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Relationship between thrust, anthropometrics, and dry-land strength in a national junior swimming team

Jorge E Morais^{1,2,4} (PhD), Mário Marques^{1,4} (PhD), David Rodríguez-Rosell⁵ (PhD),
Tiago Barbosa^{2,3,4} (PhD), Daniel Marinho^{1,4} (PhD)

¹University of Beira Interior, Convento de Sto. António, 6201-001, Covilhã, Portugal.
Department of Sport Sciences, University of Beira Interior, Covilhã, Portugal

²Instituto Politécnico de Bragança, Campus de Santa Apolónia, 5300-223 Bragança,
Portugal

³National Institute of Education, NIE5-03-32, 1 Nanyang Walk, Singapore 637616,
Singapore. National Institute of Education, Nanyang Technological University,
Singapore

⁴Research Centre in Sports, Health and Human Development (CIDESD). University of
Beira Interior, Convento de Sto. António, 6201-001, Covilhã, Portugal. Department of
Sport Sciences, University of Beira Interior, Covilhã, Portugal

⁵Physical Performance & Sports Research Center, Universidad Pablo de Olavide,
Seville, Spain

Contact Author:

Jorge E Morais

Department of Sport Sciences

University of Beira Interior

Convento de Sto. António, 6201-001, Covilhã, Portugal

Tel: (351) 275 319 700

Fax: (351) 275 329 183

Email: morais.jorgestrela@gmail.com

Abstract

Objectives: This study aimed to (i) assess an anthropometric and thrust inter-limb asymmetry, and; (ii) determine the contribution of anthropometrics, and dry-land upper-body strength and power to the thrust of talented adolescent swimmers. **Methods:** Eighteen talented adolescent swimmers (12 boys and 6 girls: 15.81 ± 1.62 yearsold) were evaluated. A set of anthropometric, dry-land upper-body strength and power, and in-water thrust were assessed. **Results:** Despite the fact that the dominant side presented higher values in anthropometrics (except for the hand surface area) and thrust, non-significant inter-limb differences were found. The symmetry index indicated a symmetry between upper-limbs. Hierarchical linear modelling retained as main predictors of each upper-limb thrust the respective hand surface area (dominant upperlimb: estimate = 0.293, 95CI: 0.117;0.469, $p = 0.005$; non-dominant upperlimb: estimate = 0.295, 95CI: 0.063;0.526, $p = 0.025$). The full stroke cycle retained the upper-body dry-land strength as main predictor (estimate = 0.397, 95CI: 0.189;0.605, $p = 0.002$). **Conclusion:** The hand surface area and upper-body strength were the main predictors of each upper-limb and full stroke cycle thrust, respectively. Hence, coaches and practitioners should aim to carefully maximize the hand surface area (by finger spreading) while performing the stroke, as well as dry-land upper-body strength in order to enhance the performance.

Keywords: swimming; strength; body dimensions; in-water force

Introduction

Swimmers should minimize drag and increase thrust to enhance the swim speed [1]. During the clean swimming phase swimmers are submitted to water resistance, i.e. active drag[1]. In this context, although the drag effect (namely active) on swimmers is vastly reported in the literature[2], less is known about the thrust. Indeed, the assessment of the swimmer's propulsive force (i.e. thrust) is still difficult to quantify, and hence an interesting topic among researchers and practitioners [3,4].

Video-recording methods were used to measure the swimmer's hand and/or arm movements based on three-dimensional reconstructions [5,6]. However, it was noted that the thrust forces were not measured directly but estimated, this being a major limitation of the kinematic method [3]. Others used tethered swimming as a method to measure the maximum force (i.e. thrust) [7]. It is suggested that when swimming at constant velocity, the propulsive forces produced by the swimmer should equal the resistive ones [8]. On the other hand, there is no evidence that the force produced is equal when swimming "freely" and tethered [9]. Conversely, the pressure on propelling surfaces over each stroke can be measured by sensors placed at strategic positions on the hand's surface, and hence measured directly[10,11]. In the front crawl, the thrust force is primarily created by the swimmer's upper-limbs as they move through the water[12]. The swimmers' hands might be seen as the key body part responsible for the major source of the upperlimbs' thrust, since their trajectory and orientation are responsible for controlling the thrust generated by the upper-limbs [13]. Thus, it is reasonable to think that it is an important performance area for optimizing swimming thrust, which could present a positive effect on swim velocity [14,15].

