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Is the underwater gliding test a valid procedure to estimate the swimmers' drag?

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Abstract

Objective: The aim of this study was to develop a structural equation model for underwater gliding distance based on its determinant variables, in order to confirm whether it is an informative test of young swimmers' hydrodynamic profile. **Methods:** Twenty-three subjects (twelve boys and eleven girls with a mean age of 13.61 ± 0.83 years old) were evaluated. The following were determined: (i) the underwater gliding distance; (ii) the squat jump performance; (iii) the passive drag; (iv) the passive drag coefficient; (v) the trunk transverse surface area and; (vi) the gliding velocity. **Results:** The underwater gliding distance was significantly correlated with the squat jump ($r_s = 0.47$; $p = 0.038$) and with the coefficient of passive drag ($r_s = -0.55$; $p < 0.01$) but not with passive drag ($r_s = 0.41$; $p = 0.09$). The overall model explained 45% of the underwater gliding distance ($x^2/df = 3.138$). **Conclusion:** The underwater gliding distance seems to be more dependent from the squat jump than from the passive drag. Therefore it seems as if the underwater gliding test is not representative of the swimmers' passive drag or his /her passive drag coefficient. **Keywords:** hydrodynamics, passive drag, path-flow analysis, swimming

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Introduction

Swimming velocity depends on two external forces: (i) thrust and; (ii) drag. To displace him/herself, the swimmer must produce at least the same amount of thrust equal to drag intensity[1]. Therefore, drag force determination is a key issue for competitive swimming. There are two types of drag: (i)

active drag (D_a) and; (ii) passive drag (D_p). Active drag is the water resistance associated to a swimming technique[2]. The Velocity Perturbation Method[3] and the Measuring Active Drag System[4] are two direct methods to measure D_a. Active drag can also be indirectly measured through the oxygen cost of resisted and assisted swimming[5]. Passive drag is the water resistance when a non-swimming subject displaces in a prone streamlined position[6]. There are several techniques to measure D_p reported in literature: (i) by towing a subject in water[7,8]; (ii) by Computational Fluid Dynamics[9,10] and; (iii) by inverse dynamics[11,12]. However, these are highly complex and/or expensive procedures to be used on regular basis by coaches. An affordable and easy way to estimate D_p is applying the underwater gliding test[13]. This is a less expensive, complex and time consuming test for coaches and researchers. Indeed, practitioners use such test to assess young swimmers' hydrodynamic profile on regular basis[13-16].

There seems to be a rationale behind using the underwater gliding test as an estimation of D_p. According to Newton's second law of motion, the gliding negative acceleration depends on the resistive forces applied to a body and its inertial properties. The resistive forces act opposite to the displacement direction and their magnitude is highly related to velocity. Inertia of a gliding body is the sum of the body mass plus the mass of water entrained with the body[17]. The lower the resistive force and the higher the virtual mass, the lower the negative acceleration at each corresponding velocity and thus the higher the glide efficiency[18].

A higher gliding efficiency (i.e., gliding distance) seems to be associated to a decrease of the D_p[10]. At least practitioners use the gliding test considering this phenomenon and because it is easier to assess than remaining direct and indirect testing procedures reported on literature[13,19]. A higher underwater gliding distance is related to D_p and the coefficient of passive drag (C_{Dp}). It is also reported that the position of the head is determinant for a better gliding performance. These authors[20] reported that a neutral alignment of the head with the trunk allows a drag decrease of 17 to 20% between 2.2 and 3.1 [$m \cdot s^{-1}$]

gliding velocities. As this test starts from a wall push-off, other variables might be related to the gliding distance. This can impose a bias in the rationality of using the gliding test as an estimator of drag force. At least one study reported that lower limbs muscle power is a determinant factor to enhance the turns[21]. Probably the gliding distance (i.e., performed during this test) depends not only from one external force (i.e., drag) but also from the second one (i.e., propulsion by lower limbs power) affecting a subject on aquatic environment as reported in the fluid mechanics domain. So, it is questionable if underwater gliding test is an appropriate (i.e., valid) technique to estimate the swimmers' drag.

To test the variables that might influence the gliding distance structural equation modelling can be used. The path analysis model allows understanding the relationships between observed variables, providing a quantitative test of a hypothesised theoretical model[22]. With such data analysis procedure it is possible to analyse if the gliding distance depends only from the resistance (i.e., drag force and/or drag coefficient) or also by propulsive forces (i.e., lower limb's power). In addition, if several variables influence the gliding distance, it may be possible to understand: (i) their relationship to the gliding test and; (ii) the relationships among them.

