Publishing House and Copyright:

Georg Thieme Verlag KG
Postbox 30 11 20
70451 Stuttgart, Germany
ISSN

Thieme

Propulsive Force of Upper Limbs and its Relationship to Swim Velocity in the Butterfly Stroke

Authors
Jorge Morais[1, 2], Tiago M. Barbosa[1, 2], Vitor P. Lopes[1, 2], Mario C. Marques[2, 3], Daniel Almeida Marinho[2, 3]

Affiliations
1 Department of Sport Sciences, Instituto Politécnico de Bragança, Bragança, Portugal
2 Research Center in Sports, Health and Human Development (CIDESD), Vila Real, Portugal
3 Department of Sport Sciences, Universidade da Beira Interior, Covilhã, Portugal

Key words
biomechanics, kinetics, performance, youth

accepted 20.01.2021
published online 2021

Bibliography
Int J Sports Med
DOI 10.1055/a-1386-4985
ISSN 0172-4622

Georg Thieme Verlag KG, Rüdigerstraße 14,
70469 Stuttgart, Germany

Correspondence
Jorge Morais
Department of Sport Sciences
Instituto Politécnico de Bragança
5300-253 Braganca
Portugal
Tel.: + 351 273 303 000, Fax: + 351 273 303 135
morais.jorgestrela@gmail.com

ABSTRACT

The aims of this study were to: (1) verify the sex effect; (2) assess upper limb asymmetry in anthropometrics and propulsive force variables; and (3) identify the main determinants of butterfly swim velocity based on a set of anthropometrics, kinematics, and propulsive force variables. Twenty swimmers (10 males: 15.40 ± 0.30 years; 10 females: 14.43 ± 0.23 years) at the national level were recruited for analysis. A set of anthropometrics, kinematics, and propulsive force variables were measured. Overall, a significant sex effect was verified ($p \leq 0.05$). Non-significant differences between upper-limbs were noted for males and females in all variables, except for the dF in males ($t = -2.66$, $p = 0.026$, $d = 0.66$). Stroke frequency presented the highest contribution, where a one unit increase in the stroke frequency imposed an increase of 0.375 m · s-1 (95CI: 0.105;0.645, $p = 0.010$) in the swim velocity. The swim velocity was predicted by the mean propulsive force, intra-cyclic variation of the swim velocity, and stroke frequency. Overall, swimmers exhibit non-significant differences in the variables assessed. Swim velocity in the butterfly stroke was determined by an interaction of propulsive force and kinematic variables in young swimmers.

Introduction

Swimming is characterised as being an early specialization sport [1]. To achieve high-performance in adulthood, swimmers must begin training at an early age. Performance of age-group swimmers and its determinants has been extensively studied in the front crawl stroke [2, 3]. However, there is a scarce body of knowledge on remaining strokes such as the butterfly [4, 5].

The main goal in competitive swimming is to travel a given distance in the shortest time. Thus, researchers and practitioners put their focus on how to improve swimmers' velocity. Swim velocity depends on the interaction between drag and propulsive forces [6]. In the butterfly stroke, the drag and propulsive forces affect the velocity, but they are influenced by butterfly technique, mainly in young swimmers [7]. Moreover, the synchronization between upper and lower limbs is extremely important for velocity. Besides, better swimming performance was also related to higher propulsion continuity while simultaneously minimizing non-propulsive upper body gliding phases [8].

Additionally, in the butterfly stroke the upper limbs account for 90 % of total body velocity in boys and 80 % in girls [4]. Hence, one can argue that the propulsive force of the upper limbs is a key determinant of swim velocity in this stroke. In front-crawl youth swimming, higher propulsive forces are related to an increase in the swim velocity [9]. Propulsive force in the butterfly stroke is produced by a symmetrical and simultaneous motion of both upper limbs with intra-cycle variation in displacement of the center of mass as low as possible [7]. Thus, one may expect that swimmers should produce a similar amount of propulsive force by both upper limbs (i. e., non-significant differences between sides) [10].

In adults/elite swimmers, one study noted a very high correlation between swim velocity and the predicted maximum velocity, measured by semi-tethered swimming, in the butterfly stroke [11]. Tethered or semi-tethered swimming is a very common technique to measure tethered force as a proxy of propulsive force in the butterfly stroke [10, 11] as well as in remaining swim strokes [3]. In the front crawl, for instance, significant upper limb asymmetries were verified in adult/elite swimmers in variables related to propulsive force (peak and mean force) [12]. The authors also noted that swim level (i. e., faster versus slower swimmers) presented a significant effect, i. e., faster swimmers were less asymmetric than their slower counterparts [12]. However, it was argued that tethered measurements may not assess the propulsive force directly [13]. A cable connects a sensor to the swimmer's waist and may not accurately represent the propulsive force on the acceleration of the swimmer's centre of mass [13]. Therefore, one can suggest that measuring the propulsive force with sensors placed on the upper limbs could yield a more accurate measurement of the propulsive force [9, 14]. Moreover, it is not possible to independently measure the propulsive force of each upper limb in the butterfly stroke. Independent measurements of each limb enable the assessment of hypothetical contralateral asymmetries.

