro. J. Sport Soc.* 14, 138–165. doi: 10.1080/16138171.2017.1318198

Zacca, R., Azevedo, R., Chainok, P., Vilas-Boas, J. P., Castro, F. A. S., Pyne, D. B., et al. (2020a). Monitoring age-group swimmers over a training macrocycle: energetics technique, and anthropometrics. *J. Strength Condition. Res.* 34, 818–827. doi: 10.1519/JSC.0000000000002762

Zacca, R., Azevedo, R., Ramos, V. R., Abraldes, J. A., Vilas-Boas, J. P., Castro, F. A. S. (2020b). Biophysical follow-up of age-group swimmers during a traditional three-peak preparation, program. *J. Strength Condition. Res*. 34, 2585–2595. doi: 10.1519/JSC.0000000000002964

Zamparo, P., Cortesi, M., and Gatta, G. (2020). The energy cost of swimming and its determinants. *Eur. J. Appl. Physiol.* 120, 41–66. doi: 10.1007/s00421-019-04270-y

Zamparo, P., Gatta, G., Pendergast, D., and Capeli, C. (2009). Active and passive drag: the role of trunk incline. *Eur. J. Appl. Physiol.* 106, 195–205. doi: 10.1007/s00421-009-1007-8

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Sprint Performance in Arms-Only Front Crawl Swimming Is Strongly Associated With the Power-To-Drag Ratio

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To date, optimal propulsion in swimming has been studied predominantly using physical or computational models of the arm and seldom during real-life swimming. In the present study we examined the contributions of selected power, technique and anthropometric measures on sprint performance during arms-only front crawl swimming. To this end, 25 male adult competitive swimmers, equipped with markers on their arms and hands, performed four 25-m sprint trials, which were recorded on video. For the fastest trial of each swimmer, we determined the average swim speed as well as two technique variables: the average stroke width and average horizontal acceleration. Each participant also swam 10–12 trials over a custom-made system for measuring active drag, the MAD system. Since the propelling efficiency is 100% while swimming over the MAD system, the power output of the swimmer is fully used to overcome the drag acting on the body. The resulting speed thus represents the ratio between power output and drag. We included this power-to-drag ratio, the power output and the drag coefficient of the fastest trial on the MAD system in the analysis. Finally, the body height and hand surface area of each swimmer were determined as anthropometric variables. A model selection procedure was conducted to predict the swim speed from the two technique variables, three power variables and the two anthropometric variables. The ratio between power output and the drag was the only significant predictor of the maximal swimming speed ($v = 0.86 \cdot power/drag$). The variations in this ratio explained 65% of the variance in swimming performance. This indicates that sprint performance in arms-only front crawl swimming is strongly associated with the power-to-drag ratio and not with the isolated power variables and the anthropometric and technique variables selected in the present study.

Keywords: 3d hand kinematics, swimming technique, power, anthropometrics, front crawl, MAD system

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INTRODUCTION

The overarching aim of competitive swimming is to transverse a given race distance as fast as possible. Swim coaches are therefore constantly looking for ways to improve the swim speed and thus the race performance of their swimmers, as indeed the swimmers do themselves. Two main domains that coaches work on with their swimmers are the mechanical power that can be delivered by the swimmer and the swimming technique employed to convert that power into speed. It is generally understood and experienced that both domains can be altered by training. A third domain that is important for swimming performance concerns the swimmer's anthropometric properties. After maturation the swimmer's anthropometrics are fixed and cannot (or only marginally) be adjusted by training. These three domains have all received attention in studies aimed at identifying relevant performance related variables in speed swimming. In the following sections important findings within each domain are highlighted. An a priori selection of potentially relevant variables from each domain was made based on those findings.

The power balance is a commonly used approach to gain insight into how power, drag and swimming technique affect swimming speed. It posits that the total mechanical power produced by the swimmer (P_o) is equal to the power to overcome drag (P_d) and the power expended in pushing away masses of water (P_k). Unlike the ground surface in running, water is a non-stationary medium that is brought into motion during the push-off (van Ingen Schenau and Cavanagh, 1990; Rodríguez and Mader, 2011). The theoretical relationship between swim speed (v), power output (P_o), propelling efficiency (e_p) and drag (represented by the drag coefficient K) shows how power output and propelling efficiency both contribute to swimming speed (Toussaint and Truijens, 2006; Rodríguez and Mader, 2011):

$$v = \sqrt[3]{\frac{P_o \cdot e_p}{K}} \tag{1}$$

The power balance for swimming illustrates that swimmers have two main options to swim faster, namely to increase their overall power and to decrease the power losses associated with overcoming drag and bringing water into motion. The first option may be realized through strength training, which makes swimmers stronger and capable of generating greater power, while the second option may be realized by optimizing swimming technique, resulting in a higher propelling efficiency.

In the power domain, numerous studies have determined power output on land and some in water. Several studies reported a significant relationship between swimming performance and dry land power tests in which power output was determined with an upper-body ergometer (e.g., Hawley and Williams, 1991; Hawley et al., 1992; Zamparo et al., 2014), swim bench (arms only: e.g., Sharp et al., 1982, whole-body: e.g., Gatta et al., 2017) or during strength exercises (e.g., Pérez-Olea et al., 2018), although some of these studies also included variables and/or considerations related to the technique and anthropometric domain. Significant correlations were also found between power tests in the pool and swimming performance. In the water, power was determined with semi-tethered (e.g., Costill et al., 1983; Dominguez-Castells et al., 2013) swimming tests and by using the MAD system (Toussaint and Vervoorn, 1990). However, the high correlation coefficients found in some of these studies should be regarded with caution since the participants in these studies were heterogeneous in terms of age and gender (Morouço et al., 2012). Nevertheless, the general conclusion that can be drawn from the literature is that the power output of the swimmer in relation to drag is an important determinant of swimming performance.

In the technique domain, the trajectory, orientation, speed and acceleration of the hand are aspects of the swimming technique that have been studied extensively, particularly in front crawl swimming, while other aspects such as leg, trunk and head movements have received considerably less attention. In an encompassing literature review, van Houwelingen et al. (2017) summarized the current state of knowledge regarding the hydrodynamic aspects of hand and arm movements in front crawl swimming. Since the influential work of Counsilman (1971), there has been considerable debate in the literature whether or not the hand trajectory in the front crawl stroke should contain lateral (sculling) movements. van Houwelingen et al. (2017) concluded from the literature that excessive sculling movements generally lead to lower propulsive forces than a (roughly) straight underwater stroke and should therefore be avoided. With respect to optimal hand orientation no firm conclusions could be drawn, since the results reported on this variable were too inconsistent. van Houwelingen et al. (2017) further concluded that accelerating the hand leads to a higher propulsive force compared to a stroke performed at constant speed, implying that a high acceleration would be desirable for effective propulsion.

In the anthropometric domain, body height, hand surface area and arm span have been associated with swimming performance. In several studies (Klentrou and Montpetit, 1991; Geladas et al., 2005; Lätt et al., 2010) a significant correlation between body height and swimming performance was found in young swimmers. Moura et al. (2014) found that body height was a significant predictor of the propulsive arm force in young swimmers, even after having controlled for maturation stage. Two potential mechanisms are described in the literature through which body height could be positively related to swimming speed. First, it has been suggested that an increased body height could reduce the wave drag acting on the body (Toussaint et al., 1990, 2000; Toussaint and Beek, 1992). Second, taller swimmers were found to have larger arm spans, which in turn were found to be associated with increased stroke length and swimming performance (Grimston and Hay, 1986; Mazzilli, 2019).

The beneficial effect of a large hand surface area on swimming performance can be understood best from the equations that describe the forces acting on the hand and arm during the stroke. These forces are typically described in a component parallel to the line of hand motion, the so-called drag forces, and a component perpendicular to the line of hand motion, the so-called lift forces. The drag and lift forces acting on the hand can be derived from the following equation:

$$F_{D,L} = \frac{1}{2} \rho A v_{hand}^2 C_{D,L} \tag{2}$$

where ρ is the water density, A is the hand surface as projected on a plane perpendicular to the mean flow (for the drag force), v_{hand} is the hand speed, and $C_{D,L}$ is the drag/lift coefficient (Toussaint and Beek, 1992; van Houwelingen et al., 2017). Since the projected hand surface area A is directly related to the forces acting on the hand, a large hand surface area seems an important anthropometric asset for competitive swimmers besides body height.

The cited findings in the three domains suggest that factors related to power, propulsion technique and anthropometrics all contribute to swimming performance. One point of concern is that for the most part, the conclusions drawn by van Houwelingen et al. (2017) about optimal swimming technique are either based on studies in which physical arm models were equipped with actuators and/or sensors or studies in which a computational fluid dynamics model was simulated, while only few studies investigated optimal swimming technique during actual swimming. Another point of concern is that most studies only looked at the effect of one of the domains of swimming performance distinguished here, instead of adopting an integral approach covering variables from all three domains. In one of the few studies that looked at more than one domain, Klentrou and Montpetit (1991) found that height, arm span, maximal stroke rate and power, measured using a tethered swim, were predictors of 100 m performance in 25 male age-group swimmers. The model containing height and arm span explained 56% of the variance. After adding the measured power to the model, the explained variance increased by 10% to a total of 66%. The maximal stroke rate added another 5% of the explained variance. Whereas the participants in the study of Klentrou and Montpetit (1991) were age-group swimmers, Lätt et al. (2010) concluded that technique factors (stroke rate and stroke index) explained 90.3% of the variance in 100 m sprint performance in adolescent male swimmers. Anthropometric factors explained 45.8% of the variance. The participants in the studies of both Klentrou and Montpetit (1991) and Lätt et al. (2010) were youth swimmers. For adult swimmers the contribution of each domain might be different. Moreover, in none of the studies in question factors from all three domains—i.e., power generation, propulsion technique and anthropometrics—were included and compared.

In the present study we adopted an integral approach aimed at determining and comparing the contributions of selected power, technique and anthropometric measures on sprint performance during arms-only front crawl swimming in adult, male competitive swimmers. Based on the literature, we expected that variables from each of the three domains would contribute to swimming performance.

MATERIALS AND METHODS

Twenty-five healthy, male adult competitive swimmers [age: 22 ± 5 years, body weight: 77.6 ± 9.2 kg, body height: 184.8 ± 6.4 cm; all measures mean ± standard deviation (SD)] participated in the study. For each participant, the highest FINA score (based on the FINA 2018 points table; Kaufmann, 2018) during competition within the period between 90 days before and 90 days after the measurement day was obtained from www.swimrankings.net. The participants scored 593 ± 108 FINA points within this period. Their average personal best time (also obtained from swimrankings.net) on the 50 meter and 100 meter freestyle (long course) were, respectively, 25.8 ± 1.5 s and 56.1 ± 2.5 s. The participants volunteered to partake in the study following an informal recruitment procedure via their swimming club or coach, and provided informed consent prior to the start of the study. Only male swimmers, 18 years or older, with a personal best below 60 s on the 100 m freestyle (long course) were included in the study. The protocol for the study was approved by the local ethics committee of the Faculty of Behavioural and Movement Sciences of the Vrije Universiteit Amsterdam (VCWE, VCWE-2018-054). The protocol consisted of three parts: (1) anthropometric measurement, (2) measurement of hand kinematics during arms-only front crawl swimming, and (3) measurements of power output and drag.

Anthropometric Measurements

Upon arrival at the InnoSportLab De Tongelreep at Eindhoven, where the study was conducted, participants were informed about the general aim and the experimental procedures of the study. Subsequently, a series of anthropometric measures were taken, including body height and hand surface area. The hand surface was measured using the available equipment in the testing environment. This was done as follows. First, one of the experimenters marked the location of the ulnar and radial styloid on the skin of the right arm with a pencil. Next, the participant placed his right hand flat on a vertical surface with fingers spread. Perpendicular to the surface, a camera (Sony NEX-VG20E) was positioned to take a picture of the hand. A sheet of A4 paper was placed on the same surface close to the participant's hand. The resulting image was postprocessed in ImageJ and rescaled using the known distance of the long side of the A4 paper. Finally, the hand surface area was determined by tracing the hand until the skin marks of the ulnar and radial styloid.

Measurement of Hand Kinematics During Arms-Only Front Crawl Swimming

After the participants had been prepared for measurement, they swam for 15 min to warm up and familiarize themselves with swimming with clusters of LED markers attached to the ventral and dorsal side of both forearms and markers placed on the tip of the middle fingers. Immediately thereafter they performed four trials in front crawl starting from the middle of the 50-m long pool (i.e., at 25 meters) toward the wall. The swimming movements were recorded within a calibrated volume of 2 × 1 × 1 m (i.e., 2 m long in the swimming direction). The participants were instructed to swim as fast as possible in each trial. Their legs were supported by a pull-buoy and they were instructed not to use the leg kick. Since breathing has an effect on the stroke kinematics, they were also instructed not to breathe around the calibrated volume.

In the pool, cameras (scA1400-30gc, Basler AG, Ahrensburg, Germany, 50 fps) in the sidewall of the pool positioned at, respectively, 15 and 5 m from the start edge of the pool were used to determine the average swimming speed (v_{trial}) in this segment, while six cameras (avA1900-50gc, Basler AG, Ahrensburg, Germany, 50 fps) in underwater housings placed at the bottom of the pool were used to capture the movement of the right arm. The intrinsic parameters of the cameras at the bottom of the pool were determined with the Camera Calibration Toolbox in Matlab

(Bouguet, 2008) using a checkerboard, while the Direct Linear Transformation (DLT) parameters were calculated based on a 2 × 1 × 1 m calibration frame containing 60 control points. These parameters were combined with the tracked marker positions to reconstruct the real-world coordinates in 3D. The position of the marker on the middle finger was tracked frame-by-frame by the experimenter using custom-made software. If the experimenter could not judge the position of a marker, the missing data were filled by linear interpolation. These raw data were filtered using a second order low-pass Butterworth filter. A cut-off frequency of 10 Hz was used to filter the coordinates of the marker on the tip of the middle finger. This cut-off frequency was chosen based on the results of a previous study showing that the optimal dynamic precision of a marker cluster modeled on the forearm was smallest with a cut-off frequency of 10 Hz (Schreven et al., 2015). The tracking procedure was only conducted on one stroke of the right arm in the fastest trial of each swimmer, resulting in 25 observations. Since the aim of the present study was to predict maximal swim speed from power, technique and anthropometric variables, only the fastest trial of each swimmer was included in the analysis.

Based on the processed real-world coordinates, two technique variables were calculated: the stroke width (standard deviation of the lateral position of the tip of the middle finger) and $a_{hand,hor}$ (mean absolute horizontal acceleration of the tip of the middle finger). Ideally, the technique variables would be calculated over the full backward part of the stroke from the moment that the tip of the middle finger starts moving backwards (t_0, $t = 0\%$) until the last frame in which the tip of the middle finger was visible in the underwater recordings (t_{100}, $t = 100\%$). However, since the markers were not visible in each trial from t_0 to t_{100} the part of the stroke in which data was available for all participants had to be determined. The marker at the tip of the middle finger was visible for all participants from $t = 0$ to $t = 90\%$ (t_{90}) and therefore the technique variables stroke width and $a_{hand,hor}$ were calculated between t_0 and t_{90}.

Measurement of Power Output and Drag

To obtain variables describing drag and power output, a system dedicated to this purpose was used, the so-called measuring active drag or MAD system (Hollander et al., 1986). The MAD system is one of the established methods to measure active drag (for an overview of all established methods for this purpose see Toussaint et al., 2000; Wilson and Thorp, 2003). The MAD system consists of a 23-meter long rod with 17 push-off pads attached to it. The rod is positioned 0.8 meters below the water surface. The distance between the pads is 1.35 m and the top edge of the push-off pads is positioned 0.56 m below the water surface. The dimensions of each push-off pad are 25.5 × 16.5 cm. The rod is attached to a waterproof force transducer (BSP-603, Vishay Precision Group, Malvern, Pennsylvania, USA) connected to the wall. The force signal is digitized with an A/D converter (NI 9237 and cDAQ-9171, National Instruments, Austin, Texas, USA) at a sampling rate of 100 Hz. The participant swims over the system by pushing off against the fixed push-off pads. The propelling efficiency is 100% while swimming over the MAD system, because the swimmer pushes off against a fixed surface and no power is lost by pushing away masses of water. The speed reached by the participant is therefore determined by the power-to-drag ratio and thus represents a direct measure for this ratio.

Each participant swam five trials of 23 m on the MAD system to become familiar with swimming over the system. Next, the participant swam 10–12 trials over the system during which data were recorded, starting at a speed around 1.2 m/s and incrementally increasing the speed each trial by ∼0.1 m/s until the maximal speed of the participant in question was reached. Next, one extra attempt was made at maximal intensity. The breaks between adjacent trials lasted ∼3 min. During all trials, participants swam over the system with a pull buoy between their thighs to provide support to the body without kicking their legs. They were also instructed not to breathe while swimming over the system. Using a custom made Matlab script, the force data were filtered using a 2nd order low-pass Butterworth filter with a cut-off frequency of 10 Hz. The average swim speed in each trial on the MAD system was determined by manually selecting the time interval between the onset of the push-off against the second push-off pad and the onset of the push-off against the last (17th) push-off pad. During the same interval the average push-off force was determined. For each participant the maximal power-to-drag ratio (as determined by the maximal average speed achieved on the MAD system) was used in the statistical analysis. We will refer to this as "*power/drag*". Furthermore, the power output and drag coefficient were determined for the trial in which the maximal average speed was achieved. The power output was calculated by multiplying the average push-off force by the average speed. The drag coefficient was determined by dividing the average push-off force by the average speed squared. Since we obtained three power variables (*power/drag*, power output, and drag coefficient) from two measurements (average speed and average force in the fastest trial on the MAD system), we expected redundancy between those variables. Therefore, we checked in the statistical analysis for collinearity between these (and all other) independent variables to reduce the redundancy between the power variables.

Statistical Analysis

The statistical analysis was performed in R (R Core Team, 2020) using RStudio 1.3.1056 (RStudio, Boston, Massachusetts, USA). The following R packages were used: nlme (Pinheiro et al., 2020), readxl (Wickham and Bryan, 2019) and regclass (Petrie, 2020). The aim of the analysis was to determine the optimal model to predict v_{trial} (dependent variable) from the following seven independent variables: body height, hand surface area, *power/drag*, power output, drag coefficient, stroke width and $a_{hand,hor}$. The technique variables and swim speed from the fastest trial out of the four trials were included in the dataset, resulting in a total of 25 observations. First, boxplots and histograms were made for all independent variables to detect outliers. Collinearity was assessed by calculating Pearson's correlation coefficient between all independent variables. In case two variables had a Pearson's correlation coefficient above 0.7, one independent variable was selected.

In line with the procedure described by Zuur et al. (2009), the following three steps were taken to construct the optimal model taking into account both fixed effects and the residual variance structure using the generalized least squares technique. First, the optimal residual variance structure was determined. All independent variables were entered as fixed terms in the model. Models with different residual variance structures were compared using the Akaike information criterion (AIC). A total of 14 residual variance structures were compared: seven models with a fixed variance with each of the independent variables as variance covariate and seven models with a "power of the covariate" variance structure with each of the independent variables as variance covariate; the residual variance structure that resulted in the smallest AIC was selected as the optimal residual variance structure. The various residual variance structures were also compared to a standard linear model. In this first step the model parameters were estimated using the Restricted Maximum Likelihood approach (REML). Second, using the optimal residual variance structure selected in the previous step, a step down procedure was followed to find the optimal fixed structure starting by entering all independent variables as fixed terms in the model. In each round of the parameter removal procedure all fixed terms were dropped one by one and using the likelihood ratio test each of the models in which one of the fixed terms was dropped was compared to the full model from the start of the elimination round. In case any of the fixed terms was not significant ($p > 0.05$), the parameter with the highest p-value in the likelihood ratio test was removed from the model and a new round of the elimination process was started. This process was repeated until all fixed terms in the model were significant. In this second step the model parameters were estimated using Maximum Likelihood estimation. Third, the results of the model selected in the second step were presented using the values obtained by REML estimation.

RESULTS

Table 1 shows an overview of the results for the dependent and independent variables. The swimmers could indeed swim fast (1.57 ± 0.08 m/s). As expected, they swam even faster on the MAD system (1.84 ± 0.09 m/s) because in this environment no power is lost by bringing water into motion. The variation in the anthropometric variables was smaller (coefficient of variation < 0.1) than in the technique variables. As can be seen in **Figure 1**, which shows the scatter plots of the maximal swim speed as a function of all independent variables, there were no outliers for any of the variables. A high correlation coefficient ($r > 0.70$) was found between *power/drag* and power output ($r = 0.83$) and between power output and the drag coefficient ($r = 0.80$), indicating collinearity between the variables in question. Power output was therefore excluded as independent variable, because the correlation coefficient with v_{trial} was higher for *power/drag* ($r = 0.81$) than for power output ($r = 0.66$). To indicate how a hand trajectory leads to values for the two technique variables, the hand trajectory in side-view (top, left panel) and top-view (top, right panel) and the horizontal hand acceleration (bottom panel) are shown for one of the swimmers in **Figure 2**.

TABLE 1 | Overview of the values of the dependent and independent variables.

Variable	Mean ± SD	95% Confidence interval
v_{trial} (m/s)	1.57 ± 0.08	(1.54, 1.60)
body height (cm)	184.8 ± 6.4	(182.1, 187.4)
hand surface area (cm^2)	175.5 ± 12.9	(170.2, 180.8)
power/drag (m/s)	1.84 ± 0.09	(1.80, 1.88)
power output (W)	181 ± 40	(165, 198)
drag coefficient (kg/m)	28.7 ± 3.7	(27.2, 30.3)
$a_{hand,hor}$ (m/s^2)	23.1 ± 4.7	(21.2, 25.1)
stroke width (m)	0.076 ± 0.030	(0.063, 0.088)

Values are given over the 25 observations.

In search for the optimal residual variance structure, the model with a fixed variance structure with stroke width as the variance covariate had the lowest AIC value (AIC = −20.7) and was therefore preferred over the standard linear model (AIC = −17.8), the model with a power to the covariate structure with stroke width as variance covariate (AIC = −20.2) and the models in which the other independent variables were used as variance covariates (AIC > −18.3). In search for the optimal fixed effects, the non-significant independent variables were eliminated in the following order: intercept ($L = 0.03$, $p = 0.86$), hand surface area ($L = 0.29$, $p = 0.59$), drag coefficient ($L < 0.80$, $p = 0.37$), body height ($L = 1.44$, $p = 0.23$), $a_{hand,hor}$ ($L = 1.18$, $p = 0.28$) and stroke width ($L = 0.38$, $p = 0.54$). Only *power/drag* was a significant predictor of the maximal sprint speed [mean: 0.856, 95% confidence interval (0.847, 0.865)] resulting in the following model:

$$v_{trial} = 0.856 \cdot \ power/drag \tag{3}$$

The scatter plot of *power/drag* vs. v_{trial} in **Figure 3** shows the strong relationship between both variables. A strong positive correlation ($R^2 = 0.65$) between both variables indicated that the variations in the maximal power-to-drag ratio explained 65% of the variance in swimming performance.

DISCUSSION

The aim of the present study was to determine which variables from the power, technique, and anthropometric domain contribute significantly to the prediction of maximal sprint speed during arms-only front crawl swimming. We expected variables from all three domains to be significant predictors. However, the results showed that the maximal power-to-drag ratio, determined by the maximal speed swum on the MAD system, was the only significant predictor in the model. Unexpectedly, given previous findings reported in the literature, the technique and anthropometric variables selected in this

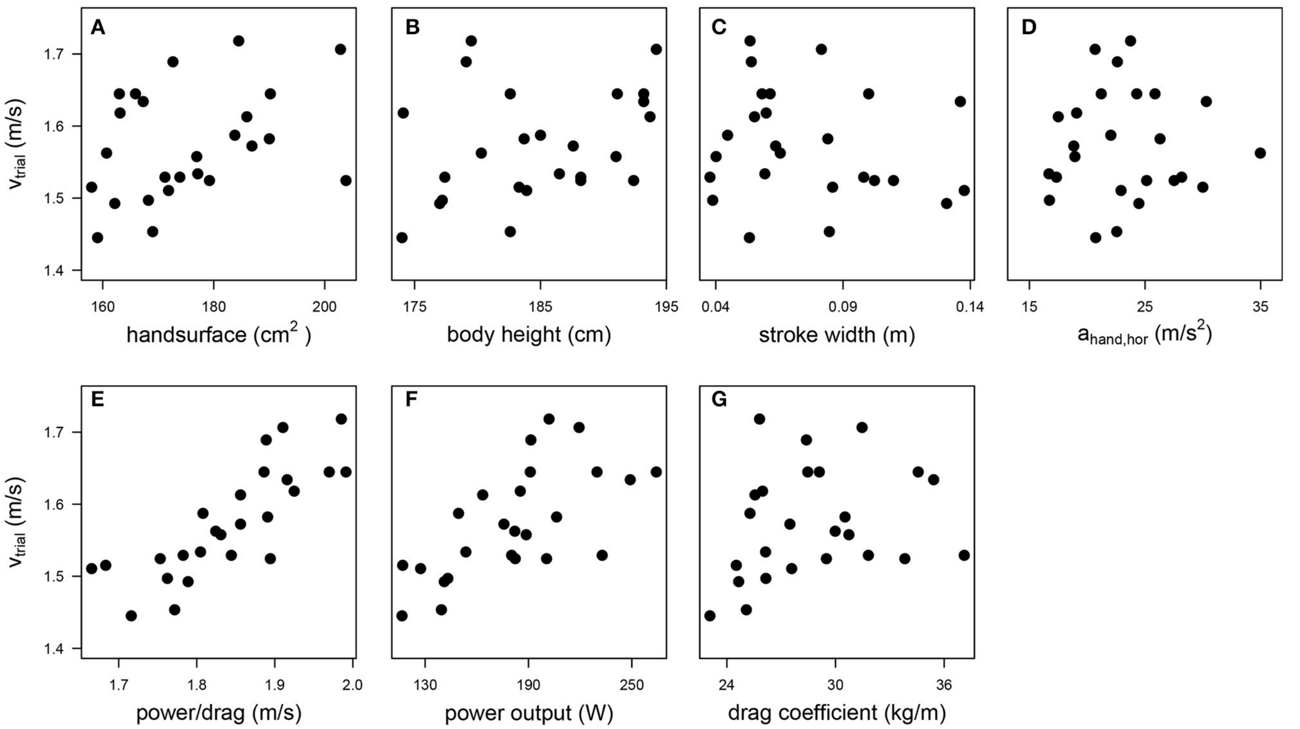

FIGURE 1 | Scatter plots of the maximal swim speed (v_{trial}) as a function of the 7 independent variables: hand surface **(A)**, body height **(B)**, stroke width **(C)**, the mean horizontal hand acceleration ($a_{hand,hor}$, **D**), power-to-drag ratio (obtained from the speed of the fastest trial on the MAD system, *power/drag*, **E**), power output **(F)**, and drag coefficient **(G)**.

study were excluded from the final model. The resulting model parameter indicates that a 1 m/s higher maximal power-to-drag ratio was related to a 0.86 m/s higher maximal sprint speed during the swimming trials. The variations in the maximal power-to-drag ratio explained 65% of the variance in the swimming performance.

The present study has several limitations that need to be discussed. The technique variables were obtained from only one stroke of the right arm, while competitive swimmers make many more strokes per lap. It may be questioned whether the technique variables obtained during that single stroke provide a valid representation of the technique of the swimmer in question as there will be a degree of variability in the arm movements and more technique variables might contribute to swimming performance than considered in the present study. For example, we intended to include hand orientation to the technique variables because it follows from Equation (2) that the hand area projected on the plane of the flow is important for the propulsion generated by the arm. Several studies (e.g., Berger et al., 1995; Bixler and Riewald, 2002; Sato and Hino, 2003) on numerical and physical arm models found that the drag and lift coefficients determined in a steady state flow varied with the angle of attack, although the results reported on this variable were too inconsistent to draw firm conclusions (van Houwelingen et al., 2017). We tried to determine this variable by means of marker clusters attached to the forearm. However, this method proved unreliable, as orientations obtained from a marker cluster placed on the dorsal side of the forearm deviated substantially from the orientation obtained from a cluster placed on the ventral side. This could have been caused by skin movement artifacts but this is uncertain; more research is needed to resolve this issue and to determine where these (rigid) marker clusters should be placed on the swimmer's body. Since we were unable to determine hand orientation reliably, we could not test whether it accounted for some of the variance in swim speed. Furthermore, the experimental task was restricted to arms-only front crawl swimming: the legs were not used for propulsion and supported by a pull buoy in all sprints, which affects the swimmer's body position in the water and leads to slower sprint speeds. Despite these restrictions, v_{trial} was significantly correlated with the personal best times on the 50 meter freestyle ($r = -0.69$, $p < 0.01$) and 100 meter freestyle ($r = -0.52$, $p < 0.01$).

Not only did we exclude the contribution of the legs, we also ignored the inter-arm coordination (which can be quantified with the index of coordination; Chollet et al., 2000), and the coordination between the arms and legs. The variables selected in this study represent a subset of all possible variables that could be included from the three domains of interest. Patently, the hydrodynamics during actual swimming is much more complex than is covered by our current quantification of technique in terms of mean stroke width and

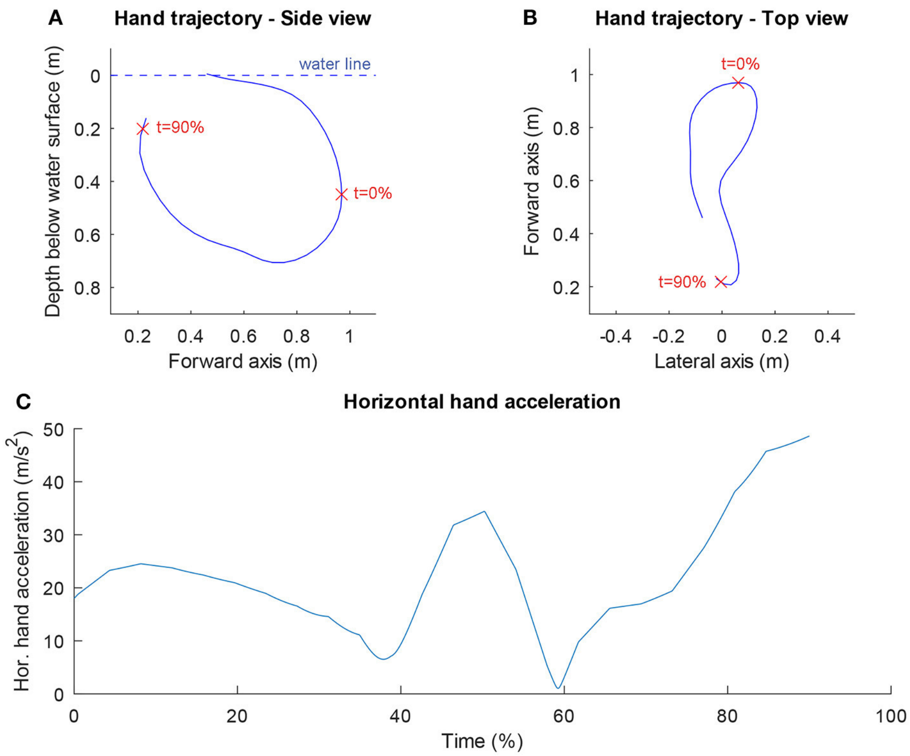

FIGURE 2 | Example of hand trajectory. The side view **(A)**, top view **(B)**, and of one of the swimmers is presented together with the horizontal hand acceleration **(C)**. The stroke width was 0.045 m and the mean horizontal hand acceleration was 22.0 m/s^2 in this trial. The red crosses in **(A,B)** indicate the limits of the part of the stroke that was analyzed (see Methods section).

mean horizontal hand acceleration. It is very likely that an interaction occurs between hand path, speed, acceleration, and orientation, which might be oversimplified with the selected technique variables.

Another limitation was the relatively small number of participants in this study. Larger sample sizes would lead to more robust results and allow independent variables with small contributions to be included in the model. Furthermore, with a larger number of observations more variables from each domain could be included. The a priori selection of variables would then likely include more variables that predict swimming speed. The digitization process to obtain the technique variables remains very time-consuming and precludes the inclusion of many participants in studies involving a detailed analysis of the hand kinematics during actual swimming. Although the participants in the present study were all competitive swimmers, the average personal best times and FINA scores as reported in the Methods section indicate that the majority of the participants were no elite swimmers. The results might well be different for a sample consisting solely of elite swimmers.

A crucial limitation is that to date no gold standard exists to determine power output and drag in swimming. All of the established methods have their limitations and underlying assumptions and cross-validations between various pairs of these methods have shown limited agreement (Toussaint et al., 2004; Formosa et al., 2012; Mason et al., 2013). In the present study, the MAD system was used to determine power output and drag. One of the limitations of the MAD system is that the push-off pads on the MAD system were placed at

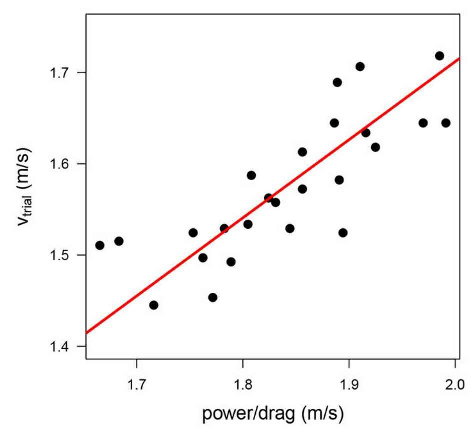

FIGURE 3 | Scatter plot of the maximal swim speed (v_{trial}) as a function of the power-to-drag ratio (obtained from the speed of the fastest trial on the MAD system, *power/drag*). The red line indicates the regression line based on the optimal model ($v_{trial} = 0.856 \cdot power/drag$).

a fixed inter-pad distance of 1.35 m. Although it was found that different inter-pad distances did not affect the measured drag (Schreven et al., 2013), it has not been studied to date whether the maximal speed achieved on the MAD system varies with inter-pad distance. Therefore, it cannot be excluded that by using a different inter-pad distance, the correlation with swimming speed would have been different. Given this discussion on the validity of the various methods to measure power and drag, it is an important open question to what extent the association between power-to-drag ratio and sprint performance depends on the method used to determine power output and drag.

In contrast to the many studies that reported important contributions of the technique and anthropometric domains to swim speed, the variables from these domains did not add significantly to the prediction of sprint speed in our study. One possible explanation for this lack of effect might be that we only selected a limited set of variables from the technique and anthropometric domain, as discussed above. However, as we chose the variables that, based on the literature, were most likely associated with swimming performance, we deem this explanation less likely. An alternative explanation might be that these variables did not contribute significantly to the variation in sprint speed between participants in the current group, as the group consisted of well-trained competitive swimmers that have passed various selection stages. Indeed, the participants in the studies that reported a significant correlation between body height and swim performance were all youth swimmers (Klentrou and Montpetit, 1991; Geladas et al., 2005; Lätt et al., 2010).

This leaves us with the general conclusion that a substantial portion (i.e., 65%) of the variance in maximal swim speed is explained by the maximal speed on the MAD system. Although we introduced the maximum speed on the MAD system as a power related variable, it represents in fact the power-to-drag ratio, as explained in the Methods section. As the drag is determined by anthropometric factors, this variable also reflects some anthropometric characteristics of the participant. Moreover, the MAD system forces the participant to use a certain stroke length, which might differ from the participant's preferred stroke length. The maximum speed on the MAD system might therefore also reflect an aspect of the technique domain.

The strong relationship between the maximal power-to-drag ratio and the maximal swim speed indicates that the maximal power-to-drag ratio is strongly associated with sprint performance. It remains to be explored whether a cause-and-effect relationship exists between both variables. The maximal power-to-drag ratio could be the swimming equivalent of power-to-bodyweight ratio that is considered a key performance indicator in for example cycling (Faria et al., 2005), especially when cycling uphill (Antón et al., 2007). The correlation suggests that increasing the power output by strength training might be beneficial for swimming performance, provided that the positive effect of the increase in power output outweighs the potentially negative effect of an increase in frontal area due to muscle hypertrophy. The MAD system allows determining the maximal power-to-drag ratio in a time effective manner. The participants did not have prior experience with the MAD system and were able to complete the protocol for the power measurements within 30 min. This system can therefore be used to evaluate changes in the maximal power-to-drag ratio due to training and might be an expedient way to identify talented swimmers, irrespective of their technique, although it remains to be established whether the maximal power-to-drag ratio determined at a young age predicts swim performance at a later, more senior age.

Future research should aim for a better understanding of the role of power, technique and anthropometrics, as well as the underlying mechanisms. Furthermore, the relative contribution of each of these domains on swim performance should be studied for swimmers of different age, sex and swim level as the (relative) contribution might be different in other populations. Also, since the maximal power-to-drag ratio was found to be an important predictor of swim speed, it would be interesting to investigate whether a causal relationship exists between both variables and if so, which strength training interventions lead to the largest improvement of this ratio and what would be the optimal muscle architecture to maximize this ratio.

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 Local Ethics Committee of the Faculty of Behavioural and Movement Sciences of the Vrije Universiteit Amsterdam (VCWE, VCWE-2018-054). The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

SS conducted the experiment and collected the data. SS and JS performed the statistical analysis. SS and PB wrote the first draft of the manuscript. All authors contributed to the conception and experimental and statistical design of the study and contributed to subsequent versions of the manuscript, read, and approved the final version.

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REFERENCES

Antón, M., Izquierdo, M., Ibáñez, J., Asiain, X., Mendiguchía, J., and Gorostiaga, E. (2007). Flat and uphill climb time trial performance prediction in elite amateur cyclists. *Int. J. Sports Med.* 28, 306–313. doi: 10.1055/s-2006-924356

Berger, M. A. M., de Groot, G., and Hollander, A. P. (1995). Hydrodynamic drag and lift forces on human hand/arm models. *J. Biomech.* 28, 125–133. doi: 10.1016/0021-9290(94)00053-7

Bixler, B., and Riewald, S. (2002). Analysis of a swimmer's hand and arm in steady flow conditions using computational fluid dynamics. *J. Biomech.* 35, 713–717. doi: 10.1016/S0021-9290(01)00246-9

Bouguet, J. Y. (2008). *Camera Calibration Toolbox for Matlab*. Available online at: http://www.vision.caltech.edu/bouguetj/calib_doc/index.html (Accessed March 29, 2018).

Chollet, D., Chalies, S., and Chatard, J. C. (2000). A new index of coordination for the crawl: description and usefulness. *Int. J. Sports Med.* 21, 54–59. doi: 10.1055/s-2000-8855

Costill, D., King, D., Holdren, A., and Hargreaves, M. (1983). Sprint speed vs. swimming power. *Swim. Tech.* 20, 20–22.

Counsilman, J. E. (1971). "The application of Bernoulli's principle to human propulsion in water," in *Proceedings: First International Symposium on Biomechanics in Swimming, Waterpolo and diving*, eds. L. Lewillie, and J. P. Clarys (Brussels: Universite libre de Bruxelles, Laboratoire de l'effort), 59–71.

Dominguez-Castells, R., Izquierdo, M., and Arellano, R. (2013). An updated protocol to assess arm swimming power in front crawl. *Int. J. Sports Med.* 34, 324–329. doi: 10.1055/s-0032-1323721

Faria, E. W., Parker, D. L., and Faria, I. E. (2005). The science of cycling. *Sport. Med.* 35, 313–337. doi: 10.2165/00007256-200535040-00003

Formosa, D. P., Toussaint, H. M., Mason, B. R., and Burkett, B. (2012). Comparative analysis of active drag using the MAD system and an assisted towing method in front crawl swimming. *J. Appl. Biomech.* 28, 746–750. doi: 10.1123/jab.28.6.746

Gatta, G., Cortesi, M., Swaine, I., and Zamparo, P. (2017). Mechanical power, thrust power and propelling efficiency: relationships with elite sprint swimming performance. *J. Sports Sci.* 36, 506–512. doi: 10.1080/02640414.2017.1322214

Geladas, N. D., Nassis, G. P., and Pavlicevic, S. (2005). Somatic and physical traits affecting sprint swimming performance in young swimmers. *Int. J. Sports Med.* 26, 139–144. doi: 10.1055/s-2004-817862

Grimston, S. K., and Hay, J. G. (1986). Relationships among anthropometric and stroking characteristics of college swimmers. *Med. Sci. Sport. Exerc.* 18, 60–68. doi: 10.1249/00005768-198602000-00011

Hawley, J., and Williams, M. (1991). Relationship between upper body anaerobic power and freestyle swimming performance. *Int. J. Sports Med.* 12, 1–5. doi: 10.1055/s-2007-1024645

Hawley, J. A., Williams, M. M., Vickovic, M. M., and Handcock, P. J. (1992). Muscle power predicts freestyle swimming performance. *Br. J. Sports Med.* 26, 151–155. doi: 10.1136/bjsm.26.3.151

Hollander, A. P., de Groot, G., van Ingen Schenau, G. J., Toussaint, H. M., de Best, H., Peeters, W., et al. (1986). Measurement of active drag during crawl arm stroke swimming. *J. Sports Sci.* 4, 21–30. doi: 10.1080/02640418608732094

Kaufmann, C. (2018). *FINA Points*. Available online at: https://wiki.swimrankings.net/index.php/swimrankings:FINA_Points (accessed December 21, 2021).

Klentrou, P. P., and Montpetit, R. R. (1991). Physiologic and physical correlates of swimming performance. *J. Swim. Res.* 7, 13–18.

Lätt, E., Jürimäe, J., Mäestu, J., Purge, P., Rämson, R., Haljaste, K., et al. (2010). Physiological, biomechanical and anthropometrical predictors of sprint swimming performance in adolescent swimmers. *J. Sports Sci. Med.* 9, 398–404.

Mason, B. R., Kolmogorov, S., Wilson, B. D., Toussaint, H. M., Sinclair, P. J., Schreven, S., et al. (2013). "Comparison between active drag values estimated using both the velocity perturbation method and the A.I.S. assisted towing method," in *Proceedings of the 31st International Conference on Biomechanics in Sports*, eds. T.-Y. Shiang, W.-H. Ho, P. C. Huang, and C.-L. Tsai (Taipei).

Mazzilli, F. (2019). Body height and swimming performance in 50 and 100 m freestyle Olympic and World Championship swimming events: 1908 - 2016. *J. Hum. Kinet.* 66, 205–213. doi: 10.2478/hukin-2018-0068

Morouço, P. G., Marinho, D. A., Amaro, N. M., Peréz-Turpin, J. A., Marques, M. C., Pérez-Turpin, J. A., et al. (2012). Effects of dry-land strength training on swimming performance: a brief review. *J. Hum. Sport Exerc.* 7, 553–559. doi: 10.4100/jhse.2012.72.18

Moura, T., Costa, M., Oliveira, S., Júnior, M. B., Ritti-Dias, R., and Santos, M. (2014). Height and body composition determine arm propulsive force in youth swimmers independent of a maturation stage. *J. Hum. Kinet.* 42, 277–284. doi: 10.2478/hukin-2014-0081

Pérez-Olea, J. I., Valenzuela, P. L., Aponte, C., and Izquierdo, M. (2018). Relationship between dryland strength and swimming performance: pull-up mechanics as a predictor of swimming speed. *J. Strength Cond. Res.* 32, 1637–1642. doi: 10.1519/JSC.0000000000002037

Petrie, A. (2020). *regclass: Tools for an Introductory Class in Regression and Modeling. R Package Version 1.6*. Available online at: https://cran.r-project.org/package=regclass (Accessed July 5, 2021).

Pinheiro, J., Bates, D., DebRoy, S., Sarkar, D., and R Core Team (2020). *nlme: Linear and Nonlinear Mixed Effects Models. R Package Version 3.1-148*. Available online at: https://cran.r-project.org/package=nlme (Accessed July 5, 2021).

R Core Team (2020). *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing. Available online at: https://www.r-project.org/ (Accessed July 5, 2021).

Rodríguez, F. A., and Mader, A. (2011). "Energy systems in swimming," in *World Book of Swimming: From Science to Performance*, eds. L. Seifert, D. Chollet, and I. Mujika (Hauppage, NY: Nova Science Publishers, Inc.), 225–240.

Sato, Y., and Hino, T. (2003). "Estimation of thrust of swimmer's hand using CFD," in *Proc. Second Int. Symp*. Aqua Bio-Mechanisms (Hawaii), 81–86.

Schreven, S., Beek, P. J., and Smeets, J. B. J. (2015). Optimising filtering parameters for a 3D motion analysis system. *J. Electromyogr. Kinesiol.* 25, 808–814. doi: 10.1016/j.jelekin.2015.06.004

Schreven, S., Toussaint, H. M., Smeets, J. B. J., and Beek, P. J. (2013). The effect of different inter-pad distances on the determination of active drag using the measuring active drag system. *J. Biomech.* 46, 1933–1937. doi: 10.1016/j.jbiomech.2013.05.020

Sharp, R. L., Troup, J. P., and Costill, D. L. (1982). Relationship between power and sprint freestyle swimming. *Med. Sci. Sport. Exerc.* 14, 53–56. doi: 10.1249/00005768-198201000-00010

Toussaint, H., and Vervoorn, K. (1990). Effects of specific high resistance training in the water on competitive swimmers. *Int. J. Sports Med.* 11, 228–233. doi: 10.1055/s-2007-1024797

Toussaint, H. M., and Beek, P. J. (1992). Biomechanics of competitive front crawl swimming. *Sport. Med.* 13, 8–24. doi: 10.2165/00007256-199213010-00002

Toussaint, H. M., de Looze, M., Van Rossem, B., Leijdekkers, M., and Dignum, H. (1990). The effect of growth on drag in young swimmers. *Int. J. Sport Biomech.* 6, 18–28. doi: 10.1123/ijsb.6.1.18

Toussaint, H. M., Hollander, A. P., van den Berg, C., and Vorontsov, A. R. (2000). "Biomechanics of swimming," in *Exercise and Sport Science*, eds. W. E. Garrett and D. T. Kirkendall (Philadelphia, PA: Lippincott, Williams & Wilkins), 639–660.

Toussaint, H. M., Roos, P. E., and Kolmogorov, S. (2004). The determination of drag in front crawl swimming. *J. Biomech.* 37, 1655–1663. doi: 10.1016/j.jbiomech.2004.02.020

Toussaint, H. M., and Truijens, M. (2006). Power requirements for swimming a world-record 50-m front crawl. *Int. J. Sports Physiol. Perform.* 1, 61–64. doi: 10.1123/ijspp.1.1.61

van Houwelingen, J., Schreven, S., Smeets, J. B. J., Clercx, H. J. H., and Beek, P. J. (2017). Effective propulsion in swimming: grasping the hydrodynamics of hand and arm movements. *J. Appl. Biomech.* 33, 87–100. doi: 10.1123/jab.2016-0064

van Ingen Schenau, G. J., and Cavanagh, P. R. (1990). Power equations in endurance sports. *J. Biomech.* 23, 865–881. doi: 10.1016/0021-9290(90)90352-4

Wickham, H., and Bryan, J. (2019). *readxl: Read Excel Files. R Package Version 1.3.1*. Available online at: https://cran.r-project.org/package=readxl (Accessed July 5, 2021).

Wilson, B. D., and Thorp, R. (2003). "Active drag in swimming," in *Biomechanics and Medicine in Swimming, IX Edn*, ed J. C. Chatard (Saint Etienne: Publications de l'Universite de Saint Etienne), 15–20.

Zamparo, P., Turri, E., Peterson Silveira, R., and Poli, A. (2014). The interplay between arms-only propelling efficiency, power output and speed in master swimmers. *Eur. J. Appl. Physiol.* 114, 1259–1268. doi: 10.1007/s00421-014-2860-7

Zuur, A. F., Ieno, E. N., Walker, N. J., Saveliev, A. A., and Smith, G. M. (2009). *Mixed Effects Models and Extensions in Ecology With R. Statistics for Biology and Health* (New York, NY: Springer).