Indeed, it was highlighted that the upper-limbs are responsible for about 90% of the total propulsion in the front crawl[16]. Zamparo et al. [17] showed that propelling efficiency plays a key-role in swimmer's thrust, and the first one is highly dependent on anthropometrics (namely the upper-limbs). Therefore, it can be suggested that upperlimbs' anthropometrics also contribute to front crawl thrust. Moreover, it was suggested that the use of only the hand and forearm to estimate a swimmer's thrust might lead to underestimated values, enhancing the importance of including the upper-arm as well [18]. There is not a solid body of knowledge about inter-limb asymmetries in anthropometric features and upper-limbs' thrust, or of their relationship[19]. In

connection with the above, it was pointed out that post-pubertal male swimmers presented an asymmetrical force exertion, where dominant upper-limbs showed higher force values in comparison to the non-dominant ones[20, 21]. However, to the best of our knowledge, there is no solid evidence about how anthropometrics (specifically the upper-limbs as an articulated segment, i.e. several segments) contribute to/influence swimming thrust.

Additionally, strength and power are required to produce in-water thrust[8]. Dry-land strength training programs seem to have a positive effect on adolescentswimmers' performance. That is, higher values of dry-land strength and power enable swimmers to produce higher in-water thrust, and consequently higher swim velocity[22, 23]. Indeed, a moderate/high association between dry-land variablesand the swimmer stroke mechanics has been verified[8]. Moreover, it was shownthat concurrentdry-land and in-water programs were more efficient than the swimming programalone in increasing performance in adolescentsprint swimmers[24]. Thus, results of these studies suggest that developing strength and power on landled to an enhancement of swimmers' performance[24],and this could occur due to the in-water thrust improvement [23]. Nonetheless, there is no clear evidence about how dry-land strength and power may contribute specifically to swimmers' in-water thrust. It has beensuggested that theupper-body strength and power needed to displace the swimmer at front crawl is based on a set of several upper-body muscles[25]. Thus, one might claim that a higher upper-body strength and power would have a positive and direct effect on swimmers' in-water thrust. Moreover, hypothetical interactions between anthropometric features and dry-land strength and power may be highly representative of front crawl in-water thrust.

Therefore, based on the above considerations, the main aims of this study were to(i) assess a hypothetical anthropometric and thrust inter-limb asymmetry, and; (ii) determine the contribution of anthropometrics, and dry-land upper-body strength and powertothe thrust of talentedadolescent swimmers. It was hypothesized thata significant inter-limb effect would be verified (for both anthropometrics and thrust). Moreover, some anthropometric features, and/or upper-body strength and power, or interactions between such variables, would have a positive and significant effect on front crawl thrust.

Materials and Methods

Participants

Eighteen talented adolescent swimmers (12 boys and 6 girls: 15.81 ± 1.62 years old; boys' FINA points: 572.17 ± 67.32 ; girls' FINA points: 636.33 ± 105.60) were recruited and evaluated. These swimmers were part of a national junior team, including swimmers participating in international championships, national record holders, and age-group national champions. They had more than five years of competitive experience and trained six to seven swimming sessions per week, and two to three hours of dry-land strength and power training per week under the direction of the same coach. Parents or guardians, and the swimmers themselves signed an informed consent form. All procedures were in accordance to the Declaration of Helsinki regarding human research, and the University Ethics Board approved the research design.

Experimental protocol

Swimmers were recruited to analyze the relationship between anthropometric features and upper-body strength with swimming thrust (cross-sectional study). At the assessment time they were in peak-performance (end of the second macro-cycle). To ensure a proper reproduction of the experimental trials, all swimmers underwent a familiarization process as part of their in-water and strength and conditioning testing. Moreover, they were asked about their upper-limb dominance (self-report) for data analysis. The in-water and strength and conditioning tests were performed on different days (72 hours) to ensure that one test would not affect the other. The in-water experimental testing took place in a 25m indoor swimming pool (water temperature: 27.5°C ; air temperature: 26.0°C ; relative humidity: 66%). Before the in-water tests, swimmers performed a 1000m standard warm-up. The dry-land strength test was conducted in a gym by a certified strength and conditioning coach who was responsible for the entire team dry-land training. Two trials were performed (on separate but consecutive days) to ensure full recovery. Only the best repetition was considered for analysis as reported elsewhere [26].