The aim of this study was to develop a structural equation model (i.e. path-flow analysis) for young swimmers' underwater gliding distance based on some selected anthropometrical, hydrodynamic, kinematical and neuromuscular variables, in order to confirm whether this is a valid test to analyse the swimmers' hydrodynamic profile. It was hypothesised that other variables, besides the D_p and C_{Dp}, might be related to the underwater gliding distance.

Methods
Subjects
Twenty-three young swimmers (twelve boys and eleven girls) participating on regular basis in regional and national level competitions volunteered as subjects (boys: 14.42 ± 1.24 years old, 166.29 ± 9.13 cm of height, 56.45 ± 10.80 kg of body mass, 3.33 ± 0.78 Tanner stages by self-evaluation, 3.50 ± 0.67 training years; girls: 12.73 ±

0.79 years old, 160.40 ± 5.34 cm of height, 47.55 ± 6.27 kg of body mass, 3.00 ± 0.89 Tanner stages by self-evaluation, 3.54 ± 0.52 training years). Swimmers performed 6.16 ± 0.72 training units per week. They also performed dry land strength and stretching exercises, but no specific plyometric tasks.

Coaches and parents gave their consent for the swimmers participation in this study and all procedures were in accordance with the Declaration of Helsinki regarding human research. The Institutional Review Board of the University of Bragança approved the study design.

Theoretical model
Figure 1 presents the theoretical model adopted for the underwater gliding distance

based on selected anthropometric, kinematical, hydrodynamic and neuromuscular variables in young competitive swimmers. It is well known that drag depends on water density, swimming velocity, trunk transverse surface area and drag coefficient[23]. A higher underwater gliding distance might be representative of lower drag intensity. It is also reported that the Squat Jump (SJ) could improve tasks involving the power of lower limbs[21], such as the wall push-off before gliding. So the sequence of the path-flow domain was based on these facts. As drag force is dependent on hydrodynamic and anthropometrical variables[23], correlations regarding the trunk transverse surface area (TTSA), C_{Dp} and velocity were also computed.
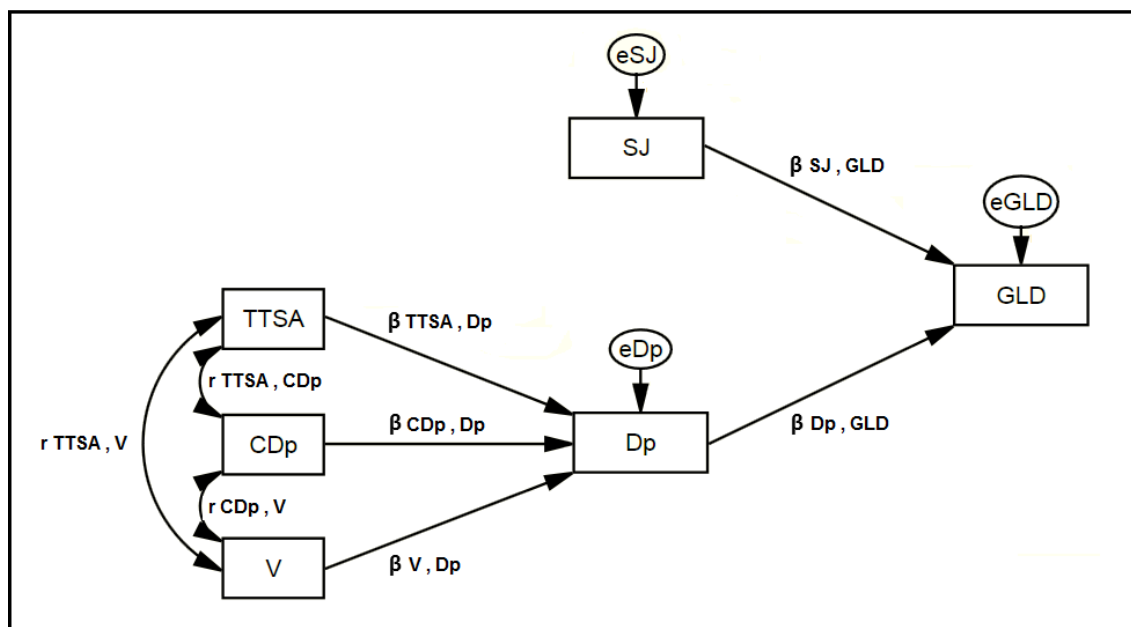