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Biomechanical Features of Backstroke to Breaststroke Transition Techniques in Age-Group Swimmers

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This study aimed to identify the biomechanical features of backstroke to breaststroke transition techniques (*open*, *somersault*, *bucket*, and *crossover*) in age-group swimmers. Eighteen preadolescent swimmers (12.2 ± 0.4 years old and 3–4 Tanner stages) underwent 4 weeks of systematic contextual interference training, comprising 16 sessions (40 min·session^{-1}). Soon after, experimental testing was conducted where swimmers randomly performed 12 × 15 m maximal turns (composed of 7.5 m turn-in and 7.5 m turn-out of the wall segments), three in each transition technique. Kinematical, kinetic, and hydrodynamic variables were assessed with a dual-media motion capture system (12 land and 11 underwater cameras), triaxial underwater force plates, and inverse dynamics. Variables were grouped in turn-in (approach and rotation) and turn-out (wall contact, gliding, and pull-out) phases, with factor analysis used to select the variables entering on multiple regressions. For the turn-in phase, 86, 77, 89, and 87% of the variance for *open, somersault*, *bucket*, and *crossover* turning techniques, respectively, was accounted by the 7.5 and 2.5 m times, mean stroke length, and rotation time. For the turn-out phase, first gliding distance and time, second gliding depth, turn-out time, and dominating peak_Z push-off force accounted for 93% in open turn, while wall contact time, first gliding distance, breakout distance and time, turn-out time, dominating peak_Y push-off force, and second gliding drag coefficient accounted for 92% in a somersault turn. The foot plant index, push-off velocity, second gliding distance, and turn-out time accounted for 92% in bucket turn while breakout and turn-out time, non-dominating peak_Y and peak_Z push-off force, first and second gliding drag force and second gliding drag coefficient accounted for 90% in crossover turn, respectively. The findings in this study were novel and provided relevant biomechanical contribution, focusing on the key kinematic–temporal determinant during turn-in, rotation, and push-off efficacy, and the kinetic and hydrodynamic during turn-out, which would lead to improved backstroke to breaststroke transition techniques in 11–13 years-old age-group swimmers.

Keywords: Exercise, aquatic locomotion, swimming, biomechanics, motion capture, force plate, hydrodynamics, performance

INTRODUCTION

Performing fast and skilled turning actions, and start and swim phases, is fundamental for improving competitive swimming performance (Arellano et al., 1994; McGibbon et al., 2018; Zacca et al., 2020a). However, conclusive information on the 200- and 400-m individual medley events, in which butterfly, backstroke, breaststroke, and freestyle swim in this order, is limited. Therefore, extensive research is required to identify the key biomechanical variables and their respective contributions to each transition technique (Chainok et al., 2021).

Among the medley turns, there are four well-described backstroke to breaststroke transition techniques (the *open*, the *somersault*, the *bucket*, and the *crossover*), which are very complex movements (i.e., performed in different planes and axes). In addition, swimmers need to comply with the FINA rules, i.e., touch the wall while on their back, maintain the shoulders at or past the vertical direction toward the breast when leaving the wall, and assume a ventral gliding position prior to the first breaststroke upper limbs action. Studies on the backstroke to breaststroke transition techniques are scarce, lacking scientific and practical validation of the specific determinant factors that play a vital role in gaining the advantage in each backstroke to breaststroke transition techniques.

Key biomechanical variables related to swimming turn performance have been studied using temporal, kinematic (Blanksby et al., 2004; Araujo et al., 2010; Pereira et al., 2015), kinetic (Prins and Patz, 2006; Pereira et al., 2015; Chainok et al., 2021), and hydrodynamic data (Benjanuvatra et al., 2001; Vilas-Boas et al., 2010; Chainok et al., 2021), but no study has examined the biomechanical determinants for optimal backstroke to breaststroke transition performance. Knowing that this information is a key factor for coaches when planning their specific training activities, we aimed to identify the key biomechanical variables that affect the performance in the four backstroke to breaststroke transition techniques in age-group swimmers. It was hypothesized that the 15 m turning time performance is described by combining contributions from the turn-in and turn-out phases, and different combinations of feature variables depending on the chosen backstroke to breaststroke transition technique.

MATERIALS AND METHODS

Subjects

A total of 18 age-group swimmers, nine boys and nine girls, from the 11–13 years old age group of a competitive swimming club, volunteered to participate in the current study. Boys and girls characteristics were (respectively): 12.5 ± 0.5 vs. 11.6 ± 0.5 years old, 48.7 ± 12.4 vs. 46.7 ± 10.8 kg of body mass, 1.59 ± 0.14 vs. 1.52 ± 0.07 m of height, 14.8 ± 5.1 vs. 21.8 ± 7.10% of fat mass, 3–4 Tanner stages (Zacca et al., 2020b) and 59 ± 9 vs. 55 ± 12% of 200 m individual medley best performances of the 2018 short-course World Junior Record. Swimmers parents were informed about the benefits and risks of participating before they were asked to sign an informed consent form (approved by the ethics board of the local university—CEFADE 08.2014) in agreement with the Declaration of Helsinki.

Procedures

Four backstroke-to-breaststroke transition techniques were identified (FINA rules; https://www.fina.org/, see **Figure 1**). Prior to the experiments, swimmers answered a questionnaire about their backstroke to breaststroke transition techniques preferences, with 18 selecting the open technique and only two the somersault. The experimental protocol took place in a 25-m (1.90 m deep) indoor pool with ∼27 and ∼26°C of water and air temperatures (respectively) and 59% relative humidity. Age-group swimmers joined 16 practice sessions throughout a 4-week training program (see details in Chainok et al., 2021) performing variants of the same task with structured increases in contextual interference (Porter and Magill, 2010). Contextual interference can be defined as the interference in performance and learning that arises from practicing one task in the context of other tasks (Schmidt and Lee, 2005; Porter and Magill, 2010). The 16 practice sessions were part of the regular training sessions, with the turning practice occurring during the last 40 min of every session. Two experienced coaches conducted all practice sessions and specific coaching feedback based on mechanical factors to ensure consistency in coaching techniques, proper familiarization (Galbraith et al., 2008; de Jesus et al., 2016). All the participants followed a scheduled program from the 1st to the 16th practice session program (see details in Chainok et al., 2021). At the end of the intervention period, swimmers were invited for an evaluation session. Thus, after a 400-m moderate-intensity warm-up including some elements of backstroke to breaststroke transition techniques (**Figure 1**), swimmers were invited to perform 12 × 15 m maximal turns (composed of 7.5 m turn-in and 7.5 m turn-out of the wall segments). Each swimmer completed three attempts of each backstroke to breaststroke transition technique (randomized order), with a 3 min rest interval between trials (see details in Chainok et al., 2021).

Dual-media motion capture system with 12 land and 11 underwater cameras (Oqus 3 and 4 series, Qualisys, Gothenburg,

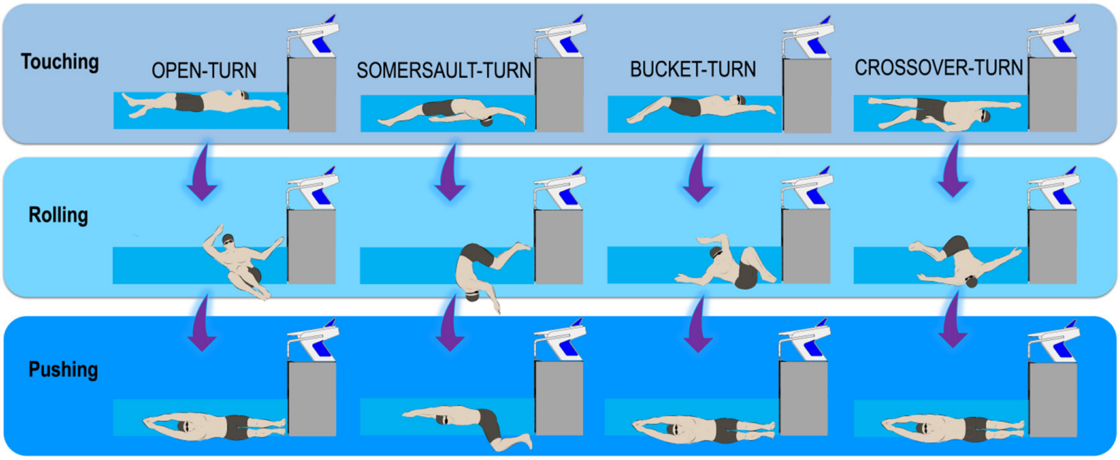

FIGURE 1 | Backstroke to breaststroke turning techniques are distinguished by the different body orientations of the swimmers throughout the touching, rolling and pushing-off phases.

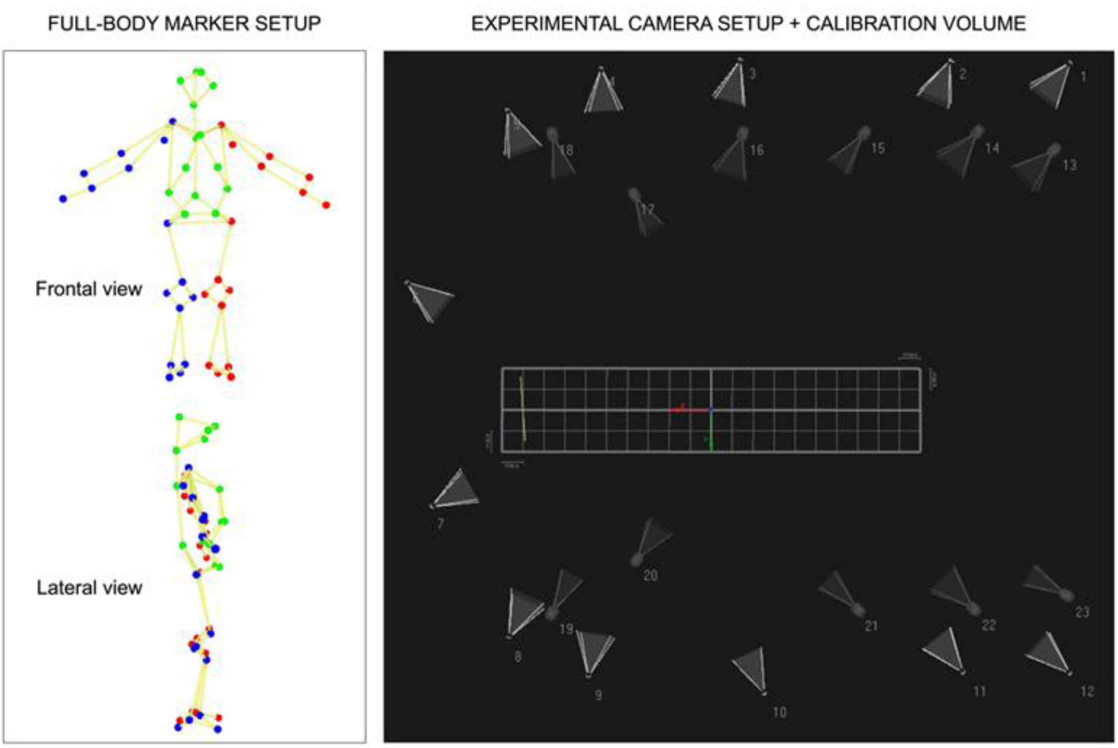

FIGURE 2 | Configuration of kinematic-temporal data: full-body marker setup in Qualisys Track, experimental camera positioning with 12 land and 11 underwater cameras, and calibration volume covered. The orthogonal axes were defined as *X*, *Y*, and *Z* for horizontal, mediolateral, and vertical ($Z = 0$ defines water surface) movements. The yellow line depicts the reference system and positioning of the triaxial two force platforms.

Sweden) and a full-body marker setup (with 51 spherical retroreflective markers, see **Figure 2**) were used to track swimmer's actions at 100 Hz (Lauer et al., 2016) (see details of camera placement and configuration and calibration in Chainok et al., 2021). The kinetic assessment was obtained with two triaxial underwater force plates (Mourão et al., 2016) operating at a 2,000 Hz sampling frequency and fixed into the pool's wall on a custom built support (see details in de Jesus et al., 2019). The limits of this structure were identified with four retroreflective markers.

The 15 m turning time performance (composed of 7.5 m turn-in and 7.5 m turn-out of the wall segments) encompassed approaching, touching (wall contact), rolling, pushing glide, and swimming resumption until the vertex passes the 7.5 m marker (**Figure 1**). The Qualisys Track Manager (Oqus 3 and 4 series, Qualisys, Gothenburg, Sweden) software was used to acquire the temporal and 3D kinematic data. Built-in spline interpolation was used to fill markers' missing trajectories (representing up to ∼50, 120, and 60 frames, i.e., 3.3, 8.0, and 4.0% of the trial duration in the approach, rotation, and turnout phases, respectively). The software Acqknowledge v.3.9.0 (BIOPAC Systems Incorporation, Santa Barbara, California, USA) was used to perform residual analysis to optimize the digital filter cutoff frequency (fast Fourier transform) and kinematic–temporal data were low-pass filtered using a digital filter with a cutoff frequency of 6 Hz (FIR—Window Blackman-61dB) (Acqknowledge, BIOPACiopac Systems Incorporation, Santa Barbara, California, USA). The bow wave effect at the beginning of the feet contact was considered negligible (not edited in the kinetic analysis) since swimmers glided in before touching the wall and rotated to push-off. Despite that, the underwater force platforms were synchronized with the motion capture system and the image-based kinematics allowed a reasonable verification of the force-to-time curve symmetry. Dominant (DPO) and non-dominant (NPO) push-off force terms were used to identify the characteristic peak force contributions in the *x*, *y*, and *z* components. Kinetic data processing was divided in to: (i) acquisition, plotting, and saving the strain readings of each triaxial force and the moment-of-force components from each force plate using a custom LabVIEW™ program (National Instruments, Austin, Texas, USA, http://www.ni.com/en-us/shop/labview.html) (Mourão et al., 2016; de Jesus et al., 2019); (ii) converting the strain readings into force values according to the previous calibration (Matlab R2014a, MathWork Inc., Natick, Massachusetts, USA), and (iii) filtering curves using a fourth-order zero-phase digital Butterworth filter

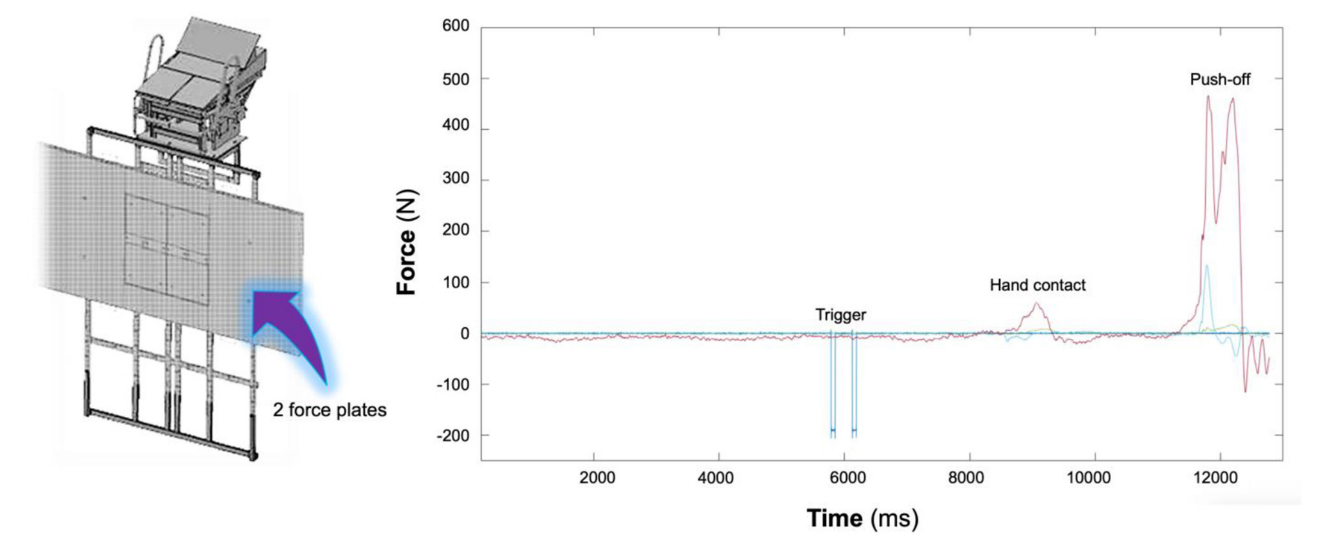

FIGURE 3 | Kinetic data setup and data processing: two triaxial force plates set up and force-time curve of two triaxial force plate profiles (left and right panels). *Fx* and *Fy* are the mediolateral (green) and up and down (blue) components, and *Fz* is the horizontal force component (red).

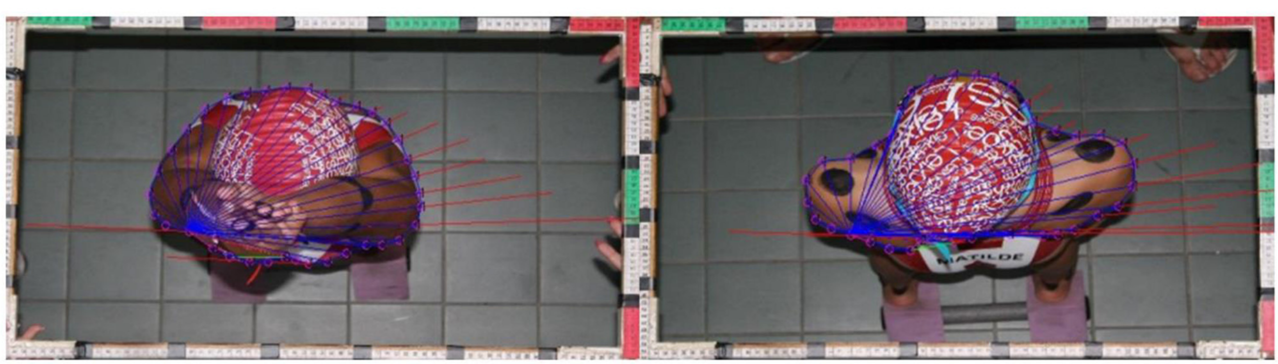

FIGURE 4 | Body surface area determined through planimetry: data processing of the first and second gliding positions.

TABLE 1 | Kinematic-temporal variables selected for studying backstroke to breaststroke turning techniques.

Variables	Definition
7.5 m time-in (s)	Time between vertex reached 7.5 m wall distance at an origin of referential system until the hand wall touch.
5 m time-in (s)	Time between vertex reached 5 m wall distance at an origin of referential system until the hand wall touch.
2.5 m time-in (s)	Time between vertex reached 2.5 m wall distance at an origin of referential system until the hand wall touch.
Last upper limbs-wall distance (m)	Middle finger to wall distance at the last upper limbs cycle.
SL at last cycle (m)	The last upper limbs cycle length that was obtained by the horizontal displacement of the one upper limbs cycle.
Average SL during turn-in (m)	The mean of the last five upper limbs cycle length that was obtained by the horizontal displacement of the one upper limbs cycle.
Touching depth (m)	Depth at the hand beginning wall touch.
Hand contact time (s)	Time at hand wall contact.
Rotation time (s)	Time between hand contacts to feet contact.
Total wall contact time (s)	Total contact time of the feet with the wall.
Push-off time (s)	Time spent with the feet against the wall as the hips moved forward until the feet exited the wall.
Tuck index	The distance between the right hip and the wall at the start of the push-off is divided by the swimmer's lower limb.
Foot plant index	Depth of the wall foot plant at the beginning of push-off divided by swimmer's lower limb.
Push-off velocity ($m \cdot s^{-1}$)	Resultant velocity of sacrum at the feet had left the wall.
First gliding distance (m)	Distance of sacrum travel from the feet had left the wall to the first frame of transition phase.
First gliding time (s)	Time of sacrum travel from the beginning of feet had left the wall to the first frame of transition.
First gliding depth (m)	Mean of sacrum depth during the gliding phase.
Transition distance (m)	Distance of sacrum travel from the initial separation of the hands or starting dolphin kick until upper limbs fully extended at sides of the body.
Transition time (s)	Time of sacrum travel from the initial of hands separate or starting dolphin kick until the upper limbs fully extended at sides of the body.
Transition gliding depth (m)	Mean of sacrum depth during transition phase.
Second gliding distance (m)	Distance of sacrum travel from the first frame of the upper limbs fully extended at sides of the body to an instant which hands begins to move up from the body side.
Second gliding time (s)	Time of sacrum travel from the first frame of the upper limbs fully extended at the sides of the body to an instant which hands begins to move up from body side.
Second gliding depth (m)	Mean of sacrum depth during the second gliding phase.
Breakout distance (m)	Distance at which the head breaks the surface for the first time.
Breakout time (s)	Time from the feet had left the wall to the vertex breaks the surface for the first time.
Time-out (s)	Time from the feet had left the wall to the vertex reach 7.5 m mark.
15 m turn time (s)	The turn time performance including 7.5 m time-in and 7.5 m time-out.

with a 10 Hz cut-off frequency (Mourão et al., 2016; de Jesus et al., 2019) (**Figure 3**). The hydrodynamic variables (drag, drag coefficient, and body cross-sectional area) were assessed through an inverse dynamics approach (Vilas-Boas et al., 2010). We used planimetry (Clarys, 1979; Vilas-Boas et al., 2010) for cross-sectional area (S) assessment (**Figure 4**; see details in Chainok et al., 2021). The description of the studied kinematic-temporal, kinetic, and hydrodynamic variables is shown in **Tables 1**, **2**.

Statistical Analysis

Basic exploratory and descriptive statistics were computed using SPSS Statistics for Windows Version 24.0 (IBM Corporation, Armonk, New York, USA) aiming to detect potential errors in data entry and eventual outliers, and assessing data distribution normality (Shapiro–Wilk test), multicollinearity (variance inflation factors), and homoscedasticity (Levene's test). A one-way ANOVA was used to observe differences in the selected kinematic-temporal, kinetic, and hydrodynamic variables among the four different backstroke to breaststroke turning techniques. If a significant effect was found, *post-hoc* pairwise comparisons using Tukey's HSD were conducted. Then, factor analysis was conducted to lower the number of variables and to analyze the relationships structures between variables. For this purpose, selected variables were grouped into turn-in and turn-out variables (approach and rotation vs. wall contact, gliding, and pull-out phases), factors were chosen on the basis of a cutoff eigenvalue of 1, principal component extraction with a varimax rotation, and the scree plot proposed (Tor et al., 2015), and best-subsets analysis was conducted to determine the best regression equation for 15 m turn time prediction (using Minitab 19, Minitab Incorporation, State College, Pennsylvania, USA). Finally, a multiple regression analysis (with the enter method) was used to determine and predict the 15 m turn time based on each turning technique selected variables. The full multiple linear regression analysis was completed with SPSS based on the largest R^2 value and the smallest error.

TABLE 2 | Kinetic and hydrodynamic variables selected for analyzing the backstroke to breaststroke turns.

Variables	Definition
Hand peak X force (N)	The highest force applied while hand pushing to the left or right on the force plate during hand contact.
Hand peak Y force (N)	The highest force applied while hand pushing up or down on the force plate during hand contact.
Hand peak Z force (N)	The highest force applied perpendicular to the force plate during hand contact.
Hand contact impulse (Z) (Ns.)	The area under the perpendicular Z force-time curve during hand contact.
Non-dominant peak_X push-off force: NPO_X (N)	The highest force applied while feet pushing to the left or right on the non-dominant force plate to the feet had left the wall.
Non-dominant peak_Y push-off force: NPO_Y (N)	The highest force applied while feet pushing up or down on the non-dominant force plate during to the feet had left the wall.
Non-dominant peak_Z push-off force: NPO_Z (N)	The highest force applied while feet horizontal pushing on the non-dominant force plate to the feet had left the wall.
Non-dominant push-off impulse (Z) (Ns)	The area under the Z force-time curve during the foot push-off non-dominant force plate to the feet had left the wall.
Dominant peak_X push-off force: DPO_X (N)	The highest force applied while feet pushing to the left or right on the dominant force plate to the feet had left the wall.
Dominant peak_Y push-off force: DPO_Y (N)	The highest force applied while feet pushing up or down on the dominant force plate during to the feet had left the wall.
Dominant peak_Z push-off force: DPO_Z (N)	The highest force applied while feet horizontal pushing on the dominant force plate to the feet had left the wall.
Dominant push-off impulse (Z) (Ns)	The area under the Z force-time curve during the foot push-off dominant force plate to the feet had left the wall.
First gliding drag force (N)	The passive drag force during the first gliding position that was assessed through inverse dynamics ($D = ma$).
Second gliding drag force (N)	The passive drag force during the second gliding position that was assessed through inverse dynamics ($D = ma$).
First gliding drag coefficient	The drag coefficient during the second gliding position that was assessed through inverse dynamics, following equation ($C_D = 2D/\rho S v^2$).
Second gliding drag coefficient	The drag coefficient during the second gliding position that was assessed through inverse dynamics, following equation ($C_D = 2D/\rho S v^2$).

RESULTS

Descriptive- and variance-related analysis on selected variables for each backstroke to breaststroke turning technique is given in **Table 3**. The turning techniques showed no significant effects on the turn-in (F3, 232 = 0.61; $p = 0.61$), rotation time (F3, 232 = 0.69; $p = 0.56$), turn-out (F3, 232 = 0.33; $p = 0.80$), and 15 m turn times (F3, 232 = 0.64; $p = 0.59$).

The best subsets regression for turn-in and turn-out to predict 15 m turning time in each backstroke to breaststroke turning technique are given in **Tables 4**, **5**. Regarding the *open* turn, there were three predictors (7.5 m time-in, average SL, and hand contact time) explained 86% ($R^2 = 0.86$; $p < 0.01$) for turn-in, five predictors (first gliding distance, first gliding time, second gliding depth, turn-out time, and DPO_Z) explained 93% ($R^2 = 0.93$; $p < 0.01$) for turn-out on the 15 m turning time. For the *somersault* turn, there were three predictors (7.5 m time-in, 2.5 m time, and rotation time) explained 78% ($R^2 = 0.78$; $p < 0.01$) for turn-in, seven predictors (wall contact time, first gliding distance, breakout distance, breakout time, turn-out time, DPO_Y, and C_{D2}) explained 92% ($R^2 = 0.92$; $p < 0.01$) for turn-out on the 15 m turning time, respectively.

For the *bucket* turn, there were three predictors (7.5 m time-in, 2.5 m time-in, and last upper limbs-wall distance) explained 89% ($R^2 = 0.89$; $p < 0.01$) for turn-in, five predictors (foot plant index, push-off velocity, second gliding distance, turn-out time, and C_{D1}) explained 92% ($R^2 = 0.92$; $p < 0.01$) for turn-out on the 15 m turning time. For the *crossover* turn, there were four predictors (7.5 m time-in, 2.5 m time-in, average SL, and rotation time) explained 87% ($R^2 = 0.87$; $p < 0.01$) for turn-in, seven predictors (breakout time, turn-out time, NPO_Y, NPO_Z, D_1, D_2, and C_{D2}) explained 90% ($R^2 = 0.90$; $p < 0.01$) for turn-out on the 15 m turning time, respectively.

DISCUSSION

The main aim of this study was to identify the biomechanical features of backstroke to breaststroke transition techniques (*open*, *somersault*, *bucket*, and *crossover*) in age-group swimmers. We believed that 15 m turning time performance is described by combining contributions from the turn-in and turn-out phases, and different combinations of feature variables depending on the chosen backstroke to breaststroke transition technique. As expected, general turn-in performance can be predicted mostly by faster times during the 7.5 m, 2.5 m to the wall. The average SL is a predictor of turn-in performance for both open and crossover turns, with faster rotation time being the most relevant variable for somersault and crossover turns. The last upper limbs-to-wall distance, which refers to kinesthetic awareness and sense of space, affects bucket turn performance. Our results from the turn-out phase highlighted the importance of the interaction between kinematic and kinetic variables at the wall contact and push-off phase, which influenced turn-out performance across all backstroke to breaststroke turns studied. However, the importance of the turn-out variables changes depending on the chosen technique.

TABLE 3 | Descriptive- and variance-related statistics of the studied variables.

Variables	Open	Somersault	Bucket	Crossover	Total
7.5 m time-in (s)	7.42 ± 0.63	7.35 ± 0.55	7.30 ± 0.65	7.45 ± 0.70	7.38 ± 0.63
5.0 m time-in (s)	5.20 ± 0.54	5.15 ± 0.47	5.12 ± 0.59	5.21 ± 0.61	5.17 ± 0.55
2.5 m time-in (s)	2.48 ± 0.32	2.45 ± 0.29	2.52 ± 0.36	2.48 ± 0.34	2.48 ± 0.33
Last upper limbs-wall distance (m)	0.45 ± 0.25^{s}	0.57 ± 0.25°	0.52 ± 0.25	0.48 ± 0.27	0.51 ± 0.26
SL at last cycle (m)	1.63 ± 0.28	1.55 ± 0.28	1.64 ± 0.31	1.63 ± 0.33	1.61 ± 0.30
Average SL during turn-in (m)	1.68 ± 0.20	1.65 ± 0.18	1.71 ± 0.21	1.70 ± 0.20	1.69 ± 0.20
Touching depth (m)	0.18 ± 0.09^{s}	0.36 ± 0.13$^{\circ,b,c}$	0.16 ± 0.09^{s}	0.13 ± 0.06^{s}	0.21 ± 0.13
Hand contact time (s)	0.49 ± 0.21^{b,c}	0.49 ± 0.18^{b,c}	0.59 ± 0.15$^{\circ,s,c}$	0.37 ± 0.16$^{\circ,s,b}$	0.48 ± 0.19
Hand peak X force (N)	1.59 ± 0.32	1.61 ± 0.23^{c}	1.68 ± 0.26^{c}	1.50 ± 0.23^{s,b}	1.60 ± 0.27
Hand peak Y force (N)	8.56 ± 1.62^{b}	8.48 ± 1.09^{b}	17.37 ± 3.18$^{\circ,s,c}$	9.05 ± 1.72^{b}	10.78 ± 4.32
Hand peak Z force (N)	24.67 ± 29.47^{s}	42.58 ± 51.80$^{\circ,c}$	41.86 ± 52.89^{c}	21.89 ± 26.11^{s,b}	32.88 ± 12.85
Hand contact impulse (Z) (Ns.)	14.77 ± 3.19^{s,b}	23.40 ± 4.41$^{\circ,c}$	24.82 ± 5.03$^{\circ,c}$	8.65 ± 1.53^{s,b}	17.63 ± 7.25
Rotation time (s)	1.24 ± 0.18	1.28 ± 0.24	1.31 ± 0.27	1.33 ± 0.24	1.29 ± 0.23
Total wall contact time (s)	0.57 ± 0.19	0.54 ± 0.12^{c}	0.53 ± 0.12^{c}	0.63 ± 0.18^{s,b}	0.57 ± 0.16
Push-off time (s)	0.38 ± 0.16	0.43 ± 0.13	0.37 ± 0.09^{c}	0.46 ± 0.14^{b}	0.41 ± 0.14
Tuck index	0.70 ± 0.15	0.75 ± 0.11	0.76 ± 0.10	0.72 ± 0.13	0.73 ± 0.13
Foot plant index	0.58 ± 0.19^{s,c}	0.68 ± 0.19$^{\circ,b,c}$	0.55 ± 0.18^{s}	0.50 ± 0.15$^{\circ,s}$	0.58 ± 0.19
Push-off velocity (m·s^{-1})	2.02 ± 0.31^{c}	2.02 ± 0.33^{c}	2.01 ± 0.29^{c}	2.17 ± 0.37$^{\circ,s,b}$	2.06 ± 0.33
First gliding distance (m)	2.40 ± 0.57	2.60 ± 0.69	2.50 ± 0.67	2.43 ± 0.69	2.47 ± 0.65
First gliding time (s)	1.21 ± 0.42	1.34 ± 0.52	1.31 ± 0.44	1.29 ± 0.41	1.28 ± 0.45
First gliding depth (m)	0.48 ± 0.09^{s,b}	0.72 ± 0.15$^{\circ,b,c}$	0.53 ± 0.14$^{\circ,s}$	0.49 ± 0.13^{s}	0.55 ± 0.16
Transition distance (s)	1.08 ± 0.20	1.08 ± 0.24	1.09 ± 0.16	1.10 ± 0.21	1.09 ± 0.20
Transition time (s)	0.98 ± 0.22	0.92 ± 0.20	0.96 ± 0.18	0.96 ± 0.19	0.96 ± 0.20
Transition gliding depth (m)	0.62 ± 0.15^{s}	0.86 ± 0.18$^{\circ,b,c}$	0.67 ± 0.20^{s}	0.65 ± 0.17^{s}	0.70 ± 0.20
Second gliding distance (m)	0.80 ± 0.24	0.86 ± 0.30	0.88 ± 0.28	0.88 ± 0.30	0.85 ± 0.28
Second gliding time (s)	0.77 ± 0.26	0.83 ± 0.36	0.86 ± 0.32	0.85 ± 0.35	0.82 ± 0.32
Second gliding depth (m)	0.61 ± 0.17^{s}	0.76 ± 0.18$^{\circ,b,c}$	0.62 ± 0.19^{s}	0.62 ± 0.17^{s}	0.65 ± 0.19
Breakout distance (m)	5.94 ± 0.86	6.12 ± 1.00	6.04 ± 0.93	6.02 ± 0.99	6.04 ± 0.94
Breakout time (s)	4.83 ± 0.95	4.99 ± 1.03	4.83 ± 0.97	4.79 ± 0.99	4.86 ± 0.98
Time-out (s)	7.30 ± 0.92	7.09 ± 0.97	7.07 ± 0.84	7.13 ± 0.89	7.12 ± 0.89
NPO_X (N)	1.64 ± 0.19	1.66 ± 0.22	1.67 ± 0.17	1.59 ± 0.24	1.64 ± 0.20
NPO_Y (N)	19.41 ± 8.25^{s,c}	15.31 ± 8.35°	21.12 ± 10.07^{c}	13.23 ± 5.42$^{\circ,b}$	17.23 ± 8.65
NPO_Z (N)	49.36 ± 24.99	45.81 ± 37.63	36.37 ± 20.59	62.84 ± 44.57	48.96 ± 34.14
NPO_ Impulse (Z) (Ns)	34.02 ± 25.07^{s,b}	21.91 ± 15.46$^{\circ,c}$	17.56 ± 8.64$^{\circ,c}$	31.14 ± 49.38^{s,b}	26.70 ± 21.33
DPO_X (N)	21.66 ± 11.03^{s,b,c}	12.99 ± 5.36°	14.74 ± 8.63$^{\circ,c}$	8.03 ± 3.24$^{\circ,b}$	14.64 ± 11.14
DPO_Y (N)	64.92 ± 37.27^{s}	37.28 ± 20.18$^{\circ,b,c}$	70.08 ± 43.10^{s}	56.07 ± 27.76^{s}	56.86 ± 35.05
DPO_Z (N)	145.45 ± 76.20^{b}	140.090 ± 65.50^{b}	194.41 ± 119.14$^{\circ,s,c}$	141.44 ± 30.50^{b}	153.65 ± 78.90
DPO_ Impulse (Z) (Ns)	53.07 ± 30.50^{b}	52.03 ± 33.61^{b}	57.75 ± 39.48$^{\circ,s,c}$	49.92 ± 33.11^{b}	53.04 ± 33.87
D_1 (N)	−33.93 ± 7.56^{c}	−36.40 ± 9.34^{c}	−36.49 ± 5.39^{c}	−40.57 ± 8.19$^{\circ,s,b}$	−36.73 ± 8.32
D_2 (N)	−62.70 ± 25.57	−62.86 ± 25.56	−63.27 ± 25.83	−67.29 ± 26.82	−62.59 ± 25.35
C_{D1}	−0.74 ± 0.11	−0.72 ± 0.10	−0.75 ± 0.10	−0.76 ± 0.09	0.74 ± 0.10
C_{D2}	−1.16 ± 0.38	−1.16 ± 0.37	−1.10 ± 0.27	−1.20 ± 0.38	−1.14 ± 0.36
15 m turn time (s)	16.53 ± 1.53	16.41 ± 1.47	16.27 ± 1.60	16.67 ± 1.52	16.48 ± 1.52

$\circ, s, b, c$ Significantly different from open, somersault, bucket and crossover turn ($p < 0.05$).

Open Turn

The 7.5 m time-in, average stroke length, and hand contact time were the three key variables for the turn-in performance, while the first gliding distance, first gliding time, second gliding depth, turn-out time, and dominant push-off_Z force were identified as key for the turn-out. Our results are consistent with some previous findings in elite swimmers that indicated that their turn-in performance was highly associated with their total turn time in the 200 and 400 m backstroke to breaststroke (Mason and Cossor, 2001). From the perspective of turn-in performance, the simple

TABLE 4 | Data obtained from multiple regression analysis for turn-in variables.

Turns	Variables	B	R	p	Full model	
Open turn	Constant	4.49		0.01**	*R*	0.93
	7.5 m time-in	1.61	0.81	0.001**	R^2	0.86
	Average SL	−1.00	−0.13	0.04*	*p*	0.001
	Hand contact time	−0.81	−0.11	0.04*		
	Equation: 15 m turn time = 4.49 + 1.61 × 7.5 m time-in – 1.00 × Average SL – 0.81 Hand contact time					
Somersault turn	Constant	2.26		0.04*	*R*	0.86
	7.5 m time-in	1.27	0.59	0.001**	R^2	0.78
	2.5 m time-in	1.86	0.36	0.01**	*p*	0.001
	Last upper limbs -wall distance	−0.69	−0.11	0.11		
	Rotation time	−0.99	−0.16	0.03*		
	Equation: 15 m turn time =2.26 + 1.27 × 7.5 m time-in + 1.86 × 2.5 m time-in) – 0.99 × Rotation time					
Bucket turn	Constant	1.56		0.04*	*R*	0.95
	7.5 m time-in	1.45	0.73	0.001**	R^2	0.89
	2.5 m time-in	0.94	0.23	0.03*	*p*	0.001
	Last upper limbs-wall distance	−0.76	−0.13	0.02*		
	Equation: 15 m turn time = 1.561 + 1.45 × 7.5 m time-in + 0.94 × 2.5 m time-in – 0.76 × Last upper limbs -wall distance					
Crossover turn	Constant	5.05		0.01**	*R*	0.93
	7.5 m time- in	2.21	1.18	0.001**	R^2	0.87
	2.5 m time- in	−1.68	−0.36	0.03*	*p*	0.001
	Average SL	−1.23	−0.16	0.03*		
	Rotation time	−0.79	−0.14	0.02*		
	Equation: 15 m turn time =5.05 + 2.21 × 7.5 m time-in – 1.68 × 2.5 m time-in – 1.29 × average SL – 0.79 × rotation time					

*, **Significant for $p < 0.05$ and 0.01, respectively.

direction switch from the supine to the prone position during the *open* turn may require specific skills to maintain the swimming speed that incorporates the fastest rotation or pivot execution (Blanksby et al., 2004; Webster et al., 2011).

It has been reported that the optimization of the relationships between the kinematic, kinetic, and hydrodynamic variables can directly influence turn-out performance (Termin and Pendergast, 1998; Vilas-Boas et al., 2010; Pereira et al., 2015). The *open* turn turn-out performance mainly depends on the interaction between the kinetic variable (dominant push-off_Z force) and the four kinematic-temporal variables (first gliding distance, first gliding time, second gliding depth, and turn-out time). Theoretically, the peak perpendicular force, total impulse, and wall contact time kinetic features are key factors of swimming turns (Prins and Patz, 2006), with the dominant peak push-off_Z force being the key kinetic variable in this study. It tended to be slightly lower than data previously obtained in the breaststroke (557 ± 109 N; Blanksby et al., 1998), rollover backstroke (229 ± 70 N; Blanksby et al., 2004), and tumble turns (693 ± 228 N; Blanksby et al., 1998) in age-group swimmers. However, this is not particularly surprising considering that the age-group

TABLE 5 | Data obtained from multiple regression analysis for turn-out variables.

Turns	Variables	B	R	p	Full model	
Open turn	Constant	−0.85		0.01	*R*	0.94
	Tuck index	−0.52	0.51	0.31	R^2	0.93
	First gliding distance	1.01	0.34	0.01**	*p*	0.01
	First gliding time	−1.09	0.41	0.01**		
	Second gliding depth	−0.92	0.35	0.01**		
	7.5 m turn-out time	1.99	0.09	0.01**		
	NPO_X	0.52	0.29	0.08		
	NPO_Y	0.01	0.01	0.12		
	NPO_Impulse	−0.00	0.00	0.07		
	DPO_Z	0.01	0.00	0.01**		
	Equation: 15 m turn time = -0.85 + 1.01 × first gliding distance – 1.09 × first gliding time – 0.92 × second gliding depth + 1.99 × turn -out time + 0.01 × DPO_Z					
Somersault turn	Constant	8.44		0.001**	*R*	0.93
	Wall contact time	0.94	0.36	0.01**	R^2	0.92
	Push-off velocity	0.37	0.20	0.08	*p*	0.01
	First gliding distance	0.33	0.15	0.04*		
	Breakout distance	−1.02	0.29	0.01**		
	Breakout time	0.61	0.22	0.01**		
	Turn out time	1.03	0.14	0.01**		
	DPO_Y	−0.01	0.00	0.01**		
	DPO_Z	−0.01	0.01	0.10		
	C_{D2}	−0.72	0.17	0.10		
	Equation: 15 m turn time = 8.44 + 0.94 × wall contact time + 0.33 × first gliding distance – 1.02 × breakout distance + 0.61 × breakout time + 1.03 × turn-out time – 0.01 × DPO_Y – 0.72 × C_{D2}					
Bucket turn	Constant	5.28		0.01**	*R*	0.94
	Foot plant index	−0.78	0.35	0.03*	R^2	0.92
	Push-off time	1.30	0.78	0.10	*p*	0.01
	Push-off velocity	−0.47	0.24	0.04*		
	Second gliding distance	−0.75	0.27	0.01**		
	Turn -out time	1.47	0.09	0.01**		
	DPO_X	0.01	0.01	0.07		
	C_{D1}	0.43	0.19	0.03*		
	Equation: 15 m turn time = 5.28 – 0.78 × foot plant index – 0.47 × push – off velocity – 0.75× second gliding distance + 1.47 × turn -out time + 0.43 × C_{D1}					
Crossover turn	Constant	5.35		0.01**	*R*	0.92
	Tuck index	−1.06	0.64	0.11	R^2	0.90
	Push-off velocity	−0.46	0.25	0.07	*p*	0.01
	Breakout time	−0.18	0.09	0.04*		
	Turn-out time	1.74	0.11	0.01**		
	NPO_Y	−0.05	0.02	0.01**		
	NPO_Z	0.01	0.00	0.01**		
	D_1	−0.01	0.01	0.02*		
	D_2	−0.01	0.00	0.03*		
	C_{D2}	0.76	0.28	0.01**		
	Equation: 15 m turn time = 5.35 – 0.18 × breakout time + 1.74 × turn-out time – 0.05 × NPO_Y + 0.01 × NPO_Z – 0.01 × D_1 – 0.01 × D_2 + 0.76 × C_{D2}					

*, **Significant for $p < 0.05$ and 0.01, respectively.

swimmers from our study depicted a slower rotation with a tendency to spend a short preparatory push-off time (33%), which could lead to a lower maximum normalized peak force and impulse.

From the perspective of turn-out efficacy, the optimization of the underwater gliding depth, gliding time, and gliding distance will directly affect turning performance (Termin and Pendergast, 1998; Chainok et al., 2021). The first gliding distance and time, second gliding depth, and turn-out time were identified as key variables and appeared to be advantageous for performing an *open* turn. In the current study, the first and second gliding distances, and the breakout distance and time, were slightly shorter in the *open turn* than in the other three turns.

Somersault Turn

The key mechanical features of the turn-in phase of the *somersault* turn mainly depended on the time-in (7.5 and 2.5 m) and rotation time. Given the high impact of the turn-in phase on the 15 m turning performance, the swimming approach (7.5 m and 2.5 m turn-in times), and rotation times should be more deeply considered. The *somersault* turn, compared to the *open* turn findings, suggests that a faster approach could directly influence the turn time. Since the execution of the *somersault* turn requires a hand touch at the wall before rotating from the supine to the prone position, the rotation is critical. At this backstroke to breaststroke transition, the rotation time tended to be slightly slower than those previously studied in the rollover backstroke (Blanksby et al., 2004) and breaststroke turns (Blanksby et al., 1998) by age-group swimmers.

The analysis of the turn-out variables revealed that the wall contact time, first gliding distance, breakout distance, breakout time, and turn-out time (kinematic-temporal), dominant push-off peak_Y force (kinetic and C_{D2} (hydrodynamic) variables were those affecting the 15 m turn time. Based on the pull-out strategy evidence, breakout distance, breakout time, and turn-out time were identified as the important variables, indicating that age-group swimmers should select their own individual strategies by considering the breakout distance and the time to maximize the pull-out performance (Blanksby et al., 2004). The longer first gliding distance in *somersault* turn may be related to a lower dominant peak push-off_Y coupled with a deeper foot plant, suggesting that age-group swimmers should try to minimize the up or down movement of the all body during push-off, which could lead to a longer and deeper gliding (Blanksby et al., 2004).

Contrary to the expectations, the dominant peak push-off_Y force (about 26% of the mean peak_Z force) was selected as a critical predictor of the 15 m turn time. Theoretically, the push-off force with the feet pushing up or down directly affects the push-off velocity and tends to be inversely related with rollover time (Blanksby et al., 2004; Pereira et al., 2015). The evidence from this study points to the notion that a suitable feet push-off position and wall contact time can directly affect the performance of the subsequent horizontal push-off force and impulse (Blanksby et al., 2004), and the push-off velocity (Pereira et al., 2015).

In the discussion of turn-out performance, it is essential to consider swimmers' hydrodynamic characteristics and pull-out strategy (Chainok et al., 2021). In the *somersault* turn, push-off from the wall that is completely ventral and without any relevant rotation of the body may eventually lead to lower hydrodynamic drag (Pereira et al., 2015). The current study C_{D2} of the *somersault* turn was slightly high, probably due to the lower foot plant index during the push-off phase that might directly affect the gliding path adopted during the pull-out phase (see **Table 3**). Even so, this value tended to be higher than those obtained in national-level breaststrokers (0.61–0.72; Vilas-Boas et al., 2010) and similar to data determined by computational fluid dynamics (0.85–1.06; Marinho et al., 2011).

Bucket Turn

Multiple linear regression analysis indicated that optimal turn-in performance mainly depends on the 7.5 and 2.5 m times-in and last upper limbs-wall distance. There was a direct relationship between 15 m turn time and 7.5 m time-in ($r = 0.93$) and 2.5 m time-in ($r = 0.85$), and a small inverse relationship between 15 m turn time and last upper limbs-wall distance ($r = -0.13$). As in the *open* and *somersault* turns, speed-in was an essential influencing factor of turning performance, in agreement with the previous literature on elite (Nicol et al., 2019) and Olympic swimmers (Mason and Cossor, 2001). The last upper limbs-wall distance was similar among the four turning techniques (range 0.45–0.57 m), evidencing a tendency for consistency in the approaching speed, resulting in an optimal last upper limbs wall distance and leading to faster turn-in.

The foot plant index, push-off velocity, second gliding distance, and turn-out time (kinematic-temporal) and C_{D1} (hydrodynamic) variables were identified as the key variables for the backstroke to breaststroke turning performance. From the perspective of push-off efficacy, it is advantageous to address the appropriate lower extremity at wall contact with a greater tuck index and optimal feet planting (30–40 cm depth), which will facilitate the best horizontal push-off velocity (Clothier et al., 2000; Prins and Patz, 2006). However, the turning technique showed no main effect on push-off velocity and the linking and interaction of the kinematic variables at the wall contact and push-off phase can be considered a partial contribution of the biomechanical variables to turning performance. In the current study, the tuck index and, concomitant with a longer wall contact time tended to be higher than those for the butterfly turn (0.56 ± 0.11 s and 0.37 ± 0.09 s; Ling et al., 2004) and for the breaststroke turn (0.58 ± 0.13 s and 0.39 ± 0.08 s; Blanksby et al., 1998), performed by age-group swimmers. The foot plant index (0.55 ± 0.18) was also higher than the one previously obtained in flip turn performed by university swimmers (0.45 ± 0.10; Prins and Patz, 2006).

As determined before using inverse dynamics, the first gliding position at the breaststroke underwater path was more hydrodynamic than the second one, allowing lower S, C_D, and D values for the same range of speeds (Vilas-Boas et al., 2010). The C_{D1} calculated in the *bucket* turn tended to be higher than that calculated in national-level breaststrokers (0.46 ± 0.08; Vilas-Boas et al., 2010), probably due to the lower gliding velocity and anthropometric characteristics of our age-group swimmers. Our data and the available literature also suggest that age-group swimmers need to be concerned about minimizing hydrodynamic drag by controlling their gliding position (body shape and length) along with their optimal gliding depth (range 0.4–0.6 m) (Lyttle et al., 2000; Vilas-Boas et al., 2010; Chainok et al., 2021).