Anthropometry

The height (H) was measured with a digital stadiometer (SECA, 242, Hamburg, Germany). The body mass (BM) was measured with a digital scale (TANITA, BC-730, Amsterdam, Netherlands). The arm span (AS), upper-limb length, and the hand's

surface area (HSA) were measured by digital photogrammetry[27]. For the AS, swimmers were photographed near a 2D calibration frame, in an orthostatic position, with both arms in lateral abduction at a 90° angle to the trunk. Both arms and fingers were fully extended. The distance between the tip of each third finger was measured. The upper-limbs' length was measured as an articulated segment. Light markers were placed on each upper-limb acromion, lateral epicondyle, and styloid process. Afterwards the arm was measured between the acromion and the lateral epicondyle, and the forearm between the lateral epicondyle and the styloid process. For the HSA, swimmers placed their hand (one at each time) on the scan surface of a copy machine, and the file was exported to a PC. The scan surface was also fitted with a 2D calibration frame. The distances and surface areas were measured with a dedicated software[27].

Dry-land strength

The bench press test (Multipower Fitness Line, Peroga, Spain) was used to evaluate the overall upper-body strength on dry-land. This is described in the literature as the most frequently used test to assess upper-body strength[28], since it recruits several muscles related to front crawl stroke [8, 29]. Moreover, in swimming, the arm's thrust is based on the ability to generate force recruiting a large set of muscles. Therefore, the bench press test seems to be the most appropriate test to evaluate all those muscles in one single test[22]. Before the test, swimmers performed bench press warm-up sets to get familiarized with the machine. The maximum upper-body strength (1RM) was estimated based on the bar velocity test[26]. To measure the bar velocity, a dynamic measurement system (T-Force Measurement System, Ergotech, Murcia, Spain) was attached to the bar. This consists of a cable-extension linear velocity transducer interfaced to a personal computer, which automatically calculates the relevant kinematic and kinetic variables of every repetition[26]. Each swimmer was instructed to lower the bar to the chest, and wait there until hearing a start command. This momentary pause is used to minimize the contribution of the rebound effect and allow more reproducible and consistent assessments[26, 30]. The swimmers were carefully instructed to always perform each trial at maximal intended velocity. The test was monitored by an experienced and certified strength and conditioning evaluator. Initial load was set at 20 kg for all swimmers, and was progressively increased in 10 kg increments until the attained mean propulsive velocity was lower than $0.5 \text{ m} \cdot \text{s}^{-1}$. Thereafter, the load was adjusted in smaller increments (1 to 5 kg), individually for each swimmer, determining the 1RM with higher

precision. The heaviest load that each swimmer could properly lift to the full extension of their elbows was considered to be their 1RM [30]. Swimmers performed three attempts with the lighter loads (mean propulsive velocity $> 1.0 \text{ m}\cdot\text{s}^{-1}$), two with the medium ($0.65 \leq \text{mean propulsive velocity} \leq 1.0 \text{ m}\cdot\text{s}^{-1}$), and one with the heaviest load (mean propulsive velocity $< 0.65 \text{ m}\cdot\text{s}^{-1}$). They rested three minutes for the lighter and medium loads, and six minutes for the heaviest one. This protocol was reproduced as reported elsewhere [26].

Thrust

Swimmers were invited to perform three maximal all-out trials of 25m in the front crawl with a push-off start. A force data acquisition equipment Aquanex + Video (Swimming Technology Research, USA) was used to measure thrust ($f=100\text{Hz}$). This system is based on sensors that estimate in-water force, with a measurement error of 0.2% [11]. The validation and reliability processes were previously presented in other study [11]. Such sensors were placed between the third and fourth metacarpals to measure the pressure differential between the palmar and dorsal surfaces. At the beginning of each trial, swimmers were asked to keep their hands immersed 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 (recording the swimmers on the sagittal plane) (Figure 1 - Panel C). The sensors and video output 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, USA) [10]. Afterwards, time-force series were imported into a signal processing software (AcqKnowledge v. 3.9.0, Biopac Systems, Santa Barbara, USA). The signal was handled with the Butterworth fourth-order low-pass filter (cut-off: 5Hz). The mean value of each thrust variable was analyzed based on three consecutive stroke cycles between the 11th and 24th mark (ICC=0.98). Afterwards, the mean of the three trials was used for analysis.

