

1 **A comprehensive allometric analysis of 2<sup>nd</sup> digit length to 4<sup>th</sup> digit length in humans**

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24 **Abstract**

25 It has been widely reported that men have a lower ratio of the 2<sup>nd</sup> and 4<sup>th</sup> human finger  
26 lengths (2D:4D). Size-scaling ratios, however, have the seldom-appreciated potential for  
27 providing biased estimates. Using an information-theoretic approach, we compared twelve  
28 candidate models, with different assumptions and error structures, for scaling untransformed  
29 2D to 4D lengths from 154 men and 262 women. In each hand, the 2-parameter power  
30 function and the straight line with intercept, both with normal, homoscedastic error, emerged  
31 as relatively superior and essentially equivalent models for normalising 2D to 4D lengths.  
32 The conventional 2D:4D ratio biased relative 2D length low for the generally bigger hands of  
33 men, and *vice versa* for women, thereby leading to an artifactual indication that mean relative  
34 2D length is lower in men than women. Conversely, use of the more appropriate allometric or  
35 linear regression models revealed that mean relative 2D length was, in fact, *greater* in men  
36 than women. We conclude that 2D does not vary in direct proportion to 4D for both men and  
37 women, rendering the use of the simple 2D:4D ratio inappropriate for size-scaling purposes  
38 and intergroup comparisons.

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49 **1. Introduction**

50 Relative index finger length (2D:4D), calculated as the ratio between the length of the  
51 2<sup>nd</sup> (2D) and 4<sup>th</sup> (4D) fingers, has interested researchers for more than a century [1]. In the  
52 human hand, three phenotypes have been defined: index shorter than ring finger (i.e.  $2D <$   
53  $4D$ ), index and ring finger being equal in length (i.e.  $2D = 4D$ ), and index longer than ring  
54 finger (i.e.  $2D > 4D$ ) [2].

55 The 2D:4D ratio has been reported to be associated with a broad range of human  
56 characteristics, such as behavioural traits, fertility, handedness, sexual orientation, sex-related  
57 diseases, and sports performance [3-9], although effect sizes are generally low to moderate.  
58 Sex differences in the 2D:4D ratio have been investigated extensively [7] where men tend to  
59 have a lower 2D:4D ratio than women [10]. In an important study on mice, endocrine  
60 signalling examined during a narrow window of embryonic exposure to differential levels of  
61 androgens and oestrogens was found to be associated with the 2D:4D ratio [11].  
62 Nevertheless, an important question is whether the index is independent of its denominator,  
63 which is an essential requirement for the accuracy of the 2D:4D ratio, and indeed any index  
64 which normalises one variable for another variable [12].

65 In the biological sciences, the construction of a simple ratio, of the form  $Y/X$ , is a  
66 common approach used to derive a standardized variable of an examined trait where the  
67 numerator, the criterion variable, is typically divided by a denominator, the predictor variable  
68 [12]. For example, oxygen uptake is conventionally normalised per-ratio standards to body  
69 weight in human samples [13]. Likewise, left ventricular ejection fraction is calculated as the  
70 ratio of stroke volume to end-diastolic volume and represents the traditional measure of  
71 contractility of the mammalian heart [14]. Additionally, previous studies in evolutionary  
72 biology revealed that the neocortex ratio, which is the resultant of the neocortex to brain size  
73 ratio, carries information about the number of social relationships in primates [15].

74 Nevertheless, the empirical and theoretical shortcomings of simple ratios as size-adjustment  
75 approaches are noteworthy [12, 13, 16-19]. Since a size-proportion ratio seldom normalises  
76 the  $Y$  variable consistently across the measurement range of the  $X$  variable [12], the  
77 unappreciated residual size-correlation inherent to ratiometric indices has, in general, led  
78 researchers to formulate untenable biological explanations [18, 19].

79         When a ratio is still substantially correlated with its denominator then, as we have  
80 demonstrated with a number of other physiological ratios [20], biased inferences can result.  
81 Another indicator of the inappropriateness of ratios is a substantial non-zero  $Y$ -intercept in the  
82 linear relationship between numerator and denominator [19], and such a non-zero intercept  
83 has been reported for 2D:4D [10, 21]. While there have been attempts to partition out the  
84 confounding effects of differences in the length of 4D to obtain unbiased interpretations of  
85 the 2D:4D ratio [21], a thorough allometric scrutiny of this morphometric index has not been  
86 published to date.