Crossover Turn

We have observed that the optimal *crossover* turn-in performance can be identified by the 7.5 and 2.5 m times-in, average stroke length, and rotation time, with the first two variables displaying strong direct relationships with 15 m turn time and the mean stroke length relating inversely with the 15 m turn time. Notably, the turn-in time and the wall approach stroke length were the key variables in all the backstroke to breaststroke turning techniques, indicating that the wall approach strategy was consistent among them.

Theoretically, from the turn-in efficacy improvement perspective, it is important to maximize the approach speed and minimize the rotation time. In the current study, the turning technique had no main effect on rotation time, which came out as a surprise because, from a theoretical and technical perspective, differences in body rotation actions—which are characteristic of the different studied techniques, may directly affect rotation speed and turning performance. Interestingly, the implemented training program significantly improved rotation in all the backstroke to breaststroke turning techniques, inclusively with higher values than those previously presented for the rollover backstroke (0.70 ± 0.10 s; Blanksby et al., 2004), pivot breaststroke (1.15 ± 0.22 s; Blanksby et al., 1998), pivot butterfly (1.11 ± 0.18 s; Ling et al., 2004), and tumble freestyle turns (2.01 $m \cdot s^{-1}$; Blanksby et al., 1996) performed by age-group swimmers.

Multiple linear regression analysis indicated that the breakout and turn out times, non-dominant peak push-off_Y and Z forces, and D_1, D_2, and C_{D2} are turn-out performance determinants and, due to the high impact of maximized breakout distance and streamlined position on the turn-out performance, the importance of those hydrodynamic variables should be emphasized. In fact, minimizing the hydrodynamic drag should be the primary consideration for improving backstroke to breaststroke turn-out performance. Typically, the first gliding position is more hydrodynamic than the second one, allowing lower S, D, and C_D values for the same range of speeds (Vilas-Boas et al., 2010; Marinho et al., 2011; Chainok et al., 2021). The *crossover* turn had g higher D_1, D_2, and C_{D2} values than the other studied turns, which may be justified by: (i) a worst streamline performance due to the lateral body movements that occur from the wall push-off to the first gliding position may (Lyttle et al., 1998; Termin and Pendergast, 1998) and (ii) the lower gliding velocity and control of the body shape and length while gliding. The current study *Crossover* D_1, D_2, and C_{D2} values were also slightly higher than previous values obtained in national-level swimmers (Vilas-Boas et al., 2010).

Our push-off force results are consistent with Araujo et al. (2010) findings indicating the highest normalized horizontal peak force contributes the most to enhancing turning performance in freestyle flip turns performed by national and international level swimmers while increasing the upward or downward wall push-off was found to have a negative impact on turn-out performance during rollover backstroke turn in age-group swimmers (Blanksby et al., 2004). Interestingly, the non-dominant Y and Z push-off forces play a critical role in determining the symmetry of lower limb push-off and subsequent gliding orientation. This finding implies that the *crossover*, in which the swimmer lateral push-off against the wall, may need a powerful extension of one of the lower limbs—possibly the dominant limb—to generate a symmetric push-off force.

CONCLUSION

The determinant variables of the different backstroke to breaststroke transition techniques change during both the turn-in and turn-out phases. Some kinematic-temporal variables are more relevant during turn-in, some kinetic variables gain relevance during turn-out (highlighting the importance of the push-off phase), and the hydrodynamic variables are important for all the studied transition techniques. Finally, the rotation and push-off phases were the stronger determinants of turning performance among all studied backstroke to breaststroke turns. Considering the key biomechanical variables that influence each turning performance in the current data, the development of a specific training program aiming to enhance turning skills, particularly focusing on the rotation and push-off phases, should be reconsidered by coaches who work with age-group swimmers, even if it implies in a longer training intervention.

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 Faculty of Sport, University of Porto. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

AUTHOR CONTRIBUTIONS

PC, RZ, RF, and JV-B: conceptualization, methodology, writing—original draft preparation, and project administration. PC, KJ, RZ, LM, and PF: data curation. PC, KJ, LM, PF, RZ, RF, and JV-B: review and editing. PC and RZ: visualization. JV-B: supervision. All the authors have read and agreed to the published version of the manuscript.

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REFERENCES

Araujo, L., Pereira, S., Gatti, R., Freitas, E., Jacomel, G., Roesler, H., et al. (2010). Analysis of the lateral push-off in the freestyle flip turn. *J. Sports Sci.* 28, 1175–1181. doi: 10.1080/02640414.2010.485207

Arellano, R., Brown, P., Cappaert, J., and Nelson, R. C. (1994). Analysis of 50-, 100-, and 200-m freestyle swimmers at the 1992 Olympic Games. *J. Appl. Biomech.* 10, 189–199. doi: 10.1123/jab.10.2.189

Benjanuvatra, N., Blanksby, B. A., and Elliott, B. C. (2001). Morphology and hydrodynamic resistance in young swimmers. *Pediatr. Exerc. Sci.* 13, 246–255. doi: 10.1123/pes.13.3.246

Blanksby, B., Gathercole, D., and Marshall, R. (1996). Force plate and video analysis of the tumble turn by age-group swimmers. *J. Swimm. Res.* 11, 40–45.

Blanksby, B., Skender, S., Elliott, B., McElroy, K., and Landers, G. (2004). Swimming: an analysis of the rollover backstroke turn by age-group swimmers. *Sports Biomech.* 3, 1–14. doi: 10.1080/14763140408522826

Blanksby, B. A., Simpson, J. R., Elliott, B. C., and McElroy, K. (1998). Biomechanical factors influencing breaststroke turns by age-group swimmers. *J. Appl. Biomech.* 14, 180–189. doi: 10.1123/jab.14.2.180

Chainok, P., Machado, L., de Jesus, K., Abraldes, J. A., Borgonovo-Santos, M., Fernandes, R. J., et al. (2021). Backstroke to breaststroke turning performance in age-group swimmers: hydrodynamic characteristics and pull-out strategy. *Int. J. Environ. Res. Public Health* 18, 1858. doi: 10.3390/ijerph18041858

Clarys, J. P. (1979). "Human morphology and hydrodynamics," in *Swimming III*, eds J. Terauds, E. W. Bedingfield (Baltimore, MD: University Park Press), 3–41.

Clothier, P. J., McElroy, K., Blanksby, B., and Payne, W. R. (2000). Traditional and modified exits following freestyle tumble turns by skilled swimmers. *South Afr. J. Res. Sport Phys. Educ. Recreat.* 22, 41–55.

de Jesus, K., de Jesus, K., Abraldes, J. A., Mourão, L., Borgonovo-Santos, M., Medeiros, A. I., et al. (2016). The effect of different foot and hand set-up positions on backstroke start performance. *Sports Biomech.* 15, 481–496. doi: 10.1080/14763141.2016.1182580

de Jesus, K., Mourão, L., Roesler, H., Viriato, N., de Jesus, K., Vaz, M., et al. (2019). 3D device for forces in swimming starts and turns. *Appl. Sci.* 9, 3559. doi: 10.3390/app9173559

Galbraith, H., Scurr, J., Hencken, C., Wood, L., and Graham-Smith, P. (2008). Biomechanical comparison of the track start and the modified one-handed track start in competitive swimming: an intervention study. *J. Appl. Biomech.* 24, 307–315. doi: 10.1123/jab.24.4.307

Lauer, J., Rouard, A. H., and Vilas-Boas, J. P. (2016). Upper limb joint forces and moments during underwater cyclical movements. *J. Biomech.* 49, 3355–3361. doi: 10.1016/j.jbiomech.2016.08.027

Ling, B., Blanksby, B., Elliott, B., and McElroy, G. (2004). Force-time characteristics of the butterfly turns by age-group swimmers. *J. Hum. Mov. Stud.* 47, 429–451.

Lyttle, A., Blanksby, B., Elliott, B., and Lloyd, D. (1998). The effect of depth and velocity on drag during the streamlined glide. *J. Swim. Res*. 13:15–22.

Lyttle, A. D., Blanksby, B. A., Elliott, B. C., and Lloyd, D. G. (2000). Net forces during tethered simulation of underwater streamlined gliding and kicking techniques of the freestyle turn. *J. Sports Sci.* 18, 801–807. doi: 10.1080/026404100419856

Marinho, D. A., Barbosa, T. M., Rouboa, A. I., and Silva, A. J. (2011). The hydrodynamic study of the swimming gliding: a two-dimensional computational fluid dynamics (CFD) analysis. *J. Hum. Kinet.* 29, 49. doi: 10.2478/v10078-011-0039-4

Mason, B., and Cossor, J. (2001). "Swim turn performance at the Sydney 2000 Olympic Games," in *Proceedings of Swim Sessions XIX International Symposium on Biomechanics in Sports*, eds J. Blackwell and R. H. Sanders (San Francisco, CA: International Society of Biomechanics in Sports), 65–69.

McGibbon, K. E., Pyne, D., Shephard, M., and Thompson, K. (2018). Pacing in swimming: a systematic review. *Sports Med.* 48, 1621–1633. doi: 10.1007/s40279-018-0901-9

Mourão, L., De Jesus, K., Viriato, N., Fernandes, R. J., Vilas-Boas, J. P., and Vaz, M. A. (2016). Design and construction of a 3D force plate prototype for developing an instrumented swimming start block. *J. Biomed. Eng. Inform.* 2, 99. doi: 10.5430/jbei.v2n2p99

Nicol, E., Ball, K., and Tor, E. (2019). The biomechanics of freestyle and butterfly turn technique in elite swimmers. *Sports Biomech.* 20, 444–457. doi: 10.1080/14763141.2018.1561930

Pereira, S. M., Ruschel, C., Hubert, M., Machado, L., Roesler, H., Fernandes, R. J., et al. (2015). Kinematic, kinetic and EMG analysis of four front crawl flip turn techniques. *J. Sports Sci.* 33, 2006–2015. doi: 10.1080/02640414.2015.1026374

Porter, J. M., and Magill, R. A. (2010). Systematically increasing contextual interference is beneficial for learning sport skills. *J. Sports Sci.* 28, 1277–1285. doi: 10.1080/02640414.2010.502946

Prins, J. H., and Patz, A. (2006). "The influence of tuck index, depth of foot-plant, and wall contact time on the velocity of push-off in the freestyle flip turn," in *Biomechanics and Medicine in Swimming X*, eds J. P. Vilas-Boas, F. Alves, and A. Marques (Porto Faculdade de Desporto da Universidade do Porto 2006), 6, 82–85.

Schmidt, R. A., and Lee, T. D. (2005). *Motor Learning and Control: A Behavioral Emphasis, 4th Edn*. Champaign, IL: Human Kinetics.

Termin, B., and Pendergast, D. R. (1998). How to optimize performance. *Swim. Tech.* 34, 41–46.

Tor, E., Pease, D. L., and Ball, K. A. (2015). Key parameters of the swimming start and their relationship to start performance. *J. Sports Sci.* 33, 1313–1321. doi: 10.1080/02640414.2014.990486

Vilas-Boas, J. P., Costa, L., Fernandes, R. J., Ribeiro, J., Figueiredo, P., Marinho, D., et al. (2010). Determination of the drag coefficient during the first and second gliding positions of the breaststroke underwater stroke. *J. Appl. Biomech.* 26, 324–331. doi: 10.1123/jab.26.3.324

Webster, J., West, A., Conway, P., and Cain, M. (2011). Development of a pressure sensor for swimming turns. *Proc. Eng.* 13, 126–132. doi: 10.1016/j.proeng.2011.05.062

Zacca, R., Azevedo, R., Chainok, P., Vilas-Boas, J. P., Castro, F. A. d. S., Pyne, D. B., et al. (2020b). Monitoring age-group swimmers over a training macrocycle: energetics, technique, and anthropometrics. *J. Strength Condit. Res.* 34, 818–827. doi: 10.1519/JSC.0000000000002762

Zacca, R., Azevedo, R., Ramos, V. R. Jr., Abraldes, J. A., Vilas-Boas, J. P., de Souza Castro, F. A., et al. (2020a). Biophysical follow-up of age-group swimmers during a traditional three-peak preparation program. *J. Strength Condit. Res.* 34, 2585–2595. doi: 10.1519/JSC.0000000000002964

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Changes in Kinematics and Muscle Activity With Increasing Velocity During Underwater Undulatory Swimming

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This study aimed to investigate the changes in kinematics and muscle activity with increasing swimming velocity during underwater undulatory swimming (UUS). In a water flume, 8 male national-level swimmers performed three UUS trials at 70, 80, and 90% of their maximum swimming velocity (70, 80, and 90%V, respectively). A motion capture system was used for three-dimensional kinematic analysis, and surface electromyography (EMG) data were collected from eight muscles in the gluteal region and lower limbs. The results indicated that kick frequency, vertical toe velocity, and angular velocity increased with increasing UUS velocity, whereas kick length and kick amplitude decreased. Furthermore, the symmetry of the peak toe velocity improved at 90%V. The integrated EMG values of the rectus femoris, biceps femoris, gluteus maximus, gluteus medius, tibialis anterior, and gastrocnemius were higher at 90%V than at the lower flow speeds, and the sum of integrated EMGs increased with increasing UUS velocity. These results suggest that an increase in the intensity of muscle activity in the lower limbs contributed to an increase in kick frequency. Furthermore, muscle activity of the biceps femoris and gastrocnemius commenced slightly earlier with increasing UUS velocity, which may be related to improving kick symmetry. In conclusion, this study suggests the following main findings: 1) changes in not only kick frequency but also in kicking velocity are important for increasing UUS velocity, 2) the intensity of specific muscle activity increases with increasing UUS velocity, and 3) kick symmetry is related to changes in UUS velocity, and improvements in kick symmetry may be caused by changes in the muscle activity patterns.

Keywords: competitive swimming, start and turn, dolphin kicking, 3D motion analysis, EMG, water flume

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INTRODUCTION

Underwater undulatory swimming (UUS), also known as dolphin kicking or butterfly kicking, is an underwater propelling technique that is used in competitive swimming. During UUS, swimmers propel themselves using undulatory body movements to minimize water resistance by taking a streamlined position with their arms outstretched and held together over their heads. In addition, during UUS, swimmers can avoid the effect of wave drag, which is an additional drag depending on the swimming depth (Lyttle et al., 2000). Therefore, UUS is the quickest form of human locomotion in water and is much faster than surface swimming.

Current international rules permit swimmers to perform UUS for a maximum of 15 m after a start dive and turn, except in breaststroke events. As the highest velocity is achieved immediately after leaving the block or pushing off the wall at the start and turning segments (Takeda et al., 2009; Puel et al., 2012), UUS is performed to minimize deceleration. Previous race analysis studies have reported that a longer underwater distance is related to a faster 15-m total start time (Cossor and Mason, 2001) and that the total time at the start or turning segments is strongly correlated with the overall race performance as well as the time of free-swimming (Mason and Cossor, 2000). Therefore, improvements in UUS could have an important impact on overall race performance (Veiga et al., 2016).

Similar to other swimming strokes, the horizontal swimming velocity during UUS is determined by the product of kick frequency (Hz = cycle/s) and kick length (m/cycle). In UUS, kick length is determined by the horizontal displacement per kick, and kick amplitude (m) is determined by the vertical displacement of the toe or ankle during a one-kick cycle. Previous studies have shown that kick frequency is more related to UUS velocity than length or amplitude (Arellano et al., 2002; Cohen et al., 2012; Houel et al., 2013; Shimojo et al., 2014a; Yamakawa et al., 2017). Several previous studies have indicated that faster vertical toe velocity and angular velocity (e.g., hip extension velocity, hip external rotation velocity, knee extension velocity, knee flexion velocity, and ankle plantar flexion velocity) are also associated with better UUS performance (Atkison et al., 2014; Connaboy et al., 2016; Higgs et al., 2017; Yamakawa et al., 2018). Furthermore, one UUS study reported that the downward toe velocity/upward toe velocity ratio was negatively correlated with the horizontal center of mass velocity and that kick symmetry is also important for UUS performance (Atkison et al., 2014).

In a previous study on front crawl swimming, changes in stroking parameters within the swimming lap were observed (Seifert et al., 2007). In recent years, underwater distances traveled during UUS have considerably increased (Veiga et al., 2014a,b). Considering that underwater distances range between 8 and 15 m for elite swimmers, changes in kicking parameters can probably occur during underwater segments. Therefore, swimmers and coaches need to understand the typical pattern of changes in UUS movements with changing swimming velocity.

A deeper understanding of UUS can be achieved by examining changes in muscular activity, as was previously done during surface swimming. Rouard et al. (1992) reported that the intensity of muscle activity in the upper arm during front crawl swimming increases non-linearly with increasing swimming velocity. Olstad et al. (2017) investigated muscle activity in the upper and lower limbs during breaststroke swimming at 60, 80, and 100% effort and reported that the mean activation pattern remained similar across the different effort levels, but the muscles showed longer activation periods relative to the stroke cycle and increased the intensity of muscle activity with increasing effort. Matsuda et al. (2016) investigated muscle activity in the rectus and biceps femoris during flutter kicking and reported that the intensity of thigh muscles increased with increasing swimming velocity, but that the co-activation level between the muscles did not change. Thus, the intensity of muscle activity in the areas related to specific swimming motions increased with increasing swimming velocity. As mentioned above, several UUS studies have reported that fast angular velocities in hip extension, hip external rotation, knee extension, knee flexion, and ankle plantar flexion are related to high UUS velocity. If these parameters contribute to increasing UUS velocity, the intensity of the related muscle activity (i.e., the activity of the quadriceps femoris, biceps femoris, gluteal muscles, and gastrocnemius) would likely increase with increasing swimming velocity. However, no study has investigated the changes in muscle activity that might occur with increasing UUS velocity.

Therefore, this study aimed to examine the changes in kinematics and muscle activity that occur with increasing swimming velocity during UUS. We hypothesized that with increasing swimming velocity, 1) the kick frequency, vertical toe velocity, and angular velocity increase, 2) kick symmetry improves, and 3) the intensity of muscle activity in the quadriceps femoris, biceps femoris, and gluteal muscles increases.

MATERIALS AND METHODS

Participants

This study included 8 male national-level competitive swimmers (age, 21.1 ± 1.0 years; height, 1.75 ± 0.06 m; and weight, 71.9 ± 7.2 kg), namely, three freestyle swimmers, one backstroke swimmer, one breaststroke swimmer, two butterfly stroke swimmers, and one individual medley swimmer. The mean Fédération Internationale de Natation point score of their personal best times in their specific stroke event was 800.4 ± 81.4 points. All participants had the experience of performing UUS during their daily training. The participants were informed of the risks, benefits, and stresses of the study, and their consent was obtained. This study was approved by the university's research Ethics Committee.

Experimental Protocol

The experiment consisted of two sessions. In the first session, all participants performed two trials of 25-m UUS at their maximum effort in a 50-m indoor pool. The water temperature was 27.0–28.0°C. The purpose of the first session was to determine the maximum UUS velocity (100%V) that the swimmer could maintain stably, excluding the effect of the push-off start technique, as described by Takeda et al. (2009). The participants had a 30-min free warm-up period before the experiment. During the maximum UUS trials, an examiner walked to match the pace of the swimmer and measured the times at which the swimmer's head passed the 15 and 25 m markers using a manual stopwatch. In an additional experiment, we compared the time measured using the method described above with the time calculated using a video filmed by cameras fixed at the 15 and 25 m points to evaluate the validity of the methodology. The results confirmed that the validity was high because the standard error was ∼0.01 s.

The average swimming velocity during a 10-m length of the faster trial was calculated as 100%V.

In the second session, the participants performed three UUS trials in a water flume (Igarashi Industrial Works Co. Ltd.; water temperature: 27.0–28.0°C). The standard error of the three-dimensional (3D) velocity distribution in the measurement area was <3% of the set speed. The flow speeds were set to 70, 80, and 90%V of 100%V (70, 80, and 90%V, respectively). In this study, 90%V was determined as the highest flow speed since it was confirmed in a preliminary experiment that swimmers could not complete the desired tasks for testing in the flume at a velocity higher than 90%V. In this study, the mean 70%V was 1.11 ± 0.08 m/s, 80%V was 1.27 ± 0.09 m/s, and 90%V was 1.43 ± 0.10 m/s. The participants had a 30-min free warm-up period before the experiment. In this session, the participants were instructed to swim using UUS at a water depth of 1.0 m as described by Lyttle et al. (2000), and within the same region of the water flume. Therefore, a familiarization session was set up between the warm-up and the experimental task, and the participants confirmed their desired space within the water flume to swim using UUS for motion analysis. Each participant performed this activity until they had completed 10 cycles continuously in a stable position at each flow speed.

FIGURE 1 | Images of a swimmer's left lower limb with active LED markers attached to 13 anatomical landmarks and surface EMG devices attached to eight muscles. Left: front view; right: lateral view.

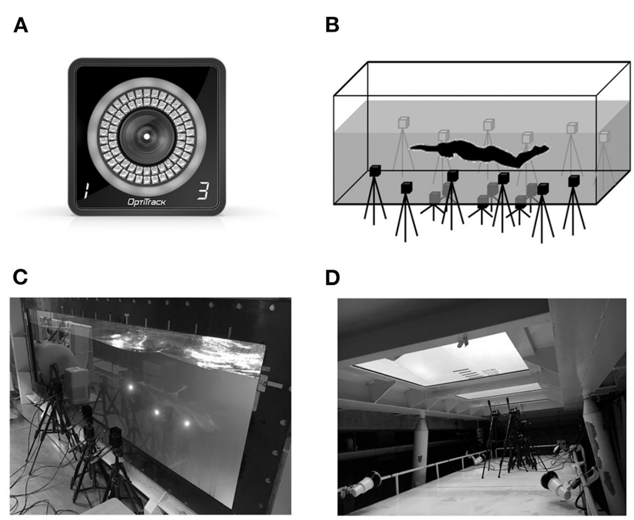

FIGURE 2 | Cameras and experimental settings. **(A)** A camera of the motion capture system. **(B)** The camera setting in the water flume. **(C)** The cameras at the side underwater window of the water flume. **(D)** The cameras at the bottom underwater window of the water flume.

Data Collection and Procedure

In the second session, we analyzed only the left lower limb movements under the assumption that the movement of both legs was symmetrical during UUS, and LED markers were attached to the participants at 13 body points (**Figure 1**). The marking points were the right and left 10th ribs at the midaxillary line ("Rib"), right and left hip greater trochanters, right and left anterior superior iliac spine (ASIS), left lateral and medial epicondyles of the femur (Knee_L/Knee_M), left lateral and medial malleoli of the ankle (Ankle_M/Ankle_L), left epiphysis of the first metatarsal (Toe_L), left epiphysis of the fifth metatarsal (Toe_M), and left calcaneal tuberosity ("Heel"). To minimize the effects of the cables used for the LED markers on the swimmer's motion, the cables were fixed with plastic tape along the swimmer's body and bundled onto the swimmer's back. The 3D coordinates during the three trials were acquired using a 3D motion capture system (VENUS-3D, Nobby Tech Inc., Tokyo, Japan; **Figure 2A**). As shown in **Figures 2B–D**, 18 cameras were set up adjacent to underwater windows positioned to the side of and below the water flume. The sampling rate of the cameras was set at 100 Hz. To measure 3D space, the origin of the global coordinate system was set at the center of the flume. Flow direction was defined as the direction of the X-axis; the X–Z plane was horizontal to the water surface, and the X–Y plane was vertical to the water surface. The standard error of the 3D coordinates in dynamic calibration was 1.14 mm.

Surface electromyography (EMG) data were collected using a waterproofed telemetric system [DL-5000; input impedance >200 MΩ; Common-mode rejection ratio (CMRR) >110 dB; gain: 400; high cut filter: 1,000 Hz (−3 dB); SandME Inc., Tokyo, Japan; **Figure 1**], and the data receiver systems included memory storage. The EMG data were measured at a sampling frequency of 1,000 Hz using a 16-bit analog-to-digital conversion, and eight muscles were selected: the left rectus femoris, left vastus lateralis, left adductor longus, left biceps femoris, left gluteus maximus, left gluteus medius, left tibialis anterior, and left gastrocnemius. EMG signals were recorded from the left side of the body using bipolar (interelectrode distance of 0.02 m) disposable Ag-AgCl circular electrodes (Blue Sensor P-00-S, Ambu Inc., Ballerup, Denmark). According to the recommendations of the SENIAM project and Cram et al. (1998), the electrodes were placed as follows: rectus femoris, at the midpoint of the line connecting the anterior superior spina iliaca to the superior part of the patella; vastus lateralis, at two-thirds of the line connecting the anterior superior spina iliaca to the lateral side of the patella; adductor longus, on the medial aspect of the thigh in an oblique direction 4 cm from the pubis; biceps femoris, at the midpoint of the line connecting the ischial tuberosity and the lateral epicondyle of the tibia; gluteus maximus, at the midpoint of the line connecting the sacral vertebrae and the greater trochanter; gluteus medius, at the midpoint of the line joining the crista iliaca to the trochanter; tibialis anterior, at one-third of the line connecting the tip of the fibula and the tip of the medial malleolus; and gastrocnemius, on the most prominent bulge of the muscle. Before the electrodes were affixed, the skin surface was shaved, abraded, and cleaned with alcohol. The electrodes were waterproofed by covering them with water-resistant tape using the methodology described by Kobayashi et al. (2017). To synchronize the kinematic and EMG data, a synchronizer (PTS-110, DKH Inc., Japan) was connected to both trigger channels.

Data Analysis

Kinematic and EMG data collected during four consecutive kick cycles were used for the following analysis. Four cycles were selected from the middle of 10 cycles because the swimmers' motions were not stable during the first and end cycles. For all kinematic and EMG parameters, the mean values were used to minimize the random error due to inter-cycle variation (Connaboy et al., 2010).

The coordinates of the right and left centers of the hip joint (COH_R/COH_L) were estimated from the coordinates of the ASIS and the greater trochanter of the hip, in accordance with the recommendations of the Clinical Gait Analysis Forum of Japan (Kurabayashi et al., 2003). For joint angle analysis, the four local coordinate systems in the trunk, thigh, leg, and foot were defined as shown in **Figure 3**, and the joint angles were calculated as Cardan angles using the four coordinate systems in accordance with Robertson (2004). In the trunk coordinate system, $\overrightarrow{X_{Tr}}$ is parallel to a line drawn between COH_R and COH_L, and $\overrightarrow{Y_{Tr}}$ is vertical to the plane of the trunk segment (**Figure 3**). In the thigh coordinate system, $\overrightarrow{X_{Th}}$ is parallel to a line drawn between Knee_M and Knee_L, and $\overrightarrow{Z_{Th}}$ is parallel to a line drawn between COH_L and the midpoint of Knee_M and Knee_L (**Figure 3**). In the leg coordinate system, $\overrightarrow{X_L}$ is parallel to a line drawn between Ankle_M and Ankle_L, and $\overrightarrow{Z_L}$ is parallel to a line drawn between the midpoint of Knee_M and Knee_L and the midpoint of Ankle_M and Ankle_L (**Figure 3**). In the foot coordinate system, $\overrightarrow{X_F}$ is parallel to a line drawn between Toe_M and Toe_L and $\overrightarrow{Z_F}$ is parallel to a line drawn between the Heel and the midpoint of Toe_M and Toe_L. The origins of the local coordinate systems are designated as O_{Tr}, O_{Th}, O_L, and O_F in **Figure 3**. Using these coordinate systems, the hip joint angle was defined as the angle represented by the trunk and thigh coordinate systems with the origin at the COH_L position; the knee joint angle was defined

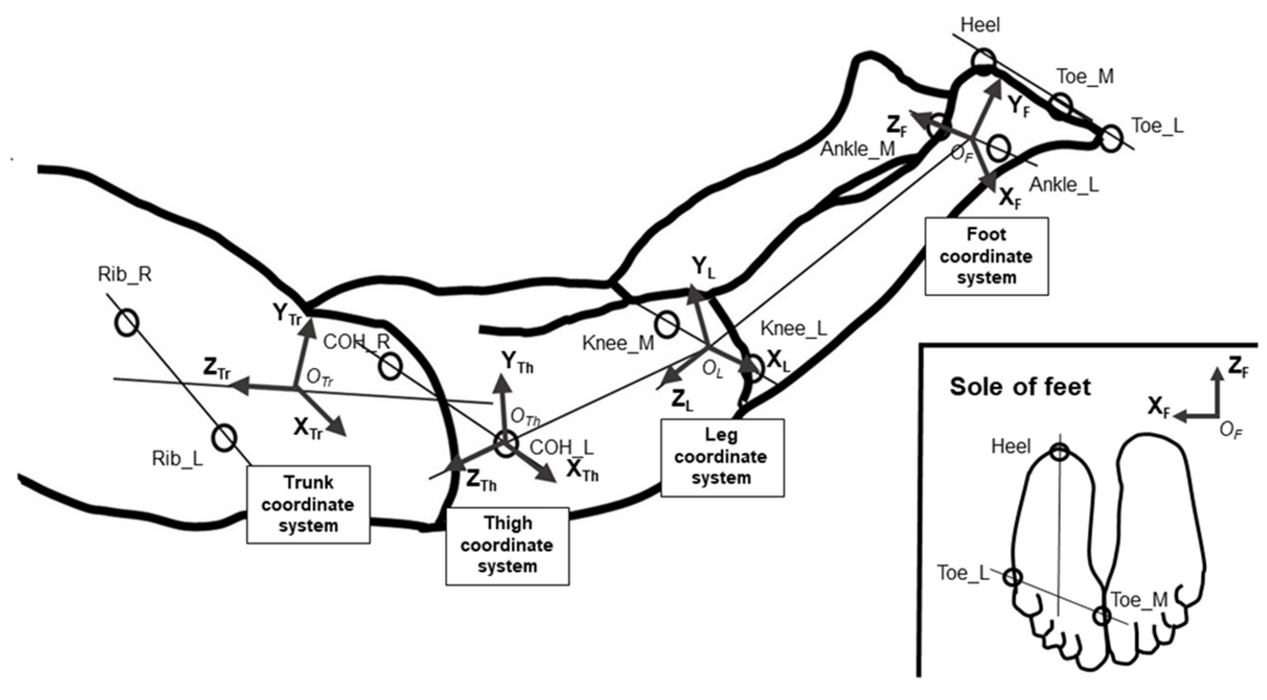

FIGURE 3 | Definitions of the segment coordinate systems.

as the angle represented by the thigh and leg coordinate systems with the origin at the midpoint between Knee_M and Knee_L; and the ankle angle was defined as the angle represented by the leg and foot coordinate systems with the origin at the midpoint between Ankle_M and Ankle_L. At these angles, the rotation around the X-axis was defined as flexion/extension, the rotation around the Y-axis as adduction/abduction, and the rotation around the Z-axis as internal/external rotation. We decided to analyze the hip extension/flexion angle, hip abduction/adduction angle, hip internal/external rotation angle, knee flexion/extension angle, ankle plantar flexion/dorsal flexion angle, and ankle abduction/adduction angle. For analysis, the peak angle, ranges of motion (ROM), and peak angular velocities were calculated. To compare joint movement patterns, joint angle data during a kick cycle were interpolated to 101 percentiles for time normalization, and an individual ensemble curve was created using data from four kick cycles to minimize inter-cycle variation. The mean ensemble curve for all participants was created for each angle using individual ensemble curves.

In this study, the UUS cycle began at the maximum peak of the Z-displacement of the toe (Toe_L) position and ended at the next highest peak, and one UUS cycle was divided into three phases as follows, as reported by Arellano et al. (2002): downward kick (DK), first upward kick (UK-1), and second upward kick (UK-2). The UK-1 and UK-2 phases were separated according to the time at which the horizontal velocity component of Toe_L was greater than the vertical velocity component during upward kicking. To compare the phase structures between the different swimming velocity trials, the relative duration was calculated (as a percentage) and normalized to the cycle duration in each phase. Kick frequency was defined as the reciprocal of the duration of a one-kick cycle. The kick amplitude was defined as the vertical distance between the highest and lowest positions of Toe_L during one UUS cycle using the absolute displacement. Swimming velocity was defined as the sum of the horizontal velocity at the midpoint between the COH and the flow speed, and the average swimming velocity during one UUS cycle was calculated. Kick length was defined as the product of the swimming velocity and the duration of a one-kick cycle. The mean and peak vertical toe velocities during the downward and upward kick phases were calculated from the coordinates of Toe_L. The symmetry between the downward and upward toe velocities was evaluated by dividing the downward values by the upward values, as described by Atkison et al. (2014).

Raw EMG signals were recorded on a computer, and signal processing was conducted using numerical analysis software (MATLAB 2013a, MathWorks Inc., USA). To remove motion artifacts and prevent aliasing, raw EMG signals were filtered using a band-pass filter (20–500 Hz). The filtered EMG signals were rectified and smoothed using a low-pass filter (15 Hz, fourth-order Butterworth). To compare muscle activity patterns, the EMG amplitude was normalized to the mean value for the UUS cycle in the 70%V trial, as described by Turpin et al. (2011). The normalized EMG data were interpolated to 101 percentiles for time normalization, and an individual ensemble curve during the UUS cycle was created using the data of four kick cycles. The mean ensemble curve for all participants was created for each muscle using individual ensemble curves. To evaluate the quantitative value of the muscle activity, the integrated EMG signal (iEMG) was calculated for a one-kick cycle. The sum of the iEMG signals during the cycle (sum iEMG) was calculated as the total muscle activity in the left lower limb.

Statistical Analysis

All parameters are reported as mean and standard deviation (mean ± SD). Statistical processing was conducted using the bell curve in Excel (SSRI Inc., Japan). To compare the data between trials, the normality of all data was confirmed using the Shapiro-Wilk test, and sphericity was checked using the Mauchly sphericity test. When the data showed normal distribution, the variables were compared between each trial using repeated-measures analysis of variance (ANOVA), and Bonferroni *post-hoc* corrections were performed to test differences between trials. Effect sizes (as partial eta-squared values) for ANOVA were used to interpret meaningful effects (Knudson, 2009). When data distribution was not normal, the variables were compared between each trial using the Friedman test, and Bonferroni *post-hoc* corrections using a Wilcoxon signed-rank test were performed to test differences between trials. In these statistical tests, the statistical significance level (a) was set at 0.05.

RESULTS

Table 1 shows the results of kinematic analyses. As shown by the ANOVA and Friedman test, there was a significant main effect of velocity on kick frequency ($p < 0.01$, ES = 0.58), kick length ($p < 0.01$, ES = 0.22), kick amplitude ($p < 0.01$, ES = 0.26), mean downward toe velocity ($p < 0.01$, ES = 0.57), peak downward toe velocity ($p < 0.01$, ES = 0.39), mean upward toe velocity ($p < 0.01$, ES = 0.39), peak upward toe velocity ($p < 0.01$, ES = 0.39), and symmetry of peak toe velocity ($p < 0.01$, ES = 0.12). The results of the *post-hoc* tests showed that kick frequency increased with increasing swimming velocity (all $p < 0.05$), whereas kick length decreased with increasing swimming velocity (all $p < 0.05$). Kick amplitude was lower in the 90%V trial than in the 70 and 80%V trials (both $p < 0.05$). Mean downward toe velocity, mean upward toe velocity, and peak upward toe velocity increased with increasing swimming velocity (all $p < 0.05$). The peak downward toe velocity was higher in the 90%V trial than in the 70 and 80%V trials (both $p < 0.05$). The symmetry of peak toe velocity was higher in the 90%V trial than in the 70%V trial ($p < 0.05$).

Table 2 summarizes the analyses of peak joint angles, ROM, and peak joint angular velocities. The results of the ANOVA and Friedman test indicated that there was a significant main effect of velocity in the peak hip extension angle ($p = 0.04$, ES = 0.03), peak hip flexion angle ($p = 0.03$, ES = 0.02), hip flexion/extension ROM ($p = 0.01$, ES = 0.08), peak knee flexion angle ($p = 0.03$, ES = 0.19), knee flexion/extension ROM ($p = 0.04$, ES = 0.12), peak ankle plantar flexion angle ($p = 0.01$, ES = 0.08), peak hip extension velocity ($p < 0.01$, ES = 0.13), peak hip flexion velocity ($p < 0.01$, ES = 0.09), peak hip internal rotation velocity ($p < 0.01$, ES = 0.32), peak hip external velocity ($p < 0.01$, ES = 0.20), peak knee flexion velocity ($p < 0.01$, ES

TABLE 1 | Results of kinematic variables in the 70, 80, and 90%V trials.

Variable	Unit	70%V	80%V	90%V	*P*-Value	ES
Kick frequency	(Hz)	1.46 ± 0.18	1.75 ± 0.26	2.11 ± 0.33	<0.01[a,b,c]	0.58
Kick length	(m/cycle)	0.77 ± 0.06	0.72 ± 0.09	0.68 ± 0.08	<0.01[a,b,c]	0.22
Kick amplitude	(m)	0.60 ± 0.03	0.58 ± 0.05	0.54 ± 0.05	<0.01[b,c]	0.26
DK phase	(%)	46.1 ± 3.7	45.4 ± 2.8	46.3 ± 2.9	0.40	0.02
UK-1phase	(%)	38.0 ± 4.1	39.0 ± 3.2	39.5 ± 3.0	0.88	NP
UK-2 phase	(%)	18.7 ± 3.0	19.0 ± 2.5	18.3 ± 2.1	0.38	0.02
Mean downward toe velocity	(m/s)	1.81 ± 0.21	2.00 ± 0.19	2.31 ± 0.19	<0.01[a,b,c]	0.57
Peak downward toe velocity	(m/s)	3.59 ± 0.27	3.76 ± 0.32	4.07 ± 0.19	<0.01[b,c]	0.39
Mean upward toe velocity	(m/s)	1.54 ± 0.20	1.72 ± 0.23	1.92 ± 0.19	<0.01[a,b,c]	0.39
Peak upward toe velocity	(m/s)	2.56 ± 0.31	2.83 ± 0.38	3.16 ± 0.28	<0.01[a,b,c]	0.39
Symmetry of mean toe velocity	(a.u.)	1.18 ± 0.08	1.17 ± 0.10	1.20 ± 0.08	0.49	0.03
Symmetry of peak toe velocity	(a.u.)	1.41 ± 0.14	1.35 ± 0.18	1.29 ± 0.09	0.04[b]	0.12

[a]*Significantly different between 70 and 80%V trials (P < 0.05);* [b]*Significantly different between 70 and 90%V trials (P < 0.05);* [c]*Significantly different between 80 and 90%V trials (P < 0.05); ES, effect size; NP, tested using a non-parametric test.*

TABLE 2 | Summary of peak joint angle, range of motion (ROM), and peak joint angular velocity in the 70, 80, and 90%V trials.

Variable	Unit	70%V	80%V	90%V	*P*-Value	ES
Peak hip extension angle	(deg.)	12.9 ± 4.2	12.9 ± 4.2	11.4 ± 4.8	0.04	0.03
Peak hip flexion angle	(deg.)	23.1 ± 6.9	20.9 ± 7.7	20.9 ± 7.7	0.03	0.02
Hip flexion/extension ROM	(deg.)	36.0 ± 4.7	33.8 ± 6.1	32.3 ± 6.8	0.01[b]	0.08
Peak knee flexion angle	(deg.)	63.7 ± 6.9	61.0 ± 3.7	58.7 ± 4.8	0.03[b]	0.19
Knee flexion/extension ROM	(deg.)	76.2 ± 7.7	73.1 ± 6.5	71.5 ± 4.5	0.04[b]	0.12
Peak ankle plantar flexion angle	(deg.)	63.8 ± 7.4	65.1 ± 7.8	66.2 ± 9.0	0.01[b]	0.08
Peak hip extension velocity	(deg./s)	174.3 ± 41.5	194.6 ± 49.8	215.5 ± 47.5	<0.01[a,b,c]	0.13
Peak hip flexion velocity	(deg./s)	181.5 ± 34.6	188.2 ± 44.2	210.2 ± 47.1	<0.01[b,c]	0.09
Peak hip internal rotation velocity	(deg./s)	181.9 ± 56.0	206.2 ± 32.6	251.1 ± 42.8	<0.01[b]	0.32
Peak hip external rotation velocity	(deg./s)	219.1 ± 68.9	242.1 ± 78.5	309.3 ± 98.7	<0.01[b,c]	0.20
Peak knee flexion velocity	(deg./s)	333.2 ± 76.2	409.0 ± 97.7[a]	498.4 ± 90.6	<0.01[a,b,c]	0.40
Peak knee extension velocity	(deg./s)	446.6 ± 39.8	454.6 ± 62.6	526.1 ± 57.8	<0.01[b,c]	0.33
Peak ankle plantar flexion velocity	(deg./s)	239.3 ± 52.3	300.7 ± 106.3	354.1 ± 113.4	<0.01[b]	0.22
Peak ankle dorsal flexion velocity	(deg./s)	185.4 ± 34.0	209.0 ± 66.9	279.3 ± 103.0	<0.01[b,c]	0.25

[a]*Significantly different between 70 and 80%V trials (P < 0.05);* [b]*Significantly different between 70 and 90%V trials (P < 0.05);* [c]*Significantly different between 80 and 90%V trials (P < 0.05); ES, effect size.*

= 0.40), peak knee extension velocity ($p < 0.01$, ES = 0.33), peak ankle plantar flexion velocity ($p < 0.01$, ES = 0.22), and peak ankle dorsal flexion velocity ($p < 0.01$, ES = 0.25). The *post-hoc* tests indicated that the hip flexion/extension ROM, peak knee flexion angle, and knee flexion/extension ROM were lower at 90%V than at 70%V (all $p < 0.05$). The peak ankle plantar flexion angle was higher at 90%V than at 70%V ($p < 0.05$). Peak hip extension velocity and peak knee flexion velocity increased with increasing swimming velocity (all $p < 0.05$). The peak hip flexion velocity, peak hip external rotation velocity, peak knee extension velocity, and peak ankle dorsiflexion velocity were higher in the 90%V trial than in the 70 and 80%V trials (all $p < 0.05$). The peak hip internal rotation velocity and peak ankle plantar flexion velocity were higher in the 90%V trial than in the 70%V trial (both $p < 0.05$). **Figure 4** shows the mean patterns of the hip, knee, and ankle joint angle data in the 70, 80, and 90%V trials.

Table 3 shows the results of iEMG for each muscle as well as the sum iEMG. The ANOVA and Friedman test revealed a significant main effect of velocity in the iEMGs of the rectus femoris ($p < 0.01$, ES = 0.41), gluteus maximus ($p < 0.01$, ES = 0.37), gluteus medius ($p < 0.01$, ES = 0.04), biceps femoris ($p < 0.01$, ES = 0.12), tibialis anterior ($p < 0.01$, ES = 0.08), gastrocnemius ($p < 0.01$, ES = 0.15), and sum iEMG ($p < 0.01$, ES = 0.41), except for those of the vastus lateralis and adductor longus. The *post-hoc* tests showed that the iEMGs of the rectus femoris, gluteus maximus, gluteus medius, and tibialis anterior were higher in the 90%V trial than in the 70 and 80%V trials (all $p < 0.05$). The iEMGs of the biceps femoris and gastrocnemius were higher in the 90%V trial than in the 70%V trial (both p

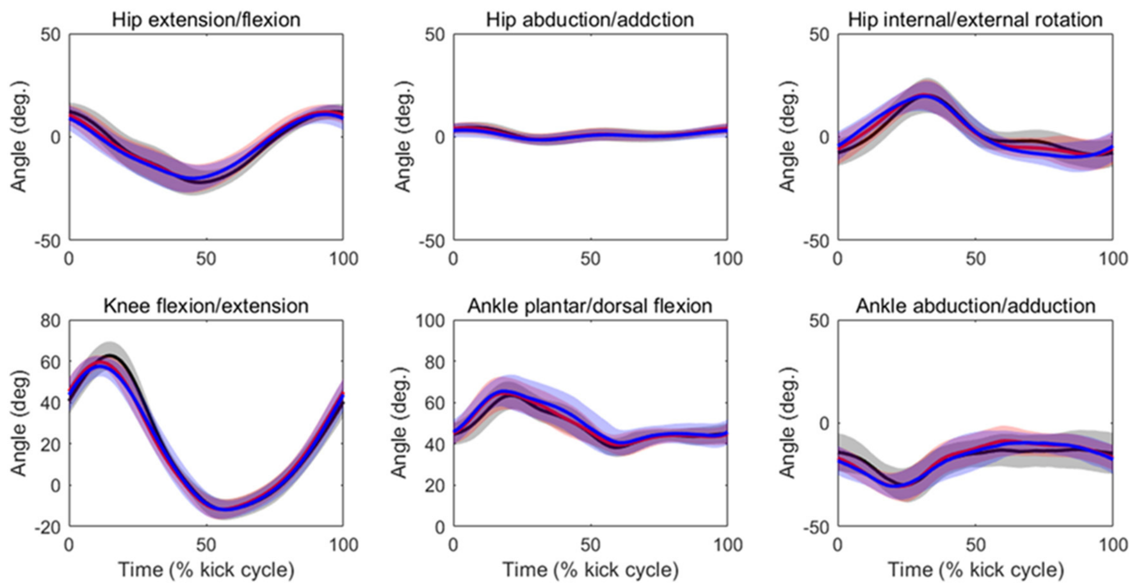

FIGURE 4 | Mean patterns and standard deviations for the hip, knee, and ankle joint angle data in the 70%V (black), 80%V (red), and 90%V (blue) trials.

TABLE 3 | Results of iEMG for each muscle and sum iEMG in the 70, 80, and 90%V trials.

Variable	Muscle	Unit	70%V	80%V	90%V	*P*-Value	ES
iEMG	Rectus femoris	(mV·s)	58 ± 14	63 ± 17	86 ± 20	<0.01[b,c]	0.41
iEMG	Vastus lateralis	(mV·s)	90 ± 16	95 ± 26	108 ± 36	0.13	0.10
iEMG	Adductor longus	(mV·s)	70 ± 62	65 ± 48	75 ± 63	0.07	NP
iEMG	Gluteus maximus	(mV·s)	20 ± 9	29 ± 17	44 ± 19	<0.01[b,c]	0.37
iEMG	Gluteus medius	(mV·s)	43 ± 23	46 ± 23	53 ± 23	<0.01[b,c]	0.04
iEMG	Biceps femoris	(mV·s)	67 ± 22	80 ± 31	90 ± 30	0.01[b]	0.12
iEMG	Tibialis anterior	(mV·s)	39 ± 17	43 ± 16	52 ± 23	<0.01[b,c]	0.08
iEMG	Gastrocnemius	(mV·s)	97 ± 25	117 ± 46	133 ± 48	0.01[b]	0.15
iEMG	Sum of muscles	(mV·s)	484 ± 83	538 ± 93	639 ± 86	<0.01[a,b,c]	0.41

[a]Significantly different between 70 and 80%V trials (P < 0.05); [b]Significantly different between 70 and 90%V trials (P < 0.05); [c]Significantly different between 80 and 90%V trials (P < 0.05); ES, effect size; NP, tested using a non-parametric test.

< 0.05). The sum iEMG increased with increasing swimming velocity (all $p < 0.05$). **Table 4** shows the changes (%) in the iEMG from 70%V. **Figure 5** shows the mean patterns for the EMG envelopes normalized to the mean of the 70%V trial in the 70, 80, and 90%V trials.

DISCUSSION

Kinematics

Our results showed that kick frequency increased with increasing UUS velocity, while the kick length decreased, and that the ES of kick frequency was the highest among all kinematic variables. In UUS, kicking frequency is the main parameter that influences UUS performance (Connaboy et al., 2009). Cohen et al. (2012) used simulation to investigate whether increasing kick frequency during UUS affects the streamwise forces on the tethered swimmer, and their simulation showed that the mean streamwise forces on the tethered swimmer increased linearly with increasing kick frequency. Accordingly, the thrust during UUS may increase with increasing kick frequency if the swimming motion does not change. However, in this study, kick length decreased with an increase in kick frequency. This suggests that the swimmers increased their kick frequency, sacrificing their propulsive ability to increase their UUS velocity.

The increase in kick frequency can be explained by changes in kick amplitude, vertical toe velocity, and joint angular velocity. Kick amplitude decreased in the 90%V trial, and the ROM of hip flexion-extension and knee flexion-extension also decreased in the 90%V trial. These results suggest that the decrease in kick amplitude owing to the decrease in ROM contributes to the increase in kick frequency. Although a small amplitude in an undulatory movement can contribute to a reduction in drag (Hochstein and Blickhan, 2014; Pacholak et al., 2014), it does

TABLE 4 | Magnitudes of changes (%) in iEMG from 70%V and from 80%V.