At least in adult/elite swimmers, it was shown that velocity was not entirely dependent on the swimmer's metabolic power, and other factors also played key roles in performance [15]. However, the literature does not yet provide insightful evidence on such determinants for the butterfly stroke in age-group swimmers (adolescent boys and girls). Very few studies can be found that identify butterfly stroke determinants at such early ages [4, 5]. As such, one can argue that variables related to swimming biomechanics (kinematics and propulsive force) as well as anthropometrics might play important roles in young swimmers' swim velocity [5, 7]. Additionally, little is known about differences between male and female swimmers in the adolescent age group for this specific swim stroke. At least in the front crawl, swimmers of these ages already showed differences in anthropometrics and kinematics [16]. However, there is still no information regarding differences (if any) in propulsive force in swimmers at the same competitive level.

The aims of this study were to: (1) verify the sex effect in the anthropometric, kinematic, and propulsive force variables selected; (2) assess the contralateral asymmetry in the anthropometrics and propulsive force produced by the upper limbs; and (3) identify the main determinants of swim velocity in the butterfly stroke based on a set of anthropometrics, kinematics, and propulsive force variables. It was hypothesised that: (1) a sex effect would be verified in all variables selected; (2) significant differences would be verified between upper-limb anthropometrics and propulsive force variables; and (3) swim velocity in the butterfly stroke would be determined by an interaction of anthropometrics, kinematics, and propulsive force determinant factors.

Materials and Methods

Subjects

The sample was composed by 20 swimmers (10 males: 15.40 ± 0.30 years, 66.88 ± 7.72 kg body mass, 1.76 ± 0.06 m in height, 1.83 ± 0.07 m arm span, 478.70 ± 62.07 and 509.20 ± 76.30 FINA points in the 50 m and 100 m butterfly event in the short course meter, respectively; 10 females: 14.43 ± 0.23 years, 54.61 ± 4.20 kg body mass, 1.61 ± 0.05 m in height, 1.66 ± 0.06 m arm span, 446.70 ± 63.72 and 502.20 ± 65.84 FINA points in the 50 m and 100 m butterfly event in the short course meter). The swimmers were recruited from a national team at the end of the second macrocycle (i. e., season's peak performance, which corresponds to the competitive period). The inclusion criteria for the participants were: (1) fastest male and female swimmers (national level) in their age group in the 50 and 100 m butterfly (sprinting events); (2) at least four years of butterfly training and competition; and (3) participation in daily training sessions from the beginning of the season. Swimmers who did not meet these criteria or suffered any injury from the beginning of the season until data collection were excluded from the study. They had more than 5 years of competitive experience and trained 6–7 swimming sessions per week, concurrent with at least one dry-land strength and conditioning session per week. Swimmers were informed about the data collection and potential risks of the study before the testing session. This was in accordance with the ethical standards proposed by Harriss et al. [17]. Parents or legal guardians and the swimmers themselves signed an informed consent form. All procedures were in accordance with the Declaration of Helsinki on human research, and the University Ethics Board approved the research design.

Research design

The butterfly stroke, as the other swim strokes in age-group swimmers, is highly influenced by technical parameters where anthropometrics and technical parameters play a major role [7]. Additionally, swimmers should be able to achieve high propulsive force and avoid intra-cyclic variation of swim velocity to promote displacement in the butterfly stroke [7, 15]. However, scarce information is found in the literature about the anthropometric, technical, and propulsive force features that may influence the butterfly stroke in age-group swimmers. Swimmers were not submitted to training on the data collection day. Before in-water data collection, swimmers performed a standardised 1000 m warm-up for sprinting events [18]. All in-water data used for further analysis was collected during three consecutive stroke cycles between the 11th and 24th meter (three consecutive measures from each swimmer). Swimmers were randomly assigned for the first trial. For the remaining two trials, they followed the same order to ensure full recovery (at least 30 minutes between trials). They were instructed to hold their breath during such intermediate distance in order to avoid changes or significant variations in coordination due to breathing [19]. The in-water experimental testing took place in a 25 m indoor swimming pool (water temperature: 27.5 °C; air temperature: 26.0 °C; relative humidity: 67 %).

Anthropometrics

The length of the upper limbs and each hand's surface area (HSA, in cm^2) were selected as anthropometric variables and measured by digital photogrammetry. For the upper-limbs' length, swimmers were close to a 2D calibration pole, and LED markers were placed on each upper-limb main anatomical landmark (acromion, lateral epicondyle, and styloid process). Afterwards, the arm (in cm) was measured between the acromion and the lateral epicondyle, and the forearm (in cm) between the lateral epicondyle and the styloid process [20]. For the HSA, swimmers placed each hand on the scan surface of a copy machine near a 2D calibration frame, and the file was thereafter exported to a laptop. The distances and surface areas were measured using dedicated software (Universal Desktop Ruler, v3.8, AVPSoft, USA) [21].

Kinematics

Swimmers were invited to perform three all-out trials of butterfly with a push-off start. A mechanical apparatus (Swim speedo-meter; Swimsportec, Hildesheim, Germany) was attached to the swimmer's hip [9]. Software developed in house (LabVIEW, v. 2010) was used to acquire (f = 50 Hz) and display velocity-time data over each trial on a laptop. Data was exported from the speedo-meter to the interface by a 12-bit resolution acquisition card (USB-6008, National Instruments, Austin, Texas, USA). Then, it was imported into signal processing software (AcqKnowledge v. 3.9.0; Biopac Systems, Santa Barbara, CA, USA). The signal was handled with a Butterworth 4th-order low-pass filter (cut-off: 5 Hz).

