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ORIGINAL ARTICLE

Modelling the relationship between biomechanics and performance of young sprinting swimmers

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Abstract
The aim of this study was to compute a swimming performance confirmatory model based on biomechanical parameters. The sample included 100 young swimmers (overall: 12.3 ± 0.74 years; 49 boys: 12.5 ± 0.76 years; 51 girls: 12.2 ± 0.71 years; both genders in Tanner stages 1–2 by self-report) participating on a regular basis in regional and national-level events. The 100 m freestyle event was chosen as the performance indicator. Anthropometric (arm span), strength (throwing velocity), power output (power to overcome drag), kinematic (swimming velocity) and efficiency (propelling efficiency) parameters were measured and included in the model. The path-flow analysis procedure was used to design and compute the model. The anthropometric parameter (arm span) was excluded in the final model, increasing its goodness-of-fit. The final model included the throw velocity, power output, swimming velocity and propelling efficiency. All links were significant between the parameters included, but the throw velocity–power output. The final model was explained by 69% presenting a reasonable adjustment (model's goodness-of-fit; $x^2/\mathrm{df} = 3.89$). This model shows that strength and power output parameters do play a mediator and meaningful role in the young swimmers' performance.

Keywords: *Prediction, strength, kinetics, kinematics*

Introduction

Nowadays, talent identification programmes are becoming more beneficial because they provide useful information on the performance determinants and its trajectories till reaching eventually an elite level (Allen, Vandenbogaerde, & Hopkins, 2014; Barreiros, Côte, & Fonseca, 2014). The main goal of such programmes is to identify and learn how the performance determinant factors interact, allowing the young athletes to excel (Morais et al., 2012).

However, the studies on the specific case of young swimmers reported mainly correlation and regression models (e.g. Jurimae et al., 2007; Vitor & Bohme, 2010). These studies only provide the magnitude of association between the performance and its determinant factors. It does not provide a deep insight on how those determinants interplay and/or interact. Structural equation modelling is a confirmatory procedure to learn about such interactions. It provides a quantitative test of a theoretical model, previously hypothesized based on exploratory findings (Schumacker & Lomax, 2004). Not only do we get as output a qualitative model describing the relationships, it is also possible to quantify it. First, a model is designed based on previous findings reported by exploratory research. Afterwards such theory (i.e. the model designed) is put to test. However, literature on the interaction between performance and determinant factors in young swimmers is rather scarce.

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The contribution of the power and strength to young swimmers' performance remains to be known. Few papers assessed the effect of muscular strength on the performance of young swimmers (Cochrane et al., 2015; Garrido et al., 2010). Recently, one study reported a positive and significant relationship between the elbow flexion and extension strength with the propulsive force (Cochrane et al., 2015). Furthermore, Garrido et al. (2010) reported that a concurrent programme of in-water and dry-land strength and conditioning (S&C) enhances young swimmers performance in comparison to only in-water sessions. Deterministic models suggest that the technique might be influenced by muscular strength parameters, and hence affects the final outcome (i.e. performance) (Barbosa, Bragada, Reis, Marinho, & Silva, 2010). Despite this claim or suggestion, the literature does not provide yet evidence on this matter. On the one side, the enhancement of strength and power parameters seems to be paired with the performance improvement (Barbosa, Morais, Marques, Costa, & Marinho, 2015; Garrido et al., 2010) but there is no solid body of knowledge on the role of these parameters (i.e. relationships) and its contribution to the performance (i.e. quantifying the partial contribution).

Therefore the aim of this study was to compute a confirmatory model for swimming performance based on anthropometrics, strength, power output and kinematics/efficiency. It was hypothesized that the model designed would have significant paths between all parameters linked, explaining the relationships between strength, power, technique and the performance.

Methods

The sample included 100 young swimmers (49 boys and 51 girls; Tanner stages 1–2 by self-report) participating on a regular basis in regional and national-level events (Table I). When the data collection was held, the swimmers had 3.1 ± 0.71 years of training experience.

Coaches and/or parents and also the swimmers gave their consent/assent for the participation in this study. All procedures were in accordance with the Helsinki Declaration regarding human research. The University of Trás-os-Montes and Alto Douro Ethic Committee also approved the study design (ethic review: UTAD-2011-219).

