Morphometric Study for Estimation and Validation of Trunk Transverse Surface Area To Assess Human Drag Force on Water

by

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The aim of this study was to compute and validate estimation equations for the trunk transverse surface area (TTSA) to be used in assessing the swimmer’s drag force in both genders. One group of 133 swimmers (56 females, 77 males) was used to compute the estimation equations and another group of 131 swimmers (56 females, 75 males) was used for its validations. Swimmers were photographed in the transverse plane from above, on land, in the upright and hydrodynamic position. The TTSA was measured from the swimmer’s photo with specific software. Also measured was the height, body mass, biacromial diameter, chest sagittal diameter (CSD) and the chest perimeter (CP). With the first group of swimmers, it was computed the TTSA estimation equations based on stepwise multiple regression models from the selected anthropometrical variables. For males TTSA=6.662*CP+17.019*CSD-210.708 (R²=0.32; Rₐ²=0.30; P<0.01) and for females TTSA=7.002*CP+15.382*CSD-255.70 (R²=0.34; Rₐ²=0.31; P<0.01). For both genders there were no significant differences between assessed and estimated mean TTSA. Coefficients of determination for the linear regression models between assessed and estimated TTSA were R²=0.39 for males and R²=0.55 for females. More than 80% of the plots were within the 95% interval confidence for the Bland-Altman analysis in both genders.

Key words: validation, accuracy, frontal surface area, drag, swimming

Introduction

Swimming is considered as a human locomotion technique in the aquatic environment. Since water is not a natural environment for human beings, there is a lot of interest regarding its research. Any body, including humans, travelling in aquatic environment, is submitted to four groups of external forces: (i) weight; (ii) buoyancy; (iii) propulsive forces and; (iv) drag force.

Drag force is dependent on several hydrodynamic and anthropometrical variables including velocity, shape, size, surface area and it is similar to the general pressure drag equation (Kjendie and Stallman, 2008):

\[ D = \frac{1}{2} \cdot \rho \cdot v^2 \cdot S \cdot C_d \]  

Where \( D \) is the drag force [N], \( \rho \) is the density of the water [kg.m⁻³], \( v \) is the swimming velocity [m.s⁻¹], \( S \) is the projected frontal surface area of the swimmers [cm²] and \( C_d \) is the drag coefficient (changing according to shape, orientation and Reynolds number).

The assessment of the drag force can be done with the swimmers towing in water and without segmental actions (i.e. passive drag) while the subject is making segmental actions to propeller him/herself (i.e. active drag) (Pendergast et al., 2006; Marinho et al., 2009). Passive and active drag can be measured with numerical simulations or experimental methods. Numerical solutions use techniques such as computer fluid dynamics (CFD) (e.g. Silva et al., 2008; Marinho et al., 2009).
2010a). For a passive drag measurement, there are some methods reported in the literature (e.g. Clarys et al., 1974; Zamparo et al., 2009). Subjects are passively towed on prone and hydrodynamic position holding a wire in the hands. An engine roll up the wire at a constant speed and the resistance force is measured by a dynamometer. On the other hand, for active drag, with more citations in the literature, there is a method describing the interpolation of oxygen uptake for null drag when swimming with extra positive and negative loads (di Prampero et al., 1974), the measuring active drag-system apparatus (Hollandier et al., 1986; Toussaint et al., 2004) and the velocity perturbation method (VPM) (Kolmogorov and Duplischeva, 1992; Kolmogorov et al., 2000).

Anthropometrics, such as body size or body density (Zamparo et al., 1996) has a significant influence on drag force. A couple of methods to assess drag force (i.e. CFD and VPM methods) need to include in the data input the trunk transverse surface area (TTSA). The TTSA on regular basis is also called by practitioners and researchers of “frontal surface area” or “projected surface area on the direction of displacement” or even “body cross-sectional diameter”. The TTSA can be directly measured in each subject and inserted in the data input of the CFD and VPM methods. TTSA is measured with a planimeter, on screen measure area software of plane 2D digital images, or body scan (Nicolas et al., 2007; Nicolas and Bideau, 2009). However, TTSA data collection and its treatment are somewhat time consuming and/or expensive. Therefore, most of the times practitioners and researchers estimate TTSA based on some selected anthropometrical variables. Clarys (1979) suggested a TTSA estimation equation based on the subject’s body mass and height ($R^2 = 0.50$):

$$TTSA = 6.9256 \cdot BM + 3.5043 \cdot H - 377.156 \quad (2)$$

Where TTSA is the trunk transverse surface area [cm$^2$], BM is the body mass [kg] and H is the height [cm].

