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

2

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16

17

18 **Abstract**

19 **Purpose:** To identify optimal body size and limb segment-length ratios associated with the
20 children and adolescents' 100m personal-best swim speeds. **Methods:** Fifty national-standard
21 youth swimmers (21 males, 29 females, ages 11-16 years, mean age \pm SD = 13.5 \pm 1.5 years)
22 participated in the study. Anthropometry comprised stature, body mass, skinfolds, maturity
23 offset, upper arm, lower arm and hand lengths and upper leg, lower leg and foot lengths.
24 Swimming performance was taken as the personal best (PB) time/speeds for the 100m
25 freestyle swim recorded in competition. To identify the optimal body-size and body-
26 composition components associated with 100m personal-best (PB) swimming speeds (having
27 controlled for age and maturity offset), we adopted a multiplicative allometric log-linear
28 regression model, refined using backward elimination. **Results:** Lean body mass was the
29 singularly most important whole-body characteristic. Stature and body mass did not
30 contribute to the model, suggesting that the advantage of longer levers was limb specific
31 rather than a general whole-body advantage. The allometric model also identified that having
32 greater limb segment-length ratios, i.e., the arm ratio=(low arm)/(upper arm) and the foot-leg
33 ratio=(foot)/(lower leg) was key to PB swimming speeds. **Conclusions:** It is only by adopting
34 multiplicative allometric models that the above ratios could have been derived. The advantage
35 of having a greater lower arm is clear but to have, at the same time, a shorter upper arm
36 (achieved by adopting a closer elbow-angle technique or possessing a naturally endowed
37 shorter upper arm) is a new insight into swimming performance. A greater foot-to-lower leg
38 ratio suggests that a combination of larger feet and a shorter lower-leg length may also benefit
39 PB swim speeds.

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

42

43 **Introduction**

44 Understanding physical and anthropometric factors that underpin children and
45 adolescent's performance in swimming is important for talent identification (19). A
46 substantial body of research, conducted with adult swimmers has indicated the importance of
47 anthropometric variables for adult swimming performance, particularly overall swim speed
48 (16, 27). Carter (3) reported that swimmers have relatively long extremities, square shoulders
49 and a pronounced muscular build using data from the 1976 Montreal Olympic Games. In
50 general, taller and bigger swimmers can produce more work per stroke (11), and therefore
51 their stroke length is longer. The smaller swimmer cannot achieve such long stroke lengths
52 thus they utilise a higher stroke rate (11). Greater stature (height) and longer segment lengths
53 have also been linked to greater propelling economy and longer stroke lengths in front crawl
54 in adult male swimmers (17, 29).

55 However, there is little information on the impact of anthropometric variables in
56 pediatric swimmers. With the use of anthropometry being prevalent in many talent
57 identification programmes, including those of the Federation Internationale De Natation
58 (FINA) (10), there is a need to understand how anthropometric variables impact on swimming
59 performance. Of those studies that have examined how anthropometric and other variables
60 predict pediatric swimming performance, there is a lack of consistency in the range and type
61 of variables examined and a corresponding lack of agreement in those studies that have
62 examined young swimmers. Morais et al (21) reported that arm span was the key
63 anthropometric variable in predicting swimming performance in adolescent swimmers. This
64 conclusion was also supported by Jurimae et al (15) who reported that arm span was the major
65 anthropometric determinant alongside VO_2 peak in 400m freestyle swim performance in a
66 group of 29 pre- and post-pubertal adolescent swimmers. Conversely, Geladas et al. (12)
67 reported that in 263, 12-14 year old boys, upper extremity length was significantly related to

68 100m freestyle swim performance whereas, in girls, upper extremity length, height and hand
69 length significantly predicted performance. Despite this, few studies appear to have
70 investigated the contribution that segment lengths appear to make on swimming performance.
71 This is surprising as a range of research studies have suggested that different limb segment
72 lengths are better predictors of athletic performance than whole limb length. For example,
73 Caruso et al (4) recently reported that upper arm length was the best predictor of vertical jump
74 performance in college athletes. Green and Gabriel (13) also recently identified that forearm
75 length and regional muscle mass were the best predictors of isometric strength in adults. Hahn
76 (14) has also identified 'optimum' ratios of upper and lower arm and leg lengths for rowing
77 performance.