Study design

The theoretical model (Figure 1) was designed by encompassing the state of the art on the performance determinant factors in young swimmers that can be found in the literature. Anthropometrics, hydrodynamics, kinematics and efficiency are highly related to young swimmers' performance (Barbosa et al., 2015; Morais et al., 2012; Strzala et al., 2015). Anthropometric features are strongly related to technical parameters (i.e. kinematics and efficiency) (Barbosa, Costa et al., 2010; Morais et al., 2012) and they may also play a role on the strength. They also influence the swimmers' hydrodynamic profile, and all these have an effect on the swimmers' technique and hence their performance (Morais et al., 2012). Swimming performance was selected as the main outcome and hence it is the variable being predicted. The interpretation of the structural equation modelling is done as follows (Morais et al., 2012): (i) the variables included (inserted into squares); (ii) the paths (i.e. an arrow between two variables means that one variable determines the other); (iii) beta values (reporting the contribution of one variable to another; when the origin variable increases by one unit the destination variable increases by the amount of the beta value) and (iv) residual errors (represents the variable predictive in the linked ellipse).

Performance

The 100 m freestyle event at a regional or national short course metre swimming pool (i.e. 25 m length) was chosen as the performance outcome. The gap between the race time and the data collection (measurement of the in-water power output, dry-land strength and power, kinematic/efficiency and anthropometric variables) was no longer than 15 days.

In-water power output

The W_d was selected as a hydrodynamic variable. To estimate the W_d, the active drag (D_a) was first assessed. It was computed using the velocity perturbation method (Kolmogorov & Duplisheva, 1992). Each swimmer performed two maximal 25 m trials of freestyle swim with push-off start (with and without carrying a perturbation device) (Kolmogorov & Duplisheva, 1992). The D_a was computed as:

$$D_a = \frac{D_b v_b v^2}{v^3 - v_b^3},\qquad(1)$$

where D_a represents the swimmers' active drag at maximal velocity (in N), D_b is the resistance of the perturbation buoy computed from the manufacturer's calibration of the buoy–drag characteristics and its velocity (in N), v_b and v are the swimming

Table I. Descriptive statistics about the swimmers evaluated.

	Overall (Mean ± 1SD)	Boys (Mean ± 1SD)	Girls (Mean ± 1SD)
Age (years)	12.3 ± 0.74	12.5 ± 0.76	12.2 ± 0.71
Body mass (kg)	48.8 ± 8.29	50.7 ± 8.58	47.0 ± 7.65
Height (cm)	158.9 ± 7.94	161.3 ± 8.34	156.6 ± 6.84

velocities with and without the perturbation device (in m s^{-1}), respectively, measured by two expert evaluators with stop watches between the 11th and 24th metre (ICC = 0.97 for absolute agreement). The W_d was calculated as (Barbosa et al., 2015):

$$W_d = D_a \cdot v, \tag{2}$$

where W_d is the power to overcome drag force (in W), D_a is the active drag (in N) and v is the swimming velocity (in m s^{-1}).

Dry-land strength and power

A Doppler radar gun (Stalker ATS II, Texas, USA), with a ±0.04 m s^{-1} accuracy within a field of 12° from the device, was used to measure the throwing velocity (TV). The radar gun was set 1 m behind the swimmers at the projection's height. The swimmers were advised to stay with both feet parallel and shoulder width apart while throwing a medicine ball (1 kg of mass and 0.72 m of circumference). They begin by holding the ball in front of them with both hands and were instructed to throw the ball as far and as fast as possible. No other movements were allowed (i.e. preliminary steps, torso or hip rotation), except the throwing movement (Van den Tillaar & Marques, 2011). A very high interval reliability was observed (ICC = 0.94 for absolute agreement).

Kinematics/efficiency

Swimming velocity and the propelling efficiency were selected as proxy of the swim kinematics and efficiency, respectively. The swimmers performed a warm-up session immediately before the data collection. Each swimmer performed three maximal 25 m trials in freestyle swimming with a push-off start. The swimmers had a 30 min rest between trials for full recovery. The average value of the three trials was used for analysis.