This estimation equation was developed using stepwise regression models that included several anthropometrical variables of 63 physical education students and 9 Olympic swimmers. Equation 2 is on regular basis used to assess drag force in children (Kjendlie and Stallman, 2008; Marinho et al., 2010b; Barbosa et al., 2010c) and adult swimmers (Kolmogorov and Duplischeva, 1992), male and female subjects (Kolmogorov et al., 2000; Toussaint et al., 2004) without a clear knowledge of the good-of-fit of the model to different cohort groups. Moreover, the research was performed in the seventies. Anthropometrical characteristics of the 70’s swimmers are not the same as the ones of the XXI century.

The aim of this study was to compute and validate TTSA estimation equations to assess the swimmer’s drag force in both genders. It was hypothesized that it is possible to compute accurate and valid equations to estimate TTSA for male and female swimmers in a broad range of ages.

**Material and methods**

**Sample**

Total sample was composed of 264 subjects (152 males and 112 females). All subjects were competitive swimmers with regular participation in competitions at the regional, national, or international level. Swimmers chronological ages ranged between 10-32 years old for males and 9-27 years old for females.

![Figure 1](http://www.johk.pl)
Total sample was divided into two groups based on gender. In each gender group the sub-sample was divided once again: (i) approximately half of subjects were used to compute the TTSA estimation equations and; (ii) the other half for its validation. One group of 133 swimmers (56 females and 77 males) was used to compute the TTSA estimation equations and another group of 131 swimmers (56 females and 75 males) was used for its validations. Figure 1 presents the split of the sample.

All procedures were in accordance to the Declaration of Helsinki in respect to Human research. The Institutional Review Board of the Polytechnic Institute of Bragança approved the study design. Subjects (or when appropriate their legal tutors) were informed of the potential experimental risks and signed an informed consent document prior to data collection.

**Data Collection**

For the TTSA measurement, subjects were photographed with a digital camera (DSC-T7, Sony, Tokyo, Japan) in the transverse plane from above (Caspersen et al., 2010). Subjects were on land, in the upright and hydrodynamic position. This position is characterized by the arms being fully extended above the head, one hand above the other, fingers also extended close together and head in neutral position. Subjects wore a regular textile swimsuit, a cap and goggles. Besides the subjects, on the camera shooting field there was a calibration frame with 0.945 [m] length at the height of the xiphoid process. TTSA was measured from the subject’s digital photo with a specific software (Udruler, AVPSoft, USA). Procedures included: (i) scale calibration; (ii) manual digitalization of the transverse trunk perimeter; (iii) output and recording of the TTSA value.

Also measured were the following selected anthropometrical variables: (i) body mass; (ii) height; (iii) biacromial diameter; (iv) chest sagittal diameter and; (v) chest perimeter. Most of these variables are reported on regular basis in competitive swimming anthropometrical reports and research papers (e.g. Mazza et al., 1994). All measurements were carried-out wearing a regular textile swimsuit, a cap and goggles. Body mass (BM) was measured in the upright position with a digital scale (SECA, 242, Hamburg, Germany). Biacromial diameter (BCD) is considered as the distance between the two acromion processes. Chest sagittal diameter (CSD) 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. Both diameters were measured once again with a specific sliding calliper (Campbell, 20, RossCraft, Canada) being the subjects in the anthropometrical position. Chest perimeter (CP), defined as the perimeter of the trunk at the level of the xiphoid process, was measured with a flexible anthropometrical tape (RossCraft, Canada). All anthropometrical evaluations were performed by an expert. Each anthropometrical variable was measured three consecutive times. For further analyses, the mean value of all three trials was considered.

**Statistical procedures**

The normality and homocedasticity assumptions were checked respectively with the Kolmogorov-Smirnov and the Levene tests. Descriptive statistics (mean, one standard deviation, minimum, maximum and coefficient of variation) from all measured variables were calculated.