For each dominant and non-dominant arm-pull (i.e. underwater phase), the mean propulsive force ($F_{\text{mean_dominant}}$ and $F_{\text{mean_non-dominant}}$, N), and the peak force ($F_{\text{peak_dominant}}$ and $F_{\text{peak_non-dominant}}$, N) were assessed. Afterwards, the $F_{\text{stroke cycle}}$ (the force produced in one full stroke cycle, N) and $F_{\text{peak_stroke cycle}}$ (the peak force produced in one full stroke cycle, N) were computed. The intra-cyclic

force variation of each upper-limb (dF_dominant and dF_non-dominant, %), and of the full stroke cycle (dF_stroke cycle, %) was calculated as follows [31]:

$$dF = \sqrt{\frac{\sum_i (Force_i - Force)^2 \cdot F_i}{n}} \cdot 100 \quad (1)$$

where dF is the intra-cyclic variation of the force (%), Force is the mean force (N), Force_i is the instant force (N), F_i is the acquisition frequency, and n is the number of observations. The symmetry index (SI) was computed as [32]:

$$SI = \frac{x_d - x_{nd}}{0.5 (x_d + x_{nd})} \cdot 100 \quad (2)$$

where x_d and x_{nd} are the mean values for the dominant and non-dominant upper-limbs' variables, respectively. The authors deemed the symmetry index within these cut-off values: -10% < SI < 10% indicates symmetry, and SI < -10% and SI > 10% indicates asymmetry [32].

Statistical analyses

Correlation agreements (thrust variables versus anthropometric and upper-body dry-land strength) between both sexes were computed with the Fischer's z-score [33]. Non-significant differences were verified between correlations (p > 0.05), suggesting that both sexes could be pooled together. The Shapiro-Wilk and the Levene tests were used to assess the normality and homoscedasticity, respectively. The mean plus one standard deviation, 95% confidence interval (95CI), minimum, and maximum were computed as descriptive statistics. One-way ANOVA (p < 0.05) was computed to verify a side effect (i.e. variation between the dominant and non-dominant limbs). Cohen's d was selected as standardized effect size, and deemed as: (i) small effect size 0 ≤ |d| ≤ 0.2; (ii) medium effect size if 0.2 < |d| ≤ 0.5 and; (iii) large effect size if |d| > 0.5 [34]. Hierarchical linear modelling (HLM) was used to verify the thrust predictors for the full stroke cycle, dominant arm-pull, and non-dominant arm-pull. For each thrust variable, all independent variables were input, and the final models only retained significant predictors. The maximum likelihood estimation was computed by HLM7 software [35].

Results

Table 1 presents the descriptive statistics for all the variables assessed. Table 2 reports the results for the inter-limb effect(i.e. dominant vs non-dominant). There was a non-significant inter-limb effect in the anthropometrics and thrust. The symmetry index indicated a symmetry between upper-limbs, since all variables were within the cut-off values previously indicated in equation 2 (Table 2). Nonetheless, the dF showed the highest symmetry index(dF_dominant versus dF_non-dominant) with large effect size (SI = -5.57; d = 0.51; p = 0.135) (Table 2).

****Please, insert Table 1 near here****

****Please, insert Table 2 near here****

Figure 1 depicts the thrust time-series for the dominant and non-dominant limbs, and full stroke. It is possible to note that the highest peak is achieved in the upsweep phase, and the lowest in the hand's entry / beginning of the downsweep (Figure 1). Overall, the dominant upper-limb did show higher (but not significant) mean (dominant: 37.88 ± 6.61 N; non-dominant: 36.18 ± 6.42 N), and peak (dominant: 64.63 ± 8.19 N; non-dominant: 64.49 ± 10.69 N) values of thrust (Tables 1 and 2). On the other hand, the dF was higher in the non-dominant side (dominant: $50.24 \pm 5.14\%$; non-dominant: $53.29 \pm 6.93\%$) (Table 1, Figure 1).

****Please, insert Figure 1 near here****

Prediction models are presented in Table 3. For both dominant and non-dominant side, the model retained as main predictors the respective HSA. For the dominant upper-limb, an increase in one unit (cm^2) by the dominant HSA led to a 0.293 N (95CI: 0.117;0.469; p = 0.005) increase in thrust. For the non-dominant HSA, an increase in one unit (cm^2) led to a 0.295 N (95CI: 0.063;0.526; p = 0.025) increase in thrust (Table 3). As for the full stroke cycle, the model retained the upper-body dry-land strength as main predictor. One unit (kg) increased by the upper-body dry-land strength, led to a 0.397 N (95CI: 0.189;0.605; p = 0.002) increase in thrust (Table 3).