A speedo-meter cable (Swim speedo-meter, Swimsportec, Hildesheim, Germany) was attached to the swimmer's hip. A 12-bit resolution acquisition card (USB-6008, National Instruments, Austin, Texas, USA) was used to transfer data (f = 50 Hz) from the speedo-meter to a software interface in LabVIEW®

(v.2009) (Barbosa et al., 2013). Data were exported to a signal processing software (AcqKnowledge v. 3.5, Biopac Systems, Santa Barbara, USA) and filtered with a 5 Hz cut-off low-pass fourth-order Butterworth filter. Swimming velocity (v) was computed in the middle 15 m (i.e. between the 5th and 20th metre marks) as $v = d/t$, where v is the mean swimming velocity (in m s^{-1}), d is the distance covered (in m) and t is the time spent (in s). The propelling efficiency was estimated as suggested by Zamparo, Pendergast, Mollendorf, Termin, & Minetti (2005):

$$\eta_p = \left[\left(\frac{v \cdot 0.9}{2\pi \cdot \mathrm{SF} \cdot l} \right) \cdot \frac{2}{\pi} \right] \cdot 100, \tag{3}$$

where η_p is the propelling efficiency (in %), v is the velocity (in m s^{-1}), SF is the stroke frequency (in Hz) and l is the distance between the shoulder and tip of the third finger during the insweep (in m, i.e. this distance was measured on dry-land, while the swimmer was simulating a stroke cycle: (i) between the acromion and the olecranon and (ii) between the olecranon and the tip of the third finger, with a measuring tape (RossCraft, Canada); ICC = 0.99 for absolute agreement).

Anthropometrics

For the arm span (AS – swimmers were only wearing a textile swimsuit and a cap) measurement, subjects were standing in an upright orthostatic position with arms and fingers fully extended in lateral abduction at a 90° angle with the trunk. The distance between the third fingertip of each hand was measured with a flexible anthropometric tape (Ross-Craft, Canada) (ICC = 0.98).

Statistical analysis

Normality and homoscedasticity assumptions were analysed with the Kolmogorov–Smirnov and Levene tests, respectively. The mean, 1 standard deviation, minimum, maximum and variance were calculated as descriptive statistics. The association between swimming performance (later on considered as dependent) and all the remaining variables (in the
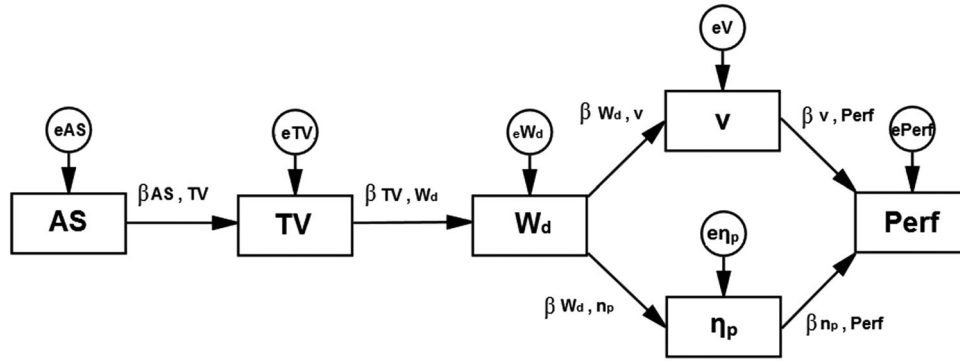
Figure 1. Theoretical path-flow model. Note: AS, arm span; TV, throw velocity; W_d , power to overcome drag; v , swimming velocity; η_p , propelling efficiency; Perf, performance; β xi,yi, beta value for regression model between exogenous (xi) and endogenous (yi) variables; exi, disturbance term for a given variable; xi→yi, variable yi depends from variable xi.

model considered as independent) was computed by the Pearson's correlation coefficient. For the qualitative analysis, the relationship between the performance and remaining variables was considered as (Costa et al., 2011; Ferguson, 2009): very high if $0.81 \leq r < 1.0$; high if $0.49 \leq r < 0.81$; moderate if $0.16 \leq r < 0.49$; weak if $0.04 \leq r < 0.16$ and very weak if $r < 0.04$. The statistical significance was set at $p < .05$.