In the first sub-sample group forward step-by-step multiple regression models were computed. TTSA was considered as endogenous variable and remaining anthropometrical variables (i.e. body mass, body height, BCD, CSD and CP) as exogenous variables. The variables entered the equation if $F \geq 4.0$ and removed if $F \leq 3.96$ as suggested elsewhere (Barbosa et al., 2008). All assumptions to perform the selected multiple regression models were taken into account. For further analyses the equation computed, the coefficient of determination ($R^2$), the adjusted coefficient of determination ($R_{adj}^2$), the error of estimation ($\sigma$) and the probability of rejecting the null hypothesis ($p \leq 0.05$). In each exogenous variables included in the final model, the t-value and the p-value were considered as well.

Validation was made in the second sub-sample group (Baldari et al., 2009; Kristensen et al., 2009; Wolfram et al., 2010): (i) comparing mean data; (ii) computing simple linear regression models and; (iii) computing Bland Altman plots. Comparison between the mean TTSA assessed and the TTSA estimated, according to the
equations previously developed, was made using paired Student’s t-test \((p \leq 0.05)\). Simple linear regression model between both assessed and estimated \(TTSA\) was computed. As a rule of thumb, for qualitative and effect size analysis, it was defined that the relationship was: (i) very weak if \(R^2 < 0.04\); weak if \(0.04 \leq R^2 < 0.16\); moderate if \(0.16 \leq R^2 < 0.49\); high if \(0.49 \leq R^2 < 0.81\) and; very high of \(0.81 \leq R^2 < 1.0\). In addition, the error of estimation \((s)\) and the confidence interval for 95\% of the adjustment line in the scatter gram was computed. The Bland Altman analysis (Bland and Altman, 1986) included the plot of the mean value of \(TTSA\) assessed and estimated versus the delta value (i.e. difference) between \(TTSA\) assessed and estimated. It was adopted as limits of agreement a bias of ± 1.96 standard deviation of the difference (average difference ± 1.96 standard deviation of the difference). For qualitative assessment, it was considered that \(TTSA\) estimated was valid and appropriate if at least 80% of the plots were within the ± 1.96 standard deviation of the difference.

**Results**

**Morphometric characteristics**

Table 1 presents the descriptive statistics for all selected anthropometrical variables, according to gender groups. Overall, it can be verified that most mean values are higher in male than in female subjects. Data dispersion can be considered as weak (i.e. \(CV \leq 15\%\)) or moderate (i.e. \(15\% < CV \leq 30\%\)) within each gender group.

**Computation of trunk transverse surface area prediction models**

For male gender, the final model \((F_{2.75} = 17.143; p < 0.001)\) included the \(CP\) \((t = 2.963; \ p < 0.001)\) and the \(CSD\) \((t = 2.333; \ p = 0.02)\) in order to predict the \(TTSA\). The equation was \((R^2 = 0.32; \ Ra^2 = 0.30; \ s = 158.93; \ p < 0.01)\):

\[
TTSA = 6.662 \cdot CP + 17.019 \cdot CSD - 210.708 \quad (3)
\]

For the female gender, the final model \((F_{2.53} = -12.871; \ p < 0.001)\) included the \(CP\) \((t = 3.760; \ p < 0.001)\) as well as the \(CSD\) \((t = 2.837; \ p = 0.01)\). The \(TTSA\) estimation equation was \((R^2 = 0.34; \ Ra^2 = 0.31; \ s = 119.22; \ p < 0.01)\):

\[
TTSA = 7.002 \cdot CP + 15.382 \cdot CSD - 255.70 \quad (4)
\]

**Validation of trunk transverse surface area prediction models**

Figure 2 presents the comparison of mean data, scatter gram and Bland Altman plots between assessed and estimated \(TTSA\) based on equations 3 and 4, for male and female genders, respectively. For male subjects, mean value of assessed \(TTSA\) was 747.27 ± 182.38 \([cm^2]\) and the estimated one was 741.54 ± 89.02 \([cm^2]\). In female subjects, mean \(TTSA\) data assessed was 630.25 ± 142.14 \([cm^2]\) and the estimated FSA was 631.57 ± 83.04 \([cm^2]\). Comparing assessed and estimated \(TTSA\), mean data was non-significant \((p > 0.05)\).

