The influence of anthropometric variables, body composition, propulsive force and maturation on 50m freestyle swimming performance in junior swimmers: An allometric approach

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Abstract

The purpose of the current article was to use allometric models to identify the best body size descriptors and other anthropometric variables, body composition, and offset maturity that might be associated with the youngsters' 50m personal-best (PB) swim speeds ($m \cdot s^{-1}$). Eighty-five competitive swimmers (male, n=50; 13.5±1.8 y; female, n=35; 12.6±1.8 y) participated in this study. Height, body mass, sitting height, arm span, skinfolds, arm muscle area (AMA), and maturity offset were assessed. Swimming performance was taken as the PB time recorded in competition, and the propulsive force of their arm (PFA) was assessed by the tied swimming test. The multiplicative allometric model relating 50m PB swim speeds ($m \cdot s^{-1}$) to all the predictor variables found percentage body fat as a negative [(BF%) β= -.121±.036; *P*=0.001], and PFA (PFA β=.108±.033; *P*=0.001) and the girl's arm span (β=.850±.301; *P*=0.006), all log-transformed, as positive significant predictors of log-transformed swim speed. The adjusted coefficient of determination, R_{adj}^2 was 54.8% with the log-transformed error ratio being 0.094 or 9.8%, having taken antilogs. The study revealed, using an allometric approach, that body fatness and PFA were significant contributors to 50m freestyle swim performance in young swimmers.

Keywords: Swim speed; allometric models; Personal-best swim speeds; propulsive force

1. Introduction

Competitive swimming is a cyclic sport where swimmers are expected to cover fixed distances in the shortest time possible (Sammoud et al., 2018). Different studies have attempted to identify putative factors related to swimming performance in young swimmers namely anthropometric, technical and physiological markers (Geladas, Nassis, & Pavlicevic, 2005; Nevill, Negra, Myers, Sammoud, & Chaabene, 2020; Sammoud et al., 2017; Sammoud et al., 2019). For example, Nevill, et al. (2020) revealed 7 "common" characteristics that benefited all swimmers suggesting that swimmers benefit from having less body fat, broad shoulders and hips, a greater arm span (but shorter lower arms) and greater forearm girths with smaller relaxed arm girths.

Anthropometric variables are recognized as important factors for identifying and developing talent, as well as being a key influence on swimming performance (Morais, Silva, Marinho, Lopes, & Barbosa, 2017; Sammoud, et al., 2019). For instance, Nevill, Oxford, & Duncan (2015) revealed that lean body mass was the singularly most important whole-body characteristic associated with front crawl swim speeds and that having greater limb segment length ratios [i.e., arm ratio = (lower arm)/(upper arm); foot-to-leg ratio = (foot)/(lower-leg)] were key to personal best swim speeds. Likewise, Morais, et al. (2017), in turn, showed that arm span, stroke length and propelling efficiency are associated with long-term performance in young swimmers of 11-12 years, followed for 3-years. During the 3-year assessment, a 1-unit increment (cm) in arm span led to a 0.59-second improvement in performance. However, time × sex interaction effect had significant effects on swimming performance. In addition, arm span (R^2 = .48) and stroke index (R^2 = .78) were reported as the best overall predictors in 100 [m] freestyle event in adolescent swimmers (Morais et al., 2012).

Children's and adolescents' swimming performances are associated with changes in their body size, proportions, and composition, as well as by their biological maturation (Nevill, et al., 2015). However, differences in body size and shape may confound the performance of swimmers

(Nevill and Holder, 2000). As such, the allometric approach provides an insightful methodology to interpret differences in children’s and adolescent's performance that are associated with changes in their body size and shape (Nevill, et al., 2015; Sammoud, et al., 2017). This approach is a method of mathematically expressing the extent to which a variable (e.g., physiologic, anatomic, or temporal) is related to a unit of body size, as size increases (Nevill, Ramsbottom, & Williams, 1992). Thus, allometric modeling is a particularly relevant way for solving this issue given its biologically driven theoretical basis and its mathematical versatility (Nevill, et al., 2015; Nevill, et al., 1992). For example, Senda Sammoud, Alan Michael Nevill, Yassine Negra, & Chaabene. (2017), observed that 100-m butterfly speed performance was strongly negatively associated with fat mass and positively associated with the segment length ratio (arm-span/forearm-length) and girth ratio (calf-girth) /(ankle-girth), having controlled for the developmental changes in age.