87         Since Julian Huxley's seminal study on the chela size of the *Uca pugnax* in 1924 [22],  
88 methods for allometric scaling have entailed, to a great extent, logarithmic transformations of  
89 the original measurements [23]. Nonetheless, logarithmic modelling might introduce an  
90 undetected systematic bias into calculations [24], and, importantly, yields a mathematical  
91 function not describing the biological relationship between the examined observations in the  
92 arithmetic domain [23]. Recent advances in the analytical procedures for studies of allometry  
93 and scaling now permit a more comprehensive appraisal of linear and non-linear regression  
94 models based on the underlying assumptions and nature of random error [25].

95         Therefore, we aimed to compare, using a formal information-theoretic approach,  
96 twelve candidate models for scaling untransformed 2D and 4D lengths, and ascertain how  
97 different model selections influence the quantification of sex differences in relative index  
98 finger length in humans.

99 **2. Methods**

100 The study sample of 416 participants comprised data collected directly by the  
101 researchers from 154 men and 262 women. The study design, methods and ethics procedures  
102 used to obtain the data have been previously described [21]. This study also adhered to the  
103 ethics and research governance procedures at Teesside University. Separate analyses were  
104 conducted for the right and left hands. Measures of centrality and dispersion were expressed  
105 as mean  $\pm$  standard deviation (SD).

106 Type I regression procedures [26] and the analytical framework outlined in a recently  
107 published article on methods for allometric analysis [25] were used to examine the  
108 morphometric relationship between the fingers. Briefly, we performed non-linear regression  
109 analyses of untransformed observations using the Model Procedure in SAS version 9.4 to fit  
110 three sets of four models, involving two straight lines and two power functions, with  
111 multiplicative, log-normal, heteroscedastic error, and additive, normal, homoscedastic or  
112 heteroscedastic error, respectively [25]. Parameter estimates for each model were solved  
113 using an iterative protocol based on the Marquardt procedure [25]. Participants' sex was also  
114 included as a categorical covariate in the statistical models. A common slope was fitted for  
115 the whole sample when the effect of the sex  $\times$  4D interaction term was found not to be  
116 substantial. Sex differences in the slope would indicate a fundamentally different relationship  
117 between 2D and 4D and preclude comparisons between men and women [27]. The Akaike  
118 Information Criterion (AIC) was adopted to assess the relative quality of each candidate  
119 model [28]. The  $\Delta$ AIC from the estimated best model (i.e. the model with the lowest AIC  
120 value;  $\Delta$ AIC = 0) was judged according to the following scale: 0-2, essentially equivalent; 2-  
121 7, plausible alternative; 7-14, weak support;  $>$  14, no empirical support [28]. Parameter  
122 estimates were interpreted from the best/essentially equivalent models for the examined data.  
123 Regression parameters are reported as point estimates and 95% confidence limits (CL). All

124 statistical analyses were conducted using SAS (PROC MODEL, SAS<sup>®</sup> Version 9.4; SAS  
125 Institute, Inc., Cary, NC), and graphs were produced using IBM Statistical Package for the  
126 Social Sciences (SPSS) Statistics version 23.0 (SPSS, Chicago, IL).

127

128 *Table 1 about here*

129 *Figure 1 about here*

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### 131 **3. Results**

132 As expected, mean lengths of 2D and 4D were larger in men than women, irrespective  
133 of the examined hand (Table 1). For the right hand, the substantial, inverse correlations  
134 between the 2D:4D ratio and 4D in both sexes indicated that the ratiometric index is not  
135 normalising for 4D length uniformly across the measurement range (Fig. 1a, b). The  
136 correlation coefficients (95%CL) describing the relationship between the index and its  
137 denominator were found to be -0.42 (-0.56 to -0.27) and -0.34 to (-0.45 to -0.22) in men and  
138 women respectively. The mean 2D:4D ratio was greater in women ( $0.993 \pm 0.037$ ) than in  
139 men ( $0.982 \pm 0.037$ ), with the 95%CL for this sex difference being 0.004 to 0.019.

140 Following our formal comparisons, in the right hand, the 2-parameter power function  
141 with normal, homoscedastic error, of the form  $Y = a \cdot X^b$ , was found to be the best out of  
142 twelve competing models (Table 2). The allometric exponent (b) describing the non-linear  
143 relationship between 2D and 4D was 0.80 (0.74 to 0.85). A ratio index is free of bias only if  
144 this exponent is 1. The 95%CL for the difference in exponent between males and females  
145 was -0.21 to 0.02. Using this most appropriate size-scaling model, women displayed a lower,  
146 and not higher, mean 2D:4D than men (Table 1). The model with straight line, intercept, and  
147 normal homoscedastic error was found to be “essentially equivalent” to the best model:  $Y =$   
148  $13.59 + 0.79 \cdot X$ . The 95%CL for the Y-intercept was 10.19 to 16.99. Table 2 reveals that the

149 3-parameter power function (relaxing the constraint of a zero  $Y$ -intercept in the 2-parameter  
150 model) was also “essentially equivalent”.

