Optimal Body Size and Limb Length Ratios Associated with 100-m Personal-Best Swim Speeds

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ABSTRACT

NEVILL, A. M., S. W. OXFORD, and M. J. DUNCAN. Optimal Body Size and Limb Length Ratios Associated with 100-m Personal-Best Swim Speeds. *Med. Sci. Sports Exerc.*, Vol. 47, No. 8, pp. 1714–1718, 2015. **Purpose**: This study aims to identify optimal body size and limb segment length ratios associated with 100-m personal-best (PB) swim speeds in children and adolescents. **Methods**: Fifty national-standard youth swimmers (21 males and 29 females age 11–16 yr; mean ± SD age, 13.5 ± 1.5 yr) participated in the study. Anthropometry comprised stature; body mass; skinfolds; maturity offset; upper arm, lower arm, and hand lengths; and upper leg, lower leg, and foot lengths. Swimming performance was taken as the PB time recorded in competition for the 100-m freestyle swim. To identify the optimal body size and body composition components associated with 100-m PB swim speeds (having controlled for age and maturity offset), we adopted a multiplicative allometric log-linear regression model, which was refined using backward elimination. **Results**: Lean body mass was the singularly most important whole-body characteristic. Stature and body mass did not contribute to the model, suggesting that the advantage of longer levers was limb-specific rather than a general whole-body advantage. The allometric model also identified that having greater limb segment length ratios [i.e., arm ratio = (low arm)/(upper arm); foot-to-leg ratio = (foot)/(lower leg)] was key to PB swim speeds. **Conclusions**: It is only by adopting multiplicative allometric models that the abovementioned ratios could have been derived. The advantage of having a greater lower arm is clear; however, having a shorter upper arm (achieved by adopting a closer elbow angle technique or by possessing a naturally endowed shorter upper arm), at the same time, is a new insight into swimming performance. A greater foot-to-lower-leg ratio suggests that a combination of larger feet and shorter lower leg length may also benefit PB swim speeds. **Key Words:** PERSONAL-BEST SWIM SPEEDS, LIMB SEGMENT LENGTHS, RATIOS, ALLOMETRIC MODELS, LOG-LINEAR REGRESSION

Understanding physical and anthropometric factors that underpin children's and adolescents' performance in swimming is important for talent identification (19). A substantial body of research conducted with adult swimmers has indicated the importance of anthropometric variables for adult swimming performance, particularly overall swim speed (16,27). Carter (3), using data from the 1976 Montreal Olympic Games, reported that swimmers have relatively long extremities, square shoulders, and pronounced muscular build. In general, taller and bigger swimmers can produce more force per stroke (11) because their stroke length is longer. Smaller swimmers cannot achieve such long stroke lengths; thus, they utilize a higher stroke rate (11). Greater stature (height) and longer segment lengths have also been linked to greater propelling economy and longer stroke lengths in front crawl in adult male swimmers (17,29).

However, there is little information on the impact of anthropometric variables on pediatric swimmers. With the use of anthropometry being prevalent in many talent identification programs, including those of the Federation Internationale De Natation (10), there is a need to understand how anthropometric variables impact on swimming performance. There has been a lack of consistency in the range and type of variables examined in those studies that have examined how anthropometric and other variables predicted pediatric swimming performance, and there has been a corresponding lack of agreement in those studies that have examined young swimmers. Morais et al. (21) reported that arm span was the key anthropometric variable in predicting swimming performance in adolescent swimmers. This conclusion was also supported by Jürimäe et al. (15), who reported that arm span, alongside $\dot{V}O_{2peak}$, was the major anthropometric determinant of 400-m freestyle swim performance in a group of 29 prepubertal and postpubertal adolescent swimmers. Conversely, Geladas et al. (12) reported that upper extremity length was related to 100-m freestyle swim performance in 12- to 14-yr-old boys (N = 263), whereas upper extremity length, height, and hand length significantly predicted performance in girls.

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Despite this, few studies appear to have investigated the contribution of segment lengths to swimming performance. This is surprising because a range of research studies have suggested that different limb segment lengths are better predictors of athletic performance than whole-limb length. For example, Caruso et al. (4) recently reported that upper arm length was the best predictor of vertical jump performance in college athletes. Green and Gabriel (13) also recently identified that forearm length and regional muscle mass were the best predictors of isometric strength in adults. Hahn (14) also identified "optimum" ratios of upper and lower arm and leg lengths for rowing performance.

