Optimal body size and limb-length ratios associated with 100-m PB swim speeds

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Title: The optimal body size and limb-length ratios associated with 100m PB swim speeds.

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Abstract

Purpose: To identify optimal body size and limb segment-length ratios associated with the children and adolescents' 100m personal-best swim speeds. **Methods**: Fifty national-standard youth swimmers (21 males, 29 females, ages 11-16 years, mean age ± SD = 13.5 ± 1.5 years) 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 personal best (PB) time/speeds for the 100m freestyle swim recorded in competition. To identify the optimal body-size and body-composition components associated with 100m personal-best (PB) swimming speeds (having controlled for age and maturity offset), we adopted a multiplicative allometric log-linear regression model, 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., the arm ratio=(low arm)/(upper arm) and the foot-leg ratio=(foot)/(lower leg) was key to PB swimming speeds. **Conclusions**: It is only by adopting multiplicative allometric models that the above ratios could have been derived. The advantage of having a greater lower arm is clear but to have, at the same time, a shorter upper arm (achieved by adopting a closer elbow-angle technique or possessing a naturally endowed shorter upper arm) is a new insight into swimming performance. A greater foot-to-lower leg ratio suggests that a combination of larger feet and a shorter lower-leg length may also benefit PB swim speeds.

Keywords: Personal-best swim speeds; limb segment lengths; ratios; allometric models; log-linear regression.

Introduction

Understanding physical and anthropometric factors that underpin children and adolescent’s 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) reported that swimmers have relatively long extremities, square shoulders and a pronounced muscular build using data from the 1976 Montreal Olympic Games. In general, taller and bigger swimmers can produce more work per stroke (11), and therefore their stroke length is longer. The smaller swimmer cannot achieve such long stroke lengths thus they utilise 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 in pediatric swimmers. With the use of anthropometry being prevalent in many talent identification programmes, including those of the Federation Internationale De Natation (FINA) (10), there is a need to understand how anthropometric variables impact on swimming performance. Of those studies that have examined how anthropometric and other variables predict pediatric swimming performance, there is a lack of consistency in the range and type of variables examined and 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 Jurimae et al (15) who reported that arm span was the major anthropometric determinant alongside VO_2peak in 400m freestyle swim performance in a group of 29 pre- and post-pubertal adolescent swimmers. Conversely, Geladas et al. (12) reported that in 263, 12-14 year old boys, upper extremity length was significantly related to

100m freestyle swim performance whereas, in girls, upper extremity length, height and hand length significantly predicted performance. Despite this, few studies appear to have investigated the contribution that segment lengths appear to make on swimming performance. This is surprising as 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) has 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 in swimming performance of children and adolescents is a matter of continuing debate. One approach that is currently viewed as a suitable mode to help solving this issue, given its sound theoretical basis, biologically driven, and its elegant and versatile statistical methodology, is the use of allometric modelling (22, 23, 24). This technique often provides a dimensionless expression of data in the form of ratios (e.g., crural index, upper arm-to-lower arm, reciprocal ponderal index RPI=stature-to-body mass$^{0.333}$). Furthermore, its modelling techniques properly address the effects of age and sex differences in 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 ratio characteristics associated with the children and adolescent~~ce~~’s 100m personal-best swim speeds.

Methods

Participants

With institutional ethics approval, informed consent and parental assent, 50 competitive youth swimmers (21 males, 29 females, ages 11-16 years, mean age ± SD = 13.5 ± 1.5 years) participated in this study. The swimmers were currently competing at national level and were part of a UK Amateur Swimming Association beacon squad. This squad sits below competitive adult international standard and forms the focus for talent development in UK swimming. There were no participant withdrawals from this sample. Individual participants were currently engaged in between 4 and 9 formal training sessions per week (mean ± SD of training sessions per week = 6.9 ±1.2 sessions/week).

Anthropometry

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

Performance quantification

In order to provide a measure of swimming performance, the personal best time recorded in competition for the 100m freestyle swim was provided for each swimmer by their coaching staff.

Statistical Methods

In order to identify the optimal body-size components, including body mass (M), stature (H), lean body mass (LBM) and limb-lengths (LL), associated with children and adolescence's 100m personal-best (PB) swimming speed ($m.s^{-1}$) having controlled for age and maturity offset (M_{off}), we adopted the following multiplicative model with allometric body size components similar to those used to model the physical performance variables of Greek (26) and Peruvian children (2).

$$\text{PB speed} = a \cdot (M)^{k_1} \cdot (H)^{k_2} \cdot (LBM)^{k_3} \cdot \Pi\, (LL_i)^{k_i} \cdot \exp(\, b \cdot age + c \cdot age^{2} + d \cdot M_{off}) \cdot \varepsilon. \quad (1)$$

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

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

$$Ln(PB)=ln(a)+k_1 \cdot ln(M)+k_2 \cdot ln(H)+k_3 \cdot ln(LBM)+\Sigma \quad k_i \cdot ln(LL_i)+b \cdot age+c \cdot age^2+d \cdot M_{off}+ln(\varepsilon). \quad (2)$$

Having fitted the saturated model (all available body size variables), an appropriate ‘parsimonious’ model can be obtained using '*backward elimination*' (8) in which at each step the least important (non-significant) body-size and limb segment-length variable is 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 Eq. 2 to vary for each group (by introducing them as fixed factors within an ANCOVA). The significance level was set at $P<0.05$.