Despite the recognized importance of anthropometric factors in swimming performance and the utility of allometric scaling approaches to better explain sports performance during childhood and adolescence, as far as we are aware, however, no study has examined performance in sprint swimming (i.e., 50m) in addition to considering important mechanical factors such as propulsive force of the arm generated whilst swimming. Thus, there remains a need to clarify the role of anthropometric variables using the allometry approach on youth swimming performance. Therefore, this study uses allometric models to identify the best body size descriptors in conjunction with other anthropometric variables, body composition, biological maturation, and propulsive force of the arm that might be associated with the children’s 50 m personal-best (PB) swim speeds ($m \cdot s^{-1}$).

2. Materials and Methods

2.1. Sample

Prior to commencing the study, the coaches, swimmers, and parents or legal guardians of each swimmer were fully informed about the aims of the research. This is a cross-sectional study with a non-probability sample. The appropriate sample size was estimated using G*Power software v. 3.0.10 (Faul, Erdfelder, Lang, & Buchner, 2007) taking into account the following conditions: effect size= 0.30; minimum power= 0.80; and α= 5%. The suggested sample size was 82 participants which can be considered a representative sample of swimmers of Recife city in Pernambuco state /Brazil. Notwithstanding the estimation, different constraints (i.e., parental and coaches requested to involve the majority of the swimmers in the research, and facility of access to data collection places), allowed a higher total number of swimmers. Thus, a total of 85 swimmers [male, n = 50, age = 13.56 ±1.80 yrs; female, n = 35, age = 12.60 ±1.88 yrs] participated in this study. Of these participants, 31 were classified as pre-pubescent, 36 pubescent and 18 as post-pubescent.

They were currently competing at the national level. This study was conducted in Recife city in Pernambuco state, northeast Brazil. All participants included in this study trained on average two hours per session, six times per week, and all were registered at the Brazilian Federation of Aquatic Sports. All youth athletes and their parents/legal representatives were informed about the design of the study and its potential risks and benefits before the commencement of the research project. None of the subjects submitted to the measures and tests were excluded from the study. Each subject visited the laboratory attended by a researcher team member who was responsible for the following: (1) description of the study, (2) anthropometric measurements, (3) body composition, and (4) assessment of propulsive force. Written informed assent (children and adolescents) / consent (legal representatives) were obtained before the start of the study. This study was approved by the Ethics Committee on Human Research of the institution of affiliation of the authors and followed the rules established by the National Commission on Research and Ethics (NCRE), resolution n° 466/2012 on research involving humans. All the procedures adhered to the guidelines of the Declaration of Helsinki (www.wma.net/e/policy/b3.htm).

2.2. Anthropometric variables and body composition

All anthropometric measurements were taken in accordance with standardized procedures of the International Society for the Advancement of Kinanthropometry (Marfell-Jones, Stewart, & De Ridder, 2012). All measures and testing were carried out in a standardized order after proper calibration of the measuring instruments. Height was measured to the nearest 1.0 cm using a portable stadiometer (Sanny, São Paulo, Brazil) with the participant's head positioned in the Frankfurt horizontal plane. Body mass (kg), without shoes and lightly dressed, was measured with a scale (Filizola, São Paulo, Brasil) to the nearest 100 g. Sitting height was obtained with the participant sitting on an adjustable-height chair at a seat height of 50 cm. Leg length was indirectly obtained by subtracting the value of the sitting height from the height.

Arm span was obtained to the nearest 0.1 cm using a tape measure (Starrett, Itu, Brasil) with the individual standing with the arms abducted with a 90° angle with the trunk, with the elbows extended and the forearms supinated. The distance between the 3rd finger of the right and left hand in this position was taken as the arm span according to the conventional techniques described by Callaway (1991). The relaxed arm circumference was measured with a flexible tape with a precision of 0.1 cm according to conventional techniques (Callaway, 1991).

Skinfolds measurements (in mm) were taken on the right-hand side of the body at two sites (triceps and subscapular) using Lange skinfold calipers (Lange, Santa Cruz, CA). Skinfold data, alongside the skinfold equation of Slaughter et al. (1988), were used to estimate the body fat percentage. Then, lean mass was calculated from the difference between body weight and fat mass expressed in kilograms.