The mean swim velocity (v_{mean}, in $m \cdot s^{-1}$), peak swim velocity (v_{peak}, in $m \cdot s^{-1}$), stroke frequency (SF, in Hz), and the intra-cyclic variation of the horizontal swim velocity (dv, in %) were assessed. The v_{mean} was retrieved from the software between the 11^{th} and 24^{th} meter. The v_{peak} was considered the highest swim velocity value achieved during each stroke. The SF was calculated by the number of cycles per unit of time, from the time it takes to complete one full stroke cycle (f = 1/P; where P is the period), and afterwards converted to Hz (ICC = 0.990). The dv was computed as:

$$dv = \frac{\sqrt{\sum_i (v_i - \bar{v})^2 F_i / n}}{\sum_i v_i F_i / n}$$

Where dv represents the intracyclic fluctuation of the swim velocity (in %), v represents the mean swim velocity in ($m \cdot s^{-1}$), v_i represents the instant swimming velocity in ($m \cdot s^{-1}$), F_i represents the absolute frequency, and n represents the number of observations [22].

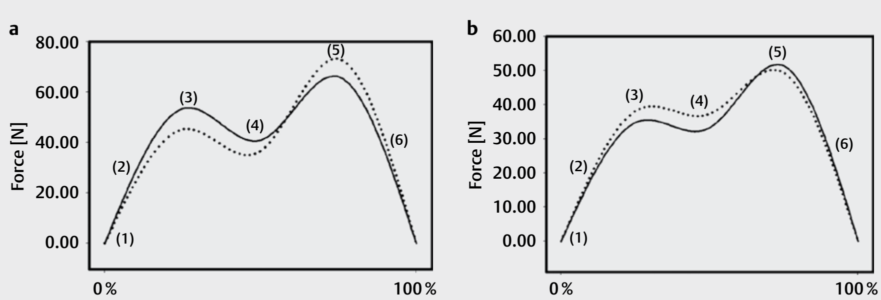
Propulsive force

The propulsive force was acquired concurrently with kinematics testing (the same three maximal all-out trials of 25 m at butterfly with a push-off). Differential pressure sensors and underwater video (Aquanex + Video; Swimming Technology Research, Tallahassee, FL, USA) was used to measure propulsive force (f = 100 Hz) [9]. The sensors were placed between the third and fourth metacarpals to measure the pressure differential between the palmar and dorsal surfaces. It is assumed this location is a good proxy of the application point of the thrust vector on the hand [23]. At the beginning of each trial, swimmers were reminded to keep their hands underwater at the waistline for 10 seconds in order to calibrate the system with the hydrostatic pressure values. The video camera was placed at the side of the swimming pool to record the swimmers on the sagittal plane. The sensors were connected to an A/D converter connected to a laptop on the pool deck with the Aquanex software (Aquanex v. 4.2 C1211; Richmond, VA, USA) [9]. ▶**Figure 1** depicts an example of the intra-cyclic force variation of each upper limb during an entire stroke cycle for males (Panel A) and females (Panel B), respectively.

Afterwards, time-propulsive force series were imported into signal processing software (AcqKnowledge v. 3.9.0; Biopac Systems, Santa Barbara, CA, USA). The signal was handled with a Butterworth 4th-order low-pass filter (cut-off: 5 Hz). For each dominant and non-dominant arm pull, the mean propulsive force (F_{mean}, in N), the peak propulsive force (F_{peak}, in N), and the intra-cyclic force variation (dF, in %) were assessed. The dF was calculated based on equation (1). The mean propulsive of the stroke cycle (F_{mean_cycle}) and the intra-cyclic force variation of the stroke cycle (dF_{cycle}) were computed as the average of the dominant and non-dominant upper limbs.

Statistical analysis

The Shapiro-Wilk and Levene tests were used to assess the normality and homoscedasticity, respectively. The mean and standard



▶ **Fig. 1** Panel **a** – Example of a male swimmer's upper limb force-time curve. Panel **b** – Example of a female swimmer's upper limb force-time curve. 1 – catch (hand's entry); 2 – outsweep; 3 – insweep; 4 – hand change from insweep to upsweep; 5 – upsweep; 6 – exit and recovery; Solid line – right upper limb; Dashed line – left upper limb.

deviation (SD) were computed as descriptive statistics. The one-way ANOVA was used to verify a sex effect ($p \leq 0.05$). The total eta square (η^2) was selected as effect size index, and deemed as: (i) without effect if $0 < \eta^2 < 0.04$; (ii) minimum if $0.04 < \eta^2 < 0.25$; (iii) moderate if $0.25 < \eta^2 < 0.64$ and; (iv) strong if $\eta^2 > 0.64$ [24].

Paired samples t-test ($p \leq 0.05$) was used to verify the differences between both upper limbs for all variables. Cohen's d was selected as the standardised effect size and interpreted as: (i) small effect size $0 \leq |d| \leq 0.2$; (ii) medium effect size if $0.2 < |d| \leq 0.5$ and; (iii) large effect size if $|d| > 0.5$ [25].