For the structural equation modelling the path-flow analysis procedure was used (Morais et al., 2012). The interpretation of this kind of approach is based on the links between variables (i.e. the capacity of one or more dependent variables to predict an independent one). These links present a beta value (i.e. standardized coefficients) that shows the contribution of one variable to the other. Standardized regression coefficients (b) were considered, and the significance of each one was assessed with the Student's t-test ($p < .05$). The residual errors and/or determination coefficient were also computed (represents the variable predictive error or the variable predictive value, respectively). The model's goodness-of-fit was measured by computing the ratio Chi-square/degrees of freedom (x^2/df). This ratio shows (Wheaton, 1987): x^2/df > 5 poor adjustment;

$5 \geq x^2$/df > 2 reasonable adjustment; $2 \geq x^2$/df > 1 good adjustment and x^2/df ~1 very good adjustment.

Results

The W_d showed the highest variance of all variables selected, ranging between 8.13 and 271.07 W (Table I). For what it is worth, the percentiles of this parameter were: P0 (8.13); P10 (29.33); P20 (38.08); P30 (45.39); P40 53.63; P50 (61.74); P60 (69.80); P70 (78.01); P80 (89.68); P90 (119.38); P100 (271.07), suggesting that the P0 and P100 are extreme cases and variance between P10 and P90 is not so high. On the other hand, the AS had the lowest variance ranging between 148.0 and 187.0 cm. Overall, all but one determinant factor showed a moderate to very high and significant correlation ($p < .05$) with the performance (Table II).

Figure 2 depicts the confirmatory models computed for the young swimmers' performance. Figure 2(a) is the first model computed, which includes all the determinant factors selected for this research. Between each path, the correspondent beta value (standardized regression weight) is showed (i.e. the contribution of one given variable

Table II. Descriptive statistics for the variables selected, and the Pearson's correlation between performance and remaining variables.

	Descriptive				Correlation	
	Mean ± 1SD	Maximum	Minimum	Variance	r	p
Perf (s)	74.25 ± 8.80	95.24	58.14	77.56	N/A	N/A
AS (cm)	1.66 ± 0.08	1.87	1.48	0.007	−0.59	< 0.001
TV (m s^{-1})	6.65 ± 1.03	8.05	4.20	1.06	−0.42	0.03
W_d (W)	71.17 ± 44.96	271.07	8.13	2022.08	−0.55	< 0.001
v (m s^{-1})	1.31 ± 0.14	1.63	0.94	0.02	−0.82	< 0.001
η_p (%)	29.82 ± 3.92	44.83	21.40	15.43	−0.18	0.06

Note: Perf, performance; AS, arm span; TV, throw velocity; W_d , power to overcome drag; v , swimming velocity; η_p , propelling efficiency.
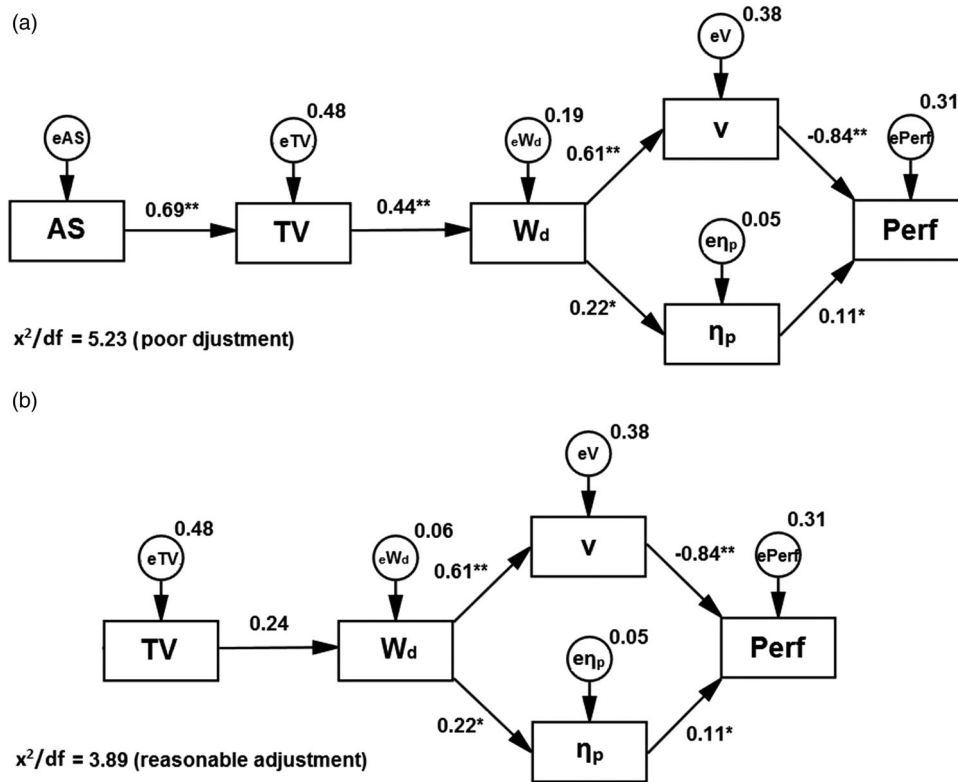
Figure 2. Confirmatory path-flow model including all variables (a), and deleting variable that allowed to increase the goodness-of-fit (b). Note: AS, arm span; TV, throw velocity; W_d, power to overcome drag; v, swimming velocity; η_p, propelling efficiency; Perf, performance; β xi,yi, beta value for regression model between exogenous (xi) and endogenous (yi) variables; exi, disturbance term for a given variable; xi→yi, variable yi depends on variable xi; $^*p < .05$. $^{**}p < .001$.