Variable	Muscle	Unit	70–80%V	70–90%V	80–90%V
Change of iEMG	Rectus femoris	(%)	9.2 ± 12.7	51.1 ± 29.5	40.8 ± 38.8
Change of iEMG	Vastus lateralis	(%)	4.2 ± 18.3	18.9 ± 33.2	13.0 ± 16.0
Change of iEMG	Adductor longus	(%)	1.7 ± 11.5	7.6 ± 11.3	7.1 ± 16.7
Change of iEMG	Gluteus maximus	(%)	34.3 ± 27.8	124.3 ± 74.4	73.8 ± 65.0
Change of iEMG	Gluteus medius	(%)	10.5 ± 13.0	29.2 ± 19.7	16.9 ± 11.2
Change of iEMG	Biceps femoris	(%)	18.9 ± 18.1	39.1 ± 38.9	17.7 ± 31.2
Change of iEMG	Tibialis anterior	(%)	13.8 ± 16.9	34.2 ± 18.1	18.5 ± 9.2
Change of iEMG	Gastrocnemius	(%)	18.2 ± 20.1	36.5 ± 30.8	16.0 ± 22.0
Change of iEMG	Sum of muscles	(%)	11.7 ± 9.1	33.0 ± 10.7	19.6 ± 12.0

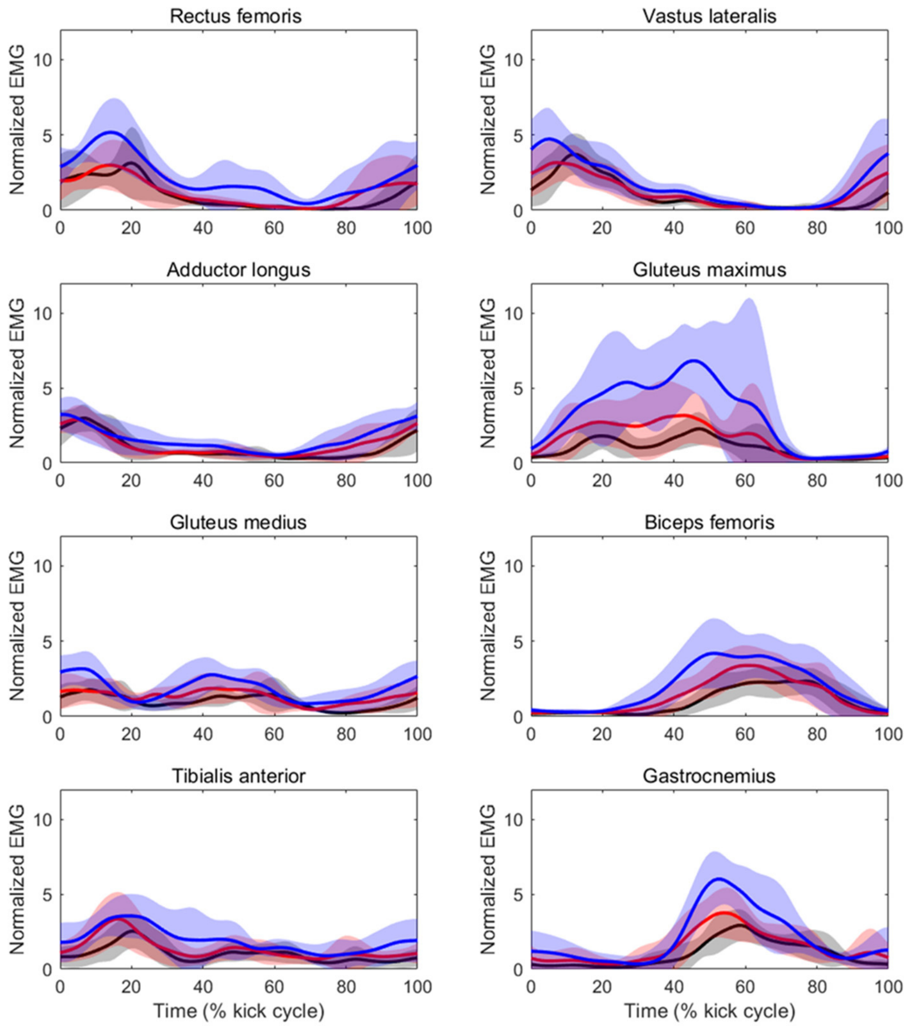

FIGURE 5 | Mean patterns and standard deviations for the EMG envelopes normalized to the mean of the 70%V trial at 70%V (black) and 80%V (red).

not lead to an increase in thrust production. In contrast, an increase in vertical toe velocity not only contributes to an increase in kick frequency but is also related to vortex generation and thrust production (Ungerechts et al., 2000). Therefore, swimmers should increase vertical toe velocity rather than reduce kick amplitude to increase UUS velocity.

In this study, both mean vertical toe velocities in the downward and upward kick phases increased with increasing

UUS velocity. Furthermore, the peak hip extension velocity and peak knee flexion velocity increased with increasing swimming velocity. These results support our hypothesis that the vertical toe velocity and angular velocity increase with increasing UUS velocity. Higgs et al. (2017) indicated that an increase in hip extension velocity contributes to an increase in vertical toe velocity during upward kicking and that an increase in knee flexion velocity contributes to a reduction in the relative duration of the deceleration phase, such as the UK-2 phase (Arellano et al., 2002). However, in this study, the relative duration of UK-2 did not change across the different UUS velocities. Therefore, we speculate that the increase in knee flexion velocity contributed to the increase in the upward toe velocity.

The peak hip internal/external rotation velocity was faster in the 90%V trial than in the other trials. Shimojo et al. (2019) indicated that the external rotation of the foot during downward kicking helps vortex generation in the sole of the foot and may contribute to an increase in propulsion. As shown in **Figure 4**, the hip joint rotated internally in the first half of the DK phase and rotated externally in its latter half, and the joint movement pattern did not change across different UUS velocities. Therefore, the external rotation velocity of the foot in the 90%V trial may have increased upon increasing the hip external rotation velocity. Although this study did not measure propulsion, our results support the notion that external rotation of the foot is related to increased UUS velocity.

Previous hydrodynamic UUS studies have indicated that efficient swimmers might obtain more propulsion during upward kicking than inefficient swimmers (Arellano et al., 2002; Hochstein and Blickhan, 2011), although the main propulsion of UUS was observed during downward kicking. Atkison et al. (2014) reported that the symmetry of the vertical toe velocity was correlated with UUS velocity and that the peak toe velocity had a higher correlation coefficient than the mean toe velocity. To explain this observation, the authors reported that vortex shedding during the UUS cycle seemed to appear depending on the timing of the peak toe velocity. Therefore, this study suggests that an improvement in the symmetry of peak toe velocity is related to an increase in UUS velocity. Based on the results of the present and previous studies, we propose that the symmetry of the peak toe velocity is a variable related not only to higher UUS performance in swimmers but also to an increase in UUS velocity.

Muscle Activation

Table 3 shows that the sum iEMG, which indicates the total muscle activity in the left lower limb, increased with increasing UUS velocity. Yamakawa et al. (2017) reported that, in the UUS, the intensity of muscle activity in the rectus abdominis, rectus femoris, biceps femoris, tibialis anterior, and gastrocnemius increased upon increasing kick frequency. In this study, kick frequency increased with increasing UUS velocity. Therefore, our results support the view that the swimmers increased their swimming velocity by increasing kick frequency, which was achieved by increasing the intensity of muscle activity.

The iEMGs of the rectus femoris at 90%V were enhanced compared with those at 70 and 80%V. Furthermore, the ES of the rectus femoris was the highest among all muscles. This result was expected. However, the iEMGs of the vastus lateralis and adductor longus did not change across the different UUS velocities, although these muscles are involved in knee extension and hip flexion. This may be because the standard deviations of the iEMGs in the vastus lateralis and adductor longus were higher than those in the rectus femoris. This suggests that the changes in the intensity of muscle activity of the vastus lateralis and adductor longus involved larger differences across individuals compared with that of the rectus femoris.

The iEMG values of the biceps femoris and gastrocnemius at 90%V were higher than those at 70%V. It was observed that activity within these muscles began slightly earlier at higher swimming velocities (as shown in **Figure 5**). The functions of the biceps femoris are hip extension and knee flexion, and those of the gastrocnemius are ankle plantar flexion and knee flexion. These results suggest that, with increasing swimming velocity, swimmers changed the intensity and start time of muscle activity for breaking the knee extension and ankle dorsiflexion quicker and for starting the hip extension and ankle plantar flexion earlier, resulting in an improvement in the symmetry of the vertical toe velocity.

The iEMG of the gluteus maximus at 90%V was enhanced compared with that at other velocities, and the magnitude of the increase was the highest among the eight muscles (**Table 4**). The timing of activation matched the start time of the hip external rotation and hip extension (**Figures 4**, **5**). The main functions of the gluteus maximus include hip extension and external hip rotation. Therefore, we speculate that the swimmers increased the intensity of gluteus maximus activity to rotate the hip joint externally more quickly as well as to extend the hip joint more quickly to increase UUS velocity.

The iEMG of the gluteus medius at 90%V was increased compared with those at other velocities, but the ES was the lowest among all muscles. Although the gluteus medius is a strong hip abductor, distinct hip abductive movements through the UUS cycle were not observed (**Figure 4**). In an anatomical atlas (Schünke et al., 2006), it was noted that the anterior part of the gluteus medius acting alone helped to flex and internally rotate the hip joint, whereas the posterior part of the gluteus medius acting alone helped to extend and externally rotate the hip joint. In this study, the gluteus medius activity had two peaks during a cycle, and the timing of activation matched the start time of hip flexion, internal rotation, and extension (as shown in **Figures 4**, **5**). However, EMG signals of the gluteus medius were collected from the middle fibers. Therefore, it was difficult to determine how the increase in gluteus medius activity contributed to the change in the kinematics.

The iEMG of the tibialis anterior at 90%V was higher than those at other velocities. The peak of tibialis anterior activity appeared during the DK phase across different UUS velocities (**Figure 5**). The main function of the tibialis anterior is ankle dorsiflexion. Connaboy et al. (2016) indicated that ankle dorsal flexion velocity is a factor that contributes to maximal UUS velocity. Therefore, fast ankle dorsiflexion is important for achieving higher maximal UUS performance. Furthermore, an increase in ankle dorsiflexion velocity can contribute to an increase in downward toe velocity. From these findings, our results suggest that the increase in tibialis anterior activity may contribute to increasing downward toe velocity, increasing the maximal UUS velocity.

Practical Implications

Our kinematic results indicate that not only does the kick frequency contribute to an increase in UUS velocity, but that the kick length, kick amplitude, vertical toe velocity, angular velocity, and kick symmetry also change with an increase in UUS velocity. Shimojo et al. (2014a) reported that swimmers could not increase their UUS velocity by reducing kick length, kick amplitude, and Froude efficiency when they were required to immediately increase their kick frequency. Accordingly, it can be speculated that swimmers should not focus only on kick frequency to increase their UUS velocity. Our results emphasize that swimmers should increase the vertical toe velocity and/or angular velocity rather than kick frequency to increase UUS velocity because these changes are important for increasing thrust during UUS.

The results of the muscle activity recordings suggest that the intensity of muscle activity of the rectus femoris, gluteus maximus, gluteus medius, biceps femoris, tibialis anterior, and gastrocnemius muscles increased with increasing UUS velocity. In particular, gluteus maximus activity increased by approximately 120% when swimming velocity increased by 20%. Thus, the load on the gluteus maximus may be very high compared with that on other muscles when a swimmer trains at a high intensity using UUS. If muscle fatigue occurs at the gluteus maximus, it is difficult for swimmers to increase the hip external rotation velocity and hip extension velocity during UUS. Therefore, we recommend that swimmers train the gluteus maximus to maintain a higher UUS performance.

Furthermore, the results of the muscle activity pattern suggest that early initiation of muscle activity in the biceps femoris and gastrocnemius contributes to an improvement in kick symmetry. Therefore, swimmers should ensure that they activate the biceps femoris and gastrocnemius earlier to improve kick symmetry, resulting in increased UUS velocity.

Limitations

As these experiments were conducted in a water flume, the conditions differed from those of a race where swimming is performed in relatively static water. For instance, the kick amplitude during UUS has been reported to be higher in a water flume than in static water because swimmers try to stay in one place (Shimojo et al., 2014b). However, we were able to accurately change the swimming velocity using a water flume. The added drag associated with wearing LED markers and wireless EMG devices might affect swimming performance. Passive drag increases when 3D markers are worn (Kjendlie and Olstad, 2012), which may compromise swimming performance (Washino et al., 2019). Therefore, we speculated that our participants could not maintain 100%V using UUS in the water flume because of the added drag. Furthermore, this study had several other limitations, including one-leg evaluation, differences from a 100% assessment in a swimming pool followed by evaluations in the swimming pool, small sample size, and the inclusion of swimmers with different main swimming strokes.

CONCLUSION

This study investigated the changes in kinematics and muscle activity with increasing swimming velocity during UUS. Our kinematic results indicate that the swimmers increased kick frequency and decreased kick length with increasing swimming velocity, and that the increases in kick frequency were caused by increases in the vertical toe velocity and joint angular velocity, and by a decrease in kick amplitude. At the highest swimming velocity, internal, and external rotation velocities of the hip increased. Changes in the hip rotational velocity may have affected the external rotation of the foot, resulting in an increase in thrust during the DK phase. These results suggest that the changes in not only the kick frequency but also in the kicking velocity are important for increasing the UUS velocity. In addition, the results indicate that the improvement in the symmetry of the peak toe velocity was related to an increase in UUS velocity. The results of muscle activity recordings indicated that the total muscle activity in the lower limbs increased with increasing UUS velocity, especially those of the rectus femoris, gluteus maximus, gluteus medius, biceps femoris, tibialis anterior, and gastrocnemius, which were at the highest levels at the highest swimming velocity. Furthermore, we observed that muscle activity in the biceps femoris and gastrocnemius began slightly earlier with increasing UUS velocity, which may be related to improving kick symmetry. These findings provide insights into improvements in UUS performance and appropriate velocity control strategies for swimmers and coaches.

DATA AVAILABILITY STATEMENT

The datasets generated for this study are available on request to the corresponding author.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Japan Women's College of Physical Education. The patients/participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

AUTHOR CONTRIBUTIONS

KY created the main conceptual ideas for the paper. All authors contributed to the manuscript writing.

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REFERENCES

Arellano, R., Pardillo, S., and Gavilán, A. (2002). "Underwater undulatory swimming: kinematic characteristics, vortex generation and application during the start, turn and swimming strokes," in *Proceedings of the XXth International Symposium on Biomechanics in Sports* (Granada: Universidad de Granada).

Atkison, R. R., Dickey, J. P., Dragunas, A., and Nolte, V. (2014). Importance of sagittal kick symmetry for underwater dolphin kick performance. *Hum. Mov. Sci.* 33, 298–311. doi: 10.1016/j.humov.2013.08.013

Cohen, R. C., Cleary, P. W., and Mason, B. R. (2012). Simulations of dolphin kick swimming using smoothed particle hydrodynamics. *Hum. Mov. Sci.* 31, 604–619. doi: 10.1016/j.humov.2011.06.008

Connaboy, C., Coleman, S., Moir, G., and Sanders, R. (2010). Measures of reliability in the kinematics of maximal undulatory underwater swimming. *Med. Sci. Sports Exerc.* 42, 762–770. doi: 10.1249/MSS.0b013e3181badc68

Connaboy, C., Coleman, S., and Sanders, R. H. (2009). Hydrodynamics of undulatory underwater swimming: a review. *Sports Biomech.* 8, 360–380. doi: 10.1080/14763140903464321

Connaboy, C., Naemi, R., Brown, S., Psycharakis, S., McCabe, C., Coleman, S., et al. (2016). The key kinematic determinants of undulatory underwater swimming at maximal velocity. *J. Sports Sci.* 34, 1036–1043. doi: 10.1080/02640414.2015.1088162

Cossor, J., and Mason, B. (2001). "Swim start performances at the Sydney 2000 olympic games," in *ISBS-Conference Proceedings Archive* (San Francisco, CA).

Cram, J. R., Kasman, G. S., and Holtz, J. (1998). *Introduction to Surface Electromyography*. Gaithersburg, MD: Aspen Publishers.

Higgs, A. J., Pease, D. L., and Sanders, R. H. (2017). Relationships between kinematics and undulatory underwater swimming performance. *J. Sports Sci.* 35, 995–1003. doi: 10.1080/02640414.2016.1208836

Hochstein, S., and Blickhan, R. (2011). Vortex re-capturing and kinematics in human underwater undulatory swimming. *Hum. Mov. Sci.* 30, 998–1007. doi: 10.1016/j.humov.2010.07.002

Hochstein, S., and Blickhan, R. (2014). Body movement distribution with respect to swimmer's glide position in human underwater undulatory swimming. *Hum. Mov. Sci.* 38, 305–318. doi: 10.1016/j.humov.2014.08.017

Houel, N., Elipot, M., Andr,é, F., and Hellard, P. (2013). Influence of angles of attack, frequency and kick amplitude on swimmer's horizontal velocity during underwater phase of a grab start. *J. Appl. Biomech.* 29, 49–54. doi: 10.1123/jab.29.1.49

Kjendlie, P. L., and Olstad, B. H. (2012). Automatic 3D motion capture of swimming: marker resistance. *Med. Sci. Sports Exerc.* 44, 476.

Knudson, D. (2009). Significant and meaningful effects in sports biomechanics research. *Sports Biomech.* 8, 96–104. doi: 10.1080/14763140802629966

Kobayashi, K., Takagi, H., Tsubakimoto, S., and Sengoku, Y. (2017). Suitability of electrodes waterproofing treatment in underwater surface electromyography measurement. *Bull. Fac. Health Sport Sci.* 40, 65–70.

Kurabayashi, J., Mochimaru, M., and Kouchi, M. (2003). Validation of the estimation methods for the hip joint center. *J. Soc. Biomech.* 27, 29–36. doi: 10.3951/sobim.27.29

Lyttle, A. D., Blanksby, B. A., Elliott, B. C., and Lloyd, D. G. (2000). Net forces during tethered simulation of underwater streamlined gliding and kicking techniques of the freestyle turn. *J. Sports Sci.* 18, 801–807. doi: 10.1080/026404100419856

Mason, B., and Cossor, J. (2000). "What can we learn from competition analysis at the 1999 pan pacific swimming championships?," in *ISBS-Conference Proceedings Archive* (Hong Kong).

Matsuda, Y., Hirano, M., Yamada, Y., Ikuta, Y., Nomura, T., Tanaka, H., et al. (2016). Lower muscle co-contraction in flutter kicking for competitive swimmers. *Hum. Mov. Sci.* 45, 40–52. doi: 10.1016/j.humov.2015.11.001

Olstad, B. H., Vaz, J. R., Zinner, C., Cabri, J. M., and Kjendlie, P. L. (2017). Muscle coordination, activation and kinematics of world-class and elite breaststroke swimmers during submaximal and maximal efforts. *J. Sports Sci.* 35, 1107–1117. doi: 10.1080/02640414.2016.1211306

Pacholak, S., Hochstein, S., Rudert, A., and Brücker, C. (2014). Unsteady flow phenomena in human undulatory swimming: a numerical approach. *Sports Biomech.* 13, 176–194. doi: 10.1080/14763141.2014.893609

Puel, F., Morlier, J., Avalos, M., Mesnard, M., Cid, M., and Hellard, P. (2012). 3D kinematic and dynamic analysis of the front crawl tumble turn in elite male swimmers. *J. Biomech.* 45, 510–515. doi: 10.1016/j.jbiomech.2011.11.043

Robertson, D. G. E. (2004). *Research Methods in Biomechanics*. Champaign, IL: Human Kinetics Publishers.

Rouard, A., Quezel, G., and Billat, R. (1992). *Effects of Speed on EMG and Kinematic Parameters in Freestyle. Biomechanics and Medicine in Swimming VI*, eds D. Maclaren, T. Reilly, and A. Lees (Cambridge: E and F N Spon).

Schünke, M., Schulte, E., and Schumacher, U. (2006). *Thieme Atlas of Anatomy: Latin Nomenclature: General Anatomy and Musculoskeletal System*. New York, NY: Thieme.

Seifert, L., Chollet, D., and Chatard, J. C. (2007). Kinematic changes during a 100-m front crawl: effects of performance level and gender. *Med. Sci. Sports Exerc.* 39, 1784–1793. doi: 10.1249/mss.0b013e3180f62f38

Shimojo, H., Gonjo, T., Sakakibara, J., Sengoku, Y., Sanders, R., and Takagi, H. (2019). A quasi three-dimensional visualization of unsteady wake flow in human undulatory swimming. *J. Biomech.* 93, 60–69. doi: 10.1016/j.jbiomech.2019.06.013

Shimojo, H., Sengoku, Y., Miyoshi, T., Tsubakimoto, S., and Takagi, H. (2014a). Effect of imposing changes in kick frequency on kinematics during undulatory underwater swimming at maximal effort in male swimmers. *Hum. Mov. Sci.* 38, 94–105. doi: 10.1016/j.humov.2014.09.001

Shimojo, H., Sengoku, Y., Tsubakimoto, S., and Takagi, H. (2014b). Kinematics and kinesthesia of competitive swimmers during dolphin kick swimming in an indoor pool and a water flume. *Jpn. Soc. Phys. Educ. Health Sport Sci.* 59, 237–249. doi: 10.5432/jjpehss.13103

Takeda, T., Ichikawa, H., Takagi, H., and Tsubakimoto, S. (2009). Do differences in initial speed persist to the stroke phase in front-crawl swimming? *J. Sports Sci.* 27, 1449–1454. doi: 10.1080/02640410903046228

Turpin, N. A., Guével, A., Durand, S., and Hug, F. (2011). Effect of power output on muscle coordination during rowing. *Eur. J. Appl. Physiol.* 111, 3017–3029. doi: 10.1007/s00421-011-1928-x

Ungerechts, B., Persyn, U., and Colman, V. (2000). "Analysis of swimming techniques using vortex traces," in *ISBS-Conference Proceedings Archive* (Hong Kong).

Veiga, S., Cala, A. G., Frutos, P., and Navarro, E. (2014a). Comparison of starts and turns of national and regional level swimmers by individualized-distance measurements. *Sports Biomech.* 13, 285–295. doi: 10.1080/14763141.2014.910265

Veiga, S., Mallo, J., Navandar, A., and Navarro, E. (2014b). Effects of different swimming race constraints on turning movements. *Hum. Mov. Sci.* 36, 217–226. doi: 10.1016/j.humov.2014.04.002

Veiga, S., Roig, A., and Gómez-Ruano, M. A. (2016). Do faster swimmers spend longer underwater than slower swimmers at world championships? *Eur. J. Sport Sci.* 16, 919–926. doi: 10.1080/17461391.2016.1153727

Washino, S., Mayfield, D. L., Lichtwark, G. A., Mankyu, H., and Yoshitake, Y. (2019). Swimming performance is reduced by reflective markers intended for the analysis of swimming kinematics. *J. Biomech.* 91, 109–113. doi: 10.1016/j.jbiomech.2019.05.017

Yamakawa, K. K., Shimojo, H., Takagi, H., Tsubakimoto, S., and Sengoku, Y. (2017). Effect of increased kick frequency on propelling efficiency and muscular co-activation during underwater dolphin kick. *Hum. Mov. Sci.* 54, 276–286. doi: 10.1016/j.humov.2017.06.002

Yamakawa, K. K., Takagi, H., and Sengoku, Y. (2018). "Three-dimensional analysis of hip and knee joint movements during dolphin kicking and butterfly swimming," in *Proceeding of the XIIIth International Symposium on Biomechanics and Medicine in Swimming* (Tsukuba: University of Tsukuba).

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Anaerobic Contribution Determined in Free-Swimming: Sensitivity to Maturation Stages and Validity

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Evaluation of anaerobic contribution is important under swimming settings (training and modification through ages), therefore, it is expected to change during maturation. The accumulated oxygen deficit (AOD) method can be used to determine the contribution of nonoxidative energy during swimming; however, it requires several days of evaluation. An alternative method to estimate anaerobic contribution evaluation (AC_{ALT}), which can also be evaluated without snorkel (i.e., free-swimming, AC_{FS}), has been proposed; however, these methods have never been compared. Thus, this study (i) analyzed the effect of maturation stage on AC_{FS} during maximal 400 m swimming (*Part I*), and (ii) compared AOD with AC_{ALT} and $AC_{FS,}$ determined in a maximal 400 m effort (*Part II*). In *Part I*, 34 swimmers were divided into three groups, according to maturation stages (early-pubertal, middle-pubertal, and pubertal), and subjected to a maximal 400 m free-swimming to determine AC_{FS}. In *Part II*, six swimmers were subjected to one 400 m maximal effort, and four submaximal constant efforts. The AOD was determined by the difference between the estimated demand and accumulated oxygen during the entire effort. The AC_{ALT} and AC_{FS} (for *Part I* as well) was assumed as the sum of lactic and alactic anaerobic contributions. AC_{FS} was higher in pubertal (3.8 ± 1.1 L) than early (2.1 ± 0.9 L) and middle pubertal group (2.4 ± 1.1 L). No difference was observed among absolute AOD (3.2 ± 1.3 L), AC_{ALT} (3.2 ± 1.5 L), and AC_{FS} (4.0 ± 0.9 L) ($F = 3.6$; $p = 0.06$). Relative AOD (51.8 ± 12.2 mL·kg^{-1}), AC_{ALT} (50.5 ± 14.3 mL·kg^{-1}), and AC_{FS} (65.2 ± 8.8 mL·kg^{-1}) presented main effect ($F = 4.49$; $p = 0.04$), without posthoc difference. The bias of AOD vs. AC_{ALT} was 0.04 L, and AOD vs. AC_{FS} was −0.74 L. The limits of agreement between AOD and AC_{ALT} were +0.9 L and −0.8 L, and between AOD and AC_{FS} were +0.7 L and −2.7 L. It can be concluded that AC_{FS} determination is a feasible tool to determine anaerobic contribution in young swimmers, and it changes during maturation stages. Also, AC_{FS} might be useful to measure anaerobic contribution in swimmers, especially because it allows greater speeds.

Keywords: anaerobic contribution, swimming, accumulated oxygen deficit, maturation, young swimmers

INTRODUCTION

Anaerobic capacity can be defined as the maximal amount of adenosine triphosphate resynthesized *via* anaerobic metabolism (by the whole organism) during a specific mode of short-duration maximal exercise (Green and Dawson, 1993). Although several methods have been proposed, there is still no gold standard method to assess anaerobic capacity (Gastin, 1994). Medbo et al. (1988) proposed the maximal accumulated oxygen deficit (MAOD) method to assess anaerobic capacity, which uses several submaximal efforts to estimate the theoretical energy demand, and one exhaustive supramaximal effort to determinate the real oxygen demand. Thus, MAOD is estimated by the difference between theoretical demand and real oxygen demand during supramaximal effort (Medbo et al., 1988).

Under swimming settings, previous studies estimated MAOD values using a snorkel and valve system in a swimming flume (Ogita et al., 2003). Reis et al. (2010b) overcame limitations of swimming flume using snorkel in a traditional swimming pool, using front crawl (Reis et al., 2010b) and breaststroke styles (Reis et al., 2010a). These authors used four submaximal efforts and maximal efforts at different distances (100–400 m). As fixed-distance effort was performed to estimate the anaerobic capacity (i.e., athletes did not reach exhaustion), the nomenclature used was accumulated oxygen deficit (AOD) instead of MAOD (Reis et al., 2010b). Besides its use in swimming, AOD and/ or, MAOD determination need(s) several submaximal and maximal efforts separated by a satisfactory recovery phase (Noordhof et al., 2010). Thus, the inclusion of this method in a sports training routine, particularly in swimming, becomes unfeasible.

Therefore, Bertuzzi et al. (2010) showed that an alternative method in cycling was effective to estimate MAOD ($MAOD_{ALT}$) through a single supramaximal effort, which increases its applicability in practical settings. This method considers the sum of the fast component of excess oxygen consumption postexercise [i.e., alactic anaerobic metabolism contribution (Ana_{ALA}; Margaria et al., 1933; Di Prampero and Margaria, 1968)], and the net lactate accumulation during the effort [i.e., lactic contribution (Ana_{LA}); (di Prampero and Ferretti, 1999)]. Subsequently, several other experiments were conducted, demonstrating its reproducibility (Zagatto et al., 2016; Miyagi et al., 2017), capacity of discriminating athletes with different training levels (Zagatto et al., 2017), and responses to different supplementation strategies (Brisola et al., 2015; Milioni et al., 2016; de Poli et al., 2019), becoming, in fact, an alternative method to estimate MAOD (Valenzuela et al., 2020).

Since a single supramaximal effort is used, $MAOD_{ALT}$ is particularly attractive in a training routine. However, unlike sports where the use of face masks does not compromise the results, as in the case of cycling and running, the use of a snorkel during swimming results in some inconveniences. In this context, the use of a snorkel for swimming (i) makes it impossible to perform specific breathing and the turn in front crawl, (ii) limits breathing in breaststroke and butterfly, and (iii) limits performance of the undulatory underwater swimming. Considering these limitations, AOD determined that the use of the snorkel may be underestimated, especially when determined in a traditional swimming pool. Alternatively, the rapid phase of excessive oxygen consumption (i.e., Ana_{ALA}) may be determined in a way similar to the backward extrapolation technique (Montpetit et al., 1981; Monteiro et al., 2020), reducing any influence in swimming patterns. For this, immediately after the effort, swimmers breathe in a face mask connected to the gas analyzer. Using this method, together with net lactate accumulation (Ana_{LA})—it is possible to determine anaerobic contribution in free swimming (AC_{FS}), as demonstrated previously (Campos et al., 2017a; Andrade et al., 2021).

Despite this important advance regarding the use of AC_{FS}, the validity of this method should be tested to estimate the anaerobic contribution. Considering that changes arising from the maturation process, such as the increase in muscle mass (Boisseau and Delamarche, 2000), and the amount and activity of enzymes related to the glycolytic pathway (Inbar and Bar-Or, 1986; Kaczor et al., 2005) that result in an increase of anaerobic fitness (Inbar and Bar-Or, 1986; Falgairette et al., 1991), an increase in AC_{FS} is expected. Moreover, even though AC_{FS} presents a relation to swimming performance (Campos et al., 2017a), it is important to compare these values with previously validated methods ($MAOD_{ALT}$ and MAOD, or AC_{ALT} and AOD, snorkel when estimated in swimming, respectively (Reis et al., 2010b).

Therefore, the present study: (i) analyzed the effect of maturation stage on AC_{FS} during maximal 400 m swimming, and (ii) compared AOD, AC_{ALT}, and AC_{FS} determined in maximal swimming effort. The hypothesis was that AC_{FS} would increase through maturation stages, and that AC_{FS} would be higher than AOD and AC_{ALT} due to a greater swimming speed.

METHODS

Study Design

In order to determine (i) the modifications of AC_{FS} during maturation stages, and (ii) whether AC_{ALT} and AC_{FS} both determined in a single maximal swimming effort were similar to AOD, the present study was divided into two parts. **Figure 1** presents the experimental design of the present study. In *Part I*, swimmers were subjected one maximum front crawl (without snorkel) 400 m effort to determine AC_{FS}; and, on the other day, body composition was analyzed by the Dual-energy X-ray absorptiometry (DEXA, General Electric Medical Systems, Fairfield, USA) explained elsewhere (Campos et al., 2012). All tests were performed in a 25-m swimming pool with water temperature of 25 ± 2°C and were preceded by a warm-up of ∼1,000 m freestyle swimming of low to moderate intensity determined subjectively by the swimmers. Additionally, swimmers were instructed not to engage in strenuous activity the day before exercise tests and to maintain a consistent routine of training, sleeping, and diet throughout the study.

In *Part II*, swimmers were subjected to three experimental sessions, interspersed by at least 24 h. On the first visit, subjects performed four submaximal efforts aiming to establish VO_2-speed relationship. On the second day, the subjects were subjected to a submaximal exercise, and a maximal front crawl 400 m effort with snorkel. No warm-up was performed before the tests and the subjects started each trial when their VO_2 values exhibited two consecutive values within 2 $mL \cdot kg^{-1} \cdot min^{-1}$ of that

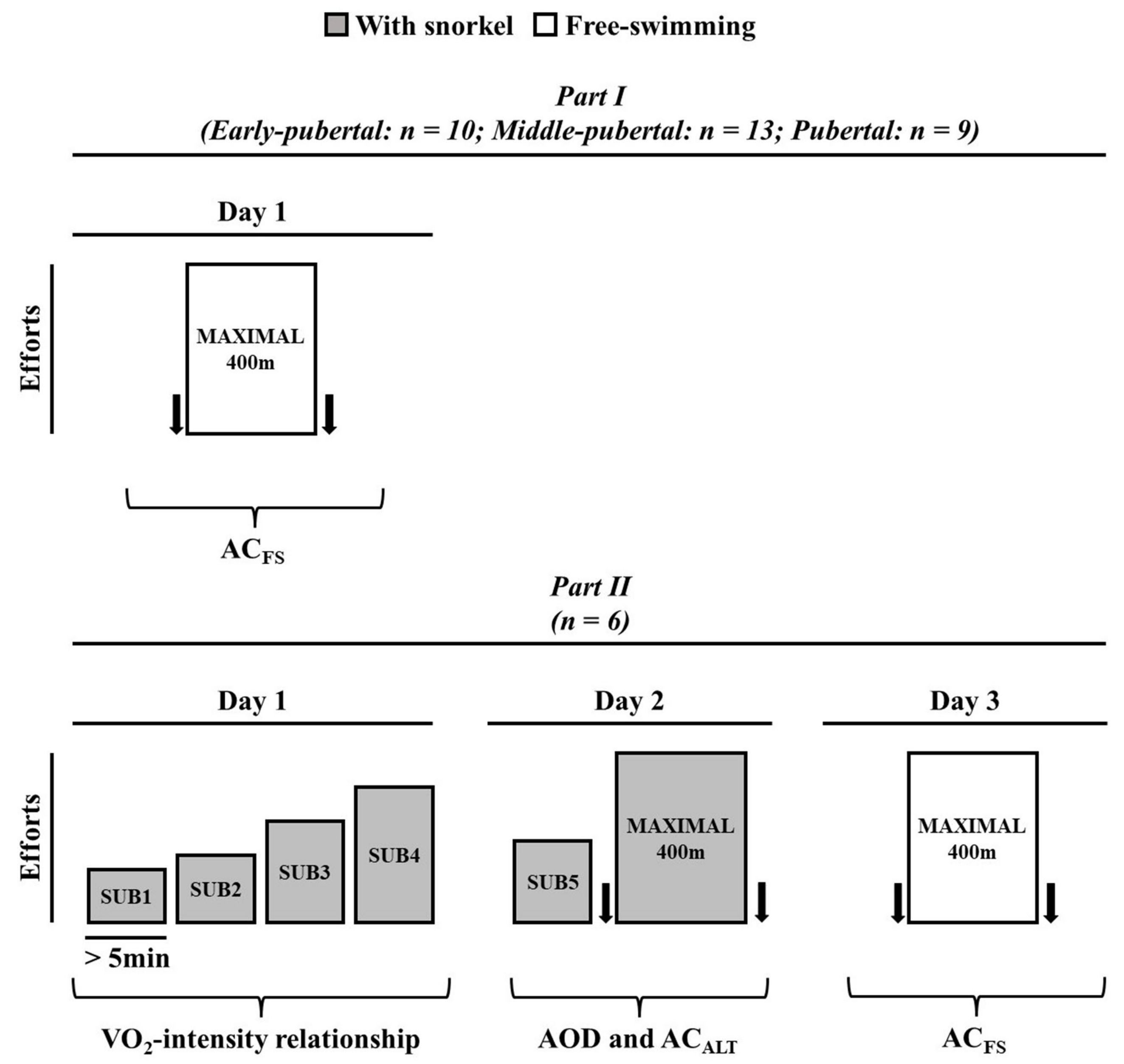

FIGURE 1 | Experimental design for Part I and Part II. Arrows represent blood sample to determine lactate concentration.

recorded before the first submaximal exercise (observed on the first day; Reis et al., 2010b). This first maximal front crawl 400 m effort (second day trial) was used to evaluate AOD and AC_{ALT} (**Figure 1**) and the swimmers used snorkel during the effort. After at least 48 h, the swimmers were subjected to another 400 m maximal effort without snorkel (AC_{FS}).

Data Collection and Peak Oxygen Uptake Analysis

Expired gases were collected breath-by-breath using either a gas analyzer (Quark PFT, Cosmed®, Rome, Italy) in *Part* I, and a portable gas analyzer (K4b^2, Cosmed®, Rome, Italy) connected to an Aquatrainer snorkel (Cosmed®, Rome, Italy) in *Part II*. The gas analyzers were calibrated immediately before and verified after each test using a certified gravimetrically determined gas mixture, while the ventilometer was calibrated preexercise and verified postexercise using a 3-L syringe, in accordance with the manufacturer's instructions. Following the removal of outliers, breath-by-breath data were interpolated to give 1s values (OriginPro 8.0, OriginLab Corporation, Microcal, Massachusetts, USA) to enhance response characteristics of excess postoxygen consumption (EPOC) (Zagatto et al., 2011). Before the maximal 400 m and after 3, 5, and 7 min of recovery, blood samples were collected to determine [La$^-$] using a blood lactate analyzer YSI-2300 (Yellow Springs Instruments®, OH, USA).

Peak oxygen consumption (VO_{2Peak}) was estimated by the backward extrapolation technique, after a maximum front crawl effort of 400 m freestyle, that is, without snorkel. For this, the subjects were instructed to immediately breathe on a face mask (Hans Rudolph, Kansas City, MO, USA) connected to a breath-by-breath gas analyzer system. The equipment was calibrated immediately before the test according to the instruction of the manufacturer. The VO_{2Peak} was obtained using a 30 s backward extrapolation technique (Campos et al., 2017b; Monteiro et al., 2020); for this, VO_2 values were transformed in $\log VO_2$, and plotted against time. Through a linear regression the y-intercept was considered as VO_{2Peak}.

Subjects

Part I

Thirty-four swimmers (19 men, and 15 women) participated in the present study (14.9 ± 2.6 yrs, 58.19 ± 11.88 kg, 161.90 ± 10.98 cm and $VO_{2Peak} = 3.30 \pm 0.94$ L·min^{-1}). All the swimmers had at least two years of competitive swimming experience and, had been training an average daily volume of 4,000 m (11–12 yrs), 6,000 m (13–14 yrs), and 8,000 m (>15 yrs), with six trainings·week^{-1} (except 11–12 yrs, that trained 5 times·week^{-1}).

Part II

Six swimmers (three men and three women) with mean age, height, total body mass, and VO_{2Peak} of 15.1 ± 1.9 yrs, 165.76 ± 8.62 cm, 59.53 ± 11.75 kg, and 3.07 ± 0.57 L·min^{-1} respectively, volunteered to participate in the investigation. All subjects had been swimming training for at least 2 years (average training volume of 7,000 m·day^{-1} and frequency of 5 days·week^{-1}).

All procedures were approved by the University's Institutional Review Board for Human Subjects (Human Research Ethics Committee - UNESP - Rio Claro/SP; Ethics Committee Number: 1413/2013), and were conducted according to the Declaration of Helsinki. The athletes and their parents were informed about the experimental procedures and risks and signed an informed consent prior to their participation in the study.

Procedures

Part I

Biological Age

Swimmers identified the closest stage representing their body characteristics, using picture boards. Evaluation of pubic hair was done for both genders. Athletes were grouped according to the biological age through the self-assessment method of evaluation of pubic hair proposed by Tanner (1962). This self-rating procedure was previously validated for breast development (B1, B2, B3, B4, and B5) for girls and genitalia (G1, G2, G3, G4, and G5) for boys. Due to the small number of subjects on stages two ($n = 4$) and three ($n = 6$) of this secondary characteristic, the athletes were aggregated into one group. The final groupings were early-pubertal (M2–M3 and G2–G3, $n = 10$), middle-pubertal (M4 and G4, $n = 14$), and pubertal (M5 and G5, $n = 10$).

Free-Swimming Anaerobic Contribution Determination (AC_{FS})

Free-swimming anaerobic contribution was determined by the sum of Ana_{ALA} and Ana_{LAC} (Bertuzzi et al., 2010; Zagatto et al., 2011; Kalva-Filho et al., 2015). Swimmers were instructed to immediately breathe on a face mask (Hans Rudolph, Kanss City, MO, USA) connected to a breath-by-breath gas analyzer system (Quark PFT, Cosmed®, Rome, Italy) for 5 min (Campos et al., 2017a). The AC_{FS} was calculated in Excel (Microsoft Corporation, Redmond, Washington, USA) and Origin (OriginPro 8.0, OriginLab Corporation, Microcal, Massachusetts, USA). Ana_{ALA} was assumed as the fast component of EPOC. For this EPOC, breath-by-breath measurements obtained during 5 min of recovery were adjusted as a function of time using a bi-exponential model (Equation 1) (Ozyener et al., 2001). The product between amplitude (A_1) and the fast component time constant (f_1) was assumed as Ana_{ALA} (Equation 2) (Knuttgen, 1970; Bertuzzi et al., 2010). Ana_{LAC} was obtained by net lactate accumulation (i.e., difference between [La-] peak and baseline values; Δ[La-]), considering a metabolic equivalent of 3 mL·O2·kg-1 for each unit of lactate elevated with maximal effort (di Prampero and Ferretti, 1999). Thus, AC_{FS} was assumed as the sum of Ana_{ALA} and Ana_{LAC} (Equation 3). AC_{FS} values were presented as absolute (L), and relative to body mass (mL·kg^{-1}).

$$VO_{2(t)} = VO_{2BASE} + A_1[e^{-((t-\delta 1)/f_1)}] + A_2[e^{-((t-\delta 2)/f_2)}] \quad (1)$$

$$Ana_{ALA} = A_1 \cdot f_1 \quad (2)$$

$$AC_{FS} = Ana_{ALA} + ANA_{LAC} \quad (3)$$

where in Equation 1, $VO_{2(t)}$ is the oxygen uptake at time t in recovery time, VO_{2BASE} was the oxygen uptake of at baseline measured before swimming, A is the amplitude, δ is the time delay, f_1 is the time constant (tau) and $_1$ and $_2$ denote the fast and slow components, respectively. In Equation 2, Ana_{ALA} is the alactic anaerobic contribution and in Equation 3 AC_{FS} is the alternative method to determine anaerobic contribution in a single effort without snorkel and Ana_{LAC} is the lactic contribution. Data of one subject are presented in **Figure 2**.

Part II

Conventional Accumulated Oxygen Deficit

Submaximal exercises were performed according to the best 400 m performance of the individual achieved 1 week before the tests (Sousa et al., 2015). The swimmers were instructed to maintain a constant speed during the four submaximal efforts by accompanying sonorous stimuli with markers placed at the bottom of the pool. The distance swam in the submaximal exercises varied from 250 to 400 m. These distances were chosen to ensure a minimal of f5 min of effort, which was related to the VO_2 plateau attained at 2–3 min (Grassi, 2000). Thus, the mean VO_2 observed during the final 30 s of the submaximal effort was assumed as the steady-state VO_2 for the corresponding speed. The linear VO_2-speed relationship was constructed with the five efforts (four submaximal, and 400 m maximal effort). The mean speed and VO_2 related to the 400 m maximal effort was also used

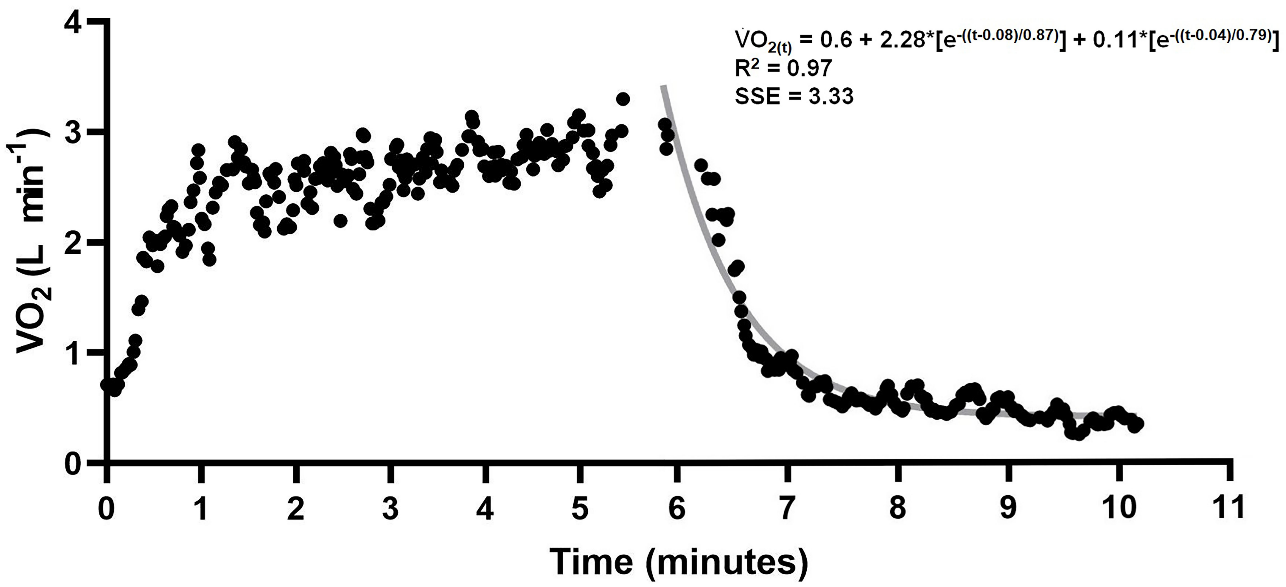

FIGURE 2 | VO_2 data from 400 m swimming and recovery. Gray line indicates bi-exponential adjustment. Alactic anaerobic contribution was assumed as the product between A1 and t_1.

in the linear regression since this speed is lower than the speed associated with maximal oxygen consumption (≈96%; Reis et al., 2010b).

The accumulated oxygen deficit was assumed as the difference between the estimated demand obtained by VO_2-speed linear regression extrapolation and the measurement of the VO_2 during the maximal effort (Medbo et al., 1988). As the swimmers did not use continuous pacing during maximal swimming effort, the estimated demand was calculated for each 25 m (**Figure 3**). For this, the speed of each 25 m was inserted in the VO_2-speed linear regression extrapolation, enabling a different estimated demand (i.e., theoretical demand) for each 25 m to be stratified by swimming VO_2. The difference of the demand for each 25 m and the VO_2 during the effort was assumed as AOD. AOD was presented in absolute (L), and relative values to body mass ($mL \cdot kg^{-1}$). The AOD calculation was done in Excel (Microsoft Corporation®, Redmond, Washington, USA).

Alternative Anaerobic Contribution (AC_{ALT})

The AC_{ALT} was determined as presented for AC_{FS}. The main differences between AC_{ALT} and AC_{FS} are due to the fact that at AC_{FS} the swimmers perform the effort without the snorkel and the fast component of values of EPOC, used to estimate the alactic anaerobic contribution, was obtained immediately after swimming (≈2 seg), while the swimmers swam with snorkel for AC_{ALT}.

Statistical Analyses

Data normality was tested and confirmed by Shapiro–Wilk's test, which permitted the use of parametric tests. Data are presented as mean ± standard deviation (SD). Significance level was set at 5%. The minimal sample size to provide a statistical power of 80% was estimated using G*Power software, version 3.1.9.4 (Franz Faul, Christian-Albrechts-Universität Kiel, Kiel, Germany).

Part I

The minimal sample size was five participants, considering that the lactic contributions was different between maturation stages during high-intensity efforts, presenting the effect size of 1.798 (Beneke et al., 2007). The comparison between physiological parameters in different biological ages was obtained by one-way ANOVA, and Tukey's posthoc when necessary.

Part II

The minimal sample size was six participants, considering that the AOD and AC_{ALT} presented correlations greater than 0.78 (Bertuzzi et al., 2010). ANOVA was used for comparisons between AOD, AC_{ALT}, and AC_{FS} repeated measurements. Sphericity was evaluated by Maucly's test, and corrected by Greenhouse–Geisser, when necessary, prior to ANOVA analyses. The Bonferroni's *post-hoc* test was used, when necessary. Moreover, possible correlations and agreements between the methodologies were tested using the Pearson's correlation test, and Bland and Altman (1986) analysis, respectively. Pearson's correlation was also used to test the heteroscedasticity. Correlation coefficients were classified as very small (0.0 – 0.2), small (0.2 – 0.4), moderate (0.4 – 0.7), strong (0.7 – 0.9), and very strong (0.9 – 1.0) (Rowntree, 1981).