151 In the left hand, we found negative correlations between 2D:4D and 4D of similar  
152 magnitudes to those observed in the right hand (Fig. 1c, d). The correlation coefficient  
153 between the 2D:4D ratio and 4D was -0.48 (-0.62 to -0.33) in men, and -0.45 to (-0.56 to -  
154 0.35) in women. Again, women had a greater mean 2D:4D ratio than men ( $0.992 \pm 0.037$  vs.  
155  $0.984 \pm 0.036$ ), with the 95%CL for this difference being 0.001 to 0.016. The AIC criteria  
156 revealed the rectilinear function with intercept and normal, homoscedastic error ( $Y = 16.10 +$   
157  $0.75 \cdot X$ ) to be the best model in the set of candidates (Table 3). The 95% confidence interval  
158 for the positive  $Y$ -intercept was 12.96 to 19.25. The 95%CL for the difference in the  
159 regression slope between the sexes was -0.17 to 0.03. The 2-parameter power function was  
160 found to be “essentially equivalent” to the best model, with an allometric exponent of 0.76  
161 (0.71 to 0.80). The 95%CL for the sex difference in the exponent was -0.17 to 0.04. The  
162 adjusted mean 2D:4D estimates from the best / essentially equivalent models were found,  
163 again, to be lower among women than men (Table 1). In line with AIC outcomes, the model  
164 residuals were well behaved in both hands (Fig. 2).

165

166 *Table 2 about here*

167 *Table 3 about here*

168 *Figure 2 about here*

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#### 170 **4. Discussion**

171 Although the 2D:4D ratio has been selected to study the association between  
172 differences in relative index finger length and biological traits, the substantial residual  
173 dependency of the 2D:4D ratio on its denominator (4D) hinders the understanding of the true

174 relationship between the 2D and 4D in human samples (Figure 1). Accordingly, the  
175 traditional approach of normalising 2D for differences in 4D length as simple ratio statistics  
176 fails to serve this purpose in an unbiased manner across the typical measurement range of  
177 finger lengths in both men and women.

178 Notably, the outcomes of the British Broadcasting Corporation (BBC) study were  
179 seemingly interpreted as an additional line of evidence supporting the description of a sexual  
180 dimorphism based on sex differences in the 4D linear regression slope [10]. Nevertheless, the  
181 Y-intercept value, and not the linear regression slope, is the criterion parameter in linear  
182 regression models indicating the validity of a ratio statistics [19]. Not only did the inverse  
183 association between the 2D:4D ratio and 4D we observed highlight the spurious size-  
184 dependence of the index (Figure 1), but the uncontrolled confounding effects of  
185 morphological differences in 4D length illustrated the degree of bias in 2D:4D estimates [10].  
186 Since the underlying assumptions of ratios were found to be violated [12, 19], the notion of a  
187 sexually dimorphic index established on the previously reported sex differences in the 4D  
188 linear regression slope is, therefore, untenable.

189 In the human foetus, the differentiation in the growth patterns of the fingers appears at  
190 a gestational age of approximately nine weeks [29]. The mechanistic interplay between  
191 androgen and oestrogen signalling regulates the network of genes involved in chondrocyte  
192 proliferation and, therefore, the morphological relationship between the fingers [11].  
193 Notwithstanding these mechanisms, the mathematical flaws of the 2D:4D ratio alter the  
194 magnitude of sex differences in relative index finger length and, consequently, lead to  
195 erroneous interpretations. The molecular pathways obviously shed light on the *absolute*  
196 differences in the length of the fingers between the sexes [11], whereas any interpretations  
197 about casual associations grounded on the biased size-proportion 2D:4D ratio are limited by  
198 non-biological factors introducing artifactual variability.