The arm muscle area (AMA) was estimated using the equation suggested by Frisancho (1981): AMA (cm^2) = {[AC (cm) - π · TST (cm_2)]/4 · π}: where AMA is relaxed AMA, AC is arm circumference, TST is triceps skinfold thickness, and π = 3.1416.

2.3. Biological Maturation

Biological maturation was assessed using the maturity offset (M_{off}), which provides an indication of somatic maturity based on measured height, sitting height and leg length, described previously by Mirwald, Baxter-Jones, Bailey, & Beunen (2002). In girls, M_{off}= -9.376 + (0.0001882·leg length and sitting height interaction) + (0.0022·age and leg length interaction) + (0.005841·age and sitting height interaction) - (0.002658·age and weight interaction) + (0.07693·weight by height ratio × 100). In boys, M_{off}= -9.236 + (0.0002708·leg length and sitting height interaction) - (0.001663·age and leg length interaction) + (0.007216·age and sitting height interaction) + (0.02292·weight by height ratio × 100). In the main analyses, biological maturation was treated as a continuous variable.

2.4. Propulsive force of the arm (PFA)

The propulsive force was measured by means of the fully tethered swimming method composed of a load cell with a maximum nominal load of 2000 N (±0.29 N), tied to the athlete's hip by a system of cables and to the starting block by an aluminum bracket. The cable system was attached at a distance of approximately three centimeters from the waterline (Papoti, Martins, Cunha, Zagatto, & Gobatto, 2003). The swimmer did not exercise during the 24 hours preceding the tests. This precaution was taken so that no acute effect resulting from the training sessions could influence the results.

A 10-minute warm-up period of exercise with moderate intensity was performed before the beginning of the tests. After warming up, a pull buoy or leg float was placed between the legs of the swimmer to prevent him from performing movements with his lower limbs (Papoti, et al., 2003). The tied swimming test consisted of applying two maximal efforts in front crawl while tied to the measurement apparatus for 30 seconds. The beginning and end of the test were determined by an audible signal (whistle) and all participants were verbally encouraged to make maximum efforts at maximum speed. Measurements for each athlete was obtained from the dynamometer (Globus Ergometer, Codigné, Italy), comprising a load cell, hardware, and software. The load cell was a force transducer with a traction capacity of 300 kg. Water temperature was kept between 25° and 28°, as recommended by the *Fédération Internationale de Natation* for swimming performance.

2.5. Performance Time

As a measure of swimming performance, the personal best time recorded in competition for the 50-m freestyle swim for each swimmer was provided by the coaching staff. The performance time was expressed in meters per second ($m \cdot s^{-1}$) and was obtained from the relation between distance and time of performance. The swimming personal best time recorded was determined from performance in a 25-m swimming pool. All measurements of swimming performance were carried out during the first half of the year, according to the competition calendar. Thus, the time between anthropometric measurements and swimming performance occurred in less than six months before or after the competitions.

2.6. Statistical analysis

Exploratory data analysis was used to identify potentially inaccurate information and outliers. The normality the data distribution was tested with the Kolmogorov-Smirnov test, and the homogeneity of variances with the Levene test. Descriptive statistics are presented as the means and standard deviations. To identify the possible significant predictor variables including body mass (X_1), height (X_2), percentage body fat (X_3), propulsive force of arm (X_4), arm span (X_5), (see list of variables in Table 1) associated with 50 m personal-best (PB) swim speeds ($m{\cdot}s^{-1}$) in children's and adolescents, having controlled for age and maturity offset (M_{off}), we adopted the following multiplicative model with allometric body size components similar to those used to model the front-crawl swim speeds adopted by Nevill, et al. (2015):

$$\text{PB speed} = a \cdot \Pi\,(X_i)^{k_i} \cdot \exp\,(b{\cdot}\text{age} + c{\cdot}\text{age}^2 + d{\cdot}M_{off}) \cdot \varepsilon. \text{ (Eq. 1)}$$

where 'a' is a constant and $\Pi\,(X_i)^{k_i}$ (i=1, 2, …) represents the product of possible predictor variables listed in Table 1 each raised to the power k_i. This model has the advantages of having proportional body-size components and the flexibility of a non-linear quadratic in age within an exponential term that will ensure that the 50 m PB swim speeds will always remain non-negative irrespective of the child's or adolescent age (see Figure 1). The relationship was r= .46; P=<0.001 between children's personal-best [(PB) swimming speed ($m.s^{-1}$] and chronological age (yrs). Note that the multiplicative error ratio 'ε' assumes the error will increase in proportion to the child's swim speed.