Figure 1: Theoretical path-flow model
TTSA - trunk transverse surface area; C_{Dp} - drag coefficient; V - swimming velocity; SJ - squat jump; D_p - passive drag; GLD - gliding; $\beta\, x_i, y_i$ - beta value for regression model between exogenous (x_i) and endogenous (y_i) variables; e_{xi} - disturbance term for a given endogenous variable; $r_{xi,yi}$ - correlation coefficient between two variables; $x_i \rightarrow y_i$ - variable y_i depends from variable(s) x_i; $x_i \leftrightarrow y_i$ - variable y_i is associated to variable x_i.

Underwater gliding distance data collection
The subjects were instructed to perform a maximal push-off from the wall, in a prone streamlined position, at a depth of approximately 0.5 to 1 [m] in the first lane, with lane ropes separating it from the lateral wall and the second lane. Thereafter they

glided in a prone hydrodynamic position with no segmental actions (i.e. head in a neutral position, arms fully extended with one hand above the other and legs also fully extended and together). The maximal horizontal distance achieved by the swimmer was measured with a fiberglass measure tape (Nadic, Brebbia, Italy). An evaluator followed closely the swimmer

during the trial to measure the distance. With the help of a vault the maximum distance that the swimmer achieved after the wall push-off parallel to the swimmers' feet was recorded, tracing a perpendicular projection between the vault and the measuring tape. The test ended when swimmers achieved the water surface and/or were not able to make any further horizontal displacement of their body gliding and/or started any limb action.

Each swimmer performed three trials of underwater gliding distance, with more than two minutes of recovery between them. The best one was considered for further analysis.

TTSA data collection
For anthropometrical assessment, the subjects were on land, wearing a regular textile swimsuit. The chest perimeter, defined as the perimeter of the trunk at the level of the xiphoid process, was measured with a flexible anthropometrical tape (Metric Tape, RossCraft, Canada) with the subject in the upright and hydrodynamic position. The chest sagittal diameter, which is considered as the distance between the back and the highest point of the chest (i.e. antero-posterior) at the level of the xiphoid process, was measured with a specific sliding caliper (Measuring Clip, RossCraft, Canada). The TTSA was estimated according to the Equations 1 and 2 developed by Morais et al.[24] for male and female swimmers, respectively:

$$TTSA = 6.662 \cdot CP + 17.019 \cdot CSD - 210.708 \tag{1}$$
$$TTSA = 7.002 \cdot CP + 15.382 \cdot CSD - 255.70 \tag{2}$$

where *TTSA* is the trunk transverse surface area in [cm^2], *CP* is the chest perimeter in [cm] and *CSD* is the chest sagittal diameter in [cm].

Velocity data collection
The kinematical variable assessed was the gliding velocity. A speedo-meter cable (Swim speedo-meter, Swimsportec, Hildesheim, Germany) was attached to the swimmers' hip and the gliding velocity decay was acquired on-line at a sampling rate of 50 [Hz], during the gliding phase. Data was exported to signal processing software (AcqKnowledge v. 3.5, Biopac Systems, Santa Barbara, USA) and filtered

with a 3 [Hz] cut-off low-pass 4th order Butterworth filter. The integrated system (hardware plus software) was validated with videometric[25] and Doppler effect[26] techniques.

The gliding mean velocity and the corresponding mean acceleration based upon the acceleration to time were calculated. The acceleration to time curve was obtained by numerical differentiation of the filtered velocity-time curve, using the 5th order centred formula[11]:

$$a_i = \frac{2v_{i-2} - 16v_{i-1} + 16v_{i+1} - 2v_{i+2}}{24\Delta t} \tag{3}$$

where a_i represents the hip's instantaneous acceleration in [m·s^{-2}], v_i represents the hip's instantaneous velocity in [m·s^{-1}] and *t* represents the time in [s].