78 The influence of body size, body composition and limb-segment lengths in swimming
79 performance of children and adolescents is a matter of continuing debate. One approach that
80 is currently viewed as a suitable mode to help solving this issue, given its sound theoretical
81 basis, biologically driven, and its elegant and versatile statistical methodology, is the use of
82 allometric modelling (22, 23, 24). This technique often provides a dimensionless expression
83 of data in the form of ratios (e.g., crural index, upper arm-to-lower arm, reciprocal ponderal
84 index $RPI = \text{stature-to-body mass}^{0.333}$). Furthermore, its modelling techniques properly address
85 the effects of age and sex differences in growth and biological maturation in motor
86 performance interpretation (18). Hence, the purpose of this study was to use allometric
87 models to identify the optimal body size and limb segment-length ratio characteristics
88 associated with the children and adolescent^{tee}'s 100m personal-best swim speeds.

89

90 **Methods**

91

92 **Participants**

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

101

102 **Anthropometry**

103 Stature (m) and mass (kg) were assessed, to the nearest 0.5cm and 0.1kg, using a SECA
104 stadiometer and weighing scales (SECA Instruments Ltd, Hamburg, Germany). Skinfolds
105 were taken on the right hand side of the body using Harpenden skinfold callipers (Harpenden
106 Instruments, Cambridge, UK) from the tricep, bicep, subscapular, iliac crest, supraspinale,
107 mid abdominal, front thigh and medial calf sites. Individual skinfolds were summed to create
108 a total sum of skinfolds measure to reflect overall adiposity (28). In addition, skinfold data
109 alongside the Durnin and Womersley (9) skinfold equation were used to estimate body fat
110 mass and lean body mass. Limb lengths were assessed using a non-stretchable tape measure
111 and consisted of measures of upper arm, lower arm and hand lengths and upper leg, lower leg
112 and foot lengths. Anthropometric measurements were assessed following guidelines from the
113 International Society for the Advancement of Kinanthropometry (ISAK) (28). Inter tester
114 technical error of measurement (TEM) were all 10% or lower for skinfolds or 2% or lower for
115 limb lengths. Intra tester TEMs were 5% or lower for skinfolds or 2% or lower for limb
116 lengths. Both inter and intra tester TEMs were consistent with ISAK guidelines for surface
117 anthropometry. In addition, physical maturation (maturity offset) was assessed using the

118 predictive equation of Mirwald et al (20) based on age, stature, leg length and sitting height
 119 by predicting the age at peak height velocity (APHV).

120

121 **Performance quantification**

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

125

126 **Statistical Methods**

127 In order to identify the optimal body-size components, including body mass (M), stature (H),
 128 lean body mass (LBM) and limb-lengths (LL), associated with children and adolescence's
 129 100m personal-best (PB) swimming speed ($\text{m}\cdot\text{s}^{-1}$) having controlled for age and maturity
 130 offset (M_{off}), we adopted the following multiplicative model with allometric body size
 131 components similar to those used to model the physical performance variables of Greek (26)
 132 and Peruvian children (2).

$$133 \quad \text{PB speed} = a \cdot (M)^{k_1} \cdot (H)^{k_2} \cdot (\text{LBM})^{k_3} \cdot \prod (LL_i)^{k_i} \cdot \exp(b \cdot \text{age} + c \cdot \text{age}^2 + d \cdot M_{\text{off}}) \cdot \varepsilon. \quad (1)$$

134 where 'a' is a constant and $\prod (LL_i)^{k_i}$ ($i=4, 5, \dots, 9$) represents the product of limb segment-
 135 length measurements raised to the power k_i ; with $i=4$ is the upper arm, 5 =lower arm, 6 =hand,
 136 7 = upper leg, 8 =lower leg, 9 =foot. This model has the advantages of having proportional
 137 body size components and the flexibility of a non-linear quadratic in age within an
 138 exponential term that will ensure that the 100 m PB swim speeds will always remain non-
 139 negative irrespective of the child or adolescent's age. Note that the multiplicative error ratio
 140 'ε' assumes the error will increase in proportion to the child's swimming performance.