199           The large  $\Delta AIC$  for the ratio standards models (straight line, no intercept) in both  
200 hands demonstrated that these models have essentially no support (Table 2 and 3). In  
201 particular, our study provides a comprehensive and novel approach for deriving 2D:4D  
202 measures standardized for differences in the 4D working directly in the raw arithmetic data  
203 space. After simple allometric or linear regression-standards normalisation, the mean 2D:4D  
204 estimates from the best models were found to be higher in men than women, irrespective of  
205 the examined hand and modelling approach (Table 1). Nonetheless, the drawbacks of power-  
206 function ratios are well-established [12]. While power-function ratios might turn out to  
207 successfully eliminate size correlations, they paradoxically introduce size-related distortions  
208 in distributional patterns compared to modelling morphometric relationships using raw data  
209 [12]. Accordingly, the adjusted 2D:4D ratios and adjusted 2D length we derived from the  
210 model residuals were both independent of 4D length and materially unaffected by  
211 distributional distortions [12]. The adjusted 2D:4D indices were derived according to the  
212 empirical and theoretical assumptions regarding the use of residuals, which reflect the true  
213 biological variability of the observed values independent of body size [12]. Our approach  
214 involved modelling the 2D:4D ratio as the dependent variable, adjusting for 4D length using  
215 the residuals method [12], and then obtaining an adjusted ratio free from the influence of 4D  
216 length. Importantly, this size-adjustment approach is mathematically equivalent to modelling  
217 2D length as the dependent variable [30], with the advantage of providing a properly adjusted  
218 ratio index rather than an expression of 2D length free from the influence of 4D length. The  
219 mathematical equivalence and concordance between these analyses ultimately substantiate  
220 the failure of simple ratio models (Tables 2 and 3) to provide unbiased 2D:4D estimates  
221 (Figure 1) [12, 30]. Furthermore, the measurement of 2D and 4D lengths carried out by  
222 trained anthropologists is another key strength of the present study that minimizes any  
223 random variability in the examined data [21]. Our results reflect a long-standing wealth of

224 evidence in the biological literature, whereby relationships between morphometric variables  
225 seldom vary in a directly proportional fashion [12, 13, 16-19].

226         We, therefore, point out that the formulation of this index as a simple ratio might  
227 cloud any potential associations between the relative length of the fingers and other human  
228 traits, particularly sex differences. To date, the formulations of simple ratios as the 2D:4D  
229 have been superseded by more comprehensive and accurate allometric analyses for  
230 addressing size-scaling problems [25]. If the relationship between the 2D and 4D was found  
231 to be directly proportional, for a given value of 4D the 2D:4D ratio would have predicted the  
232 same value of the outcome compared to what we observed after proper modelling of  
233 differences in the denominator of the index.

234         Our study demonstrates that, in human samples, failure to statistically control for the  
235 true covariation patterns associated with the 4D in the 2D:4D ratio provides biased estimates  
236 of differences between the sexes and, consequently, a spuriously sexually dimorphic index.

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249 **Authors' contributions**

250 L.L., A.M.B., and G.A. contributed to the design of the paper, conducted statistical analyses,  
251 wrote, and revised the manuscript. L.K., and J.F. provided the examined data and contributed  
252 to the manuscript revision. K.L.W. contributed to the revision of the manuscript. All authors  
253 approved the final version of the manuscript and agree to be accountable for the content  
254 herein.

255

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259 **Competing interests**

260 We declare no competing interests with regard to this publication.

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265

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### Table Legends

350

351 **Table 1.** Descriptive characteristics of the study participants (n = 416).

352

353 **Table 2.** Statistical models fitted to untransformed data for scaling 2D (mm) to 4D (mm) in  
354 the right hand.

355

356 **Table 3.** Statistical models fitted to untransformed data for scaling 2D (mm) to 4D (mm) in  
357 the left hand.

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### Figure Legends

360

361 **Figure 1.** Scatterplots showing the negative correlation between the 2D:4D ratio and the  
362 length of the 4D for men (a, c), and women (b, d) in the right and left hand, respectively.

363

364 **Figure 2.** Raw residuals against the untransformed 4D measures from the 2-parameter power  
365 function (a, c), and linear regression (b, d) model with normal, homoscedastic error in the  
366 right and left hand, respectively.