to other). For example, an increase by one unit (1 cm) in the AS leads to a 0.69 m s^{-1} increase in the TV. However, the first model (2(a)) obtained a poor goodness-of-fit (x^2/df = 5.23; i.e. poor adjustment). The path AS-TV was deleted, and it was followed up by a re-computation of the remaining data. This time around, the prediction of the model and the paths were the same albeit improved the goodness-of-fit to a reasonable adjustment (x^2/df = 3.89; reasonable adjustment). The only exception was the TV-W_d path where beta decreased from 0.44 to 0.24 (not significant). Therefore, the final model explains that the TV will influence the W_d, where the latter has an influence on both the v and η_p and hence the efficiency on the performance. The model was able to explain 69% of the performance. The TV explained the W_d in 94%. The W_d explained the v and the η_p in 62% and 95%, respectively.

Discussion

The aim of this study was to compute a path-flow model (i.e. confirmatory analysis) of young swimmers' performance based on some selected biomechanical and efficiency features. Main results showed that every path of the final model had a significant effect, explaining the performance by 69%.

Mean data are within the range and confidence intervals reported in the literature for swimmers of this age group and competitive level (Barbosa et al., 2015; Jurimae et al., 2007; Morais et al., 2013). Pearson's correlation showed significant associations between the performance and all selected co-variables (with moderate to very high effect sizes), being the η_p the only exception ($p = .06$). Most of the studies recruiting young swimmers reported associations between the performance and anthropometrics, kinematics or hydrodynamics (Barbosa, Costa et al., 2010; Marinho et al., 2010; Vitor & Bohme, 2010). However, there was not yet any insight on such association between performance, strength and power. Garrido et al. (2010) reported that a concurrent dry-land S&C programme and in-water regular practice have enhanced the performance of young swimmers. More recently, Nasirzade et al. (2014) reported that the fastest young swimmers showed the largest muscle thickness and absolute fascicle length in several muscles, including the triceps brachii. At least for adult/elite swimmers, the

mean amplitude value (i.e. muscle activation) of the triceps brachii and the biceps brachii decreased along with a decrease in the swimming velocity (Ikuta et al., 2012). This suggests that the swimming velocity is related to the muscle morphology and the neuromuscular response, being both the main determinants of muscle strength.