141 The model (Eq. 1) can be linearized with a log transformation. A linear regression on
 142 $\ln(\text{PB})$ (\ln =natural logarithms) can then be used to estimate the unknown parameters of the
 143 log-transformed model:

$$144 \quad \ln(\text{PB}) = \ln(a) + k_1 \cdot \ln(M) + k_2 \cdot \ln(H) + k_3 \cdot \ln(\text{LBM}) + \sum_{i=1}^n k_i \cdot \ln(\text{LL}_i) + b \cdot \text{age} + c \cdot \text{age}^2 + d \cdot M_{\text{off}} + \ln(\epsilon).$$

145 (2)

146 Having fitted the saturated model (all available body size variables), an appropriate
 147 'parsimonious' model can be obtained using '*backward elimination*' (8) in which at each step
 148 the least important (non-significant) body-size and limb segment-length variable is dropped
 149 from the current model. Further categorical or group differences within the population, e.g.
 150 sex, can be explored by allowing the constant intercept parameter ' $\ln(a)$ ' in Eq. 2 to vary for
 151 each group (by introducing them as fixed factors within an ANCOVA). The significance level
 152 was set at $P < 0.05$.

153

154 **Results**

155 The parsimonious solution to the backward elimination regression analysis of $\ln(\text{PB})$ resulted
 156 in the following multiple regressions model (Table 1):

157

158 ■ --Table 1 about here--

159

160 The multiplicative allometric model relating 100 m PB swim speeds ($\text{m} \cdot \text{s}^{-1}$) to the body size
 161 and limb-length variables found only lean body mass (body mass and stature were dropped
 162 from the analysis) plus 4 limb-length variables (upper arm, lower arm, lower leg and foot
 163 length, all log transformed) as significant predictors of log-transformed swim speed, together
 164 with a significant quadratic in age, as seen in Figure 1. Clearly, lean-body mass ($\text{LBM}^{0.33}$) is a
 165 key indicator of PB swim speed. Furthermore, the limb-length beta-weight signs alternated,

166 suggesting that having taken anti-logs, the arm ratio= $(\text{low arm})^{0.18}/(\text{upper arm})^{0.40}$ and the
167 foot-to-lower-leg ratio= $(\text{foot})^{0.34}/(\text{lower leg})^{0.32}$ are also key indicators of PB swimming
168 success, having controlled for the differences in age.

169

170 ■ --Figure 1 about here--

171

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

176

177 **Discussion**

178 The present study used an allometric modelling approach to identify the optimal body-
179 size and limb segment-length characteristics associated with personal-best 100m swimming
180 performances in 50 national-standard children and adolescents (having controlled for
181 differences in age). The results identified that lean-body mass was the single most important
182 whole-body size characteristic. Stature and body mass did not contribute significantly to the
183 allometric model, suggesting that the advantage of longer levers was limb-segment specific
184 rather than a more general whole-body advantage. Longer lever length (arm or leg) is
185 potentially mechanically disadvantageous in some ways because the involved muscles have to
186 exert greater force and, hence use greater energy. However, longer lever length, increases
187 reach and the distance that is available for generation of propulsion, countering the greater
188 energy requirement due to using fewer strokes.

189 The advantage of having greater lean-body mass suggests that swimmers require greater
190 muscularity to propel themselves faster through the water, having controlled for differences in

191 age. Stroke rate may also be influenced by the inertial properties of the limbs, particularly
192 their mass and distribution of mass. Although limb volume or limb mass was not determined
193 in the present study, the overall greater lean-body mass is likely to be associated with greater
194 lean-body mass in the limbs, translating into greater stroke rate and subsequent propulsion.
195 Note that the quadratic in age peaks at just over 16 years (estimated using elementary
196 differential calculus) and the maturity offset was not required in the final parsimonious
197 model, implying that children who mature either earlier or late are at no great advantage (nor
198 disadvantage) at swimming.

199 Probably the most important finding from the allometric model reported in Table 1, is
200 the advantage of having greater limb segment-length ratios, i.e., the arm ratio=(low
201 arm)/(upper arm) and the foot by lower-leg ratio=(foot)/(lower leg) at swimming speeds. (We
202 also observed that the upper leg made a negative, and the hand made a positive contribution to
203 the prediction of PB swim speed, but neither were significant contributors to the allometric
204 model and, as such, were removed during the backward elimination process). The advantage
205 of having greater lower arm is fairly obvious, in that this segment of the arm act as a paddle
206 providing the swimmer with a greater lever to propel the swimmer through the water. The
207 additional requirement that the upper arm should be shorter was initially not so obvious.
208 However, Zamparo (31) observed that “swimming with a closer elbow angle should improve
209 the propelling efficiency of the arm stroke and that subjects with a shorter arm length are
210 naturally endowed with a better ‘swimming technique’ with respect to those with longer
211 upper limbs” (P53).