The influence of body size, body composition, and limb segment lengths on swimming performance in children and adolescents is a matter of continuing debate. One approach that is currently being viewed as a suitable mode for solving this issue—given its sound theoretical basis and its biologically driven, elegant, and versatile statistical methodology—is the use of allometric modeling (22,24,25). This technique often provides a dimensionless expression of data in the form of ratios [e.g., crural index, upper-arm-to-lower-arm ratio, and reciprocal ponderal index (stature-to-body-mass$^{0.333}$ ratio)]. Furthermore, its modeling techniques properly address the effects of age and sex differences on growth and biological maturation in motor performance interpretation (18). Hence, the purpose of this study was to use allometric models to identify the optimal body size and limb segment length ratios associated with 100-m personal-best (PB) swim speeds in children and adolescents.

METHODS

Participants. With institutional ethics approval, informed consent, and parental assent, 50 competitive youth swimmers (21 males and 29 females age 11–16 yr; mean ± SD age, 13.5 ± 1.5 yr) participated in this study. The swimmers were currently competing at the national level and were part of a UK Amateur Swimming Association beacon squad. This squad sits below competitive adult international standards and is the focus of talent development in UK swimming. There were no participant withdrawals from this sample. Individual participants were currently engaged in between four and nine formal training sessions per week (mean ± SD training sessions per week, 6.9 ± 1.2).

Anthropometry. Stature (m) and mass (kg) were assessed, to the nearest 0.5 cm and 0.1 kg, using a SECA stadiometer and a SECA weighing scale (SECA Instruments Ltd, Hamburg, Germany), respectively. Skinfolds were taken on the right-hand side of the body (from the tricep, bicep, subscapular, iliac crest, supraspinale, mid abdominal, front thigh, and medial calf sites) using Harpenden skinfold callipers (Harpenden Instruments, Cambridge, UK). Individual skinfolds were summed to create a total sum of skinfolds measure reflecting overall adiposity (28). In addition, skinfold data, alongside the skinfold equation of Durnin and Womersley (9), were used to estimate body fat mass and lean body mass. Limb lengths were assessed using a nonstretchable tape measure and consisted of measures of upper arm, lower arm, and hand lengths, and upper leg, lower leg, and foot lengths. Anthropometry was undertaken following guidelines from the International Society for the Advancement of Kinanthropometry (28). Intertester technical errors of measurement (TEM) were all 10% or lower for skinfolds or 2% or lower for limb lengths. Intratester TEM were 5% or lower for skinfolds or 2% or lower for limb lengths. Both intertester and intratester TEM were consistent with International Society for the Advancement of Kinanthropometry guidelines for surface anthropometry. In addition, physical maturation (maturity offset) was assessed by predicting age at peak height velocity based on age, stature, leg length, and sitting height, using the predictive equation of Mirwald et al. (20).

Performance quantification. As a measure of swimming performance, the PB time recorded in competition for the 100-m freestyle swim for each swimmer was provided by the coaching staff.

Statistical methods. To identify the optimal body size components [including body mass (M), stature (H), lean body mass (LBM), and limb lengths (LL)] associated with 100-m PB swim speed (m·s^{-1}) in children 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 physical performance variables in Greek children (23) and Peruvian children (2):

$$\text{PB speed} = a M^{k_1} H^{k_2} \text{LBM}^{k_3} \Pi(\text{LL}_i)^{k_i} \exp\left(b \times \text{age} + c \times \text{age}^2 + d M_{\mathrm{off}}\right)\boldsymbol{\varepsilon}. \quad [1]$$

where a is a constant and $\Pi(\text{LL}_i)^{k_i}$ (i = 4, 5, …, 9) represents the product of limb segment length measurements raised to the power k_i, where i = 4 (upper arm), 5 (lower arm), 6 (hand), 7 (upper leg), 8 (lower leg), 9 (foot). This model has the advantages of proportional body size components and flexibility of a nonlinear quadratic in age within an exponential term that will ensure that the 100-m PB swim speeds will always remain nonnegative, irrespective of the age of the child or adolescent. The multiplicative error ratio ε assumes that the error will increase in proportion to the child's swimming performance.

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

$$\ln(\text{PB}) = \ln(a) + k_1 \ln(M) + k_2 \ln(H) + k_3 \ln(\text{LBM}) + \Sigma k_i \ln(\text{LL}_i) + b \times \text{age} + c \times \text{age}^2 + d M_{\mathrm{off}} + \ln(\boldsymbol{\varepsilon}). \quad [2]$$

Having fitted the saturated model (all available body size variables), an appropriate "parsimonious" model can be obtained using "backward elimination" (8), in which the least important (nonsignificant) body size and limb segment length variable at each step are dropped from the current model. Further categorical or group differences within the population (e.g., sex) can be explored by allowing the constant intercept parameter ln(a) in equation 2 to vary for each group

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TABLE 1. Estimated body size and limb segment length parameter (B) obtained from regression analysis predicting log-transformed 100-m PB swim speeds (equation 2).