Hierarchical linear modelling (HLM) was used to identify the swim velocity predictors. Three models were tested sequentially. In the first model the differences between sexes and the changes over time were tested. In the second model, the swimming performance predictors were tested (i. e., anthropometrics, dry-land strength, propulsive force, kinematics and hydrodynamics selected variables). The third and final model included only the significant predictors. Maximum likelihood estimation was calculated using HLM 7 software [26].

Results

▶ **Table 1** presents the descriptive statistics (mean ± one SD) for all variables assessed and the sex effect. A significant ($p \leq 0.05$) sex effect was verified in all anthropometric variables, where the highest gap between male and females was verified in the non-dominant HSA ($F = 52.04$, $p < 0.001$, $\eta2 = 0.74$). By contrast, mixed findings were observed in the propulsive force variables. For instance, a non-significant sex effect was verified for the $F_{mean\_dominant}$ ($F = 1.63$, $p = 0.218$, $\eta^2 = 0.08$) and a significant one for the $F_{peak\_non\text{-}dominant}$ ($F = 9.03$, $p = 0.008$, $\eta^2 = 0.35$). Kinematic variables also showed a significant ($p \leq 0.05$) sex effect, except the SF ($F = 1.76$, $p = 0.202$, $\eta^2 = 0.09$).

The contralateral asymmetry in anthropometrics and propulsive force variables is presented in ▶ **Table 2**. Non-significant differences were noted for males and females in all variables, but in the dF for males ($t = -2.66$, $p = 0.026$, $d = 0.66$). Overall, both sexes presented mixed findings on the asymmetries, i. e., some variables were higher in the dominant upper limb and other variables in the non-dominant. Nonetheless, both male and female swimmers revealed a symmetric profile, except male swimmers in dF.

▶ **Table 3** shows the fixed effects for the final model running the hierarchical linear modelling. The results suggest that males and females were significantly different at baseline but with no changes between sexes over time. This indicates that the model computed is suitable for males and females. The swim velocity was predicted by the F_{mean_cycle}, dv and SF. A one-unit increase in the F_{mean_cycle} and SF imposed an increase of $0.005\,m \cdot s^{-1}$ (95CI: 0.001;0.009, $p = 0.045$) and $0.375\,m \cdot s^{-1}$ (95CI: 0.105;0.645, $p = 0.010$) in the swim velocity, respectively. By contrast, a one-unit increase in the dv imposed a decrease of $-0.002\,m \cdot s^{-1}$ (95CI: −0.00004;−0.0040, $p = 0.011$) in the swim velocity (▶ **Table 3**).

Discussion

The main aims of this study were to: (1) verify a sex effect; (2) assess upper limb asymmetry for the anthropometric and propulsive force variables; and (3) identify the main determinants of swim velocity in the butterfly stroke based on a set of anthropometric, kinematic, and propulsive force variables. Overall, a significant sex

▶ **Table 1** Descriptive statistics and sex effect for the anthropometric, kinematic, and thrust variables.

	Mean ± SD		Sex effect	
	Males	**Females**	**F-ratio (p)**	**η^2**
$Arm_{\_dominant}$ [cm]	29.90 ± 0.74	27.20 ± 1.32	32.00 (< 0.001)	0.64
$Arm_{\_non\text{-}dominant}$ [cm]	29.50 ± 0.85	27.30 ± 1.25	21.14 (< 0.001)	0.54
$Forearm_{\_dominant}$ [cm]	26.40 ± 0.97	24.30 ± 0.48	37.80 (< 0.001)	0.68
$Forearm_{\_non\text{-}dominant}$ [cm]	26.00 ± 1.25	23.90 ± 1.20	14.76 (0.001)	0.45
$HSA_{\_dominant}$ [cm^2]	137.74 ± 10.37	109.34 ± 8.26	45.93 (< 0.001)	0.72
$HSA_{\_non\text{-}dominant}$ [cm^2]	138.08 ± 10.86	108.32 ± 7.23	52.04 (< 0.001)	0.74
$F_{mean\_dominant}$ [N]	32.59 ± 5.86	29.12 ± 6.32	1.63 (0.218)	0.08
$F_{mean\_non\text{-}dominant}$ [N]	31.95 ± 6.27	27.99 ± 4.57	4.67 (0.045)	0.22
$F_{peak\_dominant}$ [N]	58.54 ± 8.42	48.77 ± 10.61	5.20 (0.035)	0.22
$F_{peak\_non\text{-}dominant}$ [N]	60.79 ± 12.84	47.86 ± 8.86	9.03 (0.008)	0.35
$dF_{\_dominant}$ [%]	49.10 ± 9.40	42.07 ± 12.35	2.06 (0.169)	0.10
$dF_{\_non\text{-}dominant}$ [%]	55.30 ± 9.35	42.96 ± 19.95	2.91 (0.106)	0.15
F_{mean_cycle} [N]	32.27 ± 5.96	28.55 ± 5.25	4.01 (0.061)	0.19
dF_{cycle} [N]	52.21 ± 8.62	42.52 ± 15.63	2.20 (0.158)	0.12
v_{mean} [$m \cdot s^{-1}$]	1.38 ± 0.09	1.24 ± 0.10	9.99 (0.005)	0.36
v_{peak} [$m \cdot s^{-1}$]	2.25 ± 0.63	1.60 ± 0.10	10.32 (0.005)	0.37
dv [%]	37.00 ± 23.78	18.74 ± 5.57	5.59 (0.029)	0.24
SF [Hz]	0.84 ± 0.04	0.88 ± 0.10	1.76 (0.202)	0.09

HSA, hand surface area; F_{mean}, mean thrust; F_{peak}, peak thrust; dF, intra-cyclic variation of the thrust; v_{mean}, mean swim velocity; v_{peak}, peak swim velocity; dv, intra-cyclic variation of the swim velocity; SF, stroke frequency; F-ratio, one-way ANOVA value; p, ANOVA's significance value; η^2, eta square (effect size index).