For both parts the effect size and confidence interval (90%) of ES was calculated as proposed by Smithson (2001).

RESULTS

Part I

The subject's characteristics are presented on **Table 1**.

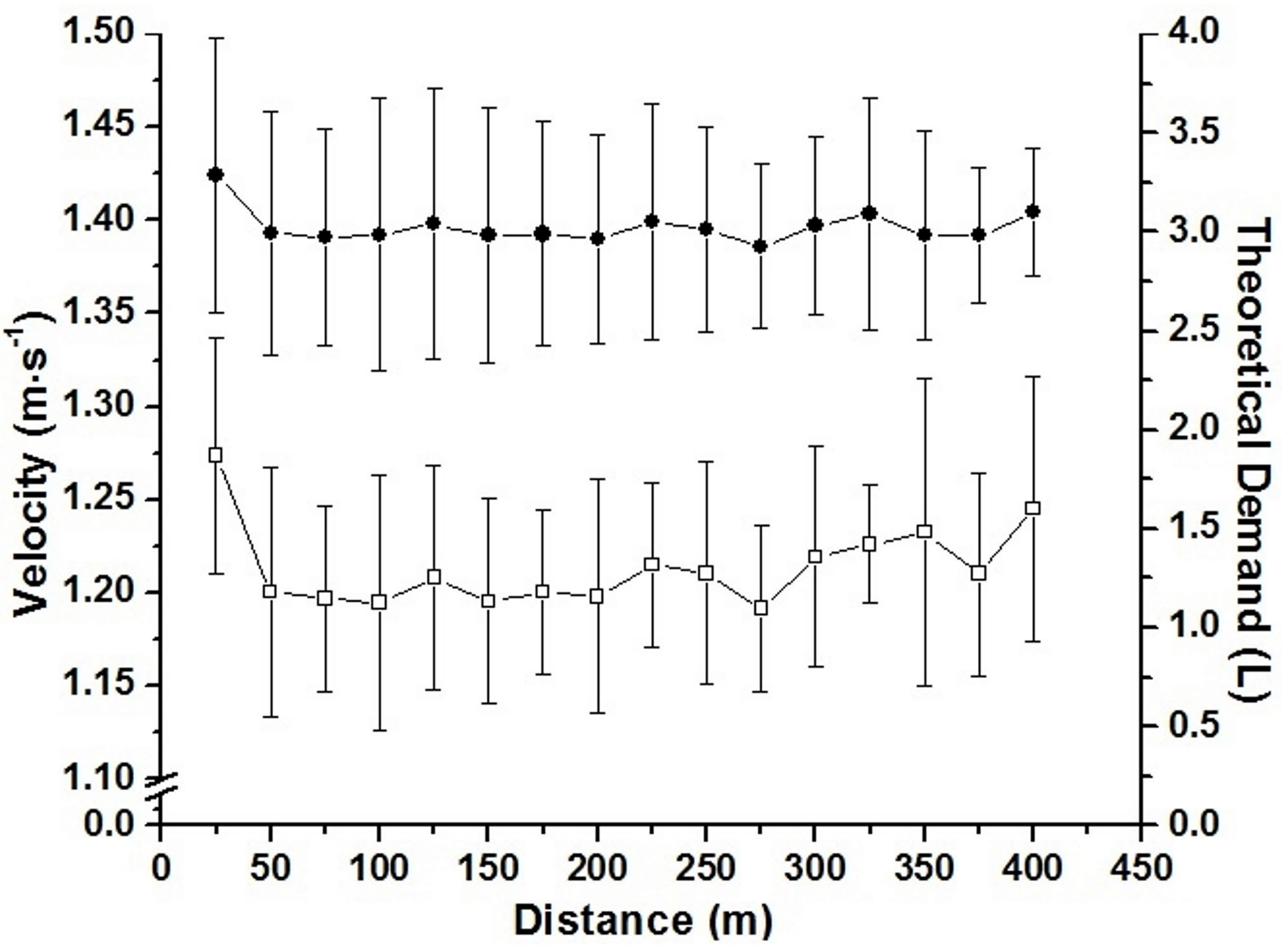

FIGURE 3 | Mean and standard deviation for speed during the 400 m partial (□; left axis), and estimated demand calculated for each 25 m portion (•; right axis).

Figure 4 presents the anaerobic contribution (i.e., AC_{FS}) of early-pubertal, middle- pubertal, and pubertal groups determined after the 400 m effort. Absolute Ana_{ALA} only tended to be different among groups [early-pubertal: 1.42 ± 0.84 L; middle-pubertal: 1.47 ± 0.69 L; pubertal: 2.11 ± 0.66 L; $F = 2.86$; $p = 0.07$; Power = 0.52; ηp2 = 0.15; 90% CI (0; 0.30)], without differences in relative Ana_{ALA} [early-pubertal: 30.27 ± 20.70 mL·kg^{-1}; middle-pubertal: 24.28 ± 10.13 mL·kg^{-1}; and pubertal: 31.63 ± 10.82 mL·kg^{-1}; $F = 0.93$; $p = 0.40$; Power = 0.19; ηp2 = 0.05; 90% CI (0; 0.17)]. Pubertal group presented greater absolute Ana_{LAC} than the other groups [early-pubertal: 0.64 ± 0.44 L; middle-pubertal: 1.01 ± 0.51 L; pubertal: 1.75 ± 0.83 L; $F = 8.72$; $p = 0.001$; Power = 0.95; ηp2 = 0.36; 90% CI (0.11; 0.49)], while no differences were found between early-pubertal and middle-pubertal.

Pubertal showed greater relative Ana_{LAC} than early-pubertal [early-pubertal: 12.77 ± 8.42 mL·kg^{-1}; middle-pubertal: 16.60 ± 7.24 mL·kg^{-1}; and pubertal: 25.44 ± 11.01 mL·kg^{-1}; F = 5.49; $p < 0.01$; Power = 0.81; ηp2 = 0.26; 90% CI (0.04; 0.41)]. AC_{FS} were greater in pubertal group than the other groups [early-pubertal: 2.10 ± 0.90 L; middle-pubertal: 2.48 ± 1.12 L; pubertal: 3.87 ± 1.12 L; $F = 7.79$; $p = 0.002$; Power = 0.93; ηp2 = 0.33; 90% CI (0.09; 0.47)], and no differences were found between early-pubertal and middle-pubertal (**Figure 4**). No differences were found for relative AC_{FS} between groups [early-pubertal: 44.82 ± 19.75 mL · kg^{-1}; middle-pubertal: 40.88 ± 15.55 mL · kg^{-1}; and pubertal: 57.08 ± 16.49 mL · kg^{-1}; $F = 2.70$; $p = 0.08$; Power = 0.49; ηp2 = 0.14; 90% CI (0; 0.29)].

Part II

Speed ranged between 64.42 ± 0.93 and 80.30 ± 6.85% of 400 m performance in submaximal efforts. The mean time for 400 m was 330.59 ± 13.20 s (mean speed = 1.20 ± 0.04 m·s^{-1}) and VO_{2Peak} was 3.07 L·min^{-1}. The VO_2-speed relationship presented values of angular, linear, and determination coefficients of 4.00 ± 1.22 (L·min^{-1})·(m·s^{-1})$^{-1}$, 1.82 ± 1.06 L·min^{-1}, and 0.94 ± 0.02, respectively. **Figure 3** demonstrates the pacing used by swimmers during the maximal 400 m effort. **Table 2** summarizes all parameters related to AOD, AC_{ALT}, and AC_{FS}.

No differences were found between absolute AOD (3.2 ± 1.3 LO_2) and AC_{ALT} (3.2 ± 1.5 LO_2), and AC_{FS} (4.0 ± 0.9 LO_2) determined in the 400 m maximal effort [$F = 3.69$; $p = 0.06$;

TABLE 1 | Mean and standard deviation of age, height, weight, total muscle mass (TMM), total body fat (TBF), peak oxygen consumption (VO_{2Peak}), baseline lactate concentration ([La^-]), amplitude of primary component (A_1), and time constant of primary component (τ_1).

	Groups		
	Early-pubertal (n = 10)	Middle-pubertal (n = 14)	Pubertal (n = 10)
Age (years)	13 ± 2	15 ± 1	18 ± 3
Height (cm)	154.7 ± 10.0	160.6 ± 10.1	170.9 ± 6.9^{ab}
Weight (kg)	46.5 ± 9.4	59.5 ± 7.4^a	68.0 ± 9.5^a
TMM (kg)	36.9 ± 7.3	46.1 ± 7.6^a	53.1 ± 8.1^a
TBF (kg)	9.5 ± 4.6	11.5 ± 5.4	12.1 ± 6.9
VO_{2Peak} (L·min-1)	2.7 ± 0.6	3.3 ± 0.8	3.8 ± 1.1^a
Baseline [La^-] (mM)	1.0 ± 0.2	1.6 ± 0.7^a	1.0 ± 0.4^b
[La^-] Peak (mM)	5.5 ± 1.5	7.1 ± 2.4	9.5 ± 3.8^a
A_1 (L·min^{-1})	2.2 ± 0.6	2.8 ± 0.8	3.3 ± 1.0^a
τ_1 (sec)	0.6 ± 0.5	0.5 ± 0.2	0.6 ± 0.2

[a] *Significantly different from early-pubertal group.*
[b] *Significantly different from middle-pubertal group.*

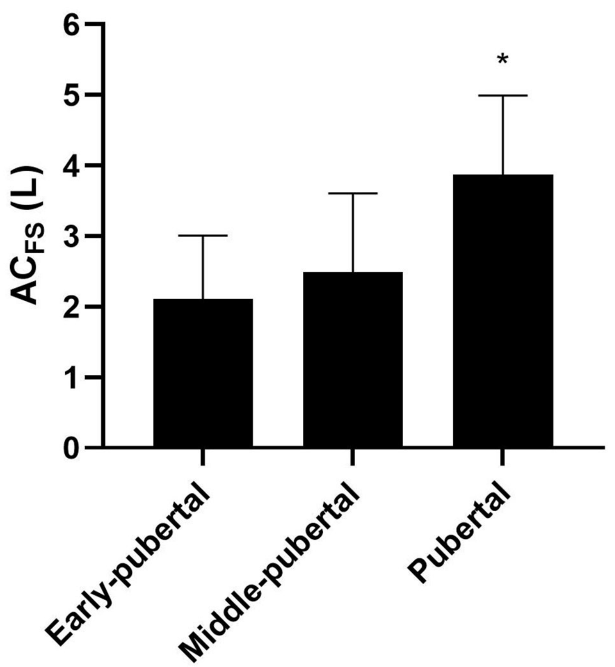

FIGURE 4 | Mean and standard deviation of AC_{FS} (anaerobic contribution) determined in free-swimming in different maturation stages. *Significantly higher than early-pubertal and middle-pubertal.

Power = 0.54; ηp2 = 0.42; 90% CI (0; 0.60)]. The relative AOD (51.8 ± 12.2 mL · kg^{-1}), AC_{ALT} (50.5 ± 14.3 mL · kg^{-1}), and AC_{FS} (65.2 ± 8.8 mL · kg^{-1}) values presented main effect [F = 4.49; p = 0.04; Power = 0.62; ηp2 = 0.47; 90% CI (0.01; 0.64)]; however, *post-hoc* analysis did not indicate any differences among values (**Figure 5**).

The agreement analysis between methods are shown in **Figure 6**. The mean error between AOD and AC_{ALT} was 0.04 L,

TABLE 2 | Mean ± standard deviation (SD) of accumulated oxygen deficit (AOD), alternative anaerobic contribution (AC_{ALT}), and free-swimming anaerobic contribution (AC_{FS}) parameters (n = 6).

	Mean	SD
AOD		
Estimated demand (L)	13.60	2.79
Accumulated VO_2 (L)	10.31	1.48
AOD error (L)	1.54	1.25
AC_{ALT}		
Ana_{ALA} (L)	1.36	0.61
Ana_{LAC} (L)	1.87	1.07
Baseline [La^-] (mM)	1.30	0.27
[La^-] peak (mM)	10.98	4.07
AC_{FS}		
Ana_{ALA} (L)	1,82	0,30
Ana_{LAC} (L)	2,21	0,79
Baseline [La^-] (mM)	0.97	0.25
[La^-] Peak (mM)	12.68	2.29

Ana_{ALA}, alactic anaerobic contribution; Ana_{LAC}, lactic anaerobic contribution.

and between AOD and AC_{FS} was −0.74 L. However, the limits of agreement of AOD and AC_{ALT} were 0.96 and 0.87 L for upper and lower limits of agreement, while between AOD and AC_{FS} were 0.77 L for upper limit and 2.26 L for lower limit (four out of six presented greater AC_{FS} than AOD). AOD was very strongly correlated with AC_{ALT} (r = 0.95; p = 0.002), and strongly correlated with AC_{FS} (r = 0.82; p = 0.04).

DISCUSSION

The aims of the present study were (i) to confirm whether AC_{FS} changes within maturation stages, and (ii) to compare conventional AOD with an alternative method to estimate anaerobic contribution using a single effort with and without snorkel (AC_{ALT} and AC_{FS}, respectively). The main findings were that AC_{FS} modifies within maturation stages, and the preliminary validation study did not show differences among AOD, AC_{ALT}, and AC_{FS}, and that they were strongly correlated (AOD with AC_{ALT}: r = 0.95; AOD with AC_{FS}: r = 0.82); however, agreement analysis between AOD and AC_{FS} showed greater lower limits (−2.26 L).

Part I

In accordance with our hypothesis, AC_{FS} was sensitive to maturation stages in swimmers, with the pubertal group presenting significantly higher absolute AC_{FS} than middle-pubertal and early-pubertal groups. The pubertal and middle-pubertal groups presented greater muscle mass than early-pubertal; however, the difference between middle-pubertal and pubertal was of ≈7 kg on average, which can have practical influence on performance, besides the absence of statistical differences. Thus, expressing AC_{FS} values relative to total body mass and muscle mass is extremely important when comparing the anaerobic indices of swimmers of different biological ages.

These results agree with the findings of Kaczor et al. (2005), which have demonstrated that the quantity and activity of

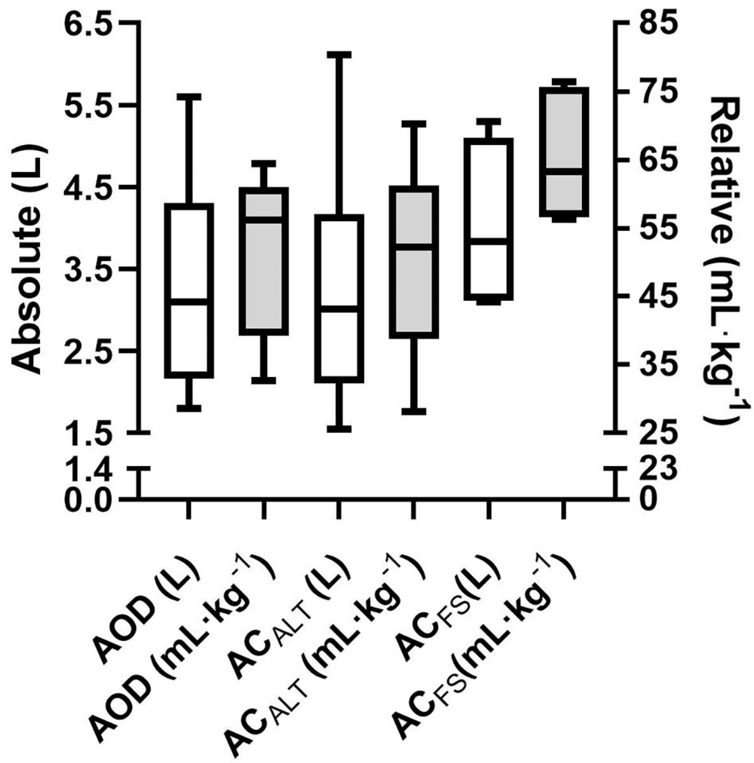

FIGURE 5 | Mean and standard deviation of absolute (white bar) and relative (gray bar) of AOD, AC_{ALT}, and AC_{FS}.

glycolytic enzymes are greater in more mature subjects. The study of Lätt et al. (2009) has also confirmed that net lactate accumulation was significantly greater when swimmers were on Tanner stages 3 and 4 than on stage 2, while no differences were found between stage 3 and 4; however, the authors did not take into account the alactic metabolism. When considering Ana_{LAC} and Ana_{ALA}, the latter only tended to be greater ($p = 0.07$) in pubertal than in the other groups. Thus, for swimmers, Ana_{LAC} is the main variable differing between maturation stages. Therefore, the difference in absolute AC_{FS} may be related to Ana_{LAC} since no differences were found in Ana_{ALA} between maturation stages. Furthermore, no differences were detected in relative AC_{FS} between maturation stages, indicating a possible influence of muscle mass on AC_{FS}.

Due to its importance in swimming context, a feasible tool to evaluate anaerobic contribution would be important, and AC_{FS} is practical because it enable swimmers to swim freely; however, it was important to compare it with currently used anaerobic contribution determination methods (i.e., AC_{ALT} and AOD).

Part II

The measurement of energy cost in swimming has received great attention on swimming, since it is important for performance (Zamparo et al., 2000). When calculating the netmetabolic power expenditure, both aerobic and anaerobic contribution must be accounted (Barbosa et al., 2006; Figueiredo et al., 2011). Faina et al. (1997) observed that the time to exhaustion at maximal aerobic speed is closely associated with anaerobic contribution in swimming, highlighting the importance of anaerobic metabolism for maximal efforts. To overcome AOD problems of excessive testing, an alternative method of AOD determination has been proposed using net lactate accumulation and off-transient oxygen consumption (Bertuzzi et al., 2010). As the oxygen consumption can be measured after swimming (Kalva-Filho et al., 2015; Campos et al., 2017a), AC_{FS} would be an even more interesting and applicable tool to evaluate the anaerobic contribution of swimmers without interfering on technique and speed.

The values of AOD observed in the present study were similar to those observed in exhaustive efforts (Ogita et al., 1996), but greater than other investigations that used fixed distance maximal efforts (Reis et al., 2010a,b). Ogita et al. (2003) investigated the possible influence of exercise duration on AOD values obtained in a swimming flume. Those authors observed that anaerobic contribution was similar when exhaustion occurred between one (≈2.8 L) and 5 min (≈2.9 L), with maximal values attained in 2–3 min (≈3.2 L). Thus, maximal AOD values (i.e., anaerobic capacity) can be obtained in a 200 m effort (2–3 min to exhaustion), with no significant differences in relation to a 400 m maximal effort (4–5 min to exhaustion) (Ogita et al., 2003). However, Reis et al. (2010b) observed lower values of AOD in a 400 m than in a 200 or 100 m maximal effort performed in front crawl (≈11.9 mL·kg^{-1}, ≈17.5 mL·kg^{-1}, and ≈21.0 mL·kg^{-1}, respectively). These results were confirmed in breaststroke for 200 and 100 m (≈23.1 mL·kg^{-1} and 22.2 mL·kg^{-1}, respectively) (Reis et al., 2010b).

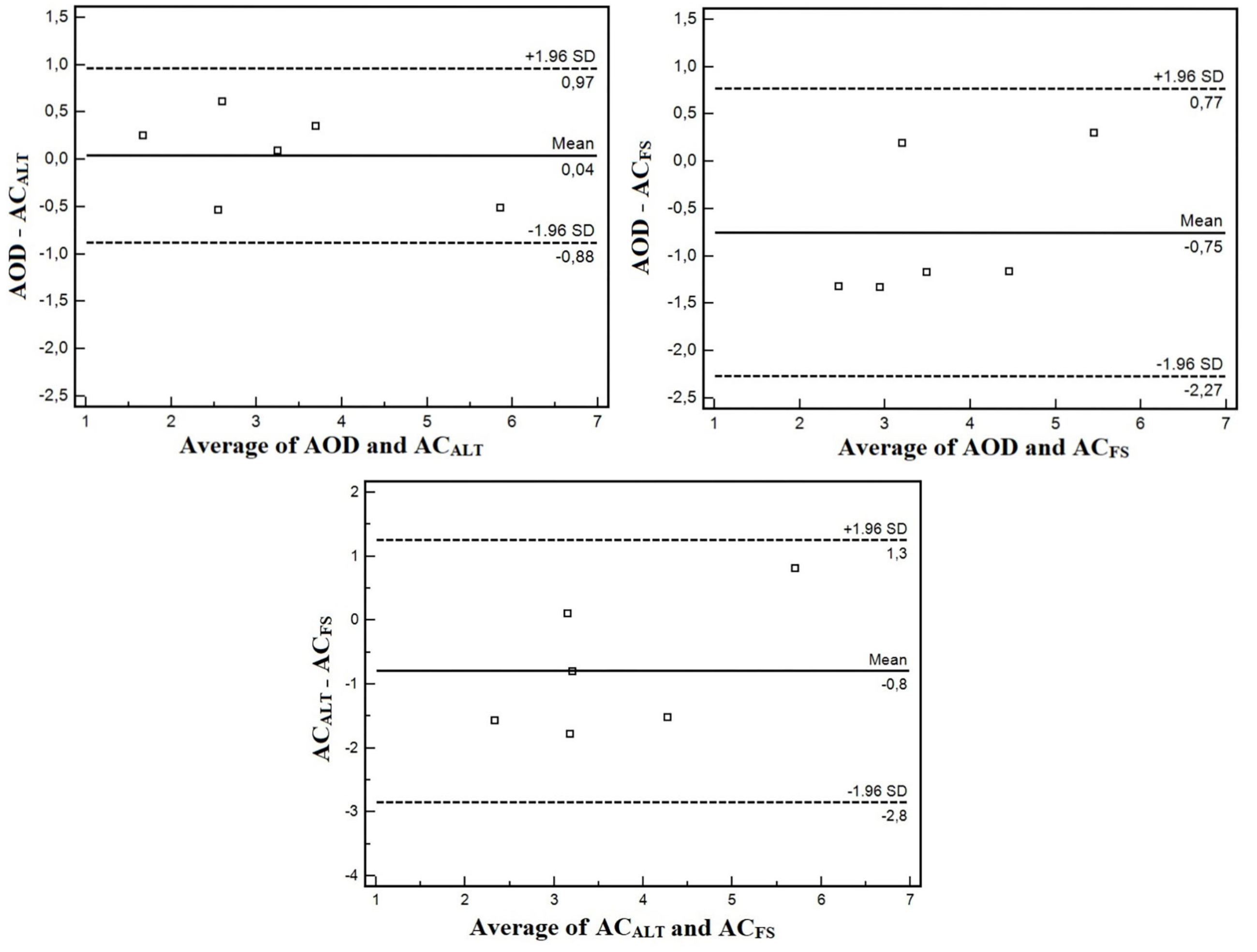

FIGURE 6 | Bland and Altman agreement analysis between AOD and AC_{ALT}, AOD and AC_{FS}, and AC_{ALT}, and AC_{FS}.

It has been suggested that combining sub and supraanaerobic threshold intensities (i.e., 30–90% of VO_{2Max}) affects the precision and validity of the AOD model (Buck and McNaughton, 1999). We did not analyze the anaerobic threshold of swimmers but ensured intensities greater than this physiological index by using the 400 m mean speed as well as a submaximal intensity (i.e., 95% of VO_{2PEAK}; unpublished data). Thus, although linear regression is the major concern for AOD calculation, this method is still considered the most acceptable for anaerobic evaluation (Noordhof et al., 2010; Reis et al., 2010b). Different from the present study, the AOD calculation performed in those above-mentioned studies used the effort mean speed to estimate demand, respecting the pace strategy of each swimmer. Thus, we calculated the estimated demand for each 25 m during the maximal effort (**Figure 3**), increasing the precision of these measurements. This approach together with the five points in the VO_2-speed relationship, indicate that AOD values were determined in a robust way during the present study, allowing its use to validate AC_{ALT} and AC_{FS}.

This is the first study to compare conventional AOD with AC_{ALT} in a maximal swimming effort in swimmers. Bertuzzi et al. (2010) compared a conventional and alternative method, in cicloergometer, to determine anaerobic contribution during an exhaustive cycling effort. Those authors observed similar values, positive significant correlation ($r = 0.78$) and a mean error very close to zero, which agrees with the present findings. Therefore, the difficulties implemented by the need for submaximal exercises to estimate VO_2-speed relationship are overcome in the alternative method. Finally, determination of AC_{ALT} allows the calculation of Ana_{LAT} and Ana_{ALA} separately, enabling the investigation of different training models on these two metabolisms.

Even though AC_{ALT} decreases the number of evaluations and allows the evaluation of Ana_{LAT} and Ana_{ALA}, it was still calculated with swimmers using snorkel during swimming. Besides changes in mechanics during swimming, the apparatus reduces the speed of the swimmers (330.5 ± 13.2 s vs. 303.6 ± 10.8 s), which might limit anaerobic contribution. Another important limitation refers to the impossibility of swimmers performing the turns and the underwater dolphin kick, a technique that has been commonly observed in swimming events. The use of snorkel also limits the use of "filipina" during breaststroke swimming, in addition to being uncomfortable for swimmers, limiting its use in practical settings.

We have shown no differences between AC_{FS} with AC_{ALT} and AOD; however, a tendency was detected in absolute values and an effect was found for relative anaerobic contribution (without detection in posthoc analysis). This might have occurred due to the reduced sample size. It is important to note that the limits of agreement between AOD and AC_{FS} highlighted a lower limit of 2.26 L. Four out of six presented significantly greater AC_{FS} than AOD (mean difference of 1.24 L). Thus, even though no statistical differences were observed, free swimming anaerobic contribution evaluation (AC_{FS}) might be recommended because it allows the athletes to perform in greater intensity, which is especially important since swimmers did not reach exhaustion during swimming.

The limitations of the present study were that athletes (both men and women) were evaluated in *Part I* which might have influenced the comparison between maturation stages, and the small sample size in Part II. It would be desirable to confirm these results with a larger sample size. Finally, for the Ana_{ALA} determination, 5 min of recovery was used. Bertuzzi et al. (2016) have observed that a minimum of 6 min is required for Ana_{ALA} evaluation; however, 5 min of recovery have been used in other studies (Kalva-Filho et al., 2015; Campos et al., 2017a; Andrade et al., 2021), and the fast component happens in the 1st min of recovery. Moreover, studies could also use bi-exponential decay equation as proposed by Scheuermann et al. (2011)—since it does not assume that athletes will reach baseline values at the end of recovery—and compare Ana_{ALA} using both Scheuermann et al. (2011) and Ozyener et al. (2001) equations.

CONCLUSION

Collectively, it can be concluded that the AC_{FS} is sensitive to maturation stages, and no differences were detected with AOD and AC_{ALT}. Therefore, AC_{FS} might be useful to estimate anaerobic contribution in swimmers, facilitating its determination in practical settings, because swimmers are able to swim freely, which increases the speed of swimming.

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 Human Research Ethics Committee - UNESP - Rio Claro/SP; Ethics Committee Number: 1413/2013. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

AUTHOR CONTRIBUTIONS

EC, MS, TA, CK-F, and RG collected the data. EC, CK-F, FM-G, and MP wrote the manuscript and delineated the study. All authors contributed to the article and approved the submitted version.

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REFERENCES

Andrade, V. L., Kalva-Filho, C. A., Ribeiro, N. X., Gobbi, R. B., de Arruda, T. B., and Papoti, M. (2021). Determination of maximum accumulated oxygen deficit using backward extrapolation. *Int. J. Sports Med.* 42, 161–168. doi: 10.1055/a-1082-1372

Barbosa, T. M., Fernandes, R., Keskinen, K. L., Colaco, P., Cardoso, C., Silva, J., et al. (2006). Evaluation of the energy expenditure in competitive swimming strokes. *Int. J. Sports Med*. 27, 894–899. doi: 10.1055/s-2006-923776

Beneke, R., Hütler, M., and Leithäuser, R. M. (2007). Anaerobic performance and metabolism in boys and male adolescents. *Eur. J. Appl. Physiol.* 101, 671–677. doi: 10.1007/s00421-007-0546-0

Bertuzzi, R., Melegati, J., Bueno, S., Ghiarone, T., Pasqua, L. A., Gáspari, A. F., et al. (2016). GEDAE-LaB: a free software to calculate the energy system contributions during exercise. *PLoS ONE* 11:e0145733. doi: 10.1371/journal.pone.0145733

Bertuzzi, R. C., Franchini, E., Ugrinowitsch, C., Kokubun, E., Lima-Silva, A. E., Pires, F. O., et al. (2010). Predicting MAOD using only a supramaximal exhaustive test. *Int. J. Sports Med*. 31, 477–481. doi: 10.1055/s-0030-1253375

Bland, J. M., and Altman, D. G. (1986). Statistical methods for assessing agreement between two methods of clinical measurement. *Lancet* 8, 307–310. doi: 10.1016/S0140-6736(86)90837-8

Boisseau, N., and Delamarche, P. (2000). Metabolic and hormonal responses to exercise in children and adolescents. *Sports Med*. 30, 405–422. doi: 10.2165/00007256-200030060-00003

Brisola, G. M. P., Miyagi, W. E., da Silva, H. S., and Zagatto, A. M. (2015). Sodium bicarbonate supplementation improved MAOD but is not correlated with 200-and 400-m running performances: a double-blind, crossover, and placebo-controlled study. *Appl. Physiol. Nutr. Metab*. 40, 931–937. doi: 10.1139/apnm-2015-0036

Buck, D., and McNaughton, L. R. (1999). Changing the number of submaximal exercise bouts effects calculation of MAOD. *Int. J. Sports Med*. 20, 28–33. doi: 10.1055/s-2007-971087

Campos, E. Z., Bastos, F. N., Papoti, M., Freitas-Junior, I. F., Gobatto, C. A., and Balikian-Junior, P. (2012). The effects of physical fitness and body composition on oxygen consumption and heart rate recovery after high-intensity exercise. *Int. J. Sports Med*. 33, 621–626. doi: 10.1055/s-0031-1295442

Campos, E. Z., Kalva-Filho, C. A., Gobbi, R. B., Barbieri, R. A., Almeida, N. P., and Papoti, M. (2017a). Anaerobic contribution determined in swimming distances: relation with performance. *Front. Physiol.* 8:755. doi: 10.3389/fphys.2017.00755

Campos, E. Z., Kalva-Filho, C. A., Loures, J. P., Manchado-Gobatto, F. B., Zagatto, A. M., and Papoti, M. (2017b). Comparison between peak oxygen consumption and its associated speed determined through an incremental test and a 400-m effort: implication for swimming training prescription. *Sci. Sports* 32, e37–e41. doi: 10.1016/j.scispo.2016.06.007

de Poli, R. D. A. B., Roncada, L. H., Malta, E. D. S., Artioli, G. G., Bertuzzi, R., and Zagatto, A. M. (2019). Creatine supplementation improves phosphagen energy pathway during supramaximal effort, but does not improve anaerobic capacity or performance. *Front. Physiol.* 10:352. doi: 10.3389/fphys.2019.00352

Di Prampero, P., and Margaria, R. (1968). Relationship between O_2 consumption, high energy phosphates and the kinetics of the O_2 debt in exercise. *Pflügers Arch.* 304, 11–19. doi: 10.1007/BF00586714 di Prampero, P. E., and Ferretti, G. (1999). The energetics of anaerobic muscle metabolism: a reappraisal of older and recent concepts. *Respir. Physiol.* 118, 103–115. doi: 10.1016/S0034-5687(99)00083-3

Faina, M., Billat, V., Squadrone, R., De Angelis, M., Koralsztein, J. P., and Dal Monte, A. (1997). Anaerobic contribution to the time to exhaustion at the minimal exercise intensity at which maximal oxygen uptake occurs in elite cyclists, kayakists and swimmers. *Eur. J. Appl. Physiol. Occup. Physiol.* 76, 13–20. doi: 10.1007/s004210050207

Falgairette, G., Bedu, M., Fellmann, N., Van-Praagh, E., and Coudert, J. (1991). Bio-energetic profile in 144 boys aged from 6 to 15 years with special reference to sexual maturation. *Eur. J. Appl. Physiol. Occup. Physiol.* 62, 151–156. doi: 10.1007/BF00643734

Figueiredo, P., Zamparo, P., Sousa, A., Vilas-Boas, J. P., and Fernandes, R. J. (2011). An energy balance of the 200 m front crawl race. *Eur. J. Appl. Physiol.* 111, 767–777. doi: 10.1007/s00421-010-1696-z

Gastin, P. B. (1994). Quantification of anaerobic capacity. *Scand. J. Med. Sci. Sports* 4, 91–112. doi: 10.1111/j.1600-0838.1994.tb00411.x

Grassi, B. (2000). Skeletal muscle VO_2 on-kinetics: set by O_2 delivery or by O_2 utilization? New insights into an old issue. *Med. Sci. Sports Exerc.* 32, 108–116. doi: 10.1097/00005768-200001000-00017

Green, S., and Dawson, B. (1993). Measurement of anaerobic capacities in humans. *Sports Med.* 15, 312–327. doi: 10.2165/00007256-199315050-00003

Inbar, O. M. R. I., and Bar-Or, O. D. E. D. (1986). Anaerobic characteristics in male children and adolescents. *Med. Sci. Sports Exerc.* 18, 264–269. doi: 10.1249/00005768-198606000-00002

Kaczor, J. J., Ziolkowski, W., Popinigis, J., and Tarnopolsky, M. A. (2005). Anaerobic and aerobic enzyme activities in human skeletal muscle from children and adults. *Pediatr. Res.* 57, 331–335. doi: 10.1203/01.PDR.0000150799.77094.DE

Kalva-Filho, C. A., Campos, E. Z., Andrade, V. L., Silva, A., Zagatto, A. M., Lima, M., et al. (2015). Relationship of aerobic and anaerobic parameters with 400 m front crawl swimming performance. *Biol. Sport.* 32, 333–337. doi: 10.5604/20831862.1188611

Knuttgen, H. G. (1970). Oxygen debt after submaximal physical exercise. *J. Appl. Physiol.* 29, 651–657. doi: 10.1152/jappl.1970.29.5.651

Lätt, E., Jürimäe, J., Haljaste, K., Cicchella, A., Purge, P., and Jürimäe, T. (2009). Physical development and swimming performance during biological maturation in young female swimmers. *Coll. Antropol.* 33, 117–122. doi: 10.2466/pms.108.1.297-307

Margaria, R., Edwards, H. T., and Dill, D. B. (1933). The possible mechanisms of contracting and paying the oxygen debt and the role of lactic acid in muscular contraction. *Am. J. Physiol.* 106, 689–715. doi: 10.1152/ajplegacy.1933.106.3.689

Medbo, J. I., Mohn, A. C., Tabata, I., Bahr, R., Vaage, O., and Sejersted, O. M. (1988). Anaerobic capacity determined by maximal accumulated O_2 deficit. *J. Appl. Physiol.* 64, 50–60. doi: 10.1152/jappl.1988.64.1.50

Milioni, F., Malta, E. D. S., Rocha, L. G. S. D.A., Mesquita, C. A. A., de Freitas, E. C., and Zagatto, A. M. (2016). Acute administration of high doses of taurine does not substantially improve high-intensity running performance and the effect on maximal accumulated oxygen deficit is unclear. *Appl. Physiol. Nutr. Metab.* 41, 498–503. doi: 10.1139/apnm-2015-0435

Miyagi, W. E., De Poli, R. D. A. B., Papoti, M., Bertuzzi, R., and Zagatto, A. M. (2017). Anaerobic capacityestimated in a single supramaximal test in cycling: validity and reliability analysis. *Sci. Rep.* 7, 1–10. doi: 10.1038/srep42485

Monteiro, A. S., Carvalho, D. D., Azevedo, R., Vilas-Boas, J. P., Zacca, R., and Fernandes, R. J. (2020). Postswim oxygen consumption: assessment methodologies and kinetics analysis. *Physiol. Meas.* 41:105005. doi: 10.1088/1361-6579/abb143

Montpetit, R. R., Léger, L. A., Lavoie, J. M., and Cazorla, G. (1981). VO_2peak during free swimming using the backward extrapolation of the O_2 recovery curve. *Eur. J. Appl. Physiol. Occup. Physiol.* 47, 385–391. doi: 10.1007/BF02332966

Noordhof, D. A., de Koning, J. J., and Foster, C. (2010). The maximal accumulated oxygen deficit method: a valid and reliable measure of anaerobic capacity. *Sports Med.* 40, 285–302. doi: 10.2165/11530390-000000000-00000

Ogita, F., Hara, M., and Tabata, I. (1996). Anaerobic capacity and maximal oxygen uptake during arm stroke, leg kicking and whole body swimming. *Acta Physiol. Scand.* 157, 435–441. doi: 10.1046/j.1365-201X.1996.490237000.x

Ogita, F., Onodera, T., Tamaki, H., Toussaint, H. M., Hollander, A., and Wakayoshi, K. (2003). Metabolic profile during exhaustive arm stroke, leg kick, and whole body swimming lasting 15 s to 10 min. *Biomech. Med. Swim. IX.* 6, 361–366.

Ozyener, F., Rossiter, H. B., Ward, S. A., and Whipp, B. J. (2001). Influence of exercise intensity on the on- and off-transient kinetics of pulmonary oxygen uptake in humans. *J. Physiol.* 533, 891–902. doi: 10.1111/j.1469-7793.2001.t01-1-00891.x

Reis, V. M., Marinho, D. A., Barbosa, F. P., Reis, A. M., Guidetti, L., and Silva, A. J. (2010a). Examining the accumulated oxygen deficit method in breaststroke swimming. *Eur. J. Appl. Physiol.* 109, 1129–1135. doi: 10.1007/s00421-010-1460-4

Reis, V. M., Marinho, D. A., Policarpo, F. B., Carneiro, A. L., Baldari, C., and Silva, A. J. (2010b). Examining the accumulated oxygen deficit method in front crawl swimming. *Int. J. Sports Med.* 31, 421–427. doi: 10.1055/s-0030-1248286

Rowntree, D. (1981). *Statistics Without Tears: A Primer for Non-mathematicians*. Londres: Penguin.

Scheuermann, B. W., Hoelting, B. D., Noble, M. L., and Barstow, T. J. (2011). The slow component of O_2 uptake is not accompanied by changes in muscle EMG during repeated bouts of heavy exercise in humans. *J. Physiol.* 15, 245–256. doi: 10.1111/j.1469-7793.2001.0245j.x

Smithson, M. (2001). Correct confidence intervals for various regression effect sizes and parameters: The importance of noncentral distributions in computing intervals. *Educ. Psychol. Meas.* 61, 605–632. doi: 10.1177/0013164012197139210.1177/00131640121971392

Sousa, A., Rodriguez, F. A., Machado, L., Vilas-Boas, J. P., and Fernandes, R. J. (2015). Exercise modality effect on oxygen uptake off-transient kinetics at maximal oxygen uptake intensity. *Exp. Physiol.* 100, 719–729. doi: 10.1113/EP085014

Tanner, J. N. (1962). *Growth at Adolescence With a General Consideration of the Effects of Hereditary and Environmental Factors Upon Growth and Maturation From Birth to Maturity, 2nd Edn*. Oxford: Blackwell Scientific Publications.

Valenzuela, J. R., Riojas, A. E., McFarlin, B. K., Vingren, J. L., and Hill, D. W. (2020). Determining MAOD using a single exhaustive severe intensity test. *Int. J. Exerc. Sci.* 13, 702–713.

Zagatto, A., Redkva, P., Loures, J., Kalva-Filho, C., Franco, V., Kaminagakura, E., et al. (2011). Anaerobic contribution during maximal anaerobic running test: correlation with maximal accumulated oxygen deficit. *Scand. J. Med. Sci. Sports* 21, e222–e230. doi: 10.1111/j.1600-0838.2010.01258.x

Zagatto, A. M., Bertuzzi, R., Miyagi, W. E., Padulo, J., and Papoti, M. (2016). MAOD determined in a single supramaximal test: a study on the reliability and effects of supramaximal intensities. *Int. J. Sports Med.* 37, 700–707. doi: 10.1055/s-0042-104413

Zagatto, A. M., Nakamura, F. Y., Milioni, F., Miyagi, W. E., de Poli, R. A., Padulo, J., et al. (2017). The sensitivity of the alternative maximal accumulated oxygen deficit method to discriminate training status. *J. Sports Sci.* 35, 2453–2460. doi: 10.1080/02640414.2016.1273539

Zamparo, P., Capelli, C., Cautero, M., and Di Nino, A. (2000). Energy cost of front-crawl swimming at supra-maximal speeds and underwater torque in young swimmers. *Eur. J. Appl. Physiol.* 83, 487–491. doi: 10.1007/s004210000318

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Are the 50 m Race Segments Changed From Heats to Finals at the 2021 European Swimming Championships?

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This study explored in the 50 m races of the four swimming strokes the performance parameters and/or technical variables that determined the differences between swimmers who reach the finals and those who do not. A total of 322 performances retrieved from the 2021 Budapest European championships were the focus of this study. The results of the performances achieved during the finals compared to the heats showed that the best swimmers did not excel during the heats, as a significant progression of performance was observed in most of the strokes as the competition progressed. Specifically, combining men and women, the swimmers had in freestyle a mean coefficient of variation (CV) of ~0.6%, with a mean range of performance improvement (Δ%) of Δ = ~0.7%; in breaststroke a mean CV of ~0.5% and Δ = −0.2%; in backstroke a mean CV of ~0.5% and Δ = −0.6%, and; in butterfly a mean CV of ~0.7% and Δ = −0.9%. For all strokes, it was a reduction of the underwater phase with the aim of increasing its speed. However, this result was not always transferred to the final performance. In any case, most of the swimmers tried to make improvements from the start of the race up to 15 m. Furthermore, the swimmers generated an overall increase in stroke rate as the rounds progressed. However, a decrease in stroke length resulted and, this balance appeared to be of little benefit to performance.

Keywords: race analysis, sprint swimming, start, performance, technique, kinematic

1 INTRODUCTION

In the sport of swimming, race analysis, when combined with video sequences, provides crucial information in the development of swimmers' performance (Gonjo and Olstad, 2021). Therefore, race performances are often analyzed during or after a championship and compared with those of other events to conduct changes in race strategy or technique for the enhancement of future events (Arellano et al., 1994; Marinho et al., 2009). In this sense, during major championships is required that swimmers qualify from the initial round (heats) to the following rounds (semi-finals and/or finals) (Tijani Jed et al., 2021; Cuenca-Fernández et al., 2021b), which means that individual performances may differ. In this regard, while the literature has provided sufficient information on the differences between strokes or distances (Morais et al., 2019; Gonjo and Olstad, 2021), or performance variability in middle- and long-distance swimming events (Hopkins et al., 1999; Skorski et al., 2013; Skorski et al., 2014), no attention has been paid to different strokes of the shorter sprint events (i.e., 50 m freestyle, breaststroke, backstroke and butterfly), probably due to only sprint freestyle is included in the Olympic swimming events list.

A widely held notion in international swimming is that progression between rounds is necessary to ensure that a swimmer qualifies from the heats to the semi-finals and then to the final, when medals are decided (Mujika et al., 2019). For instance, swimmers who participated at the 2004 Athens Olympics were 0.58% slower compared to their qualifying times (Issurin et al., 2008); however, medallists and finalists were able to progress between rounds by 0.35 and 0.12%, respectively. On this variability in performance, known as the intra-athlete coefficient of variation (CV), it has previously been reported that in closely matched competitions where swimmers strive to win a medal or reach a final, they must improve their performance by at least ~0.5% for that change to have an impact on performance (Stewart and Hopkins, 2000; Trewin et al., 2004). In this regard, a CV of ~0.5 and –0.6% was observed in United States and Australian Olympic swimmers in 50 and 100 m freestyle, respectively (Pyne et al., 2004). Thus, considering the evolution and all the rules' modifications in the last 15 years, it is necessary to know whether these variations would occur nowadays in a sample of international swimmers. If so, this raises the question of where do swimmers manage such changes over the race?

In short-duration sports, such as the 50 m swimming, an all-out strategy is often employed (Abbiss and Laursen, 2008; McGibbon et al., 2018; Morais et al., 2021); despite the short duration, fatigue evoke a decrease in swim speed throughout the race (Morais et al., 2021). In this regard, planning and executing a proper race strategy is a key factor to excel in competitive swimming (Morais et al., 2019). It was recently shown that during the European Swimming Championships 2021, swimmers competing in the 100 and 200 m events progressed in their performance from round to round by increasing performance in the first key-moments of the race (Cuenca-Fernández et al., 2021b), indicating that the fastest swimmers did not perform at their best from the very beginning until they were trying to reach the final or win a medal. This strategy was suggested as a possible way to save energy that could allow swimmers to excel when needed (Stewart and Hopkins, 2000; (Cuenca-Fernández et al., 2021b). Indeed, achieving high performance in competitive swimming requires striking a fine balance between stability and variability of performance because, although swimmers need to achieve consistent results, they also need to be able to successfully adapting their stroke parameters to changes in the performance environment (such as the level of the other contenders) (Simbaña-Escobar et al., 2018). Therefore, although the strategy during the 50 m has previously been indicated as a rapid acceleration at the start followed by a progressive reduction in swim speed throughout the race (McGibbon et al., 2018; Morais et al., 2021), it is unknown whether this strategy happens in all rounds (e.g., even during the heats).

Swimming is a cyclic sport, yet its performance should not be conceived as a whole, but as a series of different segments that make up the race and that depend on different biomechanical and physiological adaptations (Hay et al., 1983; Marinho et al., 2009). The start, the clean swim, and the finish are the three main segments that make up the 50 m race (Gonjo and Olstad, 2021). However, such analysis can be even more detailed. E.g., the lap time can be divided into sub-sections including the split times, the time from 25 to 50 m (Morais et al., 2021), and the underwater phase. Furthermore, considering that the velocity of swimming is determined by the interplay between the stroke rate and the stroke length (Wakayoshi et al., 1995), the analysis of these stroke patterns may provide additional insights into the final results (Sánchez, Arellano, and Cuenca-Fernández, 2021). On the other hand, given that the best swimmers would be trying to perform at their best during the finals compared to the early rounds of competition, these variables could entail intentional modifications between rounds aimed to progress in performance. Therefore, analysis of each of these segments could provide further information on how swimmers are able to improve their performance throughout the rounds, i.e., progression within competition, in the four different swimming strokes. For that reason, this study aimed to: 1) study the coefficient of variation (CV) and performance progress (%Δ) in total time (i.e., T50) in the four different swimming strokes, and; 2) specifically analyze which of the race segments and stroke variables are most modified to achieve improvement across the rounds. It was hypothesized that performance would improve over the rounds, and that these changes would be a consequence of the improvement in the performance variables corresponding to the different segments of the race.

2 MATERIALS AND METHODS

2.1 Participants

European swimmers who competed in 50 m individual events at the 2021 Budapest European championships were the focus of this study. As some swimmers competed in more than one event, a total of 322 performances including 56 males (23.78 ± 3.25 years) and 60 females (24.66 ± 4.12 years) were analyzed. Data were gathered from the finalists (eight finalists x three rounds (i.e., heats, semi-final, and final) x four strokes (i.e., butterfly, backstroke, breaststroke, and freestyle) x two sexes (i.e., male and female)), and semi-finalists (16 semifinalists x two rounds (i.e., heats, semi-final) x four strokes (i.e., butterfly, backstroke, breaststroke, and freestyle) x two sexes (i.e., male and female). In one of the 50 butterfly semi-final there was a last-minute withdrawal, but there were two reserves who did not make the tiebreaker, thus, there were nine semifinalists.

2.2 Data Collection

Swimmers' information and the official race times were retrieved from the official publicly available Budapest 2021 European Championships swimming website (http://len.eu). As this study was a retrospective analysis of publicly available data, without any experimental intervention, informed consent and ethical approval from the local committee was not required.