Model	B	Standard Error	P	95% Confidence Interval for B
ln(a)	−2.043	0.660	0.004	−3.376 to −0.710
ln(LBM)	0.331	0.080	<0.001	0.169 to 0.493
ln(UpperArm)	−0.400	0.137	0.006	−0.677 to −0.123
ln(LowerArm)	0.181	0.072	0.017	0.034 to 0.327
ln(LowerLeg)	−0.319	0.110	0.006	−0.542 to −0.096
ln(Foot)	0.337	0.121	0.008	0.093 to 0.582
Age	0.290	0.080	0.001	0.127 to 0.452
Age^2	−0.009	0.003	0.004	−0.015 to −0.003

(by introducing them as fixed factors within ANCOVA). The significance level was set to $P < 0.05$.

RESULTS

The parsimonious solution to the backward elimination regression analysis of ln(PB) resulted in a multiple regression model (Table 1).

The multiplicative allometric model relating 100-m PB swim speeds ($m \cdot s^{-1}$) to the body size and limb length variables found only lean body mass (body mass and stature were dropped from the analysis) plus four limb length variables (upper arm, lower arm, lower leg, and foot lengths, all log-transformed) as significant predictors of log-transformed swim speed, together with a significant quadratic in age (Fig. 1). Clearly, lean body mass ($LBM^{0.33}$) is a key indicator of PB swim speed. Furthermore, the limb length B-weight signs alternated, suggesting that, having taken antilogs, arm ratio [= $(\text{low arm})^{0.18}/(\text{upper arm})^{0.40}$] and foot-to-lower-leg ratio [= $(\text{foot})^{0.34}/(\text{lower leg})^{0.32}$] are also key indicators of PB swimming success, having controlled for differences in age.

The adjusted coefficient of determination (adjusted R^2) was 83.8%, with the log-transformed error ratio being 0.0462 or 4.7%, having taken antilogs. The constant a did not vary significantly with sex, suggesting that the model can be regarded as common for children of either sex.

DISCUSSION

The present study used an allometric modeling approach to identify the optimal body size and limb segment length characteristics associated with 100-m PB swim performance in 50 national-standard children and adolescents (having controlled for differences in age). The results indicated that lean body mass was the single most important whole-body size characteristic. Stature and body mass did not contribute significantly to the allometric model, suggesting that the advantage of longer levers was limb-segment-specific rather than a more general whole-body advantage. 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 generation of propulsion, countering the greater energy requirement of using fewer strokes.

The advantage of having greater lean body mass suggests that swimmers require greater muscularity to propel themselves faster through water, having controlled for differences in age. Stroke rate may also be influenced by the inertial properties of the limbs, particularly mass and distribution of mass. Although limb volume or limb mass was not determined in the present study, overall greater lean body mass is likely to be associated with greater lean body mass in the limbs, translating into greater stroke rate and subsequent propulsion. The quadratic in age peaks at just over 16 yr (estimated using elementary differential calculus), and maturity offset was not required in the final parsimonious model, implying that children who mature either earlier or late are at no great advantage (nor disadvantage) at swimming.

Probably the most important finding from the allometric model reported in Table 1 is the advantage of having greater limb segment length ratios [i.e., arm ratio = (low arm)/(upper arm); foot-to-lower-leg ratio = (foot)/(lower leg)] at swim speeds. (We also observed that the upper leg made a negative contribution whereas the hand made a positive contribution

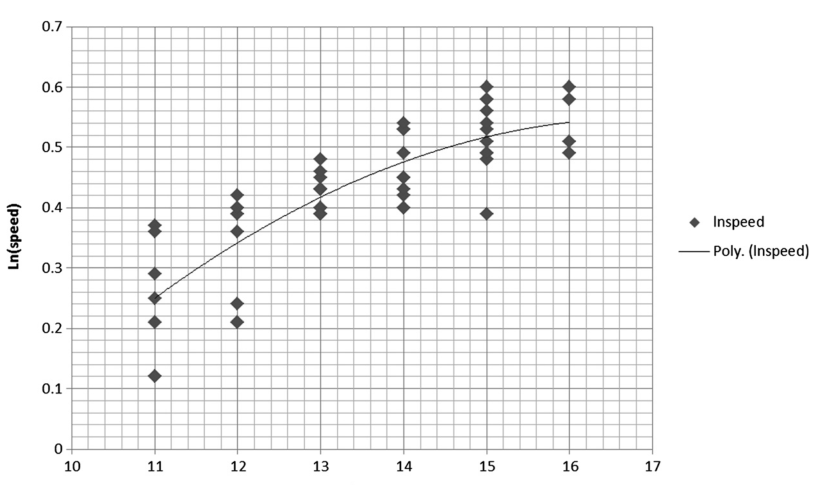

FIGURE 1—Quadratic relationship between log-transformed 100-m PB swim speed and age among 50 national-level youth swimmers.