**** Please, insert Table 3 near here****

Discussion

This study aimed to assess anthropometric and thrust inter-limb asymmetry, and determine the contribution of anthropometrics, and dry-land upper-body strength and power to the thrust of talented adolescent swimmers. The main results showed a non-significant inter-limb effect for all anthropometric and thrust variables assessed. The thrust of the dominant and non-dominant limbs was related to the correspondent HSA. On the other hand, the full stroke thrust was related to the upper-body strength and power.

Scientific knowledge has been reporting for several decades the importance of swimmer's body lengths (i.e. anthropometric features) to swimming performance [1, 36]. It has been reported that faster swimmers are taller and bigger (i.e. present higher body lengths, widths and areas) in all age-groups from pre-pubescent to adult [36, 37]. Nonetheless, anthropometric symmetries/asymmetries and their relationship with thrust are less explored by the swimming community. Our data showed a non-significant inter-limb effect for the anthropometric features (Table 2). Nevertheless, all dominant lengths were higher (but not significantly) in comparison to non-dominant ones (Table 1). Similarly to our results, the literature reported bilateral asymmetries regarding human's upper-limbs favouring the dominant side [38, 39]. Curiously, the non-dominant upper-limb showed a higher HSA. Nonetheless, hand asymmetry related to limb dominance is reported in the literature [40]. It is common for subjects to present higher hand lengths and widths in the non-dominant upper-limb [40].

The literature suggested a direct relationship between behavioural and morphological asymmetry through mechanically driven bone growth and remodelling [39]. Bilateral asymmetries in movement patterns may originate from genetic and early environmental factors [9]. Indeed, increased asymmetries were verified between the playing (dominant) and non-playing (non-dominant) arms of sports athletes where the upper-limbs are mostly used [41]. However, in the particular case of swimming, both upper-limbs are used to produce thrust. So, based in the environmental perspective of the bilateral asymmetry, one might claim that swimmers could also present such asymmetries. Present data showed that differences were noted between dominant and non-dominant upper-limb thrust (higher in the dominant upper-limb), but without a meaningful and significant inter-limb effect (Tables 1 and 2, Figure 1). Here, the symmetry index

revealed a symmetry between upper-limbs, since it was within the cut-off limits ($-10\% < SI < 10\%$). One study showed inter-limb asymmetries in force production (tethered swimming) in high-level swimmers (in similar age-group) in the front crawl [20]. The authors also compared fastest versus slowest swimmers' performances, and concluded that the inter-limbs asymmetries verified within groups (but not between groups) did not affect negatively the performance [20].

Others reported that the fastest swimmers exhibit lower peak and mean force asymmetries (tethered swimming) in comparison to the slowest swimmers, suggesting that this may be a handicap to enhancing swimming performance [7]. Indeed, it was indicated that asymmetries in swimming may limit swimming performance by reducing the capacity to produce thrust [9,32]. Moreover, such controversial outcomes were observed in the tethered swimming method. It was suggested that the forces generated by a tethered swimmer are considerably different from those generated while swimming "freely" due to the different velocity of the swimmer relative to the water [9]. Moreover, the hips (point of the body where the tether is attached) do not represent the effect of the propulsive actions on the acceleration of the centre of mass [9]. Thus, it can be suggested that more research is needed to understand this phenomenon in swimming.

Despite studies having analyzed thrust and inter-limb asymmetries [7, 10], less is known about how thrust can be determined. It could be suggested that anthropometric features and upper-body dry-land strength and power could be related/could contribute to front crawl thrust. Hierarchical linear modelling retained as main predictors of the dominant and non-dominant limbs the corresponding HSA, where a positive relationship was observed (Table 3). Propulsive force presents a direct and positive relationship to the surface area [1]. That is, an increase in the surface area will lead to an increase in the propulsive drag (i.e. thrust) [19]. Both experimental [42] and numerical studies [43] appear to indicate that an increase in the hand's area led to an increase in the propulsive force. An increase of the drag of the hand by spreading fingers reduces the slip velocity between the hand and the water, diminishing the power dissipated for propulsion [14]. Thus, it might be suggested that swimmers should "increase" their hands' surface area by spreading their fingers. It was noted that the hand surface area "enlarged" with a small distance between fingers (0.32cm) increased the projection surface area of the hand, and hence the force production [44]. It seems that in a turbulent

flow (like in an arm-pull) some kind of barrier between the fingers may be formed, leading to an “increase” in the hand’s surface area [44]. Nonetheless, this spread should be maximized but not greatly enlarged. Contrarily, a higher finger spread (0.64cm) allowed the water to flow freely, and consequently did not increase force production [44]. Despite the fact that the upper-limb (as an articulated segment) may be determinant for propelling efficiency [16], the hand plays a key-role in front crawl thrust [15].