Passive drag and passive drag coefficient calculation
Passive drag and coefficient of passive drag were selected as hydrodynamic variables. The D_p was computed through inverse dynamics based upon the velocity to time curve, as suggested by Vilas Boas et al.[11]. Passive drag force was computed considering:

$$D_p = (BM + m_a) \cdot a \tag{4}$$

where D_p represents the swimmers' passive drag in [N], *BM* the swimmers body mass in [kg], m_a the swimmers' added water mass in [kg], estimated as being approximately 28% for subject with similar age[17] and *a* the swimmers' acceleration in [m·s^{-2}]. Coefficient of passive drag (C_{Dp}) was calculated as:

$$C_{Dp} = \frac{2 \cdot D_p}{\rho \cdot S \cdot v^2} \tag{5}$$

where C_{Dp} is the passive drag coefficient [dimensionless], ρ is the density of the water (assuming to be 1000 kg·m^{-3}), D_p is the swimmers' passive drag in [N], *v* is the swimmers' velocity in [m·s^{-1}] and *S* is the frontal surface area of the swimmers in [m^2].

Squat jump data collection

The SJ test, as a neuromuscular variable, was also measured. Each subject started from a crouched position, corresponded to an angle of 90º between both thighs and legs and with their hands at waist level, followed immediately by an explosive jump. The protocol required the performance of three jumps on a trigonometric carpet (Ergojump Digitime 1000, Digest, Finland), followed by two minutes of passive rest. It assessed the maximal height reached by each subject. The average of the three jumps was considered for further analysis[27].

Statistical analysis
The normality and homocedasticity assumptions were analysed with the Shapiro-Wilk and the Levene tests. In descriptive statistics: (i) mean; (ii) minimum; (iii) maximum and; (iv) one standard deviation was calculated for all variables. The Spearman's Rank Correlation Coefficient between underwater gliding distance and remaining variables selected ($p \leq 0.05$) was also computed.

The path-flow analysis model was used to perform the estimation of linear regression standardised coefficients between exogenous and endogenous variables. Standardised regression coefficients (β) were considered, and the significance of each one was assessed with the Student's t test ($p \leq 0.05$).

To measure the quality of the model good-of-fit, it was computed: (i) the ratio Chi-square/degrees of freedom (x^2/df). It was considered qualitatively[28] if: x^2/df > 5 bad adjustment; $5 \geq x^2$/df > 2 low adjustment; $2 \geq x^2$/df > 1 good adjustment; x^2/df ~1 very good adjustment.

Results
Table 1 presents descriptive statistics for all variables evaluated. These data reveal that the sample was composed of a heterogeneous group of swimmers. Data dispersion, assessed by the standard deviation values, were moderate-high. This was especially obvious for the D_p that ranged between 12.88 [N] and 69.93 [N], as well as, for TTSA that ranged between 0.60 and 1.24 [m^2].

Table 1: Descriptive statistics of underwater gliding distance, hydrodynamics, kinematics, anthropometrics and biomechanics variables

	Mean	**Standard deviation**	**Minimum**	**Maximum**
Gliding [m]	4.72	0.83	3.20	6.70
D_p [N]	42.34	15.25	12.88	69.93
C_{Dp} [dimensionless]	0.28	0.08	0.07	0.39
SJ [m]	0.26	0.06	0.19	0.45
TTSA [m^2]	0.77	0.15	0.60	1.24
vel [$m \cdot s^{-1}$]	0.64	0.07	0.56	0.84

Table 2 presents the correlations between the underwater gliding distance and remaining variables selected. Gliding distance presented significant correlations with all exogenous variables except for the D_p. The highest correlation coefficients were verified between the underwater gliding distance and TTSA and the C_{Dp}. Underwater gliding distance had no significant association with the D_p.

Table 2: Correlation coefficients between underwater gliding distance and remaining variables selected

	r_s	**P value**
D_p [N]	0.41	0.089
C_{Dp} [dimensionless]	-0.55	0.006
SJ [m]	0.47	0.038
TTSA [m^2]	0.60	0.002
vel [$m \cdot s^{-1}$]	0.48	0.019