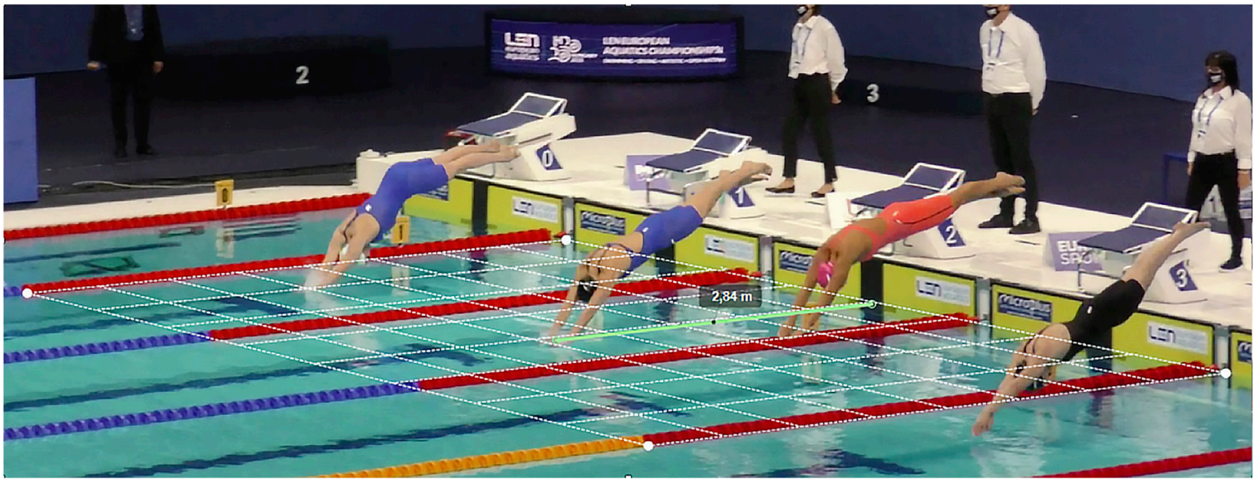

FIGURE 1 | Basic graphical description of the procedure for measuring the swimmer's entry distance into the water after the start. Similar procedures were used to measure emersion distance.

For each event, the results and changes in performance during the three rounds (i.e., heats, semi-finals, and final) were collected to analyse the process of sports performance. A Web Scraping routine in *Python*® was implemented to obtain the official data. The information was then checked by two independent researchers. To accomplish the first aim, the following variables were calculated using the final times:

- The intra-athlete CV: which represents the random variation in performance between rounds (Hopkins et al., 1999). Three different intra-athlete CVs were obtained: 1) between heats and semi-finals (H-SF); 2) between semi-finals and finals (SF-F), and; 3) between heats and finals (H-F), including all three rounds, total times and performance variables. The CV was calculated using the following equation:

$$\boldsymbol{CV} = \frac{\boldsymbol{Standard\ deviation\ (e.g.,\ \ SF\ and\ F)}}{\boldsymbol{Mean\ \ (e.g.,\ \ SF\ and\ F)}} \times \mathbf{100} \quad (1)$$

- Relative change (%Δ) in performance variables was calculated between rounds using the following equation:

$$\%\Delta = \frac{\boldsymbol{Round}\ 2\ \boldsymbol{performance} - \boldsymbol{Round}\ 1\ \boldsymbol{performance}}{\boldsymbol{Round}\ 1\ \boldsymbol{performance}} \times \mathbf{100} \quad (2)$$

where, *Round 2 performance* refers to the race time achieved on the second round and *Round 1 performance* refers to the race time achieved on the previous round. The criterion for performance progression, no change, or regression was %Δ being lower, equal, or higher than 0, respectively (Mujika et al., 2019).

The performance variables were obtained through indirect photogrammetric methodology, analysing the videos of the swimmer's performance. This is an indispensable strategy and a major tool for coaches, analysts and researchers to collect qualitative and quantitative data (Smith et al., 2002; O'Donoghue, 2006). All the videos analysed were provided by the championship organisation. A set of 10 pan-tilt-zoom cameras, one for each lane, tracked the swimmer during the race. The video setup included fullHD cameras (1920 × 1,080 pixels resolution, f = 50 Hz Each lane (for each swimmer) had a pan-tilt-zoom camera (Panasonic HC-X1,000 Hybrid O.I.S 4K) tracking the swimmers. Hence, each camera (one per lane) followed along the swimming pool back and forth each swimmer. A calibration zone was defined using the red buoys of the pool lane as a reference (i.e., a distance of 5 m) to correct for the effect of camera position and perspective (**Figure 1**). A detailed description of the scaling procedures and the calculation of the measurement accuracy can be found in one of the **Supplementary Material** documents. The starting lights, which were visible from all the cameras, were used to synchronized the official timer with the time-stamp on the race analysis (Morais et al., 2019). The swimmer's data was obtained after detailed observations by four evaluators through in-house customized software for performance analysis. The Intra-class Correlation Coefficient (ICC) was computed to verify the agreement among evaluators ($n = 4$). This ranged between 0.989 and 0.999, showing high agreement.

2.3 Performance Variables

The following variables were measured: Start variables: 1) Reaction time: Defined as the time in seconds (s) from the starting signal until the swimmer moves into the block. Taken from the official results. 2) Flight time: Defined as the time in seconds (s) from when the swimmer leaves the block until the hand touches the water after the start. 3) Entry distance: Defined as the distance in meters (m) between the block wall and the point where the hand touches the water. 4) Underwater time (Und Time): The time in seconds (s) from when the swimmer hand's touch the water until the swimmer's head comes out of the water, or if this is not appreciable, when the hands meet at the midpoint of the first stroke. 5) Underwater distance (Und Distance): The distance in meters (m) covered during the underwater phase

TABLE 1 | Freestyle performance variables' results, *p* values, and effect sizes (η^2) between the different three rounds. Men (M); Women (W) (LEN European Senior Championships 2021).

Reaction time (s)		**Heat**	**Semi-final**	**Final**	**Anova**	**η^2**	**H-SF**	**SF-F**	**H-F**
M	Semifinalist	0.64 ± 0.02	0.63 ± 0.03	-	-	-	0.892	-	-
	Finalist	0.64 ± 0.04	0.62 ± 0.06	0.63 ± 0.03	0.131	0.21	0.041	0.671	0.181
W	Semifinalist	0.65 ± 0.04	0.64 ± 0.04	-	-	-	0.669	-	-
	Finalist	0.66 ± 0.03	0.65 ± 0.02	0.65 ± 0.02	0.670	0.08	0.340	0.557	0.286
Flight time (s)		**Heat**	**Semi-final**	**Final**	**Anova**	**η^2**	**H-SF**	**SF-F**	**H-F**
M	Semifinalist	0.32 ± 0.04	0.33 ± 0.03	-	-	-	0.892	-	-
	Finalist	0.34 ± 0.03	0.35 ± 0.05	0.32 ± 0.05	0.422	0.26	0.999	0.156	0.088
W	Semifinalist	0.29 ± 0.06	0.20 ± 0.34	-	-	-	0.623	-	-
	Finalist	0.28 ± 0.05	0.29 ± 0.04	0.25 ± 0.06	0.003	0.60	0.171	0.012	0.017
Entry distance (m)		**Heat**	**Semi-final**	**Final**	**Anova**	**η^2**	**H-SF**	**SF-F**	**H-F**
M	Semifinalist	3.71 ± 0.18	3.75 ± 0.16	-	-	-	0.524	-	-
	Finalist	3.71 ± 0.19	3.68 ± 0.20	3.68 ± 0.14	0.651	0.13	0.157	0.999	0.480
W	Semifinalist	3.23 ± 0.19	3.26 ± 0.14	-	-	-	0.414	-	-
	Finalist	3.12 ± 0.26	3.21 ± 0.14	3.20 ± 0.24	0.393	0.09	0.073	0.999	0.484
Underwater Time (s)		**Heat**	**Semi-final**	**Final**	**Anova**	**η^2**	**H-SF**	**SF-F**	**H-F**
M	Semifinalist	2.79 ± 0.64	2.61 ± 0.81	-	-	-	0.123	-	-
	Finalist	2.50 ± 0.70	2.52 ± 0.70	2.41 ± 0.66	0.180	0.31	0.611	0.091	0.150
W	Semifinalist	3.42 ± 0.83	3.55 ± 0.73	-	-	-	0.726	-	-
	Finalist	3.47 ± 0.64	3.47 ± 0.73	3.44 ± 0.49	0.542	0.06	0.999	0.866	0.833
Underwater Distance (m)		**Heat**	**Semi-final**	**Final**	**Anova**	**η^2**	**H-SF**	**SF-F**	**H-F**
M	Semifinalist	7.68 ± 1.40	7.42 ± 1.90	-	-	-	0.483	-	-
	Finalist	7.07 ± 1.83	7.37 ± 1.75	7.00 ± 1.70	0.206	0.32	0.182	0.049	0.778
W	Semifinalist	8.60 ± 1.91	8.36 ± 1.66	-	-	-	0.483	-	-
	Finalist	8.69 ± 1.35	8.71 ± 1.80	8.91 ± 0.91	0.607	0.04	0.999	0.778	0.484
Underwater Speed (m/s)		**Heat**	**Semi-final**	**Final**	**Anova**	**η^2**	**H-SF**	**SF-F**	**H-F**
M	Semifinalist	2.81 ± 0.16	2.93 ± 0.26	-	-	-	0.062	-	-
	Finalist	2.84 ± 0.11	2.97 ± 0.30	2.94 ± 0.21	0.208	0.07	0.061	0.340	0.099
W	Semifinalist	2.52 ± 0.13	2.43 ± 0.16	-	-	-	0.059	-	-
	Finalist	2.51 ± 0.13	2.43 ± 0.16	2.60 ± 1.51	0.196	0.58	0.052	0.019	0.152
Time 15 m (s)		**Heat**	**Semi-final**	**Final**	**Anova**	**η^2**	**H-SF**	**SF-F**	**H-F**
M	Semifinalist	5.38 ± 0.14	5.42 ± 0.12	-	-	-	0.309	-	-
	Finalist	5.36 ± 0.06	5.33 ± 0.07	5.34 ± 0.07	0.717	0.07	0.293	0.670	0.670
W	Semifinalist	6.20 ± 0.12	6.16 ± 0.14	-	-	-	0.088	-	-
	Finalist	6.12 ± 0.17	6.05 ± 0.13	6.01 ± 0.18	0.004	0.59	0.027	0.176	0.011
Time 25 m (s)		**Heat**	**Semi-final**	**Final**	**Anova**	**η^2**	**H-SF**	**SF-F**	**H-F**
M	Semifinalist	10.06 ± 0.13	10.05 ± 0.11	-	-	-	0.888	-	-
	Finalist	9.99 ± 0.07	9.87 ± 0.08	9.91 ± 0.14	0.066	0.33	0.027	0.399	0.207
W	Semifinalist	11.48 ± 0.12	11.42 ± 0.10	-	-	-	0.141	-	-
	Finalist	11.32 ± 0.13	11.20 ± 0.11	11.08 ± 0.15	0.001	0.91	0.012	0.012	0.11
Time 35 m (s)		**Heat**	**Semi-final**	**Final**	**Anova**	**η^2**	**H-SF**	**SF-F**	**H-F**
M	Semifinalist	14.80 ± 0.13	14.86 ± 0.10	-	-	-	0.271	-	-
	Finalist	14.68 ± 0.12	14.62 ± 0.10	14.67 ± 0.18	0.648	0.09	0.235	0.528	0.865
W	Semifinalist	16.85 ± 0.09	16.74 ± 0.09	-	-	-	0.017	-	-
	Finalist	16.61 ± 0.16	16.40 ± 0.14	16.34 ± 0.17	0.002	0.89	0.012	0.036	0.011
Time 45 m (s)		**Heat**	**Semi-final**	**Final**	**Anova**	**η^2**	**H-SF**	**SF-F**	**H-F**
M	Semifinalist	19.66 ± 0.10	19.79 ± 0.15	-	-	-	0.068	-	-
	Finalist	19.50 ± 0.14	19.45 ± 0.13	19.50 ± 0.19	0.542	0.09	0.310	0.528	0.944
W	Semifinalist	22.34 ± 0.10	22.25 ± 0.13	-	-	-	0.058	-	-
	Finalist	21.97 ± 0.22	21.74 ± 0.22	21.71 ± 0.26	0.002	0.81	0.012	0.482	0.012
Time 50 m (s)		**Heat**	**Semi-final**	**Final**	**Anova**	**η^2**	**H-SF**	**SF-F**	**H-F**
M	Semifinalist	22.13 ± 0.09	22.14 ± 0.10	-	-	-	0.833	-	-
	Finalist	21.96 ± 0.12	21.78 ± 0.11	21.84 ± 0.18	0.053	0.42	0.017	0.398	0.093
W	Semifinalist	25.00 ± 0.11	24.97 ± 0.14	-	-	-	0.292	-	-
	Finalist	24.57 ± 0.22	24.40 ± 0.22	24.34 ± 0.24	0.002	0.78	0.012	0.159	0.012

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TABLE 1 | (*Continued*) Freestyle performance variables' results, *p* values, and effect sizes (η^2) between the different three rounds. Men (M); Women (W) (LEN European Senior Championships 2021).

Finish time (s)		Heat	Semi-final	Final	Anova	η^2	H-SF	SF-F	H-F
M	Semifinalist	2.47 ± 0.08	2.34 ± 0.09	-	-	-	0.025	-	-
	Finalist	2.45 ± 0.05	2.33 ± 0.07	2.34 ± 0.06	0.002	0.72	0.012	0.888	0.012
W	Semifinalist	2.65 ± 0.07	2.72 ± 0.09	-	-	-	0.051	-	-
	Finalist	2.60 ± 0.05	2.66 ± 0.07	2.63 ± 0.07	0.197	0.23	0.078	0.141	0.483
Split 25–50 m (s)		**Heat**	**Semi-final**	**Final**	**Anova**	η^2	**H-SF**	**SF-F**	**H-F**
M	Semifinalist	12.07 ± 0.10	12.08 ± 0.13	-	-	-	0.779	-	-
	Finalist	11.96 ± 0.08	11.91 ± 0.06	11.92 ± 0.07	0.223	0.18	0.049	0.440	0.725
W	Semifinalist	13.52 ± 0.10	13.54 ± 0.09	-	-	-	0.726	-	-
	Finalist	13.25 ± 0.12	13.19 ± 0.15	13.25 ± 0.13	0.036	0.34	0.018	0.068	0.833
SR15-25 m (cic/min)		**Heat**	**Semi-final**	**Final**	**Anova**	η^2	**H-SF**	**SF-F**	**H-F**
M	Semifinalist	61.76 ± 3.58	62.54 ± 3.83	-	-	-	0.779	-	-
	Finalist	61.85 ± 1.09	63.09 ± 1.98	63.04 ± 1.97	0.009	0.60	0.012	0.889	0.025
W	Semifinalist	62.24 ± 3.53	62.05 ± 2.79	-	-	-	0.499	-	-
	Finalist	60.87 ± 3.27	62.12 ± 3.37	62.03 ± 3.64	0.239	0.40	0.028	0.779	0.123
SR35-45 m (cic/min)		**Heat**	**Semi-final**	**Final**	**Anova**	η^2	**H-SF**	**SF-F**	**H-F**
M	Semifinalist	58.83 ± 3.31	59.77 ± 3.44	-	-	-	0.069	-	-
	Finalist	59.37 ± 2.18	60.15 ± 1.97	60.88 ± 2.29	0.107	0.29	0.091	0.237	0.123
W	Semifinalist	59.07 ± 3.64	59.32 ± 3.25	-	-	-	0.401	-	-
	Finalist	56.90 ± 2.29	57.64 ± 2.39	58.55 ± 2.84	0.011	0.60	0.036	0.036	0.017
SR finish (cic/min)		**Heat**	**Semi-final**	**Final**	**Anova**	η^2	**H-SF**	**SF-F**	**H-F**
M	Semifinalist	57.93 ± 2.55	58.11 ± 3.89	-	-	-	0.917	-	-
	Finalist	57.48 ± 2.96	58.12 ± 2.43	59.77 ± 2.27	0.303	0.27	0.484	0.050	0.123
W	Semifinalist	56.88 ± 3.64	57.59 ± 2.71	-	-	-	0.310	-	-
	Finalist	55.13 ± 2.99	55.68 ± 2.82	55.93 ± 3.18	0.497	0.05	0.484	0.735	0.484
SL15-25 m (m)		**Heat**	**Semi-final**	**Final**	**Anova**	η^2	**H-SF**	**SF-F**	**H-F**
M	Semifinalist	2.08 ± 0.11	2.07 ± 0.13	-	-	-	0.779	-	-
	Finalist	2.09 ± 0.06	2.09 ± 0.06	2.08 ± 0.05	0.417	0.20	0.889	0.161	0.161
W	Semifinalist	3.75 ± 0.38	1.82 ± 0.08	-	-	-	0.889	-	-
	Finalist	1.89 ± 0.09	1.87 ± 0.08	1.91 ± 0.09	0.197	0.18	0.208	0.069	0.674
SL35-45 m (m)		**Heat**	**Semi-final**	**Final**	**Anova**	η^2	**H-SF**	**SF-F**	**H-F**
M	Semifinalist	2.16 ± 0.12	2.09 ± 0.12	-	-	-	0.093	-	-
	Finalist	2.15 ± 0.08	2.10 ± 0.05	2.07 ± 0.06	0.072	0.52	0.036	0.123	0.036
W	Semifinalist	1.82 ± 0.09	1.90 ± 0.11	-	-	-	0.575	-	-
	Finalist	1.99 ± 0.07	2.00 ± 0.07	1.95 ± 0.08	0.034	0.06	0.401	0.017	0.025
SL finish (m)		**Heat**	**Semi-final**	**Final**	**Anova**	η^2	**H-SF**	**SF-F**	**H-F**
M	Semifinalist	2.10 ± 0.16	2.21 ± 0.80	-	-	-	0.025	-	-
	Finalist	2.13 ± 0.11	2.21 ± 0.08	2.14 ± 0.09	0.223	0.24	0.123	0.050	0.779
W	Semifinalist	1.89 ± 0.13	1.92 ± 0.14	-	-	-	0.050	-	-
	Finalist	2.09 ± 0.12	2.03 ± 0.13	2.05 ± 0.14	0.417	0.18	0.093	0.401	0.327

Heat, semi-final, and final (H, SF, and F); stroke rate and length (SR and SL).

defined previously. 6) Underwater speed (Und Speed): Obtained by dividing the underwater distance by the time to cover it ($m{\cdot}s^{-1}$).

Race segments variables: Time 15–50 m (T15 to T50): Defined as the time in seconds (s), from the starting signal, until the swimmer's head crosses the 1) 15, 2) 25, 2) 35, 4) 45 and 5) 50 m mark (the last one was obtained from the official competition results). 6) Finish time: Defined as the time in seconds (s), from 45 to 50 m. 7) Split25-50 m: Defined as the time in seconds (s), elapsed from 25 to 50 m.

Stroking variables (1,2) Stroke rate (SR): Collected at 15–25 and 35–45 m mark, were obtained using frequency measuring function for each 3 arm strokes and divided by the time elapsed during this action (to obtain the rate in Hertz), and multiplied by 60 (to obtain the rate in cycles/min), 3) final SR: Collected at 45–50 m mark, were obtained using frequency measuring function for each 2 arm strokes and divided by the time elapsed during this action (to obtain the rate in Hertz), and multiplied by 60 (to obtain the rate in cycles/min) (4, 5) average Stroke length (aSL): Collected at 15–25 and 35–45 m mark, were obtained by dividing the mean speed by the mean SR (in Hertz) (to obtain the length in meters/cycle), 6) final SL: Collected at 45–50 m mark, were obtained by dividing the mean speed by the

TABLE 2 | Backstroke performance variables' results, *p* values, and effect sizes (η^2) between the different three rounds. Men (M); Women (W) (LEN European Senior Championships 2021).

Reaction time (s)		**Heat**	**Semi-final**	**Final**	**Anova**	η^2	**H-SF**	**SF-F**	**H-F**
M	Semifinalist	0.58 ± 0.03	0.58 ± 0.03	-	-	-	0.550	-	-
	Finalist	0.57 ± 0.05	0.57 ± 0.05	0.56 ± 0.05	0.331	0.19	0.245	0.389	0.121
W	Semifinalist	0.58 ± 0.02	0.57 ± 0.02	-	-	-	0.135	-	-
	Finalist	0.58 ± 0.05	0.57 ± 0.04	0.57 ± 0.04	0.738	0.07	0.480	0.595	0.416
Flight time (s)		**Heat**	**Semi-final**	**Final**	**Anova**	η^2	**H-SF**	**SF-F**	**H-F**
M	Semifinalist	0.09 ± 0.05	0.08 ± 0.06	-	-	-	0.210	-	-
	Finalist	0.13 ± 0.05	0.13 ± 0.06	0.11 ± 0.06	0.239	0.28	0.546	0.047	0.287
W	Semifinalist	0.08 ± 0.03	0.10 ± 0.04	-	-	-	0.062	-	-
	Finalist	0.10 ± 0.03	0.10 ± 0.04	0.11 ± 0.06	0.966	0.01	0.999	0.863	0.723
Entry distance (m)		**Heat**	**Semi-final**	**Final**	**Anova**	η^2	**H-SF**	**SF-F**	**H-F**
M	Semifinalist	2.60 ± 0.22	2.71 ± 0.18	-	-	-	0.091	-	-
	Finalist	2.88 ± 0.11	2.87 ± 0.10	2.91 ± 0.07	0.311	0.15	0.317	0.216	0.450
W	Semifinalist	2.37 ± 0.11	2.38 ± 0.09	-	-	-	0.705	-	-
	Finalist	2.48 ± 0.13	2.53 ± 0.11	2.48 ± 0.12	0.446	0.01	0.498	0.671	0.865
Underwater Time (s)		**Heat**	**Semi-final**	**Final**	**Anova**	η^2	**H-SF**	**SF-F**	**H-F**
M	Semifinalist	4.88 ± 0.41	4.89 ± 0.32	-	-	-	0.779	-	-
	Finalist	4.67 ± 0.22	4.74 ± 0.25	4.56 ± 0.24	0.223	0.23	0.528	0.067	0.263
W	Semifinalist	5.63 ± 0.13	5.59 ± 0.18	-	-	-	0.528	-	-
	Finalist	5.63 ± 0.23	5.55 ± 0.35	5.48 ± 0.36	0.131	0.26	0.263	0.263	0.092
Underwater Distance (m)		**Heat**	**Semi-final**	**Final**	**Anova**	η^2	**H-SF**	**SF-F**	**H-F**
M	Semifinalist	11.41 ± 0.88	11.53 ± 1.12	-	-	-	0.779	-	-
	Finalist	10.79 ± 0.60	11.13 ± 0.64	10.71 ± 0.57	0.131	0.35	0.028	0.035	0.622
W	Semifinalist	11.42 ± 0.83	11.38 ± 0.58	-	-	-	0.889	-	-
	Finalist	11.56 ± 0.30	11.58 ± 0.55	11.33 ± 0.62	0.197	0.19	0.833	0.262	0.159
Underwater Speed (m/s)		**Heat**	**Semi-final**	**Final**	**Anova**	η^2	**H-SF**	**SF-F**	**H-F**
M	Semifinalist	2.32 ± 0.06	2.34 ± 0.10	-	-	-	0.241	-	-
	Finalist	2.30 ± 0.04	2.34 ± 0.05	2.35 ± 0.06	0.091	0.64	0.128	0.325	0.022
W	Semifinalist	2.04 ± 0.06	2.06 ± 0.07	-	-	-	0.365	-	-
	Finalist	2.05 ± 0.06	2.08 ± 0.08	2.06 ± 0.07	0.452	0.32	0.358	0.681	0.805
Time 15 m (s)		**Heat**	**Semi-final**	**Final**	**Anova**	η^2	**H-SF**	**SF-F**	**H-F**
M	Semifinalist	6.09 ± 0.14	6.09 ± 0.20	-	-	-	0.999	-	-
	Finalist	6.09 ± 0.11	5.98 ± 0.13	5.97 ± 0.12	0.030	0.64	0.035	0.933	0.012
W	Semifinalist	7.05 ± 0.19	7.03 ± 0.20	-	-	-	0.672	-	-
	Finalist	6.92 ± 0.20	6.80 ± 0.24	6.88 ± 0.24	0.036	0.33	0.018	0.093	0.441
Time 25 m (s)		**Heat**	**Semi-final**	**Final**	**Anova**	η^2	**H-SF**	**SF-F**	**H-F**
M	Semifinalist	11.38 ± 0.15	11.41 ± 0.21	-	-	-	0.307	-	-
	Finalist	11.34 ± 0.13	11.21 ± 0.15	11.16 ± 0.13	0.003	0.80	0.017	0.063	0.012
W	Semifinalist	13.00 ± 0.17	12.99 ± 0.24	-	-	-	0.574	-	-
	Finalist	12.81 ± 0.17	12.66 ± 0.23	12.73 ± 0.22	0.025	0.43	0.018	0.091	0.176
Time 35 m (s)		**Heat**	**Semi-final**	**Final**	**Anova**	η^2	**H-SF**	**SF-F**	**H-F**
M	Semifinalist	16.81 ± 0.08	16.87 ± 0.13	-	-	-	0.078	-	-
	Finalist	16.67 ± 0.19	16.51 ± 0.20	16.42 ± 0.17	0.002	0.81	0.025	0.021	0.012
W	Semifinalist	19.04 ± 0.15	19.07 ± 0.30	-	-	-	0.674	-	-
	Finalist	18.79 ± 0.24	18.59 ± 0.23	18.63 ± 0.21	0.021	0.50	0.012	0.483	0.092
Time 45 m (s)		**Heat**	**Semi-final**	**Final**	**Anova**	η^2	**H-SF**	**SF-F**	**H-F**
M	Semifinalist	22.41 ± 0.08	22.47 ± 0.13	-	-	-	0.088	-	-
	Finalist	22.13 ± 0.30	21.93 ± 0.29	21.86 ± 0.29	0.001	0.72	0.018	0.092	0.012
W	Semifinalist	25.22 ± 0.12	25.27 ± 0.33	-	-	-	0.933	-	-
	Finalist	24.83 ± 0.29	24.63 ± 0.28	24.72 ± 0.27	0.044	0.50	0.012	0.141	0.123
Time 50 m (s)		**Heat**	**Semi-final**	**Final**	**Anova**	η^2	**H-SF**	**SF-F**	**H-F**
M	Semifinalist	25.10 ± 0.11	24.25 ± 1.13	-	-	-	0.499	-	-
	Finalist	24.80 ± 0.36	24.64 ± 0.34	24.59 ± 0.37	0.072	0.55	0.050	0.139	0.017
W	Semifinalist	28.24 ± 0.12	28.34 ± 0.37	-	-	-	0.575	-	-
	Finalist	27.88 ± 0.33	27.69 ± 0.32	27.78 ± 0.26	0.016	0.45	0.012	0.075	0.161

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TABLE 2 | (*Continued*) Backstroke performance variables' results, *p* values, and effect sizes (η^2) between the different three rounds. Men (M); Women (W) (LEN European Senior Championships 2021).

Finish time (s)		Heat	Semi-final	Final	Anova	η^2	H-SF	SF-F	H-F
M	Semifinalist	2.60 ± 0.07	2.75 ± 0.07	-	-	-	0.035	-	-
	Finalist	2.66 ± 0.07	2.70 ± 0.07	2.72 ± 0.11	0.197	0.19	0.049	0.889	0.326
W	Semifinalist	3.02 ± 0.06	3.07 ± 0.07	-	-	-	0.012	-	-
	Finalist	3.01 ± 0.05	3.05 ± 0.06	3.05 ± 0.09	0.223	0.14	0.079	0.575	0.233
Split 25–50 m (s)		**Heat**	**Semi-final**	**Final**	**Anova**	η^2	**H-SF**	**SF-F**	**H-F**
M	Semifinalist	13.71 ± 0.23	13.81 ± 0.24	-	-	-	0.012	-	-
	Finalist	13.45 ± 0.30	13.42 ± 0.28	13.43 ± 0.31	0.798	0.03	0.623	0.726	0.779
W	Semifinalist	15.24 ± 0.17	15.35 ± 0.25	-	-	-	0.080	-	-
	Finalist	15.06 ± 0.25	15.02 ± 0.24	15.04 ± 0.25	0.197	0.14	0.079	0.622	0.441
SR15-25 m (cic/min)		**Heat**	**Semi-final**	**Final**	**Anova**	η^2	**H-SF**	**SF-F**	**H-F**
M	Semifinalist	57.06 ± 3.39	57.95 ± 2.89	-	-	-	0.063	-	-
	Finalist	56.60 ± 2.74	57.01 ± 2.61	57.85 ± 3.35	0.005	0.40	0.093	0.093	0.036
W	Semifinalist	56.18 ± 2.67	56.20 ± 2.52	-	-	-	0.401	-	-
	Finalist	53.51 ± 2.21	53.78 ± 2.61	54.41 ± 3.01	0.131	0.39	0.400	0.036	0.069
SR35-45 m (cic/min)		**Heat**	**Semi-final**	**Final**	**Anova**	η^2	**H-SF**	**SF-F**	**H-F**
M	Semifinalist	54.10 ± 3.87	54.69 ± 2.91	-	-	-	0.401	-	-
	Finalist	54.01 ± 2.76	54.65 ± 2.31	55.65 ± 3.29	0.008	0.57	0.028	0.036	0.017
W	Semifinalist	54.21 ± 2.36	54.34 ± 3.12	-	-	-	0.484	-	-
	Finalist	52.00 ± 2.99	52.58 ± 3.32	52.69 ± 3.38	0.215	0.21	0.327	0.398	0.043
SR finish (cic/min)		**Heat**	**Semi-final**	**Final**	**Anova**	η^2	**H-SF**	**SF-F**	**H-F**
M	Semifinalist	52.24 ± 2.07	53.24 ± 2.28	-	-	-	0.128	-	-
	Finalist	54.56 ± 3.27	53.27 ± 3.01	54.90 ± 3.36	0.485	0.19	0.173	0.176	0.779
W	Semifinalist	53.79 ± 2.54	53.63 ± 3.33	-	-	-	0.889	-	-
	Finalist	51.80 ± 3.92	51.65 ± 3.57	51.79 ± 3.27	0.582	0.01	0.917	0.833	0.753
SL15-25 m (m)		**Heat**	**Semi-final**	**Final**	**Anova**	η^2	**H-SF**	**SF-F**	**H-F**
M	Semifinalist	1.99 ± 0.10	1.95 ± 0.09	-	-	-	0.012	-	-
	Finalist	2.02 ± 0.09	2.01 ± 0.08	2.00 ± 0.10	0.607	0.05	0.674	0.779	0.575
W	Semifinalist	1.79 ± 0.07	1.79 ± 0.06	-	-	-	0.575	-	-
	Finalist	1.90 ± 0.08	1.91 ± 0.10	1.88 ± 0.11	0.417	0.19	0.674	0.093	0.263
SL35-45 m (m)		**Heat**	**Semi-final**	**Final**	**Anova**	η^2	**H-SF**	**SF-F**	**H-F**
M	Semifinalist	2.05 ± 0.13	2.01 ± 0.08	-	-	-	0.263	-	-
	Finalist	2.09 ± 0.11	2.07 ± 0.08	2.05 ± 0.11	0.197	0.23	0.327	0.208	0.123
W	Semifinalist	1.83 ± 0.08	1.81 ± 0.09	-	-	-	0.161	-	-
	Finalist	1.93 ± 0.11	1.92 ± 0.12	1.93 ± 0.11	0.882	0.04	0.674	0.575	0.999
SL finish (m)		**Heat**	**Semi-final**	**Final**	**Anova**	η^2	**H-SF**	**SF-F**	**H-F**
M	Semifinalist	1.92 ± 0.11	1.91 ± 0.14	-	-	-	0.735	-	-
	Finalist	2.06 ± 0.16	2.08 ± 0.10	2.01 ± 0.13	0.325	0.05	0.575	0.050	0.327
W	Semifinalist	1.84 ± 0.09	1.82 ± 0.11	-	-	-	0.575	-	-
	Finalist	1.93 ± 0.13	1.90 ± 0.11	1.90 ± 0.13	0.223	0.07	0.327	0.575	0.263

Heat, semi-final, and final (H, SF, and F); stroke rate and length (SR and SL).

mean SR (in Hertz) (to obtain the length in meters/cycle). The selected variables are noted by the literature on regular basis (Arellano et al., 1994; Mason and Cossor, 2000; Veiga et al., 2014; Morais et al., 2019; Gonjo and Olstad, 2021; Sánchez et al., 2021).

2.4 Statistical Analysis

The Shapiro-wilk and Levene test were used to verify the normality and homoscedasticity of the data, respectively. All analyses were conducted differentially by sex (Shapiro et al., 2021). Linear mixed-effects models were applied between rounds (e.g., heats, semi-finals, and final), for all swimmers and performance variables to estimate means (fixed effects) and within-swimmer variations (random effects, modelled as variances) in accordance with **Equation 1**, as explained in previous studies (Stewart and Hopkins, 2000; Pyne et al., 2004). The fixed main effects were event (50 m freestyle, breaststroke, backstroke and butterfly), performance variables (i.e., the ones presented in **Table 1**) and rounds (e.g., heats, semi-finals, and final). The performance variables between rounds were compared with repeated-measures ANOVA and the differences between pairs of rounds (e.g., SF to F) were verified with Bonferroni post-hoc test. The effect sizes (η^2) of the obtained variances were calculated and categorized (small = 0.01; medium = 0.06; large = 0.14). Pearson product-moment correlation coefficients (r) between all variables and times

TABLE 3 | Breaststroke performance variables' results, *p* values, and effect sizes (η^2) between the different three rounds. Men (M); Women (W) (LEN European Senior Championships 2021).

Reaction time (s)		**Heat**	**Semi-final**	**Final**	**Anova**	**η^2**	**H-SF**	**SF-F**	**H-F**
M	Semifinalist	0.65 ± 0.02	0.66 ± 0.02	-	-	-	0.202	-	-
	Finalist	0.65 ± 0.03	0.65 ± 0.03	0.65 ± 0.03	0.687	0.07	0.234	0.496	0.916
W	Semifinalist	0.67 ± 0.03	0.67 ± 0.04	-	-	-	0.865	-	-
	Finalist	0.69 ± 0.03	0.67 ± 0.02	0.67 ± 0.03	0.039	0.37	0.016	0.395	0.126
Flight time (s)		**Heat**	**Semi-final**	**Final**	**Anova**	**η^2**	**H-SF**	**SF-F**	**H-F**
M	Semifinalist	0.34 ± 0.01	0.34 ± 0.03	-	-	-	0.306	-	-
	Finalist	0.34 ± 0.05	0.34 ± 0.04	0.33 ± 0.04	0.236	0.19	0.305	0.336	0.121
W	Semifinalist	0.29 ± 0.04	0.28 ± 0.04	-	-	-	0.119	-	-
	Finalist	0.30 ± 0.03	0.31 ± 0.03	0.31 ± 0.05	0.961	0.16	0.914	0.680	0.932
Entry distance (m)		**Heat**	**Semi-final**	**Final**	**Anova**	**η^2**	**H-SF**	**SF-F**	**H-F**
M	Semifinalist	3.87 ± 0.08	3.86 ± 0.14	-	-	-	0.730	-	-
	Finalist	3.81 ± 0.25	3.72 ± 0.30	3.85 ± 0.18	0.595	0.09	0.553	0.309	0.461
W	Semifinalist	3.36 ± 0.43	3.16 ± 0.19	-	-	-	0.088	-	-
	Finalist	3.32 ± 0.12	3.26 ± 0.13	3.28 ± 0.20	0.582	0.05	0.357	0.751	0.671
Underwater Time (s)		**Heat**	**Semi-final**	**Final**	**Anova**	**η^2**	**H-SF**	**SF-F**	**H-F**
M	Semifinalist	4.83 ± 0.67	4.60 ± 0.45	-	-	-	0.123	-	-
	Finalist	4.73 ± 0.51	4.73 ± 0.56	4.53 ± 0.33	0.195	0.23	0.624	0.176	0.106
W	Semifinalist	4.62 ± 0.41	4.49 ± 0.51	-	-	-	0.034		
	Finalist	4.32 ± 0.46	4.32 ± 0.36	4.30 ± 0.35	0.197	0.04	0.889	0.624	0.362
Underwater Distance (m)		**Heat**	**Semi-final**	**Final**	**Anova**	**η^2**	**H-SF**	**SF-F**	**H-F**
M	Semifinalist	10.15 ± 1.41	9.90 ± 0.89	-	-	-	0.482	-	-
	Finalist	10.50 ± 0.70	10.35 ± 1.07	9.71 ± 0.83	0.104	0.37	0.726	0.080	0.035
W	Semifinalist	9.07 ± 0.67	9.07 ± 0.63	-	-	-	0.776	-	-
	Finalist	8.72 ± 0.72	8.80 ± 0.62	8.80 ± 0.46	0.291	0.02	0.726	0.865	0.114
Underwater Speed (m/s)		**Heat**	**Semi-final**	**Final**	**Anova**	**η^2**	**H-SF**	**SF-F**	**H-F**
M	Semifinalist	2.16 ± 0.18	2.17 ± 0.08	-	-	-	0.358	-	-
	Finalist	2.23 ± 0.22	2.19 ± 0.10	2.14 ± 0.11	0.131	0.01	0.526	0.070	0.036
W	Semifinalist	1.99 ± 0.11	2.03 ± 0.07	-	-	-	0.698	-	-
	Finalist	2.01 ± 0.09	2.03 ± 0.08	2.05 ± 0.06	0.291	0.17	0.702	0.751	0.242
Time 15 m (s)		**Heat**	**Semi-final**	**Final**	**Anova**	**η^2**	**H-SF**	**SF-F**	**H-F**
M	Semifinalist	6.29 ± 0.25	6.35 ± 0.19	-	-	-	0.362	-	-
	Finalist	6.23 ± 0.23	6.22 ± 0.24	6.21 ± 0.25	0.303	0.01	0.673	0.498	0.575
W	Semifinalist	7.57 ± 0.22	7.58 ± 0.20	-	-	-	0.866	-	-
	Finalist	7.56 ± 0.22	7.51 ± 0.24	7.47 ± 0.20	0.250	0.18	0.235	0.326	0.161
Time 25 m (s)		**Heat**	**Semi-final**	**Final**	**Anova**	**η^2**	**H-SF**	**SF-F**	**H-F**
M	Semifinalist	12.39 ± 0.13	12.30 ± 0.15	-	-	-	0.125	-	-
	Finalist	12.17 ± 0.22	12.09 ± 0.25	12.11 ± 0.30	0.417	0.11	0.091	0.483	0.400
W	Semifinalist	14.15 ± 0.17	14.05 ± 0.15	-	-	-	0.091	-	-
	Finalist	13.96 ± 0.25	13.90 ± 0.21	13.82 ± 0.17	0.073	0.43	0.183	0.048	0.034
Time 35 m (s)		**Heat**	**Semi-final**	**Final**	**Anova**	**η^2**	**H-SF**	**SF-F**	**H-F**
M	Semifinalist	18.38 ± 0.16	18.28 ± 0.13	-	-	-	0.092	-	-
	Finalist	18.03 ± 0.26	17.92 ± 0.27	17.97 ± 0.35	0.607	0.14	0.106	0.674	0.528
W	Semifinalist	20.78 ± 0.22	20.76 ± 0.17	-	-	-	0.573	-	-
	Finalist	20.41 ± 0.38	20.39 ± 0.36	20.23 ± 0.26	0.024	0.39	0.999	0.036	0.025
Time 45 m (s)		**Heat**	**Semi-final**	**Final**	**Anova**	**η^2**	**H-SF**	**SF-F**	**H-F**
M	Semifinalist	24.45 ± 0.24	24.38 ± 0.20	-	-	-	0.325	-	-
	Finalist	23.90 ± 0.35	23.86 ± 0.33	23.93 ± 0.45	0.542	0.06	0.400	0.499	0.673
W	Semifinalist	27.58 ± 0.35	27.63 ± 0.33	-	-	-	0.017	-	-
	Finalist	27.05 ± 0.44	26.90 ± 0.41	26.88 ± 0.44	0.093	0.40	0.042	0.833	0.042
Time 50 m (s)		**Heat**	**Semi-final**	**Final**	**Anova**	**η^2**	**H-SF**	**SF-F**	**H-F**
M	Semifinalist	27.44 ± 0.22	27.44 ± 0.22	-	-	-	0.933	-	-
	Finalist	26.89 ± 0.35	26.87 ± 0.35	26.95 ± 0.43	0.542	0.09	0.674	0.204	0.400
W	Semifinalist	31.00 ± 0.33	31.07 ± 0.23	-	-	-	0.233	-	-
	Finalist	30.45 ± 0.48	30.35 ± 0.47	30.26 ± 0.43	0.021	0.43	0.208	0.036	0.035

(Continued on following page)

TABLE 3 | (*Continued*) Breaststroke performance variables' results, *p* values, and effect sizes (η^2) between the different three rounds. Men (M); Women (W) (LEN European Senior Championships 2021).

Finish Time (s)		Heat	Semi-final	Final	Anova	η^2	H-SF	SF-F	H-F
M	Semifinalist	2.99 ± 0.07	3.06 ± 0.14	-	-	-	0.160	-	-
	Finalist	2.98 ± 0.12	3.01 ± 0.08	3.02 ± 0.16	0.417	0.06	0.484	0.889	0.161
W	Semifinalist	3.42 ± 0.08	3.44 ± 0.14	-	-	-	0.674	-	-
	Finalist	3.39 ± 0.15	3.45 ± 0.14	3.38 ± 0.09	0.607	0.18	0.182	0.183	0.726
Split 25–50 m (s)		**Heat**	**Semi-final**	**Final**	**Anova**	η^2	**H-SF**	**SF-F**	**H-F**
M	Semifinalist	15.05 ± 0.23	15.14 ± 0.28	-	-	-	0.049	-	-
	Finalist	14.71 ± 0.22	14.77 ± 0.20	14.84 ± 0.28	0.223	0.35	0.068	0.183	0.092
W	Semifinalist	16.85 ± 0.21	17.02 ± 0.16	-	-	-	0.035	-	-
	Finalist	16.49 ± 0.29	16.45 ± 0.33	16.44 ± 0.30	0.748	0.17	0.325	0.624	0.176
SR15-25 m (cic/min)		**Heat**	**Semi-final**	**Final**	**Anova**	η^2	**H-SF**	**SF-F**	**H-F**
M	Semifinalist	62.38 ± 3.79	64.18 ± 3.72	-	-	-	0.017	-	-
	Finalist	65.83 ± 4.93	66.19 ± 4.98	67.32 ± 5.24	0.088	0.32	0.499	0.123	0.093
W	Semifinalist	58.81 ± 5.38	59.58 ± 5.64	-	-	-	0.263	-	-
	Finalist	63.76 ± 5.50	62.97 ± 4.69	64.34 ± 5.33	0.081	0.23	0.327	0.018	0.263
SR35-45 m (cic/min)		**Heat**	**Semi-final**	**Final**	**Anova**	η^2	**H-SF**	**SF-F**	**H-F**
M	Semifinalist	61.84 ± 3.20	61.85 ± 3.23	-	-	-	0.674	-	-
	Finalist	64.39 ± 6.21	65.01 ± 4.94	66.04 ± 4.74	0.044	0.39	0.624	0.018	0.036
W	Semifinalist	57.04 ± 5.62	57.66 ± 5.43	-	-	-	0.273	-	-
	Finalist	62.95 ± 5.31	62.01 ± 4.61	62.91 ± 4.94	0.197	0.21	0.944	0.036	0.171
SR finish (cic/min)		**Heat**	**Semi-final**	**Final**	**Anova**	η^2	**H-SF**	**SF-F**	**H-F**
M	Semifinalist	58.96 ± 2.94	61.16 ± 3.37	-	-	-	0.018	-	-
	Finalist	62.68 ± 5.61	63.72 ± 4.93	64.87 ± 5.61	0.197	0.16	0.326	0.327	0.208
W	Semifinalist	56.06 ± 5.21	58.05 ± 5.80	-	-	-	0.345	-	-
	Finalist	61.75 ± 4.51	61.67 ± 1.95	62.03 ± 4.61	0.250	0.01	0.779	0.161	0.893
SL15-25 m (m)		**Heat**	**Semi-final**	**Final**	**Anova**	η^2	**H-SF**	**SF-F**	**H-F**
M	Semifinalist	1.58 ± 0.12	1.57 ± 0.08	-	-	-	0.779	-	-
	Finalist	1.54 ± 0.09	1.55 ± 0.12	1.51 ± 0.12	0.197	0.15	0.674	0.263	0.161
W	Semifinalist	1.56 ± 0.11	1.56 ± 0.12	-	-	-	0.770	-	-
	Finalist	1.48 ± 0.14	1.49 ± 0.11	1.47 ± 0.13	0.417	0.06	0.674	0.327	0.484
SL35-45 m (m)		**Heat**	**Semi-final**	**Final**	**Anova**	η^2	**H-SF**	**SF-F**	**H-F**
M	Semifinalist	1.62 ± 0.08	1.62 ± 0.08	-	-	-	0.889	-	-
	Finalist	1.60 ± 0.14	1.59 ± 0.12	1.55 ± 0.11	0.093	0.39	0.484	0.025	0.036
W	Semifinalist	1.59 ± 0.14	1.56 ± 0.16	-	-	-	0.123	-	-
	Finalist	1.51 ± 0.13	1.49 ± 0.09	1.49 ± 0.11	0.882	0.06	0.779	0.779	0.575
SL finish (m)		**Heat**	**Semi-final**	**Final**	**Anova**	η^2	**H-SF**	**SF-F**	**H-F**
M	Semifinalist	1.70 ± 0.08	1.60 ± 0.11	-	-	-	0.025	-	-
	Finalist	1.61 ± 0.14	1.57 ± 0.12	1.54 ± 0.14	0.135	0.20	0.263	0.401	0.123
W	Semifinalist	1.57 ± 0.15	1.51 ± 0.19	-	-	-	0.575	-	-
Finalist	1.43 ± 0.13	1.41 ± 0.06	1.43 ± 0.11	0.607	0.07	0.327	0.327	0.779	

Heat, semi-final, and final (H, SF, and F); stroke rate and length (SR and SL).

performances at 15, 25 and 50 m were obtained and interpreted as follows: 0.1 (low), 0.3 (moderate), 0.5 (large), 0.7 (very high) and 0.9 (nearly perfect) (Hopkins et al., 2009). Simple linear regression analyses were applied to evaluate the associations. All the statistical analyses were conducted in SPSS 24.0 (IBM, Chicago, IL, United States) with significance level set at $p < 0.05$.

3 RESULTS

Mean and Standard Deviations (SD) were obtained for all the variables and presented in conjunction with the result of the ANOVA test in **Tables 1** to **4**, the results for one stroke and both sexes are described in each table.

The values obtained of the linear mixed-effects model analyses, intra-subject CVs and Δ% progression are presented in **Tables 5** to **8**. A significant progression of performance was observed in most of the events over the rounds (i.e., from heats to semi-finals and then finals). The largest CV and Δ was noted in butterfly events (CV~0.7%; Δ = –0.9%), followed-up by freestyle (CV~0.6%; Δ~0.7%), backstroke (CV~0.5%; Δ = –0.6%) and breaststroke (CV~0.5%; Δ = –0.2%). The CV changed in several key moments related to the start underwater variables. However, it is unclear which variable (distance or time) had a larger partial contribution to underwater speed.

Correlation analyses between the different variables studied and T15, T25 and T50 on each sex group, stroke and differentiating the rounds are presented in **Tables 9** to **12**. In most events the correlation between T15 and T25, and between T25 and T50 was very large, however, the correlation between T15 and T50 was moderate or only large for the finalists. So, the improvements in the start and underwater segments of the race abovementioned did not have a strong impact on the final race time (i.e., T50). SR15-25 m and SR35-45 m increased over the competitions (freestyle and butterfly in both sexes, breaststroke and backstroke in men). Meanwhile, the SL was prone to decrease most of the times, trading off with the faster SR.

The regression analysis for each variable and stroke are presented as **Supplementary Material**. Additionally, the final time achieved by the medallists in the different rounds (i.e., T50) was plotted against the performances achieved by the finalists, semi-finalists and rest of participants and presented as supplementary material (**Supplementary Material**).

4 DISCUSSION

The first aim of this research was to study the coefficient of variation (CV) and the progression of performance (%Δ) in the 50 m event among swimmers who participated in different rounds of the same championship. It was hypothesised that if faster swimmers took the heats slower, a change in performance over the rounds would be detected. The results of the performances achieved during the finals compared to the heats showed that the best swimmers did not excel during the heats, as a significant progression of performance was observed in most of the strokes as the competition progressed. However, when comparing the performances in the final with those in the semi-finals, the progressions of performances in some strokes were poorer or not significant, due to the better performances achieved during the semi-final.