Results

The parsimonious solution to the backward elimination regression analysis of Ln(PB) resulted in the following multiple regressions model (Table 1):

■ --Table 1 about here--

The multiplicative allometric model relating 100 m PB swim speeds ($m.s^{-1}$) to the body size and limb-length variables found only lean body mass (body mass and stature were dropped from the analysis) plus 4 limb-length variables (upper arm, lower arm, lower leg and foot length, all log transformed) as significant predictors of log-transformed swim speed, together with a significant quadratic in age, as seen in Figure 1. Clearly, lean-body mass ($LBM^{0.33}$) is a key indicator of PB swim speed. Furthermore, the limb-length beta-weight signs alternated, suggesting that having taken anti-logs, the arm ratio=(low arm)$^{0.18}$/(upper arm)$^{0.40}$ and the foot-to-lower-leg ratio=(foot)$^{0.34}$/(lower leg)$^{0.32}$ are also key indicators of PB swimming success, having controlled for the differences in age.

■ --Figure 1 about here--

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 modelling approach to identify the optimal body-size and limb segment-length characteristics associated with personal-best 100m swimming performances in 50 national-standard children and adolescents (having controlled for differences in age). The results identified 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, longer lever length, increases reach and the distance that is available for generation of propulsion, countering the greater energy requirement due to using fewer strokes.

The advantage of having greater lean-body mass suggests that swimmers require greater muscularity to propel themselves faster through the water, having controlled for differences in age. Stroke rate may also be influenced by the inertial properties of the limbs, particularly their mass and distribution of mass. Although limb volume or limb mass was not determined in the present study, the 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. Note that the quadratic in age peaks at just over 16 years (estimated using elementary differential calculus) and the 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., the arm ratio=(low arm)/(upper arm) and the foot by lower-leg ratio=(foot)/(lower leg) at swimming speeds. (We also observed that the upper leg made a negative, and the hand made a positive contribution to the prediction of PB swim speed, but neither were significant contributors to the allometric model and, as such, were removed during the backward elimination process). The advantage of having greater lower arm is fairly obvious, in that this segment of the arm act as a paddle providing the swimmer with a greater lever to propel the swimmer through the water. The additional requirement that the upper arm should be shorter was initially not so obvious. However, Zamparo (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” (P53).

Similar to having a longer lower arm, having a greater foot length will also act to increase the surface area thus leading to greater propelling efficiency (31). The need to have longer legs in swimming is not needed as an increased leg length will alter the flotation of the swimmer, potentially resulting in a sinking of the legs. An increase in the downward inclination of the legs would increase the resistance through the water; therefore increasing the energy cost of swimming (5, 6, 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) explain why, theoretically, the energy demand of running or swimming a relatively short distance (reflected in the maximum speed) should be approximately dimensionless in terms of body size across a range of similar animals of different sizes. Note that this in contrast with the energy demand of running longer distances (run times) thought to be proportional to $M^{0.333}$, a difference that probably reflects the gravitational effects of running longer distances that is absent when swimming. The authors go 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 provide the example of “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 of the assumption that the animals are “geometrically” similar. In humans, this is not the case (25). The current study was able to support this theory to some extent. The limb segment-length exponents (the numerator and denominator) nearly cancel themselves out as seen with the limb-segment length ratios in Table 1, the exception being lean body mass exponent (k=0.331). This suggests that swim speed is approximately proportion a linear $L= M^{0.333}$ dimension of body size (in this case lean body mass), recognizing that in humans, muscle mass 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 personal best swim speeds of national-standard children and adolescents was strongly associated (adjusted R^2 = 83.8%; standard error being 0.0462 or expressed as an error ratio = 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 of age and maturation. Collectively, the results of the present study suggest that where coaches and scientists employ anthropometry for talent identification or athlete monitoring purposes, they would benefit from an awareness of the above mentioned 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 but to have, at the same time, a shorter upper arm (either by adopting a closer elbow angle technique or possessing a naturally endowed shorter upper arm) is a new insight into better swimming performance. The same could be said of having a greater foot-to-lower leg ratio, with a greater foot size and a shorter lower leg length to reduce the downward inclination of longer legs that may reduce drag and hence water resistance. Identifying these ratios was made possible by adopting a multiplicative allometric model that was able to confirm, theoretically, swimming speeds are close to being body-size independent. The exponents (the numerator and denominator) of both ratios appear to cancel each other out, suggesting that the advantage of having longer levers is site- or segment-length specific rather than a general whole-body advantage. The only exception to the independence assumption (that assumes humans are geometrically similar) was the observation that having a greater lean body mass, $(LBM)^{0.331}$ was an additional advantage to personal-best 100 m 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 that LBM makes to 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 greater rate than that assumed by geometrically similarity in athletic populations (25).

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TABLE CAPTIONS

Table 1 The estimated body-size and limb segment-length parameter (B) obtained from the regression analysis predicting log-transformed 100 m PB swim speeds (Eq. 2).

FIGURE CAPTIONS

Figure 1. The quadratic relationship between log-transformed 100 m PB swim speeds and age, for 50 national-level youth swimmers.