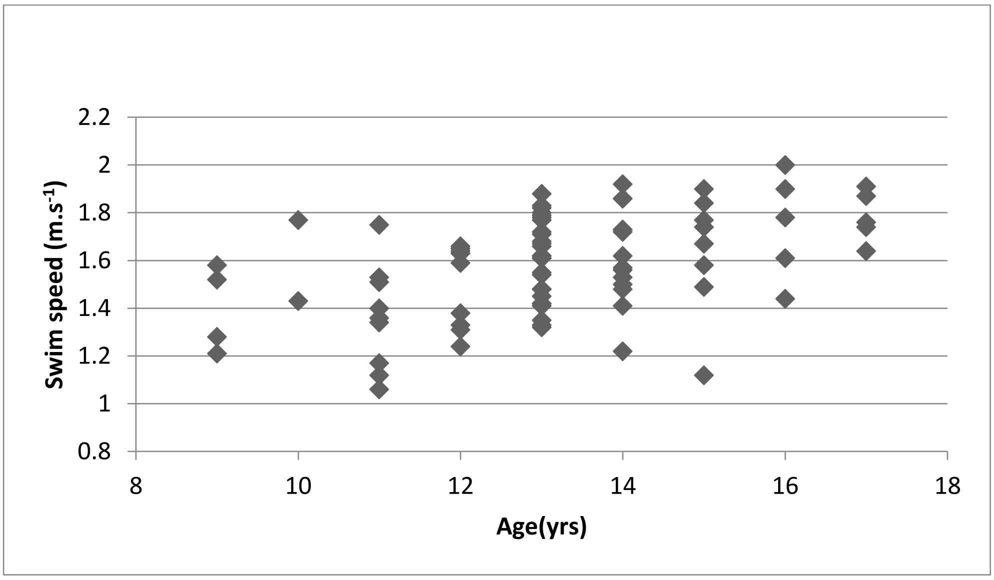

Figure 1. The relationship between the children's personal-best [(PB) swimming speed ($m.s^{-1}$] and age (yrs).

The model (Eq. 1) can be linearized with a log transformation. A linear regression on ln(PB) (Ln=natural logarithms) can then be used to estimate the unknown parameters of the log-transformed model:

$$\text{Ln (PB)}=\ln(a) + \Sigma\, k_i \cdot \ln(X_i) + b \cdot age + c \cdot age^2 + d \cdot M_{off} + \ln(\varepsilon) \quad \text{(Eq.2)}$$

Having fitted the saturated model (all available predictor variables), an appropriate 'parsimonious' model can be obtained using '*backward elimination*' (Draper and Smith, 1981), in which at each step, the least important (non-significant) predictor variable is dropped from the current model. Further categorical differences within the population, e.g., sex, can be explored by allowing the constant intercept parameter 'ln(a)' or slope parameters in Equation 2 to vary by sex in the regression analysis and/or ANCOVA. The significance level was set at $P<0.05$.

3. Results

Descriptive statistics (means ± SD=standard deviations) of all the personal-best swimming performance and predictor variables (demographic and somatic measurements) by sex are given in Table 1.

Table 1. Means (±SD) of the swimming performance variables (both times and average speeds) together with the predictor variables by sex

	Male (n=50)		Female (n=35)		*P-value*
	Mean	SD	Mean	SD	
Age	13.56	1.80	12.60	1.88	0.021
Body mass (kg)	54.72	10.08	47.63	10.88	0.003
Height (cm)	165.07	11.06	154.68	8.82	0.001
Body Fat (%)	17.88	6.76	27.94	5.89	<0.001
Fat mass (kg)	9.86	4.40	13.74	5.66	0.001
Lean mass (kg)	44.85	8.68	33.92	6.08	<0.001
Arm span (cm)	169.35	12.51	157.29	11.23	0.001
Sitting height (cm)	80.90	7.95	74.44	8.49	0.001
Arm Muscle Area (cm^2)	23.50	2.66	21.27	2.30	0.001
Leg length (cm)	84.17	11.12	80.24	7.12	0.051
Maturity offset (years)	-0.59	1.65	0.23	1.44	0.021
PFA (kgf)	26.01	10.82	19.51	7.88	0.003
Time (s)	30.68	3.70	34.39	5.20	0.001
Speed ($m \cdot s^{-1}$)	1.65	0.18	1.48	0.21	0.001

PFA: propulsive force of the Arm

The parsimonious solution to the backward elimination regression analysis of Ln (PB) resulted in the following multiple regressions model (Table 2):

Table 2. The estimated parameters (β) obtained from the backward elimination regression analysis predicting log-transformed 50 m PB swim speeds (Eq. 2).