With reference to the 50 m freestyle, there were differences in CV between performances obtained in the finals and semi-finals compared to the heats (**Table 5**). These CV changes entailed a progressive reduction in the T50 as swimmers progressed between rounds. However, the performance achieved by the men during the final was worse compared to the semi-final (**Table 1**). Possibly, this failure could be the result of ineffective planning, or the swimmers' inability to perform at their best under the pressure of international competition (Mujika et al., 2019), but also, it is likely that as the level of the contenders was quite even, many of them tried to perform really well in the semi-final to avoid being left out of the final. In breaststroke, only women obtained differences in T50 between performances obtained in the finals compared to the heats (**Table 3**). In men, although the CV represented changes in performance (**Table 7**), it appears that some contenders had performance deteriorations during the final, resulting in a mean Δ = 0.2%. In any case, it is worth mentioning that, although their CV change was not positive for performance, some managed to reach medal positions, which means that this deterioration came from the difference result after having performed extraordinarily well during the heats. For further information on the performance of the medallists in comparison to the other contenders, it is recommended to consult supplementary material (**Supplementary Material**).

In the 50 m backstroke, the men showed differences in T50 CV between performances obtained in the finals compared to the heats (**Table 6**), without differences in women. For the men, these changes in CV meant a progressive reduction in T50 as swimmers progressed between rounds; however, the women's time performances were better in the semi-final than in the rest of the rounds (**Table 3**). Therefore, the best male swimmers either did not excel during the heats and/or were able to obtain progressions in performance as the competition progressed. In this sense, it is important to mention that apart from the fact that the level of the finalists was quite similar, the world record in this event was broken in the final, so this influenced the results obtained. Finally, in the men's 50 butterfly there were differences in the CV T50 for both men and women between the performances obtained in the finals and semi-finals compared to the heats (**Table 8**). These changes in CV meant a progressive reduction in T50 as the swimmers progressed between rounds, with the exception of the performance achieved by the men during the finals, which was the same as that achieved during the semi-finals (**Table 4**). Therefore, although the men and women did not excel during the heats, possibly the men were not able to achieve further performance progressions as the competition progressed because performance in the semi-finals was already really of high-level.

On the other hand, this study aimed to specifically analyse which of the key moments of the race or its subfactors are most modified to achieve improvement across the rounds. It was hypothesized that these changes would be a consequence of the improvement in the performance variables of the initial segment. This hypothesis was only partially confirmed as for some races the improvement came in the variables collected at the final stages of the race.

4.1 Swimming Start Variables (Reaction Time, Flight Time and Distance of Entry)

In sprint swimming, improving the start could make the difference between winning or not get a medal (García-Hermoso et al., 2017; Arellano et al., 2018; Sánchez et al., 2021). Therefore, several investigations have shown that swimmers should optimise the force-time distribution during the impulse phase (de Jesus et al., 2014; Vantorre et al., 2014; Cuenca-Fernández et al., 2015). Despite swimming start speed was not calculated, a good start is understood as an increase in speed since the swimmer leaves the block and reach the water could be achieved by either a combination of a reduction in execution time and an increase in distance of entry or a combination of both (Vantorre et al., 2014). Therefore, a good start cannot simply be explained by a single parameter (Gonjo and Olstad, 2020).

4.1.1 Freestyle

A change in flight time CV with a corresponding Δ% reduction (**Table 5**) was a common factor in both men and women progressing between heats and the final (**Table 1**). It appears

TABLE 4 | Butterfly performance variables' results, *p* values, and effect sizes (η^2) between the different three rounds. Men (M); Women (W) (LEN European Senior Championships 2021).

Reaction time (s)		**Heat**	**Semi-final**	**Final**	**Anova**	**η^2**	**H-SF**	**SF-F**	**H-F**
M	Semifinalist	0.65 ± 0.02	0.64 ± 0.02	-	-	-	0.864	-	-
	Finalist	0.62 ± 0.05	0.63 ± 0.06	0.64 ± 0.04	0.772	0.05	0.735	0.917	0.495
W	Semifinalist	0.66 ± 0.02	0.67 ± 0.02	-	-	-	0.233	-	-
	Finalist	0.67 ± 0.04	0.67 ± 0.03	0.66 ± 0.04	0.368	0.10	0.496	0.609	0.167
Flight time (s)		**Heat**	**Semi-final**	**Final**	**Anova**	**η^2**	**H-SF**	**SF-F**	**H-F**
M	Semifinalist	0.38 ± 0.03	0.37 ± 0.04	-	-	-	0.733	-	-
	Finalist	0.36 ± 0.06	0.36 ± 0.07	0.33 ± 0.03	0.576	0.13	0.672	0.395	0.068
W	Semifinalist	0.28 ± 0.05	0.27 ± 0.05	-	-	-	0.258	-	-
	Finalist	0.28 ± 0.05	0.29 ± 0.04	0.28 ± 0.04	0.228	0.11	0.336	0.288	0.779
Entry distance (m)		**Heat**	**Semi-final**	**Final**	**Anova**	**η^2**	**H-SF**	**SF-F**	**H-F**
M	Semifinalist	3.73 ± 0.16	3.70 ± 0.17	-	-	-	0.524	-	-
	Finalist	3.71 ± 0.19	3.68 ± 0.20	3.68 ± 0.14	0.651	0.05	0.157	0.999	0.480
W	Semifinalist	3.14 ± 0.15	3.13 ± 0.16	-	-	-	0.763	-	-
	Finalist	3.10 ± 0.14	3.17 ± 0.08	3.13 ± 0.09	0.692	0.14	0.234	0.414	0.461
Underwater Time (s)		**Heat**	**Semi-final**	**Final**	**Anova**	**η^2**	**H-SF**	**SF-F**	**H-F**
M	Semifinalist	3.30 ± 0.60	3.33 ± 0.50	-	-	-	0.401	-	-
	Finalist	3.31 ± 0.43	3.45 ± 0.64	3.26 ± 0.38	0.875	0.12	0.293	0.674	0.624
W	Semifinalist	4.26 ± 0.74	4.23 ± 0.59	-	-	-	0.779	-	-
	Finalist	4.53 ± 0.35	4.46 ± 0.51	4.44 ± 0.26	0.284	0.08	0.674	0.623	0.128
Underwater Distance (m)		**Heat**	**Semi-final**	**Final**	**Anova**	**η^2**	**H-SF**	**SF-F**	**H-F**
M	Semifinalist	9.23 ± 1.33	9.26 ± 1.19	-	-	-	0.888	-	-
	Finalist	9.10 ± 1.00	9.51 ± 1.23	8.95 ± 0.93	0.035	0.37	0.041	0.028	0.441
W	Semifinalist	9.91 ± 1.61	8.73 ± 3.24	-	-	-	0.260	-	-
	Finalist	10.73 ± 0.73	10.70 ± 0.97	10.72 ± 0.37	0.875	0.01	0.623	0.916	0.779
Underwater Speed (m/s)		**Heat**	**Semi-final**	**Final**	**Anova**	**η^2**	**H-SF**	**SF-F**	**H-F**
M	Semifinalist	2.78 ± 0.19	2.79 ± 0.18	-	-	-	0.541	-	-
	Finalist	2.75 ± 0.18	2.79 ± 0.17	2.75 ± 0.22	0.250	0.26	0.061	0.078	0.741
W	Semifinalist	2.35 ± 0.09	2.24 ± 0.54	-	-	-	0.014	-	-
	Finalist	2.38 ± 0.07	2.41 ± 0.08	2.42 ± 0.09	0.635	0.17	0.513	0.814	0.689
Time 15 m (s)		**Heat**	**Semi-final**	**Final**	**Anova**	**η^2**	**H-SF**	**SF-F**	**H-F**
M	Semifinalist	5.41 ± 0.16	5.43 ± 0.18	-	-	-	0.340	-	-
	Finalist	5.40 ± 0.16	5.35 ± 0.14	5.35 ± 0.17	0.043	0.25	0.105	0.916	0.054
W	Semifinalist	6.36 ± 0.17	6.33 ± 0.21	-	-	-	0.262	-	-
	Finalist	6.10 ± 0.14	6.06 ± 0.09	6.03 ± 0.15	0.343	0.18	0.249	0.396	0.257
Time 25 m (s)		**Heat**	**Semi-final**	**Final**	**Anova**	**η^2**	**H-SF**	**SF-F**	**H-F**
M	Semifinalist	10.49 ± 0.13	10.50 ± 0.14	-	-	-	0.672	-	-
	Finalist	10.43 ± 0.12	10.35 ± 0.12	10.34 ± 0.17	0.026	0.42	0.018	0.888	0.042
W	Semifinalist	12.01 ± 0.18	11.89 ± 0.18	-	-	-	0.011	-	-
	Finalist	11.68 ± 0.21	11.55 ± 0.10	11.53 ± 0.15	0.034	0.41	0.050	0.778	0.017
Time 35 m (s)		**Heat**	**Semi-final**	**Final**	**Anova**	**η^2**	**H-SF**	**SF-F**	**H-F**
M	Semifinalist	15.62 ± 0.09	15.62 ± 0.13	-	-	-	0.999	-	-
	Finalist	15.52 ± 0.11	15.39 ± 0.13	15.38 ± 0.18	0.010	0.48	0.012	0.888	0.017
W	Semifinalist	17.69 ± 0.17	17.58 ± 0.22	-	-	-	0.013	-	-
	Finalist	17.32 ± 0.28	17.17 ± 0.16	17.08 ± 0.19	0.008	0.46	0.067	0.325	0.012
Time 45 m (s)		**Heat**	**Semi-final**	**Final**	**Anova**	**η^2**	**H-SF**	**SF-F**	**H-F**
M	Semifinalist	20.86 ± 0.07	20.83 ± 0.08	-	-	-	0.260	-	-
	Finalist	20.72 ± 0.14	20.56 ± 0.16	20.56 ± 0.19	0.093	0.40	0.058	0.944	0.021
W	Semifinalist	23.48 ± 0.16	23.40 ± 0.26	-	-	-	0.172	-	-
	Finalist	23.06 ± 0.33	22.89 ± 0.18	22.79 ± 0.23	0.036	0.46	0.068	0.123	0.028

(Continued on following page)

TABLE 4 | (*Continued*) Butterfly performance variables' results, *p* values, and effect sizes (η^2) between the different three rounds. Men (M); Women (W) (LEN European Senior Championships 2021).

Time 50 m (s)		Heat	Semi-final	Final	Anova	η²	H-SF	SF-F	H-F
M	Semifinalist	23.50 ± 0.05	23.47 ± 0.07	-	-	-	0.362	-	-
	Finalist	23.36 ± 0.15	23.19 ± 0.16	23.20 ± 0.22	0.030	0.40	0.025	0.999	0.035
W	Semifinalist	26.45 ± 0.17	26.38 ± 0.28	-	-	-	0.123	-	-
	Finalist	25.94 ± 0.31	25.77 ± 0.15	25.66 ± 0.20	0.044	0.43	0.093	0.092	0.050
Finish time (s)		**Heat**	**Semi-final**	**Final**	**Anova**	**η²**	**H-SF**	**SF-F**	**H-F**
M	Semifinalist	2.63 ± 0.06	2.63 ± 0.09	-	-	-	0.866	-	-
	Finalist	2.64 ± 0.08	2.62 ± 0.07	2.63 ± 0.06	0.587	0.03	0.624	0.752	0.327
W	Semifinalist	2.97 ± 0.08	2.98 ± 0.07	-	-	-	0.406	-	-
	Finalist	2.88 ± 0.09	2.87 ± 0.08	2.87 ± 0.09	0.875	0.01	0.917	0.999	0.673
Split 25–50 m (s)		**Heat**	**Semi-final**	**Final**	**Anova**	**η²**	**H-SF**	**SF-F**	**H-F**
M	Semifinalist	13.01 ± 0.15	12.97 ± 0.11	-	-	-	0.160	-	-
	Finalist	12.93 ± 0.08	12.84 ± 0.16	12.86 ± 0.13	0.206	0.29	0.092	0.725	0.107
W	Semifinalist	14.43 ± 0.14	14.49 ± 0.16	-	-	-	0.192	-	-
	Finalist	14.13 ± 0.11	13.26 ± 0.11	14.25 ± 0.09	0.034	0.34	0.362	0.058	0.093
SR15-25 m (cic/min)		**Heat**	**Semi-final**	**Final**	**Anova**	**η²**	**H-SF**	**SF-F**	**H-F**
M	Semifinalist	62.09 ± 3.50	63.19 ± 4.64	-	-	-	0.161	-	-
	Finalist	64.64 ± 2.35	64.91 ± 2.87	65.85 ± 2.69	0.417	0.15	0.327	0.161	0.779
W	Semifinalist	65.48 ± 3.94	66.74 ± 3.70	-	-	-	0.015	-	-
	Finalist	63.42 ± 2.70	64.09 ± 2.66	64.14 ± 2.60	0.012	0.45	0.025	0.999	0.017
SR35-45 m (cic/min)		**Heat**	**Semi-final**	**Final**	**Anova**	**η²**	**H-SF**	**SF-F**	**H-F**
M	Semifinalist	60.21 ± 3.78	61.09 ± 3.95	-	-	-	0.123	-	-
	Finalist	61.63 ± 2.62	63.35 ± 2.43	63.33 ± 2.22	0.061	0.41	0.035	0.866	0.036
W	Semifinalist	62.15 ± 3.49	62.33 ± 2.85	-	-	-	0.441	-	-
	Finalist	60.16 ± 2.05	61.24 ± 2.34	61.96 ± 1.94	0.002	0.76	0.012	0.123	0.012
SR finish (cic/min)		**Heat**	**Semi-final**	**Final**	**Anova**	**η²**	**H-SF**	**SF-F**	**H-F**
M	Semifinalist	59.22 ± 2.73	59.63 ± 3.19	-	-	-	0.463	-	-
	Finalist	60.35 ± 1.94	61.80 ± 2.71	60.44 ± 3.01	0.417	0.10	0.327	0.161	0.779
W	Semifinalist	60.20 ± 3.58	60.53 ± 2.07	-	-	-	0.953	-	-
	Finalist	61.09 ± 2.65	60.04 ± 2.90	61.25 ± 2.66	0.140	0.17	0.397	0.092	0.575
SL15-25 m (m)		**Heat**	**Semi-final**	**Final**	**Anova**	**η²**	**H-SF**	**SF-F**	**H-F**
M	Semifinalist	1.90 ± 0.12	1.88 ± 0.15	-	-	-	0.484	-	-
	Finalist	1.84 ± 0.08	1.85 ± 0.08	1.83 ± 0.06	0.325	0.06	0.889	0.674	0.263
W	Semifinalist	1.62 ± 0.10	1.62 ± 0.10	-	-	-	0.515	-	-
	Finalist	1.69 ± 0.07	1.70 ± 0.05	1.70 ± 0.06	0.882	0.05	0.779	0.889	0.999
SL35-45 m (m)		**Heat**	**Semi-final**	**Final**	**Anova**	**η²**	**H-SF**	**SF-F**	**H-F**
M	Semifinalist	1.94 ± 0.13	1.92 ± 0.13	-	-	-	0.161	-	-
	Finalist	1.91 ± 0.07	1.88 ± 0.08	1.87 ± 0.05	0.417	0.23	0.123	0.999	0.093
W	Semifinalist	1.70 ± 0.09	1.69 ± 0.09	-	-	-	0.678	-	-
	Finalist	1.77 ± 0.05	1.74 ± 0.07	1.74 ± 0.05	0.072	0.28	0.123	0.889	0.069
SL finish (m)		**Heat**	**Semi-final**	**Final**	**Anova**	**η²**	**H-SF**	**SF-F**	**H-F**
M	Semifinalist	1.92 ± 0.11	1.91 ± 0.14	-	-	-	0.735	-	-
	Finalist	1.88 ± 0.10	2.08 ± 0.10	1.88 ± 0.11	0.325	0.60	0.575	0.327	0.999
W	Semifinalist	1.68 ± 0.14	1.66 ± 0.07	-	-	-	0.767	-	-
	Finalist	1.70 ± 0.09	1.74 ± 0.09	1.71 ± 0.11	0.930	0.12	0.208	0.069	0.889

Heat, semi-final, and final (H, SF, and F); stroke rate and length (SR and SL).

that swimmers during the final intentionally tried to get to the water fast rather than trying to increase the hand's entry distance. According to other authors (Kilani and Zeidan, 2004; Simbaña-Escobar et al., 2018; Morais et al., 2021), the best freestyle swimmers are especially faster in the start sections; however, a shorter flight time obtained a low magnitude on the correlations with any performance variable (i.e., T15, T25 and T50) (**Table 9**). In addition, during heats and semi-finals, men who achieved a longer entry distance obtained better performance results, while a slight increase was observed in women in semi-finals and finals compared to heats (**Table 1**). Therefore, it cannot be ruled out that both a reduction in flight time and an increase in entry distance can be modified by the swimmers to influence the speed of the start.

TABLE 5 | Freestyle intra-athletes' coefficient of variation (CV) and relative change in performance (%Δ). Men (M); Women (W); Heat (H); Semi-final (SF); Final (F) (LEN European Senior Championships 2021).

		H-F (*n* = 8)			H-SF (n = 16)			SF-F (*n* = 8)		
		CV	p	%Δ	CV	p	%Δ	CV	p	%Δ
Reaction Time	M	0.09 ± 0.01	0.232	−0.07 ± 0.01	0.08 ± 0.01	0.065	−0.09 ± 0.01	0.15 ± 0.01	0.575	0.06 ± 0.01
	W	0.06 ± 0.01	0.386	−0.03 ± 0.01	0.07 ± 0.01	0.291	−0.03 ± 0.01	0.05 ± 0.01	0.616	0.01 ± 0.01
Flight Time	M	0.10 ± 0.01	0.044*	−0.13 ± 0.01	0.07 ± 0.01	0.871	0.01 ± 0.01	0.12 ± 0.01	0.093	−0.14 ± 0.01
	W	0.10 ± 0.01	0.003*	−0.15 ± 0.01	0.14 ± 0.01	0.451	0.13 ± 0.03	0.13 ± 0.01	0.005	−0.02 ± 0.01
Entry Distance	M	0.25 ± 0.01	0.734	−0.17 ± 0.01	0.16 ± 0.01	0.735	0.02 ± 0.01	0.16 ± 0.01	0.305	−0.14 ± 0.01
	W	0.38 ± 0.01	0.672	0.14 ± 0.01	0.16 ± 0.01	0.067	0.12 ± 0.01	0.23 ± 0.01	0.659	−0.05 ± 0.01
Underwater Time	M	0.40 ± 0.01	0.083	−0.41 ± 0.01	0.70 ± 0.02	0.259	−0.50 ± 0.01	0.41 ± 0.01	0.038*	−0.51 ± 0.01
	W	0.65 ± 0.01	0.847	−0.07 ± 0.01	0.82 ± 0.02	0.505	0.18 ± 0.01	0.68 ± 0.01	0.767	−0.01 ± 0.01
Underwater Distance	M	0.55 ± 0.01	0.570	−0.09 ± 0.01	0.94 ± 0.02	0.926	−0.11 ± 0.01	0.65 ± 0.01	0.025*	−0.81 ± 0.01
	W	0.98 ± 0.01	0.376	0.50 ± 0.01	0.95 ± 0.02	0.602	−0.38 ± 0.01	1.15 ± 0.02	0.688	0.56 ± 0.01
Underwater Velocity	M	3.02 ± 0.02	0.055	2.98 ± 4.62	4.51 ± 0.03	0.060	3.40 ± 7.33	3.59 ± 0.02	0.712	−1.16 ± 6.28
	W	2.30 ± 0.03	0.046*	3.12 ± 4.14	3.94 ± 0.04	0.097	−3.88 ± 8.99	3.72 ± 0.04	0.036*	3.40 ± 7.20
Time 15 m	M	0.25 ± 0.01	0.517	−0.11 ± 0.01	0.23 ± 0.01	0.957	0.01 ± 0.01	0.16 ± 0.01	0.894	0.04 ± 0.01
	W	0.31 ± 0.01	0.001*	−0.44 ± 0.01	0.19 ± 0.01	0.002*	−0.21 ± 0.01	0.20 ± 0.01	0.126	−0.17 ± 0.01
Time 25 m	M	0.42 ± 0.01	0.049*	−0.35 ± 0.01	0.33 ± 0.01	0.034*	−0.29 ± 0.01	0.26 ± 0.01	0.752	0.18 ± 0.01
	W	0.68 ± 0.01	0.001*	−0.98 ± 0.01	0.27 ± 0.01	0.001*	−0.36 ± 0.01	0.35 ± 0.01	0.001*	−0.50 ± 0.01
Time 35 m	M	0.36 ± 0.01	0.551	−0.03 ± 0.01	0.36 ± 0.01	0.864	0.02 ± 0.01	0.40 ± 0.01	0.989	0.21 ± 0.01
	W	0.79 ± 0.01	0.001*	−1.12 ± 0.01	0.44 ± 0.01	0.001*	−0.63 ± 0.01	0.23 ± 0.01	0.010*	−0.27 ± 0.01
Time 45 m	M	0.34 ± 0.01	0.508	0.01 ± 0.01	0.44 ± 0.01	0.326	0.18 ± 0.01	0.40 ± 0.01	0.854	0.24 ± 0.01
	W	0.75 ± 0.01	0.001*	−1.07 ± 0.01	0.49 ± 0.01	0.001*	−0.66 ± 0.01	0.32 ± 0.01	0.241	−0.14 ± 0.01
Time 50 m	M	0.58 ± 0.01	0.009*	−0.53 ± 0.86	0.47 ± 0.01	0.034*	0.19 ± 0.34	0.40 ± 0.01	0.774	0.26 ± 0.69
	W	0.68 ± 0.01	0.001*	−0.96 ± 0.28	0.39 ± 0.01	0.003*	0.21 ± 0.25	0.34 ± 0.01	0.083	−0.25 ± 0.48
Split25-50 m	M	0.29 ± 0.01	0.032*	−0.19 ± 0.01	0.30 ± 0.01	0.418	−0.10 ± 0.01	0.22 ± 0.01	0.974	0.08 ± 0.01
	W	0.14 ± 0.01	0.806	0.01 ± 0.01	0.17 ± 0.01	0.449	−0.07 ± 0.01	0.20 ± 0.01	0.085	0.24 ± 0.01
Finish time	M	0.36 ± 0.01	0.001*	−0.53 ± 0.01	0.42 ± 0.01	0.001*	−0.58 ± 0.01	0.17 ± 0.01	0.904	0.03 ± 0.01
	W	0.21 ± 0.01	0.804	0.09 ± 0.01	0.20 ± 0.01	0.003*	−0.22 ± 0.01	0.13 ± 0.01	0.085	−0.12 ± 0.01
SR15-25 m	M	1.47 ± 0.01	0.006*	1.87 ± 1.52	1.72 ± 0.01	0.042*	1.55 ± 2.98	0.92 ± 0.01	0.925	−0.09 ± 1.58
	W	1.93 ± 0.01	0.091	1.82 ± 2.82	1.21 ± 0.01	0.013*	1.23 ± 1.77	0.84 ± 0.01	0.762	−0.16 ± 1.48
SR35-45 m	M	2.47 ± 0.01	0.065	2.41 ± 3.71	1.47 ± 0.01	0.012*	1.41 ± 2.12	1.78 ± 0.01	0.204	1.14 ± 2.74
	W	2.05 ± 0.01	0.006*	2.70 ± 2.09	0.91 ± 0.01	0.021*	0.85 ± 1.33	1.26 ± 0.01	0.017*	1.46 ± 1.47
SR Final	M	4.53 ± 0.02	0.201	3.70 ± 6.40	2.33 ± 0.01	0.461	0.69 ± 4.00	2.49 ± 0.01	0.038*	2.71 ± 3.37
	W	1.84 ± 0.01	0.508	0.77 ± 2.95	2.08 ± 0.01	0.174	1.11 ± 3.30	1.88 ± 0.02	0.634	−0.27 ± 4.15
SL15-25 m	M	0.88 ± 0.01	0.142	−0.75 ± 1.37	1.50 ± 0.01	0.774	−0.26 ± 3.15	0.56 ± 0.01	0.089	−0.56 ± 0.88
	W	2.11 ± 0.01	0.370	0.62 ± 3.51	1.18 ± 0.01	0.280	−0.55 ± 2.08	1.64 ± 0.01	0.037*	1.71 ± 2.29
SL35-45 m	M	3.15 ± 0.02	0.013*	−4.13 ± 3.86	2.35 ± 0.01	0.002*	−2.98 ± 3.18	1.48 ± 0.01	0.111	−1.37 ± 2.20
	W	1.71 ± 0.01	0.021*	−2.13 ± 2.06	0.84 ± 0.01	0.320	0.38 ± 1.43	1.80 ± 0.01	0.002*	−2.58 ± 1.69
SL Final	M	4.07 ± 0.02	0.571	0.62 ± 6.95	3.94 ± 0.02	0.002*	4.26 ± 4.69	2.53 ± 0.01	0.019*	−3.18 ± 3.27
	W	3.07 ± 0.01	0.513	−1.83 ± 5.08	2.94 ± 0.01	0.002*	−3.38 ± 3.83	3.00 ± 0.02	0.284	1.10 ± 5.37

**Significant differences.*

4.1.2 Backstroke

The reaction time did not differ between rounds, although the male finalists showed a significant reduction in flight time together with a non-significant increase in distance compared to previous rounds, which could be translated into an increase in speed (**Table 2**). On the contrary, in the women, this combination yielded worse results than those obtained in previous rounds. A previous study has shown that men react faster to an auditory stimulus when large muscle groups are involved (Spierer et al., 2010). In this study, the reaction time of men and women was similar, however, this yielded different results. In men, the best performers were those with a slower reaction time, but also those who combined a shorter flight time and a longer entry distance, attaining large to very high correlations (**Table 10**), which seems to be an indicative of a higher impulse achieved at the start (García-Hermoso et al., 2017). In contrast, the women with a slower reaction time seemed to achieve worse performances at T15 and T25, so for them this did not lead to a higher impulse at the start (**Table 10**). These differences could be explained by sex, as absolute leg power is higher in men than in women (García-Hermoso et al., 2017; Simbaña-Escobar et al., 2018).

4.1.3 Breaststroke

Changes in start variables were not significant for either men or women (**Table 7**) and no decreasing or increasing trends were observed between rounds as the competition progressed to the final (**Table 3**). It is important to mention that the men did not obtain overall performance progressions in the final time (T50). However, apparently the women also did not vary the swim start variables as they progressed between rounds. Therefore, it is possible that the modifications in breaststroke come from other variations occurring in the underwater phase (Olstad et al., 2020; Sánchez et al., 2021).

TABLE 6 | Backstroke intra-athlete's coefficient of variation (CV) and relative change in performance (%Δ). Men (M); Women (W); Heat (H); Semi-final (SF); Final (F) (LEN European Senior Championships 2021).

		H-F (*n* = 8)			H-SF (*n* = 16)			SF-F (*n* = 8)		
		CV	p	%Δ	CV	p	%Δ	CV	p	%Δ
Reaction Time	M	0.05 ± 0.01	0.088	−0.06 ± 0.01	0.04 ± 0.01	0.230	−0.02 ± 0.01	0.04 ± 0.01	0.395	−0.03 ± 0.01
	W	0.04 ± 0.01	0.336	−0.02 ± 0.01	0.04 ± 0.01	0.721	−0.03 ± 0.01	0.17 ± 0.01	0.260	−0.02 ± 0.01
Flight Time	M	0.11 ± 0.01	0.327	−0.15 ± 0.01	0.22 ± 0.01	0.298	−0.05 ± 0.01	0.12 ± 0.01	0.804	−0.12 ± 0.01
	W	0.07 ± 0.01	0.381	0.01 ± 0.01	0.07 ± 0.01	0.936	−0.01 ± 0.01	0.04 ± 0.01	0.243	−0.04 ± 0.01
Entry Distance	M	0.12 ± 0.01	0.214	0.06 ± 0.01	0.13 ± 0.01	0.140	0.10 ± 0.01	0.10 ± 0.01	0.103	0.09 ± 0.01
	W	0.21 ± 0.01	0.262	−0.02 ± 0.01	0.12 ± 0.01	0.548	0.03 ± 0.01	0.13 ± 0.01	0.755	−0.04 ± 0.01
Underwater Time	M	0.74 ± 0.01	0.095	−0.49 ± 0.01	0.49 ± 0.01	0.452	0.15 ± 0.01	0.76 ± 0.01	0.029*	−0.75 ± 0.01
	W	0.52 ± 0.01	0.051	−0.52 ± 0.01	0.43 ± 0.01	0.260	−0.23 ± 0.01	0.37 ± 0.01	0.242	−0.23 ± 0.01
Underwater Distance	M	0.67 ± 0.01	0.421	−0.17 ± 0.01	0.55 ± 0.01	0.069	0.43 ± 0.01	0.72 ± 0.01	0.014*	−0.85 ± 0.01
	W	0.61 ± 0.01	0.196	−0.51 ± 0.01	0.51 ± 0.01	0.911	−0.04 ± 0.01	0.61 ± 0.01	0.219	−0.54 ± 0.01
Underwater Velocity	M	1.47 ± 0.01	0.013*	1.72 ± 1.59	1.85 ± 0.02	0.316	0.94 ± 3.91	1.06 ± 0.01	0.880	0.08 ± 1.94
	W	1.03 ± 0.01	0.297	0.56 ± 2.14	1.20 ± 0.01	0.071	0.87 ± 1.92	1.10 ± 0.01	0.391	−0.98 ± 2.43
Time 15 m	M	0.32 ± 0.01	0.001*	−0.45 ± 0.01	0.21 ± 0.01	0.026	−0.21 ± 0.01	0.15 ± 0.01	0.596	−0.04 ± 0.01
	W	0.28 ± 0.01	0.268	−0.15 ± 0.01	0.29 ± 0.01	0.062	−0.25 ± 0.01	0.21 ± 0.01	0.118	0.23 ± 0.01
Time 25 m	M	0.53 ± 0.01	0.001*	−0.76 ± 0.01	0.29 ± 0.01	0.072	−0.22 ± 0.01	0.19 ± 0.01	0.024*	−0.22 ± 0.01
	W	0.35 ± 0.01	0.071	−0.26 ± 0.01	0.38 ± 0.06	0.050*	−0.32 ± 0.01	0.20 ± 0.04	0.097	0.25 ± 0.01
Time 35 m	M	0.72 ± 0.01	0.001*	−1.03 ± 0.01	0.37 ± 0.01	0.164	−0.22 ± 0.01	0.27 ± 0.01	0.003*	−0.37 ± 0.01
	W	0.48 ± 0.01	0.011*	−0.51 ± 0.01	0.44 ± 0.01	0.155	−0.30 ± 0.01	0.18 ± 0.01	0.396	0.13 ± 0.01
Time 45 m	M	0.75 ± 0.01	0.001*	−1.07 ± 0.01	0.41 ± 0.01	0.120	−0.29 ± 0.01	0.28 ± 0.01	0.049*	−0.27 ± 0.01
	W	0.49 ± 0.01	0.021*	−0.47 ± 0.01	0.53 ± 0.01	0.198	−0.34 ± 0.01	0.27 ± 0.01	0.100	0.29 ± 0.01
Time 50 m	M	0.64 ± 0.01	0.002*	−0.85 ± 0.64	0.43 ± 0.01	0.729	−0.07 ± 0.79	0.32 ± 0.01	0.145	−0.20 ± 0.45
	W	0.51 ± 0.01	0.062	−0.36 ± 0.78	0.48 ± 0.01	0.498	−0.18 ± 0.99	0.33 ± 0.01	0.110	0.34 ± 0.49
Split25-50 m	M	0.34 ± 0.01	0.457	−0.10 ± 0.01	0.30 ± 0.01	0.217	0.15 ± 0.01	0.24 ± 0.02	0.886	0.02 ± 0.01
	W	0.17 ± 0.01	0.369	−0.07 ± 0.01	0.25 ± 0.01	0.314	0.13 ± 0.01	0.13 ± 0.01	0.637	0.06 ± 0.01
Finish time	M	0.23 ± 0.01	0.108	0.21 ± 0.01	0.19 ± 0.01	0.001*	0.21 ± 0.01	0.22 ± 0.01	0.946	0.05 ± 0.01
	W	0.23 ± 0.01	0.199	0.14 ± 0.01	0.14 ± 0.01	0.002*	0.16 ± 0.01	0.17 ± 0.01	0.949	0.01 ± 0.01
SR15-25 m	M	1.74 ± 0.01	0.024*	2.09 ± 2.14	1.02 ± 0.01	0.008*	1.14 ± 1.56	1.22 ± 0.01	0.103	1.36 ± 2.07
	W	1.47 ± 0.01	0.660	1.56 ± 2.07	0.93 ± 0.01	0.536	0.24 ± 1.69	0.89 ± 0.01	0.023*	1.10 ± 1.16
SR35-45 m	M	2.20 ± 0.01	0.003*	2.89 ± 2.01	1.22 ± 0.01	0.048*	1.16 ± 2.17	1.34 ± 0.01	0.004*	1.71 ± 2.11
	W	1.04 ± 0.01	0.022*	1.25 ± 1.31	1.19 ± 0.01	0.219	0.60 ± 2.21	1.00 ± 0.01	0.887	0.16 ± 2.20
SR Final	M	2.62 ± 0.01	0.389	0.52 ± 4.39	2.20 ± 0.02	0.799	−0.35 ± 4.66	3.19 ± 0.02	0.084	2.83 ± 5.01
	W	1.88 ± 0.02	0.767	−0.01 ± 4.24	2.58 ± 0.02	0.808	−0.40 ± 4.81	1.30 ± 0.01	0.967	0.25 ± 3.18
SL15-25 m	M	1.53 ± 0.01	0.509	−0.71 ± 2.54	1.06 ± 0.01	0.015*	−1.10 ± 1.67	1.16 ± 0.01	0.735	−0.57 ± 2.66
	W	1.43 ± 0.01	0.481	−1.02 ± 2.54	0.91 ± 0.01	0.852	0.06 ± 1.66	1.08 ± 0.01	0.051	−1.22 ± 1.43
SL35-45 m	M	1.91 ± 0.01	0.127	−1.76 ± 3.03	1.55 ± 0.01	0.081	−1.26 ± 2.39	1.14 ± 0.01	0.278	−1.07 ± 2.37
	W	0.38 ± 0.01	0.826	0.01 ± 0.71	1.02 ± 0.01	0.127	−0.70 ± 1.72	1.19 ± 0.01	0.436	0.42 ± 2.22
SL Final	M	3.85 ± 0.02	0.118	−2.77 ± 6.52	2.85 ± 0.02	0.168	−1.84 ± 5.19	3.57 ± 0.02	0.059	−3.71 ± 4.96
	W	2.79 ± 0.02	0.535	−1.68 ± 4.83	3.09 ± 0.02	0.393	−1.29 ± 5.39	0.97 ± 0.01	0.563	−0.49 ± 1.80

**Significant differences.*

4.1.4 Butterfly

Both men and women produced no variation in performance in any of the start variables to progress between rounds (**Table 8**). According to a previous study (Kilani and Zeidan, 2004), the swim start was a differentiating factor between finalists and semi-finalists in 50 m butterfly success. However, the large variations in performance were possibly caused by other variables rather than by the actions taken on the block. By the large magnitude of the correlations, those men who achieved a longer entry distance in the semi-finals were the ones who performed better in T15 and T25 (**Table 12**).

4.2 Underwater Variables (Underwater Time, Distance and Speed)

In previous studies, the underwater phase has been divided into two parts: the glide and the undulatory swim, differentiated by the moment at which the movement of the lower limbs begins (de Jesus et al., 2014; Vantorre et al., 2014). However, a limitation of current methods of competition analysis is that the camera setup is limited to the above-water view only, which means that underwater kinematic information cannot be assessed in detail (Gonjo and Olstad, 2021). In any case, the underwater swim during the start and turn segments must be adjusted to maximise average speed (Veiga et al., 2014), which means that good underwater performances cannot simply be explained by a single parameter (e.g., only underwater distance) (Sánchez et al., 2021).

4.2.1 Freestyle

The male finalists showed CV changes in underwater time and distance that represented a significant Δ% reduction (**Table 5**). However, the underwater speed of the final did

TABLE 7 | Breaststroke intra-athlete's coefficient of variation (CV) and relative change in performance (%Δ). Men (M); Women (W); Heat (H); Semi-final (SF); Final (F) (LEN European Senior Championships 2021).

		H-F (*n* = 8)			H-SF (*n* = 16)			SF-F (*n* = 8)		
		CV	p	%Δ	CV	p	%Δ	CV	p	%Δ
Reaction Time	M	0.04 ± 0.01	0.959	0.01 ± 0.01	0.04 ± 0.01	0.069	0.03 ± 0.01	0.04 ± 0.01	0.348	−0.02 ± 0.01
	W	0.05 ± 0.01	0.124	−0.05 ± 0.01	0.05 ± 0.01	0.170	−0.03 ± 0.01	0.03 ± 0.01	0.401	0.01 ± 0.01
Flight Time	M	0.03 ± 0.01	0.094	−0.03 ± 0.01	0.04 ± 0.01	0.159	−0.03 ± 0.01	0.02 ± 0.01	0.402	-0.02 ± 0.01
	W	0.05 ± 0.01	0.765	−0.01 ± 0.01	0.03 ± 0.01	0.456	−0.02 ± 0.01	0.03 ± 0.01	0.724	−0.02 ± 0.01
Entry Distance	M	0.13 ± 0.01	0.517	0.08 ± 0.01	0.34 ± 0.01	0.509	−0.13 ± 0.01	0.40 ± 0.01	0.458	0.24 ± 0.01
	W	0.30 ± 0.01	0.635	−0.10 ± 0.01	0.24 ± 0.01	0.058	−0.26 ± 0.01	0.21 ± 0.01	0.399	0.03 ± 0.01
Underwater Time	M	0.68 ± 0.01	0.047*	−0.73 ± 0.01	0.65 ± 0.01	0.189	−0.45 ± 0.01	0.69 ± 0.01	0.121	−0.73 ± 0.01
	W	0.33 ± 0.01	0.256	−0.15 ± 0.01	0.40 ± 0.01	0.108	−0.26 ± 0.01	0.30 ± 0.01	0.516	−0.10 ± 0.01
Underwater Distance	M	1.14 ± 0.01	0.016*	−1.68 ± 0.01	0.83 ± 0.01	0.316	−0.46 ± 0.01	0.85 ± 0.01	0.040*	−1.29 ± 0.01
	W	0.29 ± 0.01	0.570	0.17 ± 0.01	0.57 ± 0.01	0.733	0.06 ± 0.01	0.43 ± 0.01	0.829	0.01 ± 4.35
Underwater Velocity	M	3.90 ± 0.05	0.536	−4.37 ± 9.99	3.59 ± 0.04	0.946	0.06 ± 8.60	3.51 ± 0.03	0.385	−2.36 ± 6.73
	W	2.28 ± 0.01	0.092	1.83 ± 3.27	1.81 ± 0.01	0.007*	2.07 ± 2.85	1.53 ± 0.01	0.468	0.53 ± 2.61
Time 15 m	M	0.42 ± 0.01	0.692	−0.08 ± 0.01	0.24 ± 0.01	0.420	0.09 ± 0.01	0.34 ± 0.01	0.699	−0.02 ± 0.01
	W	0.37 ± 0.01	0.116	−0.31 ± 0.01	0.25 ± 0.01	0.525	−0.08 ± 0.01	0.25 ± 0.01	0.307	−0.12 ± 0.01
Time 25 m	M	0.49 ± 0.01	0.151	−0.24 ± 0.01	0.36 ± 0.01	0.016*	−0.33 ± 0.01	0.30 ± 0.01	0.875	0.07 ± 0.01
	W	0.35 ± 0.01	0.050*	−0.44 ± 0.01	0.27 ± 0.01	0.035*	−0.25 ± 0.01	0.23 ± 0.01	0.018*	−0.25 ± 0.01
Time 35 m	M	0.54 ± 0.03	0.178	−0.23 ± 0.01	0.38 ± 0.03	0.013*	−0.39 ± 0.01	0.41 ± 0.05	0.941	0.19 ± 0.01
	W	0.46 ± 0.01	0.007*	−0.60 ± 0.01	0.30 ± 0.02	0.597	−0.07 ± 0.01	0.41 ± 0.01	0.007*	−0.53 ± 0.01
Time 45 m	M	0.51 ± 0.03	0.860	0.08 ± 0.01	0.38 ± 0.03	0.165	−0.22 ± 0.01	0.44 ± 0.06	0.774	0.26 ± 0.01
	W	0.45 ± 0.01	0.014*	−0.57 ± 0.01	0.29 ± 0.03	0.195	−0.18 ± 0.01	0.27 ± 0.01	0.577	−0.05 ± 0.01
Time 50 m	M	0.54 ± 0.01	0.792	0.22 ± 0.86	0.37 ± 0.01	0.790	−0.04 ± 0.63	0.34 ± 0.01	0.324	0.30 ± 0.65
	W	0.55 ± 0.01	0.007*	−0.61 ± 0.57	0.38 ± 0.01	0.761	−0.05 ± 0.62	0.24 ± 0.01	0.012*	−0.30 ± 0.28
Split25-50 m	M	0.36 ± 0.01	0.064	0.45 ± 0.01	0.26 ± 0.01	0.005*	0.28 ± 0.01	0.32 ± 0.01	0.298	0.23 ± 0.01
	W	0.21 ± 0.01	0.106	−0.17 ± 0.01	0.30 ± 0.01	0.163	0.20 ± 0.01	0.11 ± 0.01	0.381	−0.05 ± 0.01
Finish time	M	0.18 ± 0.01	0.138	0.13 ± 0.01	0.30 ± 0.01	0.121	0.17 ± 0.01	0.25 ± 0.01	0.960	0.02 ± 0.01
	W	0.23 ± 0.01	0.536	−0.05 ± 0.01	0.24 ± 0.01	0.192	0.12 ± 0.01	0.31 ± 0.01	0.178	−0.25 ± 0.01
SR15-25 m	M	2.08 ± 0.01	0.031*	2.16 ± 2.77	1.60 ± 0.01	0.008*	1.58 ± 2.14	1.94 ± 0.01	0.065*	1.63 ± 2.68
	W	2.01 ± 0.01	0.318	0.88 ± 3.41	1.63 ± 0.01	0.985	0.01 ± 3.11	1.48 ± 0.01	0.016*	2.04 ± 2.10
SR35-45 m	M	2.48 ± 0.01	0.020*	2.63 ± 2.90	1.31 ± 0.01	0.382*	0.53 ± 2.18	1.14 ± 0.01	0.001*	1.58 ± 1.01
	W	1.75 ± 0.01	0.106	1.54 ± 2.85	1.48 ± 0.01	0.391	0.61 ± -2.66	1.12 ± 0.01	0.021*	1.39 ± 1.50
SR Final	M	4.89 ± 0.03	0.064	3.12 ± 7.82	2.86 ± 0.01	0.012*	2.59 ± 3.71	2.93 ± 0.02	0.179	1.57 ± 5.01
	W	1.50 ± 0.01	0.517	0.37 ± 3.26	2.72 ± 0.04	0.363	1.52 ± 6.43	2.36 ± 0.02	0.505	0.24 ± 5.38
SL15-25 m	M	1.95 ± 0.01	0.212	−1.53 ± 3.49	1.96 ± 0.01	0.790	0.19 ± 3.31	3.04 ± 0.01	0.143	−2.17 ± 4.19
	W	1.84 ± 0.01	0.681	−0.30 ± 3.44	2.30 ± 0.01	0.456	0.72 ± 3.84	1.98 ± 0.01	0.208	−1.54 ± 3.50
SL35-45 m	M	2.26 ± 0.01	0.017*	−2.82 ± 3.02	1.63 ± 0.01	0.679	−0.27 ± 2.75	1.64 ± 0.01	0.008*	−2.19 ± 1.91
	W	1.54 ± 0.01	0.338	−0.92 ± 3.39	2.09 ± 0.01	0.074	−1.54 ± 3.32	1.45 ± 0.01	0.897	−0.13 ± 2.33
SL Final	M	5.00 ± 0.02	0.030*	−4.93 ± 7.09	3.82 ± 0.02	0.003*	−4.51 ± 5.33	4.79 ± 0.02	0.344	−2.26 ± 7.62
	W	3.48 ± 0.02	0.678	−0.17 ± 5.79	4.17 ± 0.04	0.184	−3.32 ± 9.98	3.87 ± 0.02	0.618	1.57 ± 6.70

**Significant differences.*

not prove to be superior as a result (**Table 1**). In this regard, a previous study reported that a long underwater distance is not necessarily related to a fast finish time and suggested that some fast swimmers (as seen during this championship) might prioritise breaking the water quickly to maximise average forward speed (Veiga and Roig, 2016). However, those who achieved higher underwater speeds did not obtain correlations with race times (**Table 9**), questioning the current paradigm on the best approach to take to the underwater phase of the 50 m freestyle. Only the female finalists showed significant changes in their CV in the final compared to the previous rounds that involved increases in underwater speed (**Table 1**). As with the men, different profiles were observed with swimmers attempting to reduce distance underwater causing a loss of speed, and others gaining an increase in speed as a result of that reduction. Therefore, it seems that swimmers attempted different manners to increase such speed in order to improve final performance (**Table 5**).

4.2.2 Backstroke

There was a significant CV in the men between the final and semi-final which showed that the finalists reduced the time and distance of the underwater swim during the final to gain speed in the first few metres of the event, although these improvements were only significant when compared to the heats (**Table 6**). It has been reported that, in backstroke sprint events, swimmers move faster when performing dolphin kicks than swimming on the surface (Collard, 2007). In some cases (i.e., men in the semi-finals and women in the heats), swimmers with higher underwater distances obtained large correlations with T15 (**Table 10**); however, swimmers with superior underwater speeds were the best performers at T15 and T25 in most rounds. This is consistent with other research

TABLE 8 | Butterfly intra-athlete's coefficient of variation (CV) and relative change in performance (%Δ). Men (M); Women (W); Heat (H); Semi-final (SF); Final (F) (LEN European Senior Championships 2021).