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to the prediction of PB swim speed, but neither was a significant contributor to the allometric model and, as such, was removed during the backward elimination process.) The advantage of having a greater lower arm is fairly obvious in that this segment of the arm acts as a paddle, providing the swimmer a greater lever to propel through water. The additional requirement that the upper arm should be shorter was initially not so obvious. However, Zamparo et al. (31) observed that "swimming with a closer elbow angle should improve the propelling efficiency of the arm stroke and that subjects with a shorter arm length are naturally endowed with a better 'swimming technique' with respect to those with longer upper limbs" (p. 53).

Similar to having a longer lower arm, having a greater foot length will also act to increase surface area, thus leading to greater propelling economy (31). Longer legs are not needed in swimming, as increased leg length will alter the flotation of the swimmer, potentially resulting in sinking of the legs. An increase in the downward inclination of the legs would increase resistance through water, therefore increasing the energy cost of swimming (5–7,30). This may at least partially explain the advantage of having shorter lower legs.

In their well-read and highly cited book, Astrand and Rodahl (1) explained why, theoretically, the energy demand of running or swimming a relatively short distance (reflected in maximal speed) should be approximately dimensionless in terms of body size across a range of similar animals of different sizes. This is in contrast to the energy demand of running longer distances (run times), which is thought to be proportional to $M^{0.333}$—a difference that probably reflects the gravitational effects of running longer distances, which are absent in swimming. Astrand and Rodahl (1) went on to explain that speed is a function of stride or stroke length and the number of movements per unit of time. Hence, maximal speed is proportional to a linear length of body size (L) divided by (T) (also proportional to L) (i.e., $L \cdot L^{-1} = 1$). They provided an example: "a blue whale of 100 tons and a dolphin of 80 kg attain the same steady-state speed of about 15 knots." Of course, the theory relies on the assumption that the animals are "geometrically" similar. In humans, this is not the case (26). The current study was able to support this theory to some extent. The limb segment length exponents (numerator and denominator) nearly cancel themselves out, as seen with the limb segment length ratios in Table 1, the exception being the lean body mass exponent (k = 0.331). This suggests that swim speed is approximately proportional to a linear $L = M^{0.333}$ dimension of body size (in this case lean body mass), recognizing that muscle mass in humans increases at a rate *greater* than that assumed by geometric similarity (24). 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 maturation. Future research employing a longitudinal design would be needed to establish the impact of geometric dissimilarity on athletic performance through adolescence.

In conclusion, the 100-m PB swim speeds of national-standard children and adolescents were strongly associated (adjusted R^2 = 83.8%; standard error is 0.0462 or expressed as an error ratio of 4.7%, having taken antilogs) with lean body mass and with two segment length ratios [(low arm)/(upper arm) and (foot)/(lower leg)], having controlled for the developmental changes in age and maturation. Collectively, the results of the present study suggest that, where coaches and scientists employ anthropometry for talent identification or athlete monitoring, they would benefit from an awareness of the abovementioned segment length ratios. How such limb length ratios relate to swimming performance over time would be an interesting future research avenue, although a longitudinal design would be needed to accomplish this.

The advantage of having a longer lower arm is fairly obvious; however, having a shorter upper arm (either by adopting a closer elbow angle technique or by possessing a naturally endowed shorter upper arm) at the same time is a new insight into better swimming performance. The same could be said of having a greater foot-to-lower-leg ratio, with greater foot size and shorter lower leg length reducing the downward inclination of longer legs, which may reduce drag and, hence, water resistance. Identification of these ratios was made possible by adopting a multiplicative allometric model that was able to confirm, theoretically, that swim speeds are nearly independent of body size. The exponents (numerator and denominator) of both ratios appear to cancel each other out, suggesting that the advantage of having longer levers is site-specific or segment-length-specific rather than a general whole-body advantage. The only exception to the independence assumption (which assumes that humans are geometrically similar) was the observation that having a greater lean body mass ($LBM^{0.331}$) was an additional advantage for 100-m PB swim speeds. Apart from the obvious interpretation that greater lean body mass is associated with greater muscle mass and, hence, with greater PB swim speeds, the positive contribution of lean body mass to the allometric model could be explained by the fact that humans are not geometrically similar and that human muscle mass has been shown to increase at a rate *greater* than that assumed by geometrically similarity in athletic populations (26).

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