For the full stroke cycle, the model retained the upper-body strength and power variable (Table 3). In order to produce thrust, swimmers should be able to move water backwards (both upper-limbs) with as much force as possible. In this sense, it could be speculated that a direct and positive relationship between the force that a swimmer can produce on dry-land and in-water should occur. Indeed, such a relationship between dry-land strength and swimming performance has been suggested in similar age-groups of swimmers (age and competitive level) [8, 23]. However, less is known about such a relationship between dry-land and in-water force production (i.e. thrust). Dry-land strength and power training have been used by the swimming community as an in-water training complement. Aspenes et al. [23] reported that after a dry-land strength training, swimmers significantly increased their dry-land strength output, as well as their in-water force production. Moreover, it was shown that upper-limbs’ dry-land strength measured on a bench press presented a high correlation with in-water force production [8]. Thus, it might be suggested that a direct and positive effect between dry-land strength and in-water force production (i.e. thrust) exists [8, 23].

Talented adolescent swimmers exhibit a non-significant inter-limb asymmetry (i.e. symmetry) in anthropometric and thrust variables. Nonetheless, the dominant upper limb presented higher lengths (but lower HSA). The same trend was verified for the thrust. The dominant upper-limb presented a higher thrust (but non-significant), revealing a symmetry. Indeed, in the front crawl both upper-limbs are responsible for the majority of the total thrust [12, 16]. Nevertheless, others did show inter-limb asymmetries in a similar age-group of swimmers [20]. It might be argued that such inter-limb asymmetries indicate that swimmers use the dominant upper-limb to produce higher thrust, and the non-dominant for balance [21]. However, and accepting this rationality, it could be pointed out that such a phenomenon may occur even without inter-limb asymmetries (as the present data showed). Indeed, swimmers’ dominant upper-limb

presented higher values of thrust, despite a lower HSA (when comparing to the non-dominant). This could be due to: (i) the dominant upperlimb only could have higher indexes of dry-land strength than the non-dominantlimb [45], and; (ii) despite presenting lower HSA, the dominant upper-limb may overcome this factor with a higher motor control of that specific upper-limb. This may lead to a higher efficient use of force [21].

Nonetheless, each HSA (anthropometric) was responsible for the corresponding upper-limb thrust. The upper-body dry-land strength and power variables were responsible for the full stroke cycle thrust. Consequently, coaches and practitioners should aim to minimize notable differences (significant or not) between upperlimbs, as this may negatively affect the full stroke cycle thrust, and potentially the performance [9]. Coaches should be aware that “maximizing” the swimmer’s HSA with a small finger spread, and increasing their upper-body strength and power could lead to a higher thrust, and hence to a performance enhancement.

The main limitations of this study can be considered to be as follows: (i) other upper-body anthropometric variables could be included (such as upper-limb girths and chest perimeters), and; (ii) individual upper-limbs’ strength (i.e. dominant and non-dominant) could give deeper insights. Additionally, it is suggested to measure the force production in each arm-pull phase (i.e. downstroke, insweep, and upstroke), and relate it to the pitch and sweepback angles performed.

Conclusion/Summary

Talented adolescent swimmers exhibit a non-significant inter-limb asymmetry in anthropometric and thrust variables. Each HSA (anthropometric) was responsible for the corresponding upper-limb thrust (i.e. dominant and non-dominant). The upper-body dry-land strength and power variable was responsible for the full stroke cycle thrust. Coaches should be aware that maximizing the swimmer’s HSA through a small finger spread, and increasing their upper-body strength and power could lead to a higher thrust, and possibly to a performance enhancement.

Conflict of Interests Statements

The authors have no conflict of interest.

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Conflict of Interests Statements

The authors have no conflict of interest.

Table 1. Descriptive statistics and 95% confidence interval (95CI) for all variables assessed.