212 Similar to having a longer lower arm, having a greater foot length will also act to
213 increase the surface area thus leading to greater propelling efficiency (31). The need to have
214 longer legs in swimming is not needed as an increased leg length will alter the flotation of the
215 swimmer, potentially resulting in a sinking of the legs. An increase in the downward

216 inclination of the legs would increase the resistance through the water; therefore increasing
217 the energy cost of swimming (5, 6, 7, 30). This may at least partially explain the advantage of
218 having shorter lower legs. In their well-read and highly-cited book, Astrand and Rodahl (1)
219 explain why, theoretically, the energy demand of running or swimming a relatively short
220 distance (reflected in the maximum speed) should be approximately dimensionless in terms of
221 body size across a range of similar animals of different sizes. Note that this in contrast with
222 the energy demand of running longer distances (run times) thought to be proportional to
223 $M^{0.333}$, a difference that probably reflects the gravitational effects of running longer distances
224 that is absent when swimming. The authors go on to explain that speed is a function of stride
225 or stroke length and the number of movements per unit of time. Hence maximal speed is
226 proportional to a linear length of body size (L) divided by (T) (also proportional to L), i.e., $L \cdot$
227 $L^{-1} = 1$. They provide the example of “a blue whale of 100 tons and a dolphin of 80 kg attain
228 the same steady-state speed of about 15 knots”. Of course, the theory relies of the assumption
229 that the animals are “geometrically” similar. In humans, this is not the case (25). The current
230 study was able to support this theory to some extent. The limb segment-length exponents (the
231 numerator and denominator) nearly cancel themselves out as seen with the limb-segment
232 length ratios in Table 1, the exception being lean body mass exponent ($k=0.331$). This
233 suggests that swim speed is approximately proportion a linear $L= M^{0.333}$ dimension of body
234 size (in this case lean body mass), recognizing that in humans, muscle mass increases at a rate
235 greater than that assumed by geometric similarity (24). Geometric dissimilarity, i.e.,
236 allometric change may also be important when further change may occur, as is the case with
237 changes in growth as adolescents undergo maturation. Future research employing a
238 longitudinal design would be needed to establish the impact of geometric dissimilarity on
239 athletic performance through adolescence.

240 In conclusion, the 100 m personal best swim speeds of national-standard children and
241 adolescents was strongly associated (adjusted $R^2 = 83.8\%$; standard error being 0.0462 or
242 expressed as an error ratio = 4.7%, having taken antilogs) with lean body mass and with two
243 segment-length ratios, (low arm)/(upper arm) and (foot)/(lower leg), having controlled for the
244 developmental changes of age and maturation. Collectively, the results of the present study
245 suggest that where coaches and scientists employ anthropometry for talent identification or
246 athlete monitoring purposes, they would benefit from an awareness of the above mentioned
247 segment-length ratios. How such limb length ratios relate to swimming performance over
248 time would be an interesting future research avenue, although a longitudinal design would be
249 needed to accomplish this.

250 The advantage of having a longer lower arm is fairly obvious but to have, at the same
251 time, a shorter upper arm (either by adopting a closer elbow angle technique or possessing a
252 naturally endowed shorter upper arm) is a new insight into better swimming performance.
253 The same could be said of having a greater foot-to-lower leg ratio, with a greater foot size and
254 a shorter lower leg length to reduce the downward inclination of longer legs that may reduce
255 drag and hence water resistance. Identifying these ratios was made possible by adopting a
256 multiplicative allometric model that was able to confirm, theoretically, swimming speeds are
257 close to being body-size independent. The exponents (the numerator and denominator) of
258 both ratios appear to cancel each other out, suggesting that the advantage of having longer
259 levers is site- or segment-length specific rather than a general whole-body advantage. The
260 only exception to the independence assumption (that assumes humans are geometrically
261 similar) was the observation that having a greater lean body mass, $(LBM)^{0.331}$ was an
262 additional advantage to personal-best 100 m swim speeds. Apart from the obvious
263 interpretation that greater lean body mass is associated with greater muscle mass and hence
264 with greater PB swim speeds, the positive contribution that LBM makes to allometric model

265 could be explained by the fact that humans are not geometrically similar and that human
266 muscle mass has been shown to increase at a greater rate than that assumed by geometrically
267 similarity in athletic populations (25).

268

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273

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- 353
- 354

355 **TABLE CAPTIONS**

356

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

359

360 **FIGURE CAPTIONS**

361

362 **Figure 1.** The quadratic relationship between log-transformed 100 m PB swim speeds and

363 age, for 50 national-level youth swimmers.

364