▶ **Table 2** Inter-upper limb difference between dominant and non-dominant variables.

Dominant vs. non-dominant	Males			Females		
	Mean difference (95CI)	t-test (p)	d	Mean difference (95CI)	t-test (p)	d
Arm [cm]	0.40 (−0.10 to 0.90)	1.81 (0.104)	0.50	−0.10 (−0.51 to 0.31)	−0.56 (0.591)	0.08
Forearm [cm]	0.40 (−0.44 to 1.24)	1.08 (0.309)	0.36	0.40 (−0.29 to 1.09)	1.31 (0.223)	0.44
HSA [cm²]	−0.34 (−1.98 to 1.29)	−0.48 (0.646)	0.03	1.01 (−2.55 to 4.57)	0.64 (0.536)	0.13
F_{mean} [N]	0.65 (−0.99 to 2.89)	0.89 (0.395)	0.11	1.13 (−1.28 to 3.54)	1.06 (0.316)	0.20
F_{peak} [N]	−2.25 (−7.95 to 3.46)	−0.89 (0.396)	0.21	0.91 (−6.94 to 8.77)	0.26 (0.798)	0.09
dF [%]	−6.20 (−11.48 to −0.92)	−2.66 (0.026)	0.66	−0.90 (−8.84 to 7.04)	−0.26 (0.804)	0.05

95CI, 95 % confidence interval; d, Cohen's d (effect size index); t-test, t-test value; p, significance value; HSA, hand surface area; F_{mean}, mean thrust; F_{peak}, peak force; dF, intra-cyclic force variation; (-), non-dominant presents higher values.

▶ **Table 3** Fixed effects of the final model computed with standard errors (SE) and 95 % confidence intervals (95CI).

Parameter Fixed Effect	Estimate (SE)	95CI	p value
Intercept	0.896 (0.154)	0.594 to 1.198	<0.001
Sex	0.191 (0.039)	0.114 to 0.267	<0.001
F_{mean_cycle}	0.005 (0.002)	0.001 to 0.009	0.045
dv	−0.002 (0.001)	−0.00004 to −0.0040	0.011
SF	0.375 (0.138)	0.105 to 0.645	0.010

F_{mean_cycle}, mean thrust of both upper limbs; dv, intra-cyclic variation of swim velocity; SF, stroke frequency.

effect was verified. Non-significant differences were noted between upper limbs in the anthropometric and propulsive force variables measured for boys and girls. Swim velocity in the butterfly stroke (both sexes) was determined by an interaction of propulsive force (F_{mean_cycle}) and kinematic variables (dv and SF).

Sex effect and inter-limb asymmetry

Overall, swimmers exhibit a sex effect. With the onset of puberty, young swimmers undergo different body changes leading to significant differences between sexes in anthropometric features [27, 28]. Thus, these differences may also have an effect on swimmers' significant differences in the kinematics, such as the swim velocity [16]. Notwithstanding, swimmers did not show a significant sex effect in the SF (kinematics) or in the propulsive force variables (▶ **Table 1**). But male swimmers did show higher values than females. There is evidence of significant differences in SF between sexes in age-group swimmers performing the front crawl [16] and backstroke [28]. However, the literature does not provide information on propulsive force and kinematic differences in the butterfly stroke in age-group swimmers. Even for adult/elite swimmers, there is no experimental evidence on this topic, since studies pooled males and females in one single sample [29–31]. One study reported the kinematics between males and females in the butterfly stroke [32]. Males and females did not show differences in the SF (four males: mean SF = 0.82 Hz; three females: mean SF = 0.82 Hz). But differences were noted in v (four males: mean $v = 1.59\ m \cdot s^{-1}$; three females: mean $v = 1.37\ m \cdot s^{-1}$) [32]. Our data revealed a similar trend for the same variables (▶ **Table 1**).

Regarding propulsive force and v, it was noted that male swimmers presented higher values than their female counterparts in both variables [33]. This was also noted in the front crawl in a similar age group of swimmers for propulsive force [3] and v [34]. Until now, the literature did not provide any information about sex effect in the butterfly stroke in age-group swimmers. Swim acceleration can be integrated to compute the velocity as the balance of propulsive force and drag, taking into account the inertial term (body mass and added mass of water) [35]. It is well reported that adult/elite male swimmers are under more drag and reach faster velocities than their female counterparts [36]. Therefore, if male swimmers are under more resistance and yet can be faster, it means that, at least theoretically, they must produce greater propulsive force. At least in in front crawl swimming, young male swimmers displayed a significant positive correlation between arm muscle area and propulsive force [37].