| Table 1 |
| --- |
| **Anthropometrical characteristics of male (M) and female (F) subjects for body mass (BM), body height (H), biacromial diameter (BCD), chest sagittal diameter (CSD), chest perimeter (CP) and measured trunk transverse surface area (TTSA)** |
| BM | H | BCD | CSD | CP | TTSA |
| [kg] | [cm] | [cm] | [cm] | [cm] | [cm²] |
| M | F | M | F | M | F | M | F | M | F |
| Mean | 63.61 | 50.04 | 169.41 | 157.46 | 35.41 | 33.13 | 22.43 | 21.57 | 86.90 | 78.08 | 747.46 | 634.23 |
| 1 SD | 15.10 | 10.04 | 12.12 | 9.37 | 5.07 | 4.85 | 3.00 | 2.85 | 9.31 | 8.41 | 184.59 | 144.56 |
| Minimum | 28.00 | 27.80 | 134.00 | 133.00 | 19.90 | 19.90 | 24.20 | 24.20 | 11.50 | 15.50 | 61.50 | 64.00 |
| Maximum | 108.60 | 72.20 | 189.00 | 178.00 | 50.50 | 44.00 | 31.00 | 28.10 | 112.00 | 97.00 | 1371.00 | 1125.20 |
| CV | 23.74 | 20.06 | 7.15 | 5.95 | 14.32 | 14.64 | 13.37 | 13.21 | 10.71 | 10.77 | 24.70 | 22.79 |
Figure 2

Comparison of mean data, scatter gram and Bland Altman plots between assessed and estimated trunk transverse surface areas (TTSA).

The scatter gram analysis for male ($R^2 = 0.39; s = 70.14; p < 0.001$) and female ($R^2 = 0.55; s = 71.68; p < 0.001$) genders revealed statistically significant coefficients of determination ranging from moderate to high relationships.

For the Bland Altman plots, in the female group, none dot was located beyond the 1.96 SD limits. In the male plots, only two dots were beyond the agreement limits. So, the cut-off value of at least 80% of the plots within the ± 1.96 SD was accomplished for male and female groups.
Discussion

The aim of this study was to compute and validate estimation equations for the trunk transverse surface area in order to be used to assess the swimmer’s drag force in both genders. The computed TTSA equations based on the CP and CSD can be considered as valid to assess drag force in both genders in a broad range of ages from children to young adults.

Morphometric characteristics

In order to compute and validate TTSA estimation equations, a somewhat high sample size was selected. Previous research reported that some anthropometrical variables are related to TTSA. Clarys (1979) verified that the height and body mass were the exogenous variables able to predict TTSA with a higher coefficient of determination. Huijing et al. (1988) observed significant relationships between TTSA and several other variables besides height and body mass in 17 male swimmers. Indeed, in the mentioned paper, the variables with significant association level to TTSA were the estimated body surface, all measured segmental circumference, arm’s and leg’s lengths. However, authors did not report significant associations with most of the distances, such as BCD and thorax depths. This lack of significant association might be related to the reduce of data statistical power, since a small and homogeneous sample size was used. TTSA from a geometrical point of view is quite similar to a circle or an oval shape. Geometrically, a circle area is computed as:

\[ A_c = \pi \cdot r^2 \]  
(5)

Where \( A_c \) is the circle area [m²], \( \pi \) a constant value of 3.14 and \( r \) is the radius [m]. The area of an oval or ellipse is found:

\[ A_o = w \cdot l \cdot 0.8 \]  
(6)

Where \( A_o \) is the oval area [m²], \( w \) is the width [m] and \( l \) the length [m]. So, transferring the geometrical knowledge to anthropometrics, it seems that the breasts are the exogenous variables that might be able to predict more powerful TTSA estimation equations. Added to this we had approximately 75 male and 55 female subjects to compute and additional ones to validate the estimation equations using forward step-by-step multiple regression models. When computing multiple regression models it is stated that it is necessary to consider at least 15 subjects for each exogenous variables inserted in the model (i.e. K > 15). Therefore, our decision was to insert 5 exogenous variables (i.e. body mass, height, BCD, CSD and CP) trying to maintain some data consistency. Body mass and height were inserted because they are the variables used in equation 2. The BCD, CSD and CP were added because geometrically they seem to be the variables that allow a higher TTSA estimation.