The final model featured the TV, W_d, v, and η_p, predicting the swim performance. The TV had a positive effect on the W_d, and this on the v and η_p. The v showed a positive effect on the performance (i.e. negative beta value meaning that less time was needed to cover the distance) and the η_p had a negative effect on the performance (i.e. positive beta value suggesting that more time was needed to perform the 100 m). The TV is an effective and straightforward way to monitor the upper limbs' strength (Van den Tillaar & Marques, 2011). A very high correlation was verified between the height (i.e. also strongly related to the AS) and the forearm flexion peak torque ($r = 0.84$; $p \leq .05$), and the forearm extension peak torque ($r = 0.87$; $p \leq .05$) (Cochrane et al., 2015). At least for novice handball players, the AS did show a strong correlation ($r = 0.342$; $p = .008$) with the TV (Skoufas, Kotzamanidis, Hatzikotoylas, Bebetsos, & Patikas, 2003). Hence, it was hypothesized that the AS would have a positive and significant effect on the TV (i.e. a higher AS would determine a higher TV). However, no relationship was found in the literature between the AS and upper limbs strength in young swimmers. Yet, in our research, despite the AS–TV path presenting a positive and significant effect ($\beta = 0.69$; $p < .001$), its deletion allowed an increase in the model's goodness-of-fit from poor to reasonable adjustment (Figure 2(b)).

It was hypothesized that dry-land strength and power (TV) would be related to in-water strength and power (W_d). Despite that the TV– W_d path was not significant ($\beta = 0.24$; $p > .05$), the TV surprisingly explained 94% of the W_d. Some studies showed that upper limbs strength is related to sprinting performance (Garrido et al., 2010; Girold, Maurin, Dugué, Chatard, & Millet, 2007). It was also suggested that greater strength is related to a higher production of propulsive forces in water and in-water power output. It was found earlier that the correlation between the maximal power output and young sprinting swimmers' performance was high ($r = -0.69$) (Toussaint, de Looze, van Rossem, Leijdekkers, & Dignum, 1990). Therefore, there is evidence to substantiate the idea that there is at least a moderate relationship between dry-land and in-water strength and power. The W_d explained the v and the η_p by 62% and 95%, respectively. Added to that, it presented significant paths to both v ($\beta = 0.61$; p

$< .001$) and η_p ($\beta = 0.22$; $p < .05$). Overall, the swimmers delivering the highest W_d are able to be both effective (higher v) and efficient (higher η_p). These two variables (v and η_p) had significant paths to the performance (v: $\beta = -0.84$, $p < .001$; η_p: $\beta = 0.11$, $p < .05$). Indeed, the literature supports that technical parameters are strongly related to the performance enhancement in young swimmers, notably the sprinting performance (Figueiredo, Silva, Sampaio, Vilas-Boas, & Fernandes, 2015; Jurimae et al., 2007; Morais et al., 2012).

Overall, this model highlights the holistic phenomenon that swimming performance is. Swimming performance depends on the anthropometrics, kinematics and efficiency as reported earlier in the literature. However, the novelty here is that dry-land as well as in-water power output and strength play determinant roles. Both influence the technique and ultimately the performance. These data suggest that concurrent dry-land S&C and in-water sessions should be included as part of young swimmers' programmes. The S&C programmes will allow young swimmers to build up strength, and having a positive direct effect on their stroke mechanics (i.e. technique) and hence performance. Such programmes aim not only to help one to excel but also prevent injuries (Batalha, Marmeleira, Garrido, & Silva, 2015); which is a concern that several S&C coaches have regarding the high rate of shoulder injuries in swimmers at such young age (Batalha, Raimundo et al., 2015).

The following can be addressed as main limitations of this research: (i) this model may be only reliable for the prediction of performance in short-distance events (i.e. sprinting); (ii) this model can only be applied in young swimmers (i.e. pre-pubescent swimmers), and a follow-up longitudinal research can be carried out to verify how relevant this model is in talent identification; (iii) it is unclear if this model output is accurate and reliable for the remaining swim strokes, such as backstroke, breaststroke and butterfly; (iv) as far as our understanding goes, the main performance determinants of adult/elite swimmers are slightly different and therefore caution should be exercised when applying these findings to older counterparts.

Conclusion

As a conclusion, the final model features dry-land strength, in-water power output and kinematic/efficiency variables, explaining 69% of the performance in young swimmers. Overall, dry-land strength has a positive and large effect on the in-water power output, and in turn on the stroke mechanics (v and

η_{p}), thus enhancing the performance. Although anthropometrics was not included in the final model, it showed a significant contribution to other determinants.

Disclosure statement

No potential conflict of interest was reported by the authors.

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