Figure 2 presents the confirmatory path-flows for underwater gliding distance. All paths defined in the theoretical model were significant. The confirmatory model

explained 45% of the underwater gliding distance. The good-of-fit of the model was $x^2/df = 3.849$ (i.e., low adjustment). Based on the rule of thumb method adopted, the confirmatory model adjustment was low regarding the theoretical model designed.
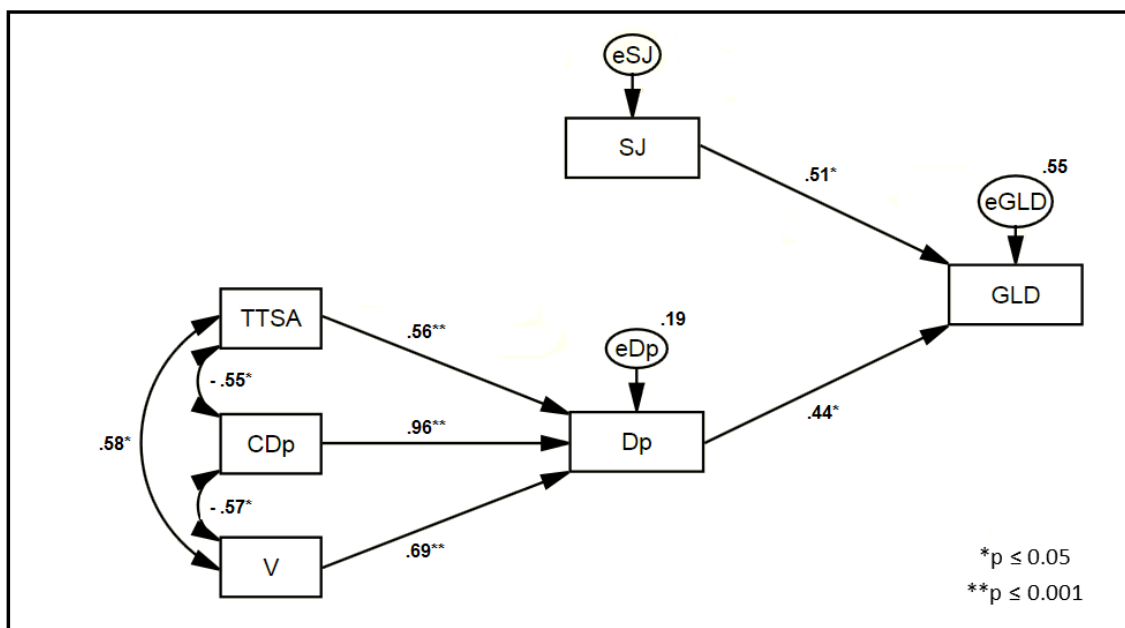

Figure 2: Confirmatory path-flow model
TTSA - trunk transverse surface area; C_{Dp} - drag coefficient; V - swimming velocity; SJ - squat jump; D_p - passive drag; GLD - gliding; $x_i \rightarrow y_i$ - variable y_i depends from variable(s) x_i; $x_i \leftrightarrow y_i$ - variable y_i is associated to variable x_i.

Discussion

The aim of this study was to confirm whether the underwater gliding test is an appropriate technique to estimate the swimmers' water resistance. The main result was that the confirmatory model explained only 45% of the underwater gliding distance. So, other variables, besides the hydrodynamic and neuromuscular ones included in the model, might be related to the underwater gliding distance.

Mean data values are within the range of those reported in the literature for swimmers with similar gender, chronological and biological ages for the selected variables evaluated[16,29]. The exception was for the drag force variables. To the best of these authors' knowledge, Tilborgh et al.[12] measured the D_p in children based on the velocity decay method (i.e. inverse dynamics) but did not report descriptive statistics on that data. Nevertheless, results of D_p computed by inverse dynamics seems to be more valid, since swimmers adopt a better hydrodynamic position (i.e. fundamental hydrodynamic position) without the constrains imposed by handling an apparatus (e.g. arms apart, hands are not fully extended but closed, the back of one hand is not touching the palm of the other) while towed in water[11].

The highest correlation coefficients were verified between the underwater gliding distance and TTSA, as well as, the C_{Dp}. The underwater gliding distance had no significant association with the D_p. Underwater gliding is adopted on a regular basis as a technique to estimate D_p[13-16] (including the C_{Dp}). It is reported that with the increase of glide velocity there is a decrease in the C_{Dp}, suggesting an inverse relationship between them[9]. The streamlined position of underwater gliding seems to allow a higher reduction of the negative hydrodynamic effects of the human body morphology especially at the head and shoulders, suggesting TTSA as a determinant variable for underwater gliding distance. In spite of this, D_p itself did not correlate with the underwater gliding distance. Drag force is dependent on several hydrodynamic and anthropometrical

variables including velocity, shape, size, frontal surface area and it is similar to the general pressure drag equation[23]:

$$D = \tfrac{1}{2} \cdot \rho \cdot v^2 \cdot S \cdot C_d \qquad (6)$$

Where D is the drag force in [N], ρ is the water density in [kg·m^3], v is the velocity in [m·s^{-1}], S is the frontal surface area in [m^2] and C_d is the drag coefficient [dimensionless] (changing according to shape, orientation and Reynolds number).