Asymmetry in young athletes' anthropometrics (i. e., differences in limb lengths) is a well-known phenomenon, especially in athletes competing in unilateral sports (i. e., where the dominance of a limb prevails over the other) such as tennis [38]. However, the butterfly stroke is characterised by a simultaneous motion of the upper limbs, i. e., both limbs should present an equal or similar spatial-temporal index [39]. Therefore, one can argue that differences between upper limb sizes could lead to propulsive force imbalances [13]. Our data showed non-significant differences between all anthropometric variables assessed in both sexes (▶ **Table 2**). As both upper limbs are used simultaneously to produce propulsive force, swimmers who might present significant differences in anthropometric features could be considered to have a handicap in force production and hence swim velocity.

Information on the propulsive force that a swimmer produces while performing the arm pull provides substantial information on the effectiveness of their technique [40]. For all swim strokes, direct propulsive force measurements are usually made by tethered swimming [3, 11]. Despite the limitations previously reported, the tethered method can be important in indicating whether the upper limb on one side of the body generates a different force than the other side [13]. However, this method does not allow for measuring the propulsive force of each upper limb independently in the butterfly stroke and breast stroke to verify hypothetical asymmetries. Therefore, even in adult/elite butterfly swimmers, information on propulsive force imbalances is limited. Overall, our data revealed non-significant contralateral differences for propulsive force variables in both sexes (i. e., symmetry). One study of young adult swimmers at the national level (butterfly and medley specialists) revealed a symmetry index of 8.90 ± 9.70 % (i. e., non-significant differences) for mean propulsive force (higher in the dominant upper limb) [30]. It can be suggested that this symmetry profile in upper-limb propulsive force is a major factor in helping swimmers to maintain swimming direction (i. e., yaw) [41]. A significant difference was observed only for the dF in males (▶ **Table 2**). The dF is the intra-cyclic variation of the propulsive force around the mean value (i. e., the coefficient of variation). A trend for a trivial change in F_{mean} and F_{peak} was noted. Consequently, compounding the F_{mean} and F_{peak} differences, the dF yielded a significant and moderate-large effect.

Swim velocity

Although a significant sex effect was verified at baseline, this was not maintained over time (sex × time interaction). This means that sexes did not differ over time, and hence the swim velocity model retained the same predictors. Hierarchical linear modelling revealed that swim velocity was determined by an interaction of variables (F_{mean_cycle}, SF, and dv), as in other swim strokes [9, 28]. The F_{mean_cycle} (propulsive force) was entered in the final model, where an increase in one unit of the F_{mean_cycle} increased the swim velocity by 0.005 $m \cdot s^{-1}$ (▶ **Table 3**). However, the relationship between propulsive force and swim velocity it is not clearly identified in the literature by experimental studies. Studies on the butterfly stroke, especially on the relationship between propulsive force and swim velocity, are extremely limited. Only one experimental study reported that the mean in-water force production during the arm pull was a significant predictor of swim velocity in the butterfly stroke [10]. Nonetheless, Schleihauf et al. [31] indicated that high propulsive forces were related to high swim velocity, and that the upsweep action was where the highest propulsive force was achieved. Moreover, elite swimmers improve propulsive actions based on the time dedicated to the coordination of the upper and lower limbs, and hence swim velocity increases [42].

The SF was the highest contributor to swim velocity (▶ **Table 3**). As in other swim strokes, it seems that whenever swimmers want to increase their swim velocity, they increase their SF [43]. In elite [43] and international level butterfly swimmers [8], it was noted that swimmers increased their SF to reach higher velocities but with a decrease in stroke length. This could be related to the short amount of time that swimmers spent during the arm pull, i. e., fast SF leads to higher propulsive force, hence increasing swim velocity [44]. The dv presented a negative and significant relationship with swim velocity (▶ **Table 3**). It was shown that for butterfly swimmers, large variations of the dv were related to poorer performance [15]. One can argue that this negative effect of the dv might be related to the swimmer's hydrodynamic profile while performing the butterfly arm pulls [7]. This swim stroke is characterised by a large variation of frontal surface area, which can negatively affect the swimmers' hydrodynamics and consequently their swim velocity [45]. Indeed, it was noted that wave characteristics in international swimmers was lower in terms of motion variability than in regional swimmers, enhancing the importance of technique in butterfly stroke [46]. Therefore, swimmers and coaches should be aware that excessive undulatory movements may meaningfully increase the frontal surface area and consequently reduce their hydrodynamics. This could have a direct effect on the dv increase and hence the decrease in swim velocity.

Swimming velocity in the butterfly stroke was characterised by an interaction of determinant factors related to kinematics and propulsive force. The literature does not provide clear information on the effect of propulsive force in swim velocity. Our data shows that swimmers should increase the propulsive force of both upper limbs and SF and decrease the dv in order to increase butterfly swim velocity. Although anthropometric variables did not enter into the final model (direct effect), such variables could play an intermediate role. Indeed, variables related to body dimensions play an important role on swimming velocity during periods of growth [47]. At least for the front-crawl arm pull, it was noted that anthropometrics had a positive and significant effect on the swimmer's propulsive force and consequently on swim velocity [20]. Overall, non-significant differences were verified (namely for the F_{mean_cycle} that entered in the final model) between the upper limbs in both sexes, indicating a symmetric profile. Indeed, in symmetrical and simultaneous swim strokes (like the butterfly) swimmers and coaches should seek to minimize asymmetries between the upper limbs while producing propulsive force in order to potentiate their displacement.