	Mean±1SD	95CI	Minimum	Maximum
Body mass [kg]	66.61±7.76	(62.62;70.60)	50.50	78.00
Height [m]	1.73±0.08	(1.69;1.78)	1.53	1.85
Arm span [m]	1.79±0.11	(1.73;1.84)	1.59	1.97
Dominant arm [cm]	32.39±3.16	(30.81;33.96)	27.00	40.50
Dominant forearm [cm]	28.25±2.19	(23.95;32.54)	23.60	31.90
Dominant upper-limb [cm]	78.97±5.88	(76.04;81.90)	69.00	91.00
Dominant hand surface area [cm²]	134.66±13.80	(127.56;141.75)	104.83	153.44
Non-dominant arm [cm]	32.11±3.19	(30.52;33.70)	26.50	40.50
Non-dominant forearm [cm]	28.02±1.92	(24.25;31.78)	24.00	31.00
Non-dominant upper-limb [cm]	78.50±5.77	(75.63;81.37)	67.50	91.00
Non-dominant hand surface area [cm²]	136.75±15.58	(128.73;144.76)	104.20	160.72
Dry-land upper-body strength [kg]	55.58±14.31	(48.22;62.94)	34.00	78.00
F_mean_dominant [N]	37.88±6.61	(34.48;41.28)	28.02	55.39
F_peak_dominant [N]	64.63±8.19	(60.41;68.84)	52.68	81.81
dF_dominant [%]	50.24±5.14	(47.60;52.89)	37.15	60.37
F_mean_non-dominant [N]	36.18±6.42	(32.87;39.48)	26.56	52.64
F_peak_non-dominant [N]	64.49±10.69	(58.99;69.99)	48.26	91.68
dF_non-dominant [%]	53.29±6.93	(49.73;56.86)	38.18	65.82
F_stroke cycle [N]	74.06±11.91	(67.93;80.18)	55.41	108.02
F_peak_stroke cycle [N]	129.13±16.50	(120.64;137.61)	102.09	173.49
dF_stroke cycle [%]	51.71±4.87	(49.28;54.13)	41.22	63.10

F_mean_dominant - mean thrust of the dominant upper-limb; F_peak_dominant - peak thrust of the dominant upper-limb; dF_dominant - intra-cyclic variation of the dominant upper-limb force; F_mean_non-dominant - mean thrust of the non-dominant upper-limb; F_peak_non-dominant - peak thrust of the non-dominant upper-limb; dF_non-

dominant - intra-cyclic variation of the non-dominant upper-limb force; $F_{\text{stroke cycle}}$ - thrust of the full stroke cycle; $F_{\text{peak_stroke cycle}}$ - peak thrust of the full stroke cycle; $dF_{\text{stroke cycle}}$ - intra-cyclic variation of the full stroke cycle force.

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Table 2. Inter-limb effect and symmetry index between dominant and non-dominant variables.

Dominant vs non-dominant	SI (95CI)	d	F-ratio (p)	Mean difference (95CI)
Arm [cm]	0.88 (-3.71;5.47)	0.09	0.069 (0.795)	0.277 (-0.076;0.631)
Forearm [cm]	0.75 (-2.89;4.39)	0.11	0.112 (0.740)	0.230 (-0.027;0.487)
Upper-limb [cm]	0.59 (-1.84;3.03)	0.08	0.059 (0.809)	0.472 (-0.014;0.958)
Hand surface area [cm²]	-1.23 (-8.48;6.03)	0.13	0.145 (0.706)	1.82 (-0.72;4.36)
F_{mean} [N]	3.94 (-23.48;31.37)	0.23	0.465 (0.500)	1.44 (-1.17;4.05)
F_{peak} [N]	0.05 (-28.54;28.63)	0.03	0.006 (0.938)	0.24 (-4.91;4.42)
dF [%]	-5.57 (-32.34;21.20)	0.51	2.346 (0.135)	3.03 (-0.33;6.39)

SI - symmetry index (%); 95CI - 95% confidence interval; d - Cohens d (effect size index); F-ratio - one-way ANOVA value; p - ANOVA's significance value; Mean difference - mean difference in S.I. units; F_{mean} - mean thrust; F_{peak} - peak thrust; dF - intra-cyclic variation of the thrust.

Table 3. Hierarchical linear models' coefficients with 95% confidence interval (95CI) are presented for all models computed.

HLM models			
Parameter fixed effect	Estimate (SE)	95CI	p
F_mean_dominant			
intercept	37.718 (1.172)	35.421;40.015	<0.001
Dominant hand surface area	0.293 (0.090)	0.117;0.469	0.005
F_mean_non-dominant			
intercept	35.528 (9.020)	17.848;53.207	0.001
Non-dominant hand surface area	0.295 (0.118)	0.063;0.526	0.025
F_stroke cycle			
intercept	51.748 (5.603)	40.766;62.730	<0.001
Dry-land upper-body strength	0.397 (0.106)	0.189;0.605	0.002

F_mean_dominant - mean thrust of the dominant upper-limb; F_mean_non-dominant - mean thrust of the non-dominant upper-limb; F_stroke cycle - thrust of the full stroke cycle.