According to equation 6 a higher velocity represents an increase in drag force, but on the other hand, an increase in velocity is necessary to also increase the underwater gliding. The variable SJ was also correlated with the underwater gliding distance. The plyometric training of the lower limbs (e.g. Squat Jump) in young swimmers improves tasks such as turns after a push-off from the wall[21]. Thus due to the major role of the turns in swimming performance, plyometric training of the lower limbs might play a major role in order to increase the underwater gliding distance[21].

In this particular case, the swimmers' velocity is related to the impulsion made during the wall push-off. Data reported that the variable responsible for the impulsion (i.e. SJ) and the gliding mean velocity had a very low co-variance (CV = 0.004) and (CV = 0.006), respectively. So it might be stated that there was no discrepancy regarding the swimmers' gliding velocity (i.e. the D_p values were measured to similar gliding velocities). On the other hand, D_p values had a high dispersion (CV = 258.07). This fact is probably related to the swimmers' anthropometrics and not to higher gliding velocities.

The confirmatory model included all variables computed and all paths were significant. Velocity, C_{D_p} and TTSA explained 81% of D_p and registered moderate correlations between them. Passive drag had a moderate standardised direct effect to the underwater gliding distance ($\beta = 0.44$; $p = 0.008$). The Squat Jump had also a moderate standardised direct effect to the underwater gliding distance ($\beta = 0.51$; $p = 0.002$). Coaches and researchers use this test (i.e. the underwater gliding distance) on a regular

basis to study young swimmers' hydrodynamic profiles. With D_p being a resistive force, swimmers with lower D_p might be able to achieve a higher displacement distance. In this sense, it was hypothesised that D_p might be the variable that would contribute with the higher direct effect to the underwater gliding distance. On the other hand, as swimmers started this test with a wall push-off, the variable SJ was also included in the model. The lower limbs' power (i.e. SJ) had a higher standardised direct effect on the underwater gliding distance than D_p, and consequently, a higher predictive value ($r^2 = 51\%$). It could be speculated that swimmers achieved a higher distance due to the power they applied during the wall push-off than due to their hydrodynamic profile (i.e. a reduction in the drag forces and as consequence a higher displacement).

The underwater gliding distance depends on the gliding velocity, and this in turn depends on thrust and drag. The same underwater gliding distance might be achieved by decreasing drag forces (i.e. optimising the hydrodynamic position) or by increasing thrust (i.e. more power from the lower limbs during the wall push-off) or by combining both. Data of this confirmatory model shows that lower limbs' power (i.e. Squat Jump) was more a determinant of the underwater gliding distance increase, in comparison to a better hydrodynamic position (represented by the passive drag). Thus some bias might occur since this test (i.e. the underwater gliding distance) is more dependent on the lower limbs' strength than from the swimmers hydrodynamic profile.

The underwater gliding test is used as an easy and affordable way to estimate the swimmers' passive drag[16,19]. The final confirmatory model data reported that D_p was not the variable that better explained the underwater gliding distance. Therefore practitioners should be more careful when using the underwater gliding test to estimate the swimmers' hydrodynamic profile, since some significant bias occurs. They should be able to manipulate and/or take into account the swimmers' lower limb power. Otherwise, an increased underwater gliding distance achieved by the swimmer might be due to a higher impulsion from the

wall push-off and not from the swimmer's hydrodynamic characteristics.

Main limitations of the study can be seen as: (i) the model is only suitable for young male and female swimmers; (ii) a more specific procedure to assess lower limb strength, besides Squat Jump, could be used; (iii) further studies should be conducted in the near future to assess and correct the bias between the underwater gliding test and the passive drag test.

Conclusion

The model only explained 45% of gliding distance, which suggests that other variables beside the hydrodynamic (i.e. passive drag and passive drag coefficient) and neuromuscular (i.e. SJ) could predict the underwater gliding distance. Also, the gliding distance was more dependent on the SJ than the drag force. As a coach-friendly conclusion it can be stated that the underwater gliding test is not representative of the swimmer's passive drag, since some bias might be verified.

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