The main limitation of this swim velocity model is that it is suitable only for this age group of swimmers. Future studies on propulsive force in the butterfly stroke are suggested to better understand the force-time curve of each upper limb in both sexes. As shown in ▶ **Figure 1**, although the dominant upper limb presented higher (but not significant) values of F_{mean_cycle} than the non-dominant, there were moments when the latter was higher. Thus, similar studies are recommended to not only measure the F_{mean_cycle} but also the propulsive force in each key phase of the butterfly arm pull. Moreover, this age group of swimmers revealed an insweep phase during the arm pull. By contrast, adult swimmers at the national level used a straight arm pull (i. e., without any insweep), hence presenting meaningfully higher values of propulsive force [30]. Therefore, studies should be conducted to better understand which type of arm pull leads to higher propulsive force (and consequently faster swim velocity) in this age group of swimmers.

Conclusions

In conclusion, young butterfly swimmers exhibit an overall sex effect on anthropometric, kinematic, and propulsive force variables. Overall, non-significant differences between upper limbs were noted for the variables selected. Nonetheless, the majority of variables assessed presented higher values in the dominant upper limb for males and females. Swim velocity (both sexes) was determined by propulsive force, SF, and dv. This shows that young swimmer's velocity in the butterfly stroke depends on an interaction of propulsive force and kinematic variables (SF and dv).

Funding

This work is supported by national funds (FCT - Portuguese Foundation for Science and Technology) under the project UIDB/DTP/04045/2020.

Conflict of Interest

The authors declare that they have no conflicts of interest.

References

[1] Staub I, Zinner C, Bieder A et al. Within-sport specialisation and entry age as predictors of success among age group swimmers. Eur J Sport Sci 2020; 20: 1160–1167

[2] Toubekis AG, Tsami AP, Tokmakidis SP. Critical velocity and lactate threshold in young swimmers. Int J Sports Med 2006; 27: 117–123

[3] Oliveira M, Henrique RS, Queiroz DR et al. Anthropometric variables, propulsive force and biological maturation: a mediation analysis in young swimmers. Eur J Sport Sci 2020; Online ahead of print. doi: 10.1080/17461391.2020.1754468

[4] Bartolomeu RF, Costa MJ, Barbosa TM. Contribution of limbs' actions to the four competitive swimming strokes: A nonlinear approach. J Sports Sci 2018; 36: 1836–1845

[5] Nevill AM, Negra Y, Myers TD et al. Key somatic variables associated with, and differences between the 4 swimming strokes. J Sports Sci 2020; 38: 787–794

[6] Zamparo P, Cortesi M, Gatta G. The energy cost of swimming and its determinants. Eur J Appl Physiol 2020; 120: 41–66

[7] Strzała M, Stanula A, Krężałek P et al. Butterfly sprint swimming technique, analysis of somatic and spatial-temporal coordination variables. J Hum Kinet 2017; 60: 51–62

[8] Chollet D, Seifert L, Boulesteix L et al. Arm to leg coordination in elite butterfly swimmers. Int J Sports Med 2006; 27: 322–329

[9] Morais JE, Forte P, Nevill AM et al. Upper-limb kinematics and kinetics imbalances in the determinants of front-crawl swimming at maximal speed in young international level swimmers. Sci Rep 2020; 10: 11683

[10] Morouço P, Keskinen KL, Vilas-Boas JP et al. Relationship between tethered forces and the four swimming techniques performance. J Appl Biomech 2011; 27: 161–169

[11] Gonjo T, Eriksrud O, Papoutsis F et al. Relationships between a load-velocity profile and sprint performance in butterfly swimming. Int J Sports Med 2020; 41: 461–467

[12] Dos Santos KB, Pereira G, Papoti M et al. Propulsive force asymmetry during tethered-swimming. Int J Sports Med 2013; 34: 606–611

[13] Sanders R, Thow J, Alcock A et al. How can asymmetries in swimming be identified and measured? J Swim Res 2012; 19: 1–15

[14] Barbosa TM, Yam JW, Lum D et al. Arm-pull thrust in human swimming and the effect of post-activation potentiation. Sci Rep 2020; 10: 8464

[15] Barbosa TM, Keskinen KL, Fernandes R et al. Relationships between energetic, stroke determinants, and velocity in butterfly. Int J Sports Med 2005; 26: 841–846

[16] Silva A, Figueiredo P, Soares S et al. Front crawl technical characterization of 11-to 13-year-old swimmers. Pediatr Exerc Sci 2012; 24: 409–419

[17] Harriss DJ, MacSween A, Atkinson G. Ethical standards in sport and exercise science research: 2020 update. Int J Sports Med 2019; 40: 813–817

[18] Neiva HP, Marques MC, Fernandes RJ et al. Does warm-up have a beneficial effect on 100-m freestyle? Int J Sports Physiol Perform 2014; 9: 145–150

[19] Seifert L, Chollet D, Sanders R. Does breathing disturb coordination in butterfly? Int J Sports Med 2010; 31: 167–173

[20] Morais JE, Marques MC, Rodríguez-Rosell D et al. Relationship between thrust, anthropometrics, and dry-land strength in a national junior swimming team. Phys Sportsmed 2020; 48: 304–311

[21] Morais JE, Jesus S, Lopes V et al. Linking selected kinematic, anthropometric and hydrodynamic variables to young swimmer performance. Pediatr Exerc Sci 2012; 24: 649–664