		H-F (*n* = 8)			H-SF (*n* = 17)			SF-F (*n* = 8)		
		CV	**p**	**%Δ**	**CV**	**p**	**%Δ**	**CV**	**p**	**%Δ**
Reaction Time	M	0.06 ± 0.01	0.276	0.05 ± 0.01	0.06 ± 0.01	0.744	0.01 ± 0.01	0.07 ± 0.01	0.565	0.03 ± 0.01
	W	0.04 ± 0.01	0.196	0.01 ± 0.01	0.04 ± 0.01	0.739	0.01 ± 0.01	0.05 ± 0.01	0.997	−0.02 ± 0.01
Flight Time	M	0.11 ± 0.01	0.327	−0.15 ± 0.01	0.22 ± 0.01	0.298	−0.05 ± 0.01	0.12 ± 0.01	0.804	−0.12 ± 0.01
	W	0.07 ± 0.01	0.381	0.01 ± 0.01	0.07 ± 0.01	0.936	−0.01 ± 0.01	0.04 ± 0.01	0.243	−0.04 ± 0.01
Entry Distance	M	0.11 ± 0.01	0.436	−0.05 ± 0.01	0.13 ± 0.01	0.317	−0.07 ± 0.01	0.14 ± 0.01	0.971	0.01 ± 0.01
	W	0.13 ± 0.01	0.621	0.01 ± 0.01	0.16 ± 0.01	0.386	0.04 ± 0.01	0.09 ± 0.01	0.728	−0.08 ± 0.01
Underwater Time	M	0.71 ± 0.01	0.571	−0.27 ± 0.01	0.31 ± 0.01	0.406	0.11 ± 0.01	0.55 ± 0.01	0.353	−0.31 ± 0.01
	W	0.40 ± 0.01	0.132	−0.34 ± 0.01	0.73 ± 0.01	0.525	−0.19 ± 0.01	0.62 ± 0.01	0.928	−0.05 ± 0.01
Underwater Distance	M	0.63 ± 0.01	0.386	−0.32 ± 0.01	0.44 ± 0.01	0.470	0.18 ± 0.01	0.42 ± 0.01	0.014*	−0.61 ± 0.03
	W	0.58 ± 0.01	0.844	−0.24 ± 0.01	0.73 ± 0.01	0.240	−0.29 ± 0.01	0.65 ± 0.01	0.789	−0.29 ± 0.01
Underwater Velocity	M	2.30 ± 0.03	0.731	−0.14 ± 5.74	1.43 ± 0.01	0.747	0.21 ± 3.33	3.51 ± 0.03	0.529	−1.57 ± 7.23
	W	0.92 ± 0.01	0.129	0.31 ± 1.93	2.02 ± 0.02	0.530	−0.20 ± 5.14	0.53 ± 0.06	0.317	0.01 ± 1.01
Time 150 m	M	0.17 ± 0.01	0.037*	−0.21 ± 0.01	0.18 ± 0.01	0.486	−0.07 ± 0.01	0.16 ± 0.01	0.976	0.01 ± 0.01
	W	0.23 ± 0.01	0.054	−0.26 ± 0.01	0.20 ± 0.01	0.104	−0.13 ± 0.01	0.23 ± 0.01	0.253	−0.12 ± 0.01
Time 25 m	M	0.31 ± 0.05	0.011*	−0.39 ± 0.01	0.19 ± 0.02	0.079	−0.15 ± 0.01	0.22 ± 0.03	0.452	−0.06 ± 0.01
	W	0.42 ± 0.07	0.007*	−0.58 ± 0.01	0.38 ± 0.06	0.001*	−0.48 ± 0.01	0.26 ± 0.04	0.255	−0.10 ± 0.01
Time 35 m	M	0.44 ± 0.01	0.001*	−0.61 ± 0.01	0.32 ± 0.03	0.035	−0.29 ± 0.01	0.36 ± 0.01	0.376	−0.04 ± 0.01
	W	0.64 ± 0.09	0.003*	−0.92 ± 0.01	0.43 ± 0.01	0.001*	−0.51 ± 0.01	0.41 ± 0.06	0.063	−0.35 ± 0.01
Time 45 m	M	0.75 ± 0.09	0.003*	−1.05 ± 0.01	0.48 ± 0.01	0.012*	−0.47 ± 0.01	0.43 ± 0.06	0.059	−0.40 ± 0.01
	W	0.75 ± 0.09	0.003*	−1.05 ± 0.01	0.48 ± 0.01	0.012*	−0.47 ± 0.01	0.43 ± 0.06	0.059	−0.40 ± 0.01
Time 50 m	M	0.64 ± 0.01	0.002*	−0.72 ± 0.82	0.41 ± 0.01	0.012*	−0.44 ± 0.64	0.45 ± 0.01	0.421	0.02 ± 0.78
	W	0.88 ± 0.01	0.004*	−1.09 ± 1.22	0.48 ± 0.01	0.023*	−0.44 ± 0.75	0.41 ± 0.01	0.043*	−0.42 ± 0.01
Split25-50 m	M	0.37 ± 0.02	0.049*	−0.34 ± 0.01	0.33 ± 0.03	0.022*	−0.30 ± 0.01	0.25 ± 0.02	0.928	0.08 ± 0.01
	W	0.51 ± 0.04	0.001*	−0.52 ± 0.01	0.30 ± 0.03	0.823	0.02 ± 0.01	0.28 ± 0.02	0.014*	−0.32 ± 0.01
Finish time	M	0.22 ± 0.05	0.798	−0.06 ± 0.01	0.22 ± 0.05	0.619	−0.06 ± 0.01	0.11 ± 0.03	0.644	0.04 ± 0.01
	W	0.28 ± 0.05	0.216	−0.05 ± 0.01	0.15 ± 0.05	0.721	0.02 ± 0.01	0.21 ± 0.06	0.260	−0.03 ± 0.01
SR15-25 m	M	1.54 ± 0.01	0.021*	1.79 ± 2.09	2.15 ± 0.01	0.264	0.94 ± 3.74	2.18 ± 0.02	0.227	1.36 ± 3.99
	W	0.81 ± 0.01	0.003*	1.13 ± 0.81	1.20 ± 0.01	0.001*	1.49 ± 1.27	0.68 ± 0.01	0.960	0.08 ± 1.31
SR35-45 m	M	2.18 ± 0.01	0.015*	2.67 ± 2.83	2.06 ± 0.01	0.005*	2.03 ± 2.71	1.35 ± 0.01	0.828	−0.04 ± 2.63
	W	2.09 ± 0.01	0.001*	2.90 ± 0.95	1.19 ± 0.01	0.035*	0.99 ± 1.78	1.08 ± 0.01	0.059	1.16 ± 1.48
SR Final	M	3.71 ± 0.01	0.545	−0.09 ± 6.28	2.99 ± 0.02	0.246	1.35 ± 5.14	3.22 ± 0.01	0.338	−2.37 ± 4.66
	W	1.96 ± 0.01	0.711	0.18 ± 3.94	2.19 ± 0.02	0.598	−0.55 ± 4.23	1.79 ± 0.01	0.060	1.94 ± 2.72
SL15-25 m	M	1.64 ± 0.01	0.199	−1.00 ± 2.51	2.14 ± 0.01	0.531	−0.72 ± 4.02	2.55 ± 0.02	0.395	−1.23 ± 4.78
	W	0.89 ± 0.01	0.416	0.36 ± 1.58	1.13 ± 0.01	0.892	0.04 ± 1.99	0.60 ± 0.01	0.894	−0.14 ± 1.33
SL35-45 m	M	1.56 ± 0.01	0.041*	−1.79 ± 2.31	1.59 ± 0.01	0.027*	−1.49 ± 2.48	1.64 ± 0.01	0.768	−0.13 ± 2.95
	W	1.42 ± 0.01	0.049*	−1.46 ± 1.69	1.21 ± 0.01	0.115	−0.87 ± 2.21	1.26 ± 0.01	0.882	−0.07 ± 1.99
SL Final	M	3.99 ± 0.02	0.751	0.17 ± 6.75	2.96 ± 0.02	0.473	−1.19 ± 5.58	3.30 ± 0.01	0.379	1.79 ± 4.90
	W	2.54 ± 0.02	0.824	0.01 ± 5.09	2.71 ± 0.02	0.880	0.01 ± 5.14	1.88 ± 0.01	0.115	−1.86 ± 2.56

**Significant differences.*

where maximising underwater speed was more important than displacing a long distance underwater (Gonjo and Olstad, 2021). In the women, no significant CVs were obtained for any of the underwater variables (**Table 6**).

4.2.3 Breaststroke

Significant CV changes were obtained for underwater time and distance in the male finalists, indicating that during the final there was a Δ% reduction compared to the heats (**Table 7**). However, if this reduction was made with the aim of generating an increase in underwater speed, this was not the case (**Table 3**), with many swimmers demonstrating very different strategies from each other, as can be seen in the high SD obtained in the Δ% for this variable. A previous study carried out in short pool showed that, in men, a long underwater distance was related to a better final time (Sánchez et al., 2021); in this study, the same relationship was only found in T15, and only during the heats. In the case of the women, no significant changes were generated between rounds in any of the underwater time and distance variables; however, an increase on the underwater speed was detected in the semi-final. Actually, it appears that a short underwater time benefited performance at T25 during the semi-finals, but these relations were only moderate and did not translate to T50 (**Table 11**). Therefore, although a possible influence was plausible, the changes that occurred in T50 likely came from changes in other variables. A similar result was obtained previously (Olstad et al., 2020; Sánchez et al., 2021) since no correlations were obtained between the variables of emersion time with final time, and no differences were obtained between finalists and non-finalists.

4.2.4 Butterfly

Only in men, there was a reduction in underwater distance during the final (**Table 8**). Interestingly, those men and

TABLE 9 | Pearson correlation coefficients (r) of the 50 m Freestyle's competition variables (LEN European Senior Championships 2021).

Variable	Round	Males			Females		
		Time 15 m	Time 25 m	Time 50 m	Time 15 m	Time 25 m	Time 50 m
Reaction Time	Heats	0.254	0.370	−0.089	0.018	−0.111	−0.223
	Semi-final	0.278	0.292	0.018	0.164	0.044	−0.064
	Final	0.517	0.617	0.611	−0.107	−0.266	0.079
Flight Time	Heats	−0.163	−0.331	−0.445	0.060	0.030	0.117
	Semi-final	−0.203	−0.206	−0.040	−0.128	−0.191	−0.165
	Final	−0.471	−0.410	−0.327	0.567	0.698	0.499
Entry Distance	Heats	−0.374	−0.678*	−0.572**	0.258	0.228	0.212
	Semi-final	−0.506**	−0.508**	−0.224	0.220	0.235	0.166
	Final	−0.699	−0.368	−0.416	0.156	0.272	0.296
Underwater Time	Heats	−0.280	−0.162	−0.283	−0.276	−0.257	−0.189
	Semi-final	−0.365	−0.064	0.203	−0.275	−0.136	−0.061
	Final	0.152	0.375	0.292	0.138	0.353	0.214
Underwater Distance	Heats	−0.366	−0.212	0.211	−0.344	−0.275	−0.189
	Semi-final	−0.358	−0.067	0.194	−0.435	−0.324	−0.247
	Final	0.045	0.306	0.259	−0.017	0.121	−0.033
Underwater Speed	Heats	−0.056	−0.017	−0.417	−0.083	0.043	0.107
	Semi-final	0.245	0.032	−0.181	−0.357	−0.433	−0.459
	Final	−0.632	−0.579	−0.483	−0.379	−0.694	−0.610
Time 15 m	Heats	-	0.785*	0.388	-	0.852*	0.570**
	Semi-final	-	0.747*	0.400	-	0.871*	0.588**
	Final	-	0.727**	0.700	-	0.846*	0.595
Time 25 m	Heats	-	-	0.646*	-	-	0.834*
	Semi-final	-	-	0.781*	-	-	0.884*
	Final	-	-	0.947*	-	-	0.859*
Split 25-50 m	Heats	-	-	0.623*	-	-	0.885*
	Semi-final	-	-	0.802*	-	-	0.945*
	Final	-	-	0.772**	-	-	0.818**
Finish time	Heats	-	-	0.132	-	-	0.434
	Semi-final	-	-	0.068	-	-	0.084
	Final	-	-	0.095	-	-	−0.088
SR 15-25 m	Heats	-	−0.296	−0.201	-	−0.191	0.035
	Semi-final	-	−0.280	−0.143	-	−0.046	−0.059
	Final	-	−0.682	−0.763**	-	−0.130	−0.448
SR 35-45 m	Heats	-	-	−0.084	-	-	0.079
	Semi-final	-	-	−0.078	-	-	0.093
	Final	-	-	0.502	-	-	−0.813**
SR Final	Heats	-	-	0.031	-	-	−0.024
	Semi-final	-	-	0.246	-	-	0.140
	Final	-	-	−0.328	-	-	−0.908*
SL 15-25 m	Heats	-	0.173	0.069	-	0.118	−0.160
	Semi-final	-	0.069	0.112	-	−0.058	0.137
	Final	-	0.121	0.265	-	0.139	0.406
SL 35-45 m	Heats	-	-	−0.135	-	-	−0.159
	Semi-final	-	-	−0.078	-	-	−0.320
	Final	-	-	0.435	-	-	0.828**
SL Final	Heats	-	-	−0.235	-	-	−0.097
	Semi-final	-	-	−0.006	-	-	−0.269
	Final	-	-	0.219	-	-	0.784**

*$p < 0.01$.
**$p < 0.05$.

women who achieved a greater underwater distance achieved better results in T15 and T25, with very high correlations only during the heats, but only the men who reached a greater underwater speed achieved better results in T15 and T25 only during the final. According to Gonjo and Olstad (2020), average forward speed during the underwater phase is highly correlated with T15. In our study, the finalists obtained the same correlation also for T25 (**Table 12**), so possibly a reduced underwater phase was adopted during the final with the aim of gaining speed, although it was not effective for all swimmers.

4.3 Time Segments (Time to 15, 25, 35 and 45 m; Split Time (From 25 to 50 m); Finish Time (45–50 m).

For the start time at 15 m and the finish segment, there is a lack of knowledge in the sprint events in the long course (Gonjo and

TABLE 10 | Pearson correlation coefficients (r) of the 50 m Backstroke's competition variables (LEN European Senior Championships 2021).

		Males			Females		
Variable	**Round**	**Time 15 m**	**Time 25 m**	**Time 50 m**	**Time 15 m**	**Time 25 m**	**Time 50 m**
Reaction Time	Heats	0.027	–0.184	–0.522*	0.489	0.533*	0.157
	Semi-final	0.194	–0.005	–0.236	0.550*	0.515*	0.301
	Final	–0.264	–0.703	–0.697	0.699	0.784	0.443
Flight Time	Heats	0.155	0.327	0.156	–0.141	–0.147	0.110
	Semi-final	–0.093	0.046	0.013	0.021	0.048	0.032
	Final	0.033	0.504	0.887**	–0.93	–0.24	0.653
Entry Distance	Heats	0.247	0.178	–0.441	0.147	0.052	–0.171
	Semi-final	–0.203	–0.246	–0.356	0.206	–0.173	–0.174
	Final	0.158	0.484	0.712*	–0.386	–0.307	0.348
Underwater Time	Heats	–0.259	0.037	0.340	–0.098	–0.105	0.044
	Semi-final	–0.310	–0.076	0.447	0.235	0.133	0.098
	Final	0.027	0.282	0.494	0.290	0.279	0.190
Underwater Distance	Heats	–0.565	–0.246	0.459	–0.597*	0.554	–0.161
	Semi-final	–0.521*	–0.302	0.269	–0.441	–0.482	–0.310
	Final	–0.495	–0.196	0.367	–0.266	–0.245	0.121
Underwater Speed	Heats	–0.749**	–0.670**	0.310	–0.946**	–0.865**	–0.400
	Semi-final	–0.555*	-0.483	–0.150	–0.962**	–0.876**	–0.591*
	Final	–0.938**	–0.850**	–0.220	–0.922**	–0.873**	–0.175
Time 15 m	Heats	-	0.805**	–0.173	-	0.919**	0.443
	Semi-final	-	0.886**	0.206	-	0.946**	0.667**
	Final	-	0.731*	–0.041	-	0.984**	0.352
Time 25 m	Heats	-	-	0.308*	-	-	0.679**
	Semi-final	-	-	0.565*	-	-	0.820**
	Final	-	-	0.603	-	-	0.483
Split 25-50 m	Heats	-	-	0.892**	-	-	0.778**
	Semi-final	-	-	0.852**	-	-	0.828**
	Final	-	-	0.941**	-	-	0.639
Finish time	Heats	-	-	0.671**	-	-	0.478
	Semi-final	-	-	0.564*	-	-	0.554*
	Final	-	-	0.766*	-	-	–0.132
SR 15-25 m	Heats	-	–0.230	–0.090	-	–0.151	0.119
	Semi-final	-	–0.028	0.012	-	–0.288	–0.103
	Final	-	–0.595	–0.321	-	–0.506	–0.510
SR 35-45 m	Heats	-	-	–0.059	-	-	0.247
	Semi-final	-	-	–0.135	-	-	–0.294
	Final	-	-	–0.358	-	-	–0.583
SR Final	Heats	-	-	–0.216	-	-	–0.321
	Semi-final	-	-	–0.270	-	-	0.184
	Final	-	-	–0.382	-	-	–0.812*
SL 15-25 m	Heats	-	0.119	–0.167	-	–0.129	–0.235
	Semi-final	-	–0.170	–0.354	-	0.122	–0.110
	Final	-	0.474	0.025	-	0.072	0.403
SL 35-45 m	Heats	-	-	–0.237	-	-	–0.131
	Semi-final	-	-	–0.305	-	-	0.020
	Final	-	-	0.089	-	-	0.416
SL Final	Heats	-	-	–0.100	-	-	0.193
	Semi-final	-	-	–0.065	-	-	0.145
	Final	-	-	–0.151	-	-	0.667

*p < *0.01.*
**p < *0.05.*

Olstad, 2021; Morais et al., 2021), even more so if what is studied is how these variables change over the different rounds.

4.3.1 Freestyle

In men, no significant CV was obtained in T15 as the time performances were similar between rounds (**Table 1**). According to other studies (Trinidad et al., 2020; Morais et al., 2021), in the comparison between faster and slower swimmers in 50 m freestyle, the largest differences are observed in T15. However, while T15 was the main predictor of T25 performance for both men and women, with very high to nearly perfect correlations, this variable did not affect T50 in the case of men (**Table 9**), possibly due to the different profiles found in the underwater phase, and the fact that some of the swimmers were able to progress even in the face of disadvantageous starts (or vice versa, fade after advantageous starts). The women showed changes in CV in T15, which led to improvements in performance in the semi-finals and final compared to the heats (**Table 1**).

TABLE 11 | Pearson correlation coefficients (r) of the 50 m Breaststroke's competition variables (LEN European Senior Championships 2021).

		Males			Females		
Variable	**Round**	**Time 15 m**	**Time 25 m**	**Time 50 m**	**Time 15 m**	**Time 25 m**	**Time 50 m**
Reaction Time	Heats	0.323	0.357	0.058	−0.125	−0.073	−0.034
	Semi-final	0.400	0.511*	0.244	0.377	0.232	0.267
	Final	0.445	0.662	0.592	−0.023	−0.021	−0.071
Flight Time	Heats	−0.193	−0.099	0.082	0.347	−0.042	−0.319
	Semi-final	−0.139	−0.138	0.046	0.047	−0.463	−0.451
	Final	−0.260	−0.380	−0.247	0.030	−0.223	−0.285
Entry Distance	Heats	−0.160	−0.232	−0.040	0.069	−0.074	−0.226
	Semi-final	−0.033	−0.141	−0.258	−0.087	−0.444	−0.418
	Final	−0.058	−0.159	−0.266	−0.620	−0.202	0.097
Underwater Time	Heats	−0.666**	−0.319	0.015	−0.264	0.484	0.303
	Semi-final	−0.220	−0.337	−0.090	0.268	0.499*	0.248
	Final	−0.044	0.004	0.034	0.429	0.449	0.184
Underwater Distance	Heats	−0.782**	−0.430	−0.109	−0.022	0.300	0.286
	Semi-final	−0.475	−0.553	−0.168	0.011	0.354	0.256
	Final	−0.482	−0.465	−0.211	0.341	0.246	0.007
Underwater Speed	Heats	−0.001	−0.036	−0.111	−490	−0.438	−0.129
	Semi-final	−0.542*	−0.420	−0.154	−607*	−0.480	−0.082
	Final	−0.820*	−0.746*	−0.394	−0.562	−0.696	−0.491
Time 15 m	Heats	-	0.731**	0.230	-	0.688**	0.354
	Semi-final	-	0.838**	0.314	-	0.583*	0.337
	Final	-	0.942*	0.577	-	0.440	−0.097
Time 25 m	Heats	-	-	0.758**	-	-	0.755**
	Semi-final	-	-	0.681**	-	-	0.820**
	Final	-	-	0.763*	-	-	0.833*
Split 25-50m	Heats	-	-	0.870**	-	-	0.925**
	Semi-final	-	-	0.838**	-	-	0.943**
	Final	-	-	0.730*	-	-	0.945**
Finish time	Heats	-	-	0.122	-	-	0.287
	Semi-final	-	-	0.416	-	-	0.084
	Final	-	-	0.068	-	-	−0.067
SR 15-25 m	Heats	-	−0.144	−0.404	-	−0.321	−0.429
	Semi-final	-	−0.139	−0.279	-	−0.690**	−0.465
	Final	-	−0.138	−0.108	-	−0.167	−0.230
SR 35-45 m	Heats	-	-	−0.308	-	-	0.416
	Semi-final	-	-	−0.388	-	-	−0.539*
	Final	-	-	0.089	-	-	−0.309
SR Final	Heats	-	-	−0.328	-	-	−0.515*
	Semi-final	-	-	−0.246	-	-	−0.505*
	Final	-	-	−0.115	-	-	−0.240*
SL 15-25 m	Heats	-	0.037	0.163	-	0.209	0.256
	Semi-final	-	0.008	0.049	-	0.635**	0.379
	Final	-	−0.280	−0.069	-	0.001	−0.077
SL 35-45 m	Heats	-	-	0.061	-	-	0.227
	Semi-final	-	-	0.164	-	-	0.308
	Final	-	-	−0.277	-	-	0.091
SL Final	Heats	-	-	0.271	-	-	0.388
	Semi-final	-	-	0.008	-	-	0.394
	Final	-	-	0.096	-	-	0.240

*p < *0.01.*
**p < *0.05.*

With the exception of T25, the men did not obtain significant CV changes for the 35 and 45 m mark, as performances during the semi-finals were better than achieved in the finals. For the same variables, the women obtained changes in CV corresponding to Δ% reductions in swim time as the race progressed, especially between the semi-final and final compared to the heats (**Table 5**). In this case, it appears that improvements in T15 not only influenced final performance, but also that those with excellent performances early in the race were difficult to beat by other contenders in the middle of the 50 m-lap (Simbaña-Escobar et al., 2018). Therefore, in the case of the women, it was much more relevant a good development in the early stages of the race (15 and 25 m) to improve the final time obtained in the previous rounds.

For the Split25-50 m and finish time, there were CV changes and Δ% reductions in the men in the final and semi-finals compared to the heats (**Table 5**), so it is possible that

TABLE 12 | Pearson correlation coefficients (r) of the 50 m Butterfly's competition variables (LEN European Senior Championships 2021).

		Males			Females		
Variable	**Round**	**Time 15 m**	**Time 25 m**	**Time 50 m**	**Time 15 m**	**Time 25 m**	**Time 50 m**
Reaction Time	Heats	0.205	0.123	0.157	0.163	0.144	0.064
	Semi-final	0.113	0.118	0.185	0.247	0.334	0.287
	Final	−0.002	0.097	0.143	−0.170	0.660	0.721*
Flight Time	Heats	−0.045	0.086	0.246	0.060	−0.073	0.023
	Semi-final	−0.046	−0.049	0.083	0.004	−0.086	−0.055
	Final	−0.039	−0.100	−0.147	0.229	0.047	0.025
Entry Distance	Heats	−0.287	−0.364	0.011	0.028	0.036	0.115
	Semi-final	−0.635**	−0.556**	0.062	−0.252	−0.235	−0.178
	Final	−0.333	−0.591	−0.503	0.306	0.205	0.140
Underwater Time	Heats	−0.565	−0.401	0.080	−0.427	−0.324	−0.299
	Semi-final	−0.317	−0.129	0.054	−0.232	−0.224	−0.238
	Final	−0.112	0.264	0.443	0.300	0.411	0.491
Underwater Distance	Heats	−0.750**	−0.574*	−0.016	−0.579*	−0.443	−0.412
	Semi-final	−0.427	−0.181	0.061	−0.383	−0.471	−0.434
	Final	−0.395	0.012	0.267	0.177	0.203	0.496
Underwater Speed	Heats	−0.086	0.118	−0.198	0.384	−0.305	−0.291
	Semi-final	−0.201	−0.088	0.032	−0.270	−0.362	−0.319
	Final	−0.717*	−0.749*	−0.604	−0.308	−0.463	−0.314
Time 15 m	Heats	-	0.906**	0.332	-	0.936**	0.844**
	Semi-final	-	0.895**	0.406	-	0.918**	0.826**
	Final	-	0.831*	0.466	-	0.949**	0.885**
Time 25 m	Heats	-	-	0.519*	-	-	0.924**
	Semi-final	-	-	0.622*	-	-	0.928**
	Final	-	-	0.789*	-	-	0.825*
Split 25-50 m	Heats	-	-	0.496	-	-	0.765**
	Semi-final	-	-	0.621*	-	-	0.897**
	Final	-	-	0.601	-	-	0.673
Finish time	Heats	-	-	0.270	-	-	0.414
	Semi-final	-	-	0.235	-	-	0.551
	Final	-	-	0.540	-	-	−0.110
SR 15-25 m	Heats	-	−0.319	−0.215	-	0.398	0.271
	Semi-final	-	−0.425	−0.241	-	0.355	0.335
	Final	-	−0.242	−0.515	-	−0.065	0.058
SR 35-45 m	Heats	-	-	−0.537*	-	-	0.247
	Semi-final	-	-	−0.419	-	-	0.179
	Final	-	-	−0.486	-	-	−0.173
SR Final	Heats	-	-	−0.557*	-	-	−0.194
	Semi-final	-	-	−0.483	-	-	−0.184
	Final	-	-	−0.462	-	-	−0.339
SL 15-25 m	Heats	-	0.347	0.158	-	−0.563*	−0.452
	Semi-final	-	0.426	0.161	-	−0.409	−0.408
	Final	-	0.042	0.228	-	0.072	0.023
SL 35-45 m	Heats	-	-	0.160	-	-	−0.410
	Semi-final	-	-	0.225	-	-	−0.367
	Final	-	-	0.381	-	-	0.049
SL Final	Heats	-	-	−0.087	-	-	−0.052
	Semi-final	-	-	0.273	-	-	−0.198
	Final	-	-	0.213	-	-	0.263

*p < *0.01*.
**p < *0.05*.

regardless of the improvements obtained in the first metres of the event, some swimmers had the ability to avoid a sharp decrease in speed at the end (Simbaña-Escobar et al., 2018; Morais et al., 2021). In the case of the women, these variables did not improve as the competition progressed.

4.3.2 Backstroke

The men increased the speed of swimming between rounds since a significant CV change was obtained in all time variables in the comparison of the time of the final and heats and in most of the comparisons between the final and the semi-finals (**Table 6**). In the case of females, it appeared to be performance improvements during the semi-finals; however, the expected improvements were not obtained during the final (**Table 3**). The variable T15 obtained a very high correlation T25 performance in most cases but did not predict T50. In the case of T25 this variable appears not to be valid to predict T50 performance during the Final.

On the other hand, both men and women obtained CV changes in the finish time, with better performance during the semi-final than during the heats, so, in terms of swimming strategy, increasing the pace in the first split of the race (15 or 25 m) seemed to be a determining factor to reduce the final time, especially in men, as improvements here translated to final performance and neither the pace of the 25–50 split, nor the finish Time, had an influence on the worsening of these results. That said, lower Split25-50 and finish times obviously benefited better T50 performances (**Table 10**).

4.3.3 Breaststroke

For both men and women, there were no changes in CV at T15 in the different rounds (**Table 7**), so the changes made in the previous underwater phase had no relevant effect on performance. Similarly, T15 was shown to predict at 25, but not T50. In other study (Sánchez et al., 2021), male and female 50 m breaststroke finalists had better T15 m values during finals compared to heats ($p < 0.05$), and these values were related to better final performance (r > 0.6); however, the participants in that study were national level swimmers and the relationships might be different among higher level contenders (i.e., international championship finalists and semi-finalists) (Hellard et al., 2008).

For T25, T35, and T45, in the men, CV changes were only significant in the semi-finals, as time performances appeared to be better than those achieved during the final (**Table 7**), confirming the fact that the winner and/or medallists may not always be the fastest of the tournament (**Supplementary Material**). On the contrary, women showed CV changes and Δ% reductions to progress between rounds, especially significant between the final and the heats (**Table 3**). Thus, performance changes in the women occurred mainly during the clean swim splits (T25, T35, and T45).

There were no variations or reductions in performance in the variables Split25-50 m and finish time, meaning that possibly the swimmers acquired high speed in the first stage of the race and found it very difficult to continue progressing in performance as the race proceeds.

4.3.4 Butterfly

Despite no improvement in the underwater phase, T15 m improved in men and almost in women (p = 0.054) to progress between rounds. In fact, the CV of T25, T35 and T45 changed in men and women in the finals, and especially in women in most of the semi-finalists (**Table 8**). These changes showed reductions in Δ% between rounds. It seems that starting the race at high speed to reduce the time to 15 m was more determinant for the women than the men to achieve better performance in T25 and T50. In this regard, Kilani and Zeidan (2004), reported that the first split of the race, including the swim start, was more determinant than the second to achieve a great result. In any case, both men and women who progressed between rounds to the final showed changes in Split25-50 CV, with significant reductions Δ% especially during the semi-finals (**Table 4**), indicating that they were able to improve performance both at the beginning and at the end of the race.

4.4 Stroke Patterns (Stroke Rate and Stroke Length)

Changes in stroke patterns have been interpreted as a strategy used by swimmers to cope with performance changes within a race (Seifert et al., 2005; Hellard et al., 2008). Stroke rate is related to neuromuscular power and energetic capacities (Wakayoshi et al., 1995), whereas stroke length depends more on technical skill resulting from the increased propulsive force generated by the arms and legs (Seifert et al., 2005). The literature, in middle-distance swimming, has reported that high-level swimmers have a higher stroke rate and length than low-level swimmers (Hellard et al., 2008). However, evidence in sprint swimming showed that swimming speed, stroke rate and stroke length are not linearly related (Craig and Pendergast, 1979; Wakayoshi et al., 1995).

4.4.1 Freestyle

Although changes in CV were not always statistically significant, an overall increase in SR15-25 and SR35-45 appeared to be determinant for those men and women who progressed between rounds (**Table 5**). A high SR helps to maintain a high swim speed between stroke cycles and to overcome drag (Barbosa et al., 2010; Ribeiro et al., 2017; Simbaña-Escobar et al., 2018). Within the race, the values of this variable decreased progressively from 15–25 to 35–45 m, possibly as a consequence of fatigue, as reported previously (Cuenca-Fernández et al., 2021a; Morais et al., 2021). In the case of the male finalists, a significant CV change (higher SR) was observed in the last metres (**Table 1**), which would be consistent with the CV and Δ% results obtained for Split25-50 m and finish time. For the women, CV changes showed increases in SR in the second half of the event (i.e., from 35 to 45 m), to move into the semi-finals and final (**Table 5**). In terms of SL, CV changes accounted for Δ% reductions for both men and women between rounds. This was in agreement with Maglischo (2003), who stated that "when swimmers want to go faster, they increase their SR, although their SL decreases". While the swimmers during the final showed higher SL values from 15 to 25 m compared to the previous rounds (**Table 1**), in most cases, the values at 35–45 m were higher than at 15–25 m, presumably as a consequence of the decrease of SR. According to some studies (Kilani and Zeidan, 2004; Arellano et al., 2018; Simbaña-Escobar et al., 2018; Morais et al., 2021), SL is one of the main factors responsible for the difference in swim speed in 50 m freestyle. In this sense, a higher SL could reflect a greater ability to transfer the propulsive thrust to the water (Cuenca-Fernández et al., 2020; Ruiz-Navarro et al., 2020). However, men did not obtain any significant correlation, and those female finalists who showed a high SL at the end of the race obtained very high positive correlations with T50, attaining worse performances (**Table 9**). Therefore, it cannot be ruled out that swimmers who were able to increase their SR while maintaining or decreasing in a non-meaningful way SL, gained advantages in progressing between rounds in the sprint freestyle.

4.4.2 Backstroke

The CV differences showed that increases in SR between rounds were common in men (**Table 6**), but these changes were not a consistent pattern in all women. As observed for the other strokes, higher SR was accompanied by reductions in SL (**Table 2**). In any case, higher or lower SR and SL were not a determining factor for those who performed better, and the SR final was only noticeable for the female finalists at the end of the race, possibly because most of them did not significantly increase SR15-25 and SR35-45 as they progressed between rounds. It has been reported that backstroke often leads to lower SR values due to the longer duration of the propulsion and recovery phases (Gonjo et al., 2020). Compared to other strokes, less propulsive drag force is applied by the hands during the push phase due to the wrist moving backwards with respect to the swimming direction. Thus, this would imply that the contribution of the other body parts to propulsion, such as the lower limbs, is much greater and could therefore be much less detectable if progressing between rounds.

4.4.3 Breaststroke

The men maintained similar SR values throughout the race, however, the CV showed the increase in Δ% SR between rounds (**Table 7**). Similarly, the women obtained significant CV reflecting that they were able to increase SR especially during the final, but only in them, relationships were observed with improved performance. Previous studies have denoted that high SR (above 60 cycles/min) and lower glide is necessary for success in breaststroke sprint swimming (Kilani and Zeidan, 2004; Strzala et al., 2013); however, as swimmers increased SR as they progressed between heats, it resulted in a reduction of the glide phase and thus SL, especially in men (**Table 3**). Therefore, within the swimmers who were able to progress between rounds, the SR increase could be a relevant factor as showed in the women; however, when the increase in SR induces a severe reduction in SL, a worsening of performance may occur as demonstrated in the men.

4.4.4 Butterfly

Both men and women obtained CV differences with clear trends towards increased SR during the final and semi-finals compared to the heats (**Table 4**). Sprint butterfly swimmers have been reported to achieve high speed with very high SR, often exceeding 60 cycles per minute, as demonstrated in previous European swimming championships (Strzała et al., 2017). Furthermore, in the study of Seifert et al. (2008), more skilled butterfly swimmers had higher SR and SL than less skilled swimmers. In our study, however, only SR showed certain relationships in men with T50 during the heats, while SL did not seem to predict final performance in any case, with low to moderate correlations (**Table 12**). Similar to what was obtained for other strokes, the increase in SR was possibly the main cause of the decreases in SL in the second part of the race (SL35-45), as in both men and women CV changes with Δ% performance reductions were obtained in the finals and semi-finals compared to the heats.

5 CONCLUSION

During the different rounds of the 50 m competitions, intra-individual performances varied in a significant range of 0.5–0.7%. With the exception of the men's breaststroke, there were significant improvements in T50 as the competition progressed, meaning that the best swimmers did not excel during the heats to perform at their best during the final. For all strokes, apart from slight improvements in the actions performed in the block, it was a common tendency to reduce the underwater phase and increase SR with the aim of increasing speed. However, this result was not always obtained or was not adequately transferred to the final performance.

It is important to bear in mind that elite sports are often composed of "outliers" performances coming from athletes with different backgrounds and, therefore, trends will always be somewhat influenced by this. In addition, high achievements are also influenced by post-training factors that increase with years of practice and the level of expertise to know how to move from heats, to semi-finals and finals. Clearly, top swimmers who are able to gather those qualities, will improve their performance in major international competitions and their chances of winning a medal.

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

RA contributed conception and design of the study and critically discussed the results. General coordination of the working group and funded project responsible. Corresponding author. FC-F and JR-N contributed conception and design of the study, collected video data, wrote the first draft of the manuscript, timecoded the video footage and manuscript review after the first draft. Statistics data analysis. TB externally reviewed the design of the study, critically discussed the results and reviewed the draft documents. GL-C, EM-O, OL-B, and AG video data collection of study variables. AG-P video and web results Python web scrapping and exporting to Excel database. All authors contributed to manuscript revision, read, and approved the submitted version.

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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.2022.797367/full#supplementary-material

REFERENCES

Abbiss, C. R., and Laursen, P. B. (2008). Describing and Understanding Pacing Strategies during Athletic Competition. *Sports Med.* 38 (3), 239–252. doi:10.2165/00007256-200838030-00004

Arellano, R., Brown, P., Cappaert, J., and Nelson, R. C. (1994). Analysis of 50-, 100-, and 200-m Freestyle Swimmers at the 1992 Olympic Games. *J. Appl. Biomechanics* 10 (2), 189–199. doi:10.1123/jab.10.2.189

Arellano, R., Ruíz-Teba, A., Morales-Ortíz, E., Gay, A., Cuenca-Fernandez, F., Llorente-Ferrón, F., et al. (2018). Short Course 50m Male Freestyle Performance Comparison between National and Regional Spanish Swimmers. *ISBS Proc. Arch.* 36 (1), 139.

Barbosa, T., Silva, A. J., Reis, A. M., Costa, M., Garrido, N., Policarpo, F., et al. (2010). Kinematical Changes in Swimming Front Crawl and Breaststroke with the AquaTrainer® Snorkel. *Eur. J. Appl. Physiol.* 109 (6), 1155–1162. doi:10.1007/s00421-010-1459-x

Collard, L. (2007). Average Swimming Speeds for 6 Sections of the 50-meter Backstroke Race: Comparison of Performance in Zones Swum Underwater or at the Surface in 12 International Short Course Events. *Int. J. Perform. Analysis Sport* 7 (3), 37–45. doi:10.1080/24748668.2007.11868408

Craig, A. B., and Pendergast, D. R. (1979). Relationships of Stroke Rate, Distance Per Stroke, and Velocity in Competitive Swimming. *Med. Sci. Sports Exerc.* 11 (3), 278–283.

Cuenca-Fernández, F., Boullosa, D., Ruiz-Navarro, J. J., Gay, A., Morales-Ortíz, E., López-Contreras, G., et al. (2021a). Lower Fatigue and Faster Recovery of Ultra-short Race Pace Swimming Training Sessions. *Res. Sports Med.* 2021, 1–14. doi:10.1080/15438627.2021.1929227

Cuenca-Fernández, F., Ruiz-Navarro, J. J., and Arellano Colomina, R. (2020). Strength-velocity Relationship of Resisted Swimming: A Regression Analysis. *ISBS Proc. Arch.* 38 (1), 99.

Cuenca-Fernández, F., Ruiz-Navarro, J. J., González-Ponce, A., López-Belmonte, Ó., Gay, A., and Arellano, R. (2021b). Progression and Variation of Competitive 100 and 200m Performance at the 2021 European Swimming Championships. *Sports Biomech.*, 1–16. doi:10.1080/14763141.2021.1998591

Cuenca-Fernández, F., Taladriz, S., López-Contreras, G., De la Fuente, B., Argüelles, J., and Arellano, R. (2015). "Relative Force and PAP in Swimming," in Paper Presented in the Proceedings of: The 33rd International Society of Biomechanics in Sports, July 3–29, 2015. (France: University of Poitiers).

de Jesus, K., Fernandes, R. J., Vilas-Boas, J. P., and Sanders, R. (2014). The Backstroke Swimming Start: State of the Art. *J. Hum. Kinet.* 42, 27–40. doi:10.2478/hukin-2014-0058

García-Hermoso, A., Saavedra, J. M., Arellano, R., and Navarro, F. (2017). Relationship between Swim Start Wall Contact Time and Final Performance in Backstroke Events in International Swimming Championships. *Int. J. Perform. Analysis Sport* 17 (3), 232–243. doi:10.1080/24748668.2017.1331573

Gonjo, T., and Olstad, B. H. (2020). Start and Turn Performances of Competitive Swimmers in Sprint Butterfly Swimming. *J. Sports Sci. Med.* 19 (4), 727–734. PMID:33239947.

Gonjo, T., Fernandes, R. J., Vilas-Boas, J. P., and Sanders, R. (2020). Upper Body Kinematic Differences between Maximum Front Crawl and Backstroke Swimming. *J. Biomechanics* 98, 109452. doi:10.1016/j.jbiomech.2019.109452

Gonjo, T., and Olstad, B. H. (2021). Race Analysis in Competitive Swimming: A Narrative Review. *Int. J. Environ. Res. Public Health* 18 (1), 69. doi:10.3390/ijerph18010069

Hay, J., Guimaraes, A., and Grimston, S. (1983). A Quantitative Look at Swimming Biomechanics. *Swim. Tech.* 20 (2), 11–17.

Hellard, P., Dekerle, J., Avalos, M., Caudal, N., Knopp, M., and Hausswirth, C. (2008). Kinematic Measures and Stroke Rate Variability in Elite Female 200-m Swimmers in the Four Swimming Techniques: Athens 2004 Olympic Semi-finalists and French National 2004 Championship Semi-finalists. *J. Sports Sci.* 26 (1), 35–46. doi:10.1080/02640410701332515

Hopkins, W. G., Hawley, J. A., and Burke, L. M. (1999). Design and Analysis of Research on Sport Performance Enhancement. *Med. Sci. Sports Exerc.* 31 (3), 472–485. doi:10.1097/00005768-199903000-00018

Hopkins, W. G., Marshall, S. W., Batterham, A. M., and Hanin, J. (2009). Progressive Statistics for Studies in Sports Medicine and Exercise Science. *Med. Sci. Sports Exerc.* 41, 3–12. doi:10.1249/mss.0b013e31818cb278

Issurin, V., Kaufman, L., Lustig, G., and Tenenbaum, G. (2008). Factors Affecting Peak Performance in the Swimming Competition of the Athens Olympic Games. *J. Sports Med. Phys. Fit.* 48 (1), 1–8. PMID:18212703.

Kilani, H., and Zeidan, W. (2004). "A Kinematc Comparison between the Semi-finals and the Finals for 50m Swimming Races of the Four Strokes," in 22th International Conference on Biomechanics in Sports (Ottawa: Springer), 125–128.

Maglischo, E. W. (2003). *Swimming Fastest*. Champaign Ill; Human kinetics.

Marinho, D. A., Garrido, N., Barbosa, T. M., Canelas, R., Silva, A. J., Costa, A. M., et al. (2009). Monitoring Swimming Sprint Performance during a Training Cycle. *J. Phys. Educ. Sport/Citius Altius Fortius* 25 (4).

Mason, B., and Cossor, J. (2000). "What Can We Learn from Competition Analysis at the 1999 Pan Pacific Swimming Championships?," in Proceedings of XVIII Symposium on Biomechanics in Sports: Applied Program: Application of Biomechanical Study in Swimming Editors R. Sanders and Y. Hong. (Hong Kong: Department of Sports Science and Physical Education the Chinese University of Hong Kong), 75–82.

McGibbon, K. E., Pyne, D. B., Shephard, M. E., and Thompson, K. G. (2018). Pacing in Swimming: A Systematic Review. *Sports Med.* 48 (7), 1621–1633. doi:10.1007/s40279-018-0901-9

Mohamed, T. J., Zied, A., Francisco, C.-F., and Abderraouf, B. A. (2021). Physiological, Perceptual Responses, and Strategy Differences in Age-Group Swimmers between Heats and Semi-finals in the 400 Metres Freestyle Event. *Int. J. Perform. Analysis Sport* 21, 953–964. doi:10.1080/24748668.2021.1963107

Morais, J. E., Barbosa, T. M., Silva, A. J., Veiga, S., and Marinho, D. A. (2021). Profiling of Elite Male Junior 50 M Freestyle Sprinters: Understanding the Speed-time Relationship. *Scand. J. Med. Sci. Sports* 32, 60–68. doi:10.1111/sms.14058

Morais, J. E., Marinho, D. A., Arellano, R., and Barbosa, T. M. (2019). Start and Turn Performances of Elite Sprinters at the 2016 European Championships in Swimming. *Sports Biomech.* 18 (1), 100–114. doi:10.1080/14763141.2018.1435713

Mujika, I., Villanueva, L., Welvaert, M., and Pyne, D. B. (2019). Swimming Fast when it Counts: A 7-year Analysis of Olympic and World Championships Performance. *Int. J. Sports Physiology Perform.* 14 (8), 1132–1139. doi:10.1123/ijspp.2018-0782

O'Donoghue, P. (2006). The Use of Feedback Videos in Sport. *Int. J. Perform. Analysis Sport* 6 (2), 1–14. doi:10.1080/24748668.2006.11868368

Olstad, B. H., Wathne, H., and Gonjo, T. (2020). Key Factors Related to Short Course 100 M Breaststroke Performance. *Ijerph* 17 (17), 6257. doi:10.3390/ijerph17176257

Pyne, D. B., Trewin, C. B., and Hopkins, W. G. (2004). Progression and Variability of Competitive Performance of Olympic Swimmers. *J. Sports Sci.* 22 (7), 613–620. doi:10.1080/02640410310001655822

Ribeiro, J., Figueiredo, P., Morais, S., Alves, F., Toussaint, H., Vilas-Boas, J. P., et al. (2017). Biomechanics, Energetics and Coordination during Extreme Swimming Intensity: Effect of Performance Level. *J. Sports Sci.* 35 (16), 1–8. doi:10.1080/02640414.2016.1227079

Ruiz-Navarro, J. J., Morouço, P. G., and Arellano, R. (2020). Relationship between Tethered Swimming in a Flume and Swimming Performance. *Int. J. Sports Physiology Perform.* 15 (8), 1087–1094. doi:10.1123/ijspp.2019-0466

Sánchez, L., Arellano, R., and Cuenca-Fernández, F. (2021). Analysis and Influence of the Underwater Phase of Breaststroke on Short-Course 50 and 100m Performance. *Int. J. Perform. Analysis Sport* 21, 307–323. doi:10.1080/24748668.2021.1885838

Seifert, L., Boulesteix, L., Carter, M., and Chollet, D. (2005). The Spatial-Temporal and Coordinative Structures in Elite Male 100-m Front Crawl Swimmers. *Int. J. Sports Med.* 26 (04), 286–293. doi:10.1055/s-2004-821010

Seifert, L., Boulesteix, L., Chollet, D., and Vilas-Boas, J. P. (2008). Differences in Spatial-Temporal Parameters and Arm-Leg Coordination in Butterfly Stroke as a Function of Race Pace, Skill and Gender. *Hum. Mov. Sci.* 27 (1), 96–111. doi:10.1016/j.humov.2007.08.001

Shapiro, J. R., Klein, S. L., and Morgan, R. (2021). Stop 'controlling' for Sex and Gender in Global Health Research. *BMJ Glob. Health* 6 (4), e005714. doi:10.1136/bmjgh-2021-005714

Simbaña-Escobar, D., Hellard, P., and Seifert, L. (2018). Modelling Stroking Parameters in Competitive Sprint Swimming: Understanding Inter- and Intra-lap Variability to Assess Pacing Management. *Hum. Mov. Sci.* 61, 219–230. doi:10.1016/j.humov.2018.08.002

Skorski, S., Faude, O., Abbiss, C. R., Caviezel, S., Wengert, N., and Meyer, T. (2014). Influence of Pacing Manipulation on Performance of Juniors in Simulated 400-m Swim Competition. *Int. J. Sports Physiology Perform.* 9 (5), 817–824. doi:10.1123/ijspp.2013-0469

Skorski, S., Faude, O., Rausch, K., and Meyer, T. (2013). Reproducibility of Pacing Profiles in Competitive Swimmers. *Int. J. Sports Med.* 34 (2), 152–157. doi:10.1055/s-0032-1316357

Smith, D. J., Norris, S. R., and Hogg, J. M. (2002). Performance Evaluation of Swimmers. *Sports Med.* 32 (9), 539–554. doi:10.2165/00007256-200232090-00001

Spierer, D. K., Petersen, R. A., Duffy, K., Corcoran, B. M., and Rawls-Martin, T. (2010). Gender Influence on Response Time to Sensory Stimuli. *J. Strength Cond. Res.* 24 (4), 957–963. doi:10.1519/JSC.0b013e3181c7c536

Stewart, A. M., and Hopkins, W. G. (2000). Consistency of Swimming Performance within and between Competitions. *Med. Sci. Sports Exerc.* 32 (5), 997–1001. doi:10.1097/00005768-200005000-00018

Strzala, M., Krezalek, P., Glab, G., Kaca, M., Ostrowski, A., Stanula, A., et al. (2013). Intra-cyclic Phases of Arm-Leg Movement and Index of Coordination in Relation to Sprint Breaststroke Swimming in Young Swimmers. *J. Sports Sci. Med.* 12 (4), 690–697. PMID:24421728.

Strzała, M., Stanula, A., Krężałek, P., Ostrowski, A., Kaca, M., and Głąb, G. (2017). Butterfly Sprint Swimming Technique, Analysis of Somatic and Spatial-Temporal Coordination Variables. *J. Hum. Kinet.* 60, 51–62. doi:10.1515/hukin-2017-0089

Trewin, C. B., Hopkins, W. G., and Pyne, D. B. (2004). Relationship between World-Ranking and Olympic Performance of Swimmers. *J. Sports Sci.* 22 (4), 339–345. doi:10.1080/02640410310001641610

Trinidad, A., Veiga, S., Navarro, E., and Lorenzo, A. (2020). The Transition from Underwater to Surface Swimming during the Push-Off Start in Competitive Swimmers. *J. Hum. Kinet.* 72, 61–67. doi:10.2478/hukin-2019-0125

Vantorre, J., Chollet, D., and Seifert, L. (2014). Biomechanical Analysis of the Swim-Start: a Review. *J. Sports Sci. Med.* 13 (2), 223–231. PMID:24790473.

Veiga, S., Cala, A., Frutos, P., and Navarro, E. (2014). Comparison of Starts and Turns of National and Regional Level Swimmers by Individualized-Distance Measurements. *Sports Biomech.* 13 (3), 285–295. doi:10.1080/14763141.2014.910265

Veiga, S., and Roig, A. (2016). Underwater and Surface Strategies of 200 M World Level Swimmers. *J. Sports Sci.* 34 (8), 766–771. doi:10.1080/02640414.2015.1069382

Wakayoshi, K., D'Acquisto, L., Cappaert, J., and Troup, J. (1995). Relationship between Oxygen Uptake, Stroke Rate and Swimming Velocity in Competitive Swimming. *Int. J. Sports Med.* 16 (01), 19–23. doi:10.1055/s-2007-972957

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