				95% Confidence Interval	
Parameters	β	SE	*P-value*	Lower Bound	Upper Bound
Boys constant (Ln(a))	-.557	1.062	.602	-2.670	1.557
Girls (Δ Ln (a))	-4.304	1.527	.006	-7.343	-1.264
Ln (Body fat %) (k_3)	-.121	.036	.001	-.194	-.049
Ln (PFA) (k_4)	.108	.033	.001	.043	.173
Ln (Arm span) (k_5)	.205	.211	.333	-.214	.624
Categorical Maturity [b]	.002	.032	0.955	-.062	.066
Interaction					
Girls* Ln (Arm span) (Δk_5)	.850	.301	.006	.251	1.450

β=estimated parameters. SE = Standard error. PFA=propulsive force of the arm. Ln=natural logarithms. Boys were taken as the baseline/reference group and girls estimates were compared with them, indicated by (Δa). [b] pre-pubescent are the reference category.

The multiplicative allometric model relating 50 m PB swim speeds ($m \cdot s^{-1}$) to all the predictor variables found percentage body fat (BF%) as a negative, and propulsive force of the arm (PFA) and the girl's arm span, all log-transformed, as positive significant predictors of log-transformed swim speed. Variables such as body mass, stature, the quadratic in age and maturity offset (continuous or categorical) were all found not to be significant and hence dropped from the regression analysis. The adjusted coefficient of determination, adjusted R^2 was 54.8% with the log-transformed error ratio being 0.094 or 9.8%, having taken antilogs.

4. Discussion

The current study examined the influence of anthropometric variables, body fatness and maturity offset on 50m freestyle swim speeds in young swimmers using an allometric approach. Although prior studies have shown the effectiveness of allometric scaling of anthropometric variables in predicting youth swimming performance (Sammoud, et al., 2018), no studies have used this approach incorporating arm propulsive forces (measured using fully tethered swimming) in sprint swimming (i.e., distances of 50m). As such, the current study adds new information to the field of the influence of body size and composition, biological maturation, and limb segment lengths on youngsters swimming performance as a matter of continuing debate.

The results of the current study are also broadly supportive of prior work that has identified anthropometric variables, including body fatness (%), as important predictors in swimming performance (Bond, Goodson, Oxford, Nevill, & Duncan, 2015; Geladas, et al., 2005; Zuniga et al., 2011). Thus, from the predictor variables used in the present study, only the percentage of body fat was the single most important "whole-body" size characteristic. Regarding body composition, this variable represents, at least in part, the fat mass and fat-free mass both that seem to contribute to the performance of swimmers (Jürimäe et al., 2007; Lätt et al., 2010; Saavedra, Escalante, & Rodríguez, 2010).

However, the swimming performance was apparently not favored by large muscle mass values because they would probably reduce floatability and impair performance (Moura et al., 2014; Perez, Bassini, Pereira, & Sarro, 2011). On the other hand, having a greater muscle mass to enhance swimming performance is supported by previous findings (Nevill, et al., 2015; Rushall, Sprigings, Holt, & Cappaert, 1994) and clearly indicates that muscle mass contributed significantly to the prediction of propulsion force, which may translate in young swimmers´ improved performance. Geometric dissimilarity (i.e., allometric change) may also be important when further change may occur, as is the case with changes in growth as adolescents undergo by different stages of maturation (Nevill, Stewart, Olds, & Holder, 2004).

In the present study stature and body mass did not significantly contribute to the parsimonious allometric model suggesting that the advantage of having longer levers and/or greater girth dimensions was "limb specific" rather than a more general whole-body advantage (Nevill, et al., 2020). Longer lever length (arm or leg) is potentially mechanically disadvantageous in some ways because the involved muscles have to exert greater force and, hence, use greater energy. However, a longer lever length increases reach and the distance available for the generation of propulsion, countering the greater energy requirement of using fewer strokes (Nevill, et al., 2015; Sammoud, et al., 2017). Thus, the fact that athletes do not support their own weight in swimming can also influence on how body composition affects performance.