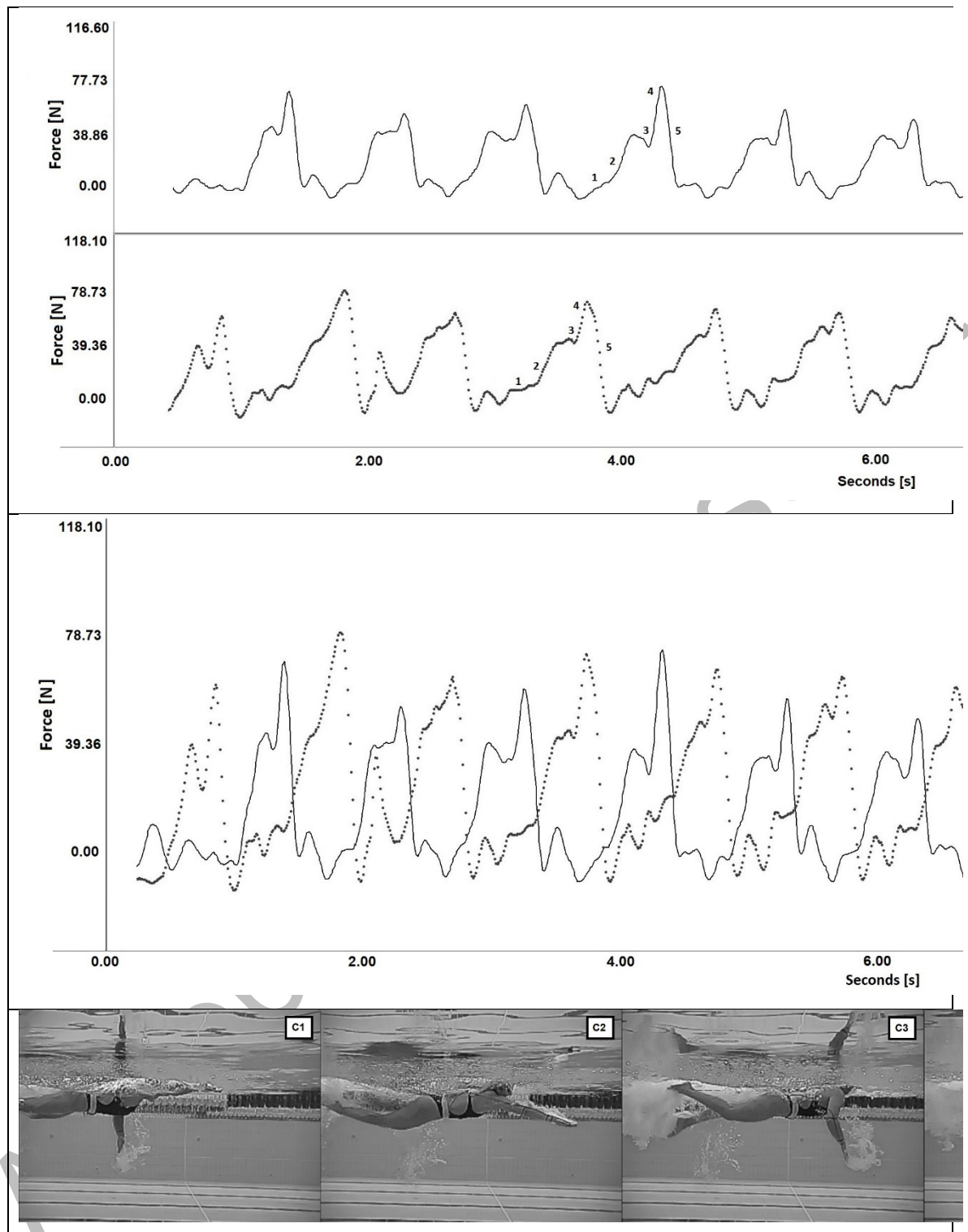


Figure 1. Panel (A) presents the thrust time-series for only the dominant (dash-line) and only the non-dominant (solid-line) upper-limbs. Panel (B) present the thrust time-series with both upper-limbs synchronized. 1 - hand's entry; 2 - downstroke; 3 - insweep; 4 - upstroke; 5 - exit and recovery. Panels (C) present an example of the right upper-limb

stroke (underwater phase): C1 - hand's entry; C2 - downsweep; C3 - insweep; C4 - upsweep; C5 - exit and recovery.

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