Analyzing the descriptive data presented in Table 1, mean values are similar or slightly lower than other papers reporting anthropometrical data (Mazza et al., 1994; Strzata et al., 2005; 2007; Knechtke et al., 2010) and TTSA (Nicolas et al. 2007; Nicolas and Bideau, 2009; Caspersen et al., 2010). This research presents a higher dispersion data, as the age range is also higher. Remaining papers focused on stricter chronological age frames or even made separate groups analysis for children and adults. In this sense, it can be speculated that data is in accordance with the main literature. The development of biomechanical models, in this case a statistical one estimating the TTSA based on selected anthropometrical variables, can be a feasible way to promote hydrodynamic evaluation (i.e. drag force) with relevant information for swimmers and coaches (Barbosa et al., 2010a). So, being descriptive statistics similar to main literature and presenting moderate dispersions it allowed to compute and validate the biomechanical models (Barbosa et al., 2010b), as in this case the TTSA estimation equations, based on these data.

Computation of trunk transverse surface area prediction models

For both male and female gender the final model for the TTSA estimation equations included the CP and the CSD. The equations were significant and with a prediction level qualitatively considered as moderate. This means that some other variables not considered for the prediction can have some impact on the TTSA estimation. Forcing new variables entering the model could increase slightly the coefficient of determination but, would also increase the error of estimation. In this sense, it was decided to maintain the true nature of the model developed and not forcing other variables to be included on it.

Equations 3 and 4 have a coefficient of determination lower than equation 2. The explanation for that might be our decision to compute estimation equations for a broad range
of ages and not only for young adults. Added to that, unfortunately, the procedures used to validate equation 2 are not known as it was reported in a review paper instead of an original research type. Moreover, such equation was developed for male swimmers but it is often used for female ones and even with children of both genders because, for the best of our knowledge, there is no other one computed and validated for those groups. That is the reason why we attempted to develop equation models that are fitted and validated not only for male, but also for female swimmers and children of both genders.

From a mathematical point of view (i.e. geometrics), we speculated that other anthropometrical variables besides height and body mass could have higher prediction ability. Indeed, the models to compute equations 3 and 4 excluded body mass and height, inserting some length variables (i.e., CP and CSD). At last, it can be stated that the prediction error can be considered as reduced, especially for the female gender.

**Validation of trunk transverse surface area prediction models**

After developing a new apparatus, technical or methodological procedure it is wise to validate it. On a regular basis the validation process included: (i) the comparison of the mean values between a gold standard and the new procedure; (ii) establishment of the relationship between the gold standard and the new procedure and; (iii) assessment if the difference between the measurements by the two methods is related to the magnitude of the measurement. Several authors considered that some of these procedures are inappropriate for such an aim. Bland and Altman (1986) do not agree with the use of the correlation/determination coefficients. On the other hand, Hopkins (2004) considered that the Bland Altman plot of difference versus mean values for the method and criterion shows a systematic proportional bias in the method’s readings, even though none is present, which do not happens on a regression analysis of the criterion versus the instrument shows no bias. It must be stressed that our paper is not about validation techniques. Because there is no consensual opinion, on a regular basis, the three procedures are used on several of fields knowledge such as Physiology (Baldari et al., 2009), Motor Control and Posture (Kristensen et al., 2009), Anthropometrics (Siahkouhian and Hedayatneja, 2010) or Biomechanics (Wolfram et al., 2010).

There were no significant differences between measured TTSA and estimated TTSA. The coefficients of determination between both variables were significant. Added to that, any Bland Altman analysis presented less than 80% of the plots within the ± 1.96 SD. So, all procedures suggest that equations 3 and 4 are valid ways to assess TTSA on male and female genders, respectively. Validations were carried-out with groups of subjects with similar characteristics of the ones used to compute TTSA. So, validation is only considered for same range of ages and gender. It is questionable if equations 3 and 4 are suitable to be used in other subjects.