**Table 1.** Descriptive characteristics of the study participants (n = 416)

Variable	Men (n = 154)	Women (n = 262)
Right hand		
2 <sup>nd</sup> finger length, mm	73.82 ± 4.19 (61.00 to 87.00)	67.77 ± 4.60 (42.80 to 79.00)
4 <sup>th</sup> finger length, mm	75.27 ± 4.61 (64.00 to 89.00)	68.31 ± 4.76 (39.80 to 79.90)
2D:4D ratio	0.982 ± 0.037	0.993 ± 0.037
2D:4D normalised index <sup>a</sup>	0.993 ± 0.034	0.986 ± 0.035
2D:4D normalised index <sup>b</sup>	0.994 ± 0.033	0.986 ± 0.035
2D:4D normalised index <sup>c</sup>	2.328 ± 0.079	2.310 ± 0.081
Adjusted 2 <sup>nd</sup> finger length, mm <sup>a</sup>	70.37 ± 2.40	69.79 ± 2.46
Adjusted 2 <sup>nd</sup> finger length, mm <sup>b</sup>	70.34 ± 2.51	69.82 ± 2.38
Left hand		
2 <sup>nd</sup> finger length, mm	74.13 ± 4.10 (61.00 to 90.00)	67.46 ± 4.36 (44.20 to 78.00)
4 <sup>th</sup> finger length, mm	75.42 ± 4.73 (62.90 to 91.00)	68.08 ± 4.79 (38.80 to 80.00)
2D:4D ratio	0.984 ± 0.036	0.992 ± 0.037
2D:4D normalised index <sup>a</sup>	1.000 ± 0.032	0.983 ± 0.033
2D:4D normalised index <sup>b</sup>	0.996 ± 0.032	0.985 ± 0.034
2D:4D normalised index <sup>c</sup>	2.775 ± 0.090	2.730 ± 0.091
Adjusted 2 <sup>nd</sup> finger length, mm <sup>a</sup>	70.67 ± 2.28	69.49 ± 2.32
Adjusted 2 <sup>nd</sup> finger length, mm <sup>b</sup>	70.64 ± 2.36	69.51 ± 2.24

Values are expressed as mean ± SD, with range in parentheses. <sup>a</sup>: 2-parameter power function with normal, homoscedastic error; <sup>b</sup>: straight line with intercept and normal, homoscedastic error; <sup>c</sup>: power function ratio. The normalised indices <sup>a,b</sup> were derived directly from the model residuals [12] in raw arithmetic space, with the 2D:4D ratio or 2D as the dependent variable and 4D and Sex as predictors. Each participant's residual was added to the predicted mean ratio for each sex at the mean 4D length in the whole sample, to obtain an adjusted 2D:4D 'ratio' or 2D free from the influence of 4D length. The normalised index <sup>c</sup> was directly derived from the ratio of 2D to 4D raised to the power of 0.80 and 0.76 in the right and left hand, respectively.



**Table 2.** Statistical models fitted to untransformed data for scaling 2D (mm) to 4D (mm) in the right hand

Model	AIC	$\Delta$ AIC	Inference
Straight line, no intercept, with lognormal heteroscedastic error	1984.1	61.0	no empirical support
Straight line, no intercept, with normal, heteroscedastic error Failed to converge. Convergence criterion changed to 0.011	1983.7	60.6	no empirical support
Straight line, no intercept, with normal, homoscedastic error	1979.9	56.8	no empirical support
3-parameter power function with normal, heteroscedastic error Failed to converge. Convergence criterion changed to 0.014	1929.0	5.9	plausible alternative
2-parameter power function with normal, heteroscedastic error Failed to converge. Convergence criterion changed to 0.013	1928.8	5.7	plausible alternative
Straight line, intercept, with lognormal heteroscedastic error	1928.1	5.1	plausible alternative
Straight line, intercept, with normal, heteroscedastic error Failed to converge. Convergence criterion changed to 0.01	1927.3	4.3	plausible alternative
3-parameter power function with lognormal, heteroscedastic error Failed to converge. Equation rearranged and converged	1926.5	3.5	plausible alternative
2-parameter power function with lognormal, heteroscedastic error	1925.9	2.8	plausible alternative
Straight line, intercept, with normal, homoscedastic error	1924.6	1.6	essentially equivalent
3-parameter power function with normal, homoscedastic error Failed to converge. Equation rearranged and converged	1923.8	0.8	essentially equivalent
2-parameter power function with normal, homoscedastic error	1923.1	0	Best

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AIC = Akaike's information criterion;  $\Delta$ AIC = Akaike difference

**Table 3.** Statistical models fitted to untransformed data for scaling 2D (mm) to 4D (mm) in the left hand

Model	AIC	$\Delta$ AIC	Inference
Straight line, no intercept, with lognormal heteroscedastic error	1978.0	103.8	no empirical support
Straight line, no intercept, with normal, heteroscedastic error Failed to converge. Convergence criterion changed to 0.013	1971.1	96.9	no empirical support
Straight line, no intercept, with normal, homoscedastic error	1962.3	88.1	no empirical support
3-parameter power function with normal, heteroscedastic error Failed to converge. Convergence criterion changed to 0.014	1882.0	7.8	weak support
3-parameter power function with lognormal, heteroscedastic error	1880.8	6.6	plausible alternative
2-parameter power function with normal, heteroscedastic error Failed to converge. Equation rearranged and converged	1880.5	6.3	plausible alternative
Straight line, intercept, with lognormal heteroscedastic error	1879.1	4