Prior research has also suggested that a larger arm span positively influences swimming performance due to a larger stroke length improving swimming efficiency (Moura, et al., 2014; Toussaint, 1994). The results of the present study only partially support this assertion as arm span was only influential in explaining 50m freestyle performance only for girls, but not for boys. The advantage of having a greater arm span is fairly obvious in that this segment acts as a paddle, providing the swimmer a greater lever to propel through water. A longer lever length increases reach and the distance available for generation of propulsion, countering the greater energy requirement of using fewer strokes (Moura, et al., 2014; Nevill, et al., 2015). It is also possible that during adolescence there is an intense spurt in stature growth (peak height velocity, PHV), and sex differences are observed concerning PHV timing that occurs, on average, 2 years earlier in girls (~12 years) than in boys (~14 years). It is then possible to speculate that these differences may also contribute to this association (Gasser, Sheehy, Molinari, & Largo, 2001; Hauspie and Roelants, 2012). Additionally, growth spurts also occur in different segments of the body and these events are not synchronous. For example, on average, maximum speed in growth is achieved three-quarters of a year later for the trunk than for the legs or arms (Beunen and Malina, 1988; Gasser, Kneip, Binding, Prader, & Molinari, 1991).

Biological maturation and other anthropometric variables did not significantly contribute to explaining swim performance in our sample implying that youngsters who mature either earlier or late are not favored in 50m freestyle swimming performance. Such results are apparently consistent with previous work examining 100m freestyle performance (Nevill, et al., 2020; Nevill, et al., 2015) who similarly reported no effect of height, body mass and maturation in youngsters swimming performance.

Although the maturation processes during pre-puberty and puberty are apparently independent, maturity markers are positively correlated, suggesting that an individual with advanced/delayed sexual maturation will have an advanced/delayed increase in body height (Beunen et al., 2002; Beunen, Rogol, & Malina, 2006). Thus, it appears that the different stages of biological maturation (i.e., the age at which various percentages of individuals reach adult body height, the age at which different stages of skeletal maturation are achieved and the age of peak height velocity), can occur together and next to one another (Malina, 2004; Malina, Bouchard, & Bar-Or, 2004). In addition, it has been reported that studies that use allometry to normalize the data have not found significant effects of biological maturation on athletic performance (Nevill, et al., 2015; Sammoud, et al., 2018).

An important addition of the present study was the assessment of propulsive force which had not previously been examined in the context of allometric approaches to explaining swimming performance. This assessment gives a direct estimation of the force through water that is specific to swimmers. Some studies have shown the existence of a relationship between power and speed, and implied that high levels of power are transferred positively to the travelling speed (Judge, Moreau, & Burke, 2003; Swaine, 2000). In this sense, although the factors that influence the drag propulsion of the swimmer are known, the capacity to generate propulsive force from a larger area of muscle is not very clear yet. However, Caputo, Oliveira, Denadai, & Greco (2006) reported that for events with a short duration in which the power production capacity is considered a key variable, physical characteristics such as body height, arm span, body composition, and somatotype can also contribute to the level of performance. These morphological attributes largely depend on genetic factors and may have a decisive influence on swimming performance (Lätt et al., 2009).

Swimming is often considered an early specialization sport as children often start heavy training for swimming at a relatively young age (Lätt, et al., 2010). Consequently, understanding which variables best explain optimal swim performance is useful for coaches concerning talent identification and development. It is however important to note that the results presented here reflect the importance anthropometric variables assessed at one single point in time. Given the age ranges in the present study where the growth and maturation processes are not yet completed, the optimum significance of anthropometric variables may also change with age. Future research using longitudinal data are useful to model how anthropometric variables influences swimming performance whilst also considering the training loads swimmers undertake during their maturation processing.

In summary, using an allometric approach, the present study showed that body fatness and arm propulsive force were significant predictors to 50m freestyle swim performance in young swimmers. Of note, biological maturation was not a significant predictor in the model. We suggest that coaches may consider adequate strategies to lower body fatness and increase propulsive force for the arm to benefit 50m freestyle swimming performance.

Disclosure statement

No potential conflict of interest was reported by the authors.

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