It can be considered as main limitations of this original research: (i) TTSA computed are only appropriate for subjects from children (i.e. approximately 6 years-old) to young adults (approximately 30 years-old) and not being valid for remaining ages; (ii) computed equations are not sensitive to the subjects sports level; (iii) adding or forcing extra anthropometrical variables to enter in the final model, it might increase the TTSA estimation level, but data collection will become more time consuming.

As a conclusion: (i) both TTSA estimation models computed were significant and with moderate coefficients of determination; (ii) between mean values of assessed and estimated, TTSA was not significantly different; (iii) coefficients of determination between assessed versus estimated TTSA ranged between moderate and high relationships and; (iv) cut-off values adopted for the Bland Altman Plots were accomplished. In this sense, it can be stated that the models developed can be used with validity to estimate TTSA for both male and female subjects in a broad range of ages, from children to young adults.

**References**

Baldari C, Bonavolontà V, Emerenziani GP, Gallotta MC, Silva AJ, Guidetti L. Accuracy, reliability, linearity of Accutrend and Lactate Pro versus EBIO plus analyzer. Eur J Appl Physiol, 2009; 107: 105-111
Barbosa TM, Fernandes RJ, Morouço P, Vilas-Boas JP. Predicting the intra-cyclic variation of the velocity of the centre of mass from segmental velocities in butterfly stroke: a pilot study. J Sport Sci Med, 2008; 7: 201-209

Barbosa TM, Bragada JA, Reis VM, Marinho DA, Carvalho C, Silva AJ. Energetics and biomechanics as determining factors of swimming performance: updating the state of the art. J Sci Med Sports, 2010a; 13: 262-269

Barbosa TM, Costa MJ, Marinho DA, Coelho J, Moreira M, Silva AJ. Modeling the links between age-group swimming performance, energetic and biomechanic profiles. Ped Exerc Sci, 2010b; 22: 379-391

Barbosa TM, Costa MJ, Marques MC, Silva AJ, Marinho DA. A model for active drag force exogenous variables in young swimmers. J Hum Sport Exerc, 2010c; 5: 379-388

Bland JM, Altman DG. Statistical method for assessing agreement between two methods of clinical measurement. The Lancet, 1986; i: 307-310

Caspersen C, Berthelsen PA, Eik M, Pâkozdi C, Kjendie P-L. Added mass in human swimmers: age and gender differences. J Biomech, 2010; 43: 2369-2373

Clarys JP, Jiskoot J, Risjken H, Brouwer PJ. Total resistance in water and its relationships to body form. In: Biomechanics IV. Eds: Nelson, RC and Morehouse, CA. Baltimore: University Park Press pp. 187-196, 1974

Clarys JP. Human morphology and hydrodynamics. In: Swimming III. Eds: Terauds, J and Bedingfield, EW. Baltimore: University Park Press pp. 3-42, 1979

di Prampero P, Pendergast D, Wilson D, Rennie D. Energetics of swimming in man. J Appl Physiol, 1974; 37: 1-5

Hollander P, de Groot G, van Ingen Schenau G, Toussaint HB, de Best W, Peeters W, Meulemans A, Schreurs W. Measurement of active drag during Crawl stroke swimming. J Sports Sci, 1986; 4: 21-30

Hopkins WG. Bias in Bland-Altman but not regression validity analyses. Sportscience, 2004; 8: 42-46

Huijing P, Toussaint H, Mackay R, Vervoorn K, Clarys JP, Hollander AP. Active drag related to body dimensions. In: Swimming Science V. Eds: Ungerechts, B, Wilke, K, and Reischle, K. Illinois: Human Kinetics Books pp.31-37, 1988

Kjendie P-L, Stallman RK. Drag characteristics of competitive swimming children and adults. J Appl Biomech, 2008; 24: 35-42

Knechtle B, Baumann B, Knechtle P, Wirth A, Rosemann T. A Comparison of Anthropometry between Ironman Triathletes and Ultra-swimmers. J Hum Kinetics, 2010; 24: 57-64

Kolmogorov S, Duplishcheva O. Active drag, useful mechanical power output and hydrodynamic force in different swimming strokes at maximal velocity. J Biomech, 1992; 25: 311-318