[22] Barbosa TM, Bragada JA, Reis VM et al. Energetics and biomechanics as determining factors of swimming performance: updating the state of the art. J Sci Med Sport 2010; 13: 262–269

[23] Gourgoulis V, Aggeloussis N, Mavridis G et al. Acute effect of front crawl sprint resisted swimming on the propulsive forces of the hand. J Appl Biomech 2013; 29: 98–104

[24] Ferguson CJ. An effect size primer: A guide for clinicians and researchers. Prof Psychol Res Pract 2009; 40: 532–538

[25] Cohen J. Statistical Power Analysis for the Behavioral Sciences. Hillsdale, NJ: Lawrence Earlbaum; 1988

[26] Raudenbush SW, Bryk AS, Cheong AS et al. HLM 7: Hierarchical Linear and Nonlinear Modeling. Lincolnwood, IL: Scientific Software International; 2011

[27] Sammoud S, Nevill AM, Negra Y et al. Key somatic variables in young backstroke swimmers. J Sports Sci 2019; 37: 1162–1167

[28] Silva AF, Figueiredo P, Seifert L et al. Backstroke technical characterization of 11-13 year-old swimmers. J Sports Sci Med 2013; 12: 623–629

[29] Mason B, Tong Z, Richards R. Propulsion in the butterfly stroke. In: MacLaren D, Reilly T, Lees AE, Eds. Biomechanics and Medicine in Swimming: Swimming Science VI. London: Spon; 1992: 81–86

[30] Pereira GS, Schutz GR, Ruschel C et al. Propulsive force symmetry generated during butterfly swimming. Rev Bras Cineantropom Desempenho Hum 2015; 17: 704–712

[31] Schleihauf R, Higgins J, Hinrichs R et al. Propulsive techniques: Front crawl stroke, butterfly, backstroke and breaststroke. In: Ungerechts B, Wilke K, Reischle K, Eds. Swimming V. Illinois: Human Kinetics Books; 1988: 53–59

[32] Sanders R. Some aspects of butterfly technique of New Zealand Pan Pacific squad swimmers. In: Troup JP, Hollander AP, Strasse D, Trappe SW, Cappaert JM, Trappe TAE, Eds. Biomechanics and Medicine in Swimming VII. London: Spon; 1996: 23–28

[33] Havriluk R. Performance level differences in swimming: relative contributions of strength and technique. In: Kjendlie P-L, Stallman RK, Cabri J, Eds. Proceedings of the XIth International Symposium for Biomechanics and Medicine in Swimming. Oslo: Norwegian School of Sport Science; 2010: 321–323

[34] Silva AF, Figueiredo P, Ribeiro J et al. Integrated analysis of young swimmers' sprint performance. Motor Control 2019; 23: 354–364

[35] Barbosa TM, Costa MJ, Morais JE et al. Characterization of speed fluctuation and drag force in young swimmers: a gender comparison. Hum Mov Sci 2013; 32: 1214–1225

[36] Toussaint HM, De Groot G, Savelberg HHCM et al. Active drag related to velocity in male and female swimmers. J Biomech 1988; 21: 435–438

[37] Dos Santos MAM, Junior MLB, de Castro Melo WV et al. Estimate of propulsive force in front crawl swimming in young athletes. Open Access J Sports Med 2012; 3: 115–120

[38] Rogowski I, Ducher G, Brosseau O et al. Asymmetry in volume between dominant and nondominant upper limbs in young tennis players. Pediatr Exerc Sci 2008; 20: 263–272

[39] Seifert L, Boulesteix L, Chollet D et al. Differences in spatial-temporal parameters and arm–leg coordination in butterfly stroke as a function of race pace, skill and gender. Hum Mov Sci 2008; 27: 96–111

[40] Havriluk R. Variability in measurement of swimming forces: a meta-analysis of passive and active drag. Res Quart Exerc Sport 2007; 78: 32–39

[41] Sanders RH, Fairweather MM, Alcock A et al. An approach to identifying the effect of technique asymmetries on body alignment in swimming exemplified by a case study of a breaststroke swimmer. J Sports Sci Med 2015; 14: 304–314

[42] Boulesteix L, Seifert L, Chollet D et al. The ratio between coordination and butterfly propulsion index for expert swimmers. In: Chatard JC, Ed. Biomechanics and Medicine in Swimming IX. Saint-Etienne: University of Saint-Etienne; 2003: 99–104

[43] Hellard P, Dekerle J, Avalos M et al. 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 2008; 26: 35–46

[44] Matsuuchi K, Miwa T, Nomura T et al. Unsteady flow field around a human hand and propulsive force in swimming. J Biomech 2009; 42: 42–47

[45] Gatta G, Cortesi M, Fantozzi S et al. Planimetric frontal area in the four swimming strokes: implications for drag, energetics and speed. Hum Mov Sci 2015; 39: 41–54

[46] Gonjo T, Olstad BH. Body wave characteristics and variability of an international and regional level swimmer in 50 m butterfly swimming. ISBS Proceedings Archive 2020; 38: 52

[47] Morais JE, Lopes VP, Barbosa TM et al. How does 11-week detraining affect 11-12 years old swimmers' biomechanical determinants and its relationship with 100 m freestyle performance? Sports Biomech 2020; Online ahead of print. doi: 10.1080/14763141.2020.1726998