Kolmogorov S, Lyapin S, Rumyantseva O, Vilas-Boas JP. Technology for decreasing active drag at maximal swimming velocity. In: Applied Proceedings of the XVIII International Symposium on Biomechanics in Sports – Swimming. Eds: Sander, RH and Hong Y. Edinburgh: Faculty of Education of the University of Edinburgh pp.39-47, 2000

Kolmogorov S, Rumyantseva O, Gordon B, Cappaert, JM. Hydrodynamic characteristics of competitive swimmers of different genders and performance levels. J Appl Biomech, 1997; 13: 88-97

Kristensen MT, Bandholm T, Holm B, Ekdahl C, Kehlet H. Timed up & go test score in patients with hip fracture is related to the type of walking aid. Arch Physio Med Rehab, 2009; 90: 1760-1765

Marinho DA, Barbosa TM, Kjendie P-L, Vilas-Boas JP, Alves FB, Rouboa AI, Silva AJ Swimming Simulation. In: Computational Fluid Dynamics for sport simulation. Eds: Peter M. Heidelberg: Springer-Verlag pp. 33-61, 2009

Marinho DA, Barbosa TM, Garrido N, Costa AM, Reis VM, Silva AJ, Marques MC. Can 8-weeks of training affect active drag in age-group swimmers? J sport Sci Med, 2010b; 9: 71-78
Marinho DA, Barbosa TM, Mantripragada N, Vilas-Boas JP, Rouard AI, Mantha VR, Rouboa AI, Silva AJ. The gliding phase in swimming: the effect of water depth. In: Biomechanics and Medicine in Swimming XI. Eds: Kjendlie, P-L, Stallman, TK and Cabri, J. Oslo: Norwegian School of Sport Sciences pp. 122-124, 2010a

Mazza J, Ackland TR, Bach T, Cosolito P. Absolute body size. In: Kineanthropometry in Aquatic Sports . Eds: Carter, L and Ackland TR. Champaign, Illinois: Human Kinetics pp. 15-54, 1994

Nicolas G, Bideau B, Colobert B, Berton E. How are Strouhal number, drag, and efficiency adjusted in high level underwater monofin-swimming? Hum Mov Sci, 2007; 26 426-442

Nicolas G, Bideau B. A kinematic and dynamic comparison of surface and underwater displacement in high level monofin swimming. Hum Mov Sci, 2009; 28: 480-493

Pendergast DR, Capelli C, Craig AB, di Prampero PE, Minetti AE, Mollendorf J, Termin II, Zamparo P. Biophysics in swimming. In: Biomechanics and Medicine in Swimming X. Eds: Vilas-Boas, JP, Alves, F and Marques, A. Porto: Portuguese Journal of Sport Science pp. 185-189, 2006.

Siahkouhian M, Hedayatneja M. Correlations of anthropometric and body composition variables with the performance of young elite weightlifters. J Hum Kinetics, 2010; 25: 125-131

Silva AJ, Rouboa A, Moreira A, Reis VM, Alves F, Vilas-Boas JP, Marinho DA. Analysis of drafting effects in swimming using computational fluid dynamics. J Sport Sci Med, 2008; 7: 60-66

Strzała M, Tyka A, Zychowska M, Woznicki P. Components of physical work capacity, somatic variables and technique in relation to 100 and 400m time trials in young swimmers. J Hum Kinetics, 2005; 14: 105-116

Strzała M, Tyka A, Krężałek P. Physical endurance and swimming technique in 400 meter front crawl race. J Hum Kinetics, 2007; 18: 73-86

Toussaint HB, Roos P, Kolmogorov S. The determination of drag in front crawl swimming. J Biomech, 2004; 37: 1655-1663

Wolfram U, Wilke HJ, Zysset PK. Valid micro finite element models of vertebral trabecular bone can be obtained using tissue properties measured with nanoindentation under wet conditions. J Biomech, 2010; 43: 1731-1737

Zamparo P, Antonutto G, Francescato MP, Girardis M, Sangoi R, Soule RG, Pendergast DR. Effects of body size, body density, gender and growth on underwater torque. Scand J Med Si Sports, 1996; 6: 273-280

Zamparo P, Gatta G, Pendergast D, Capelli C. Active and passive drag: the role of trunk incline. Eur J Appl Physiol, 2009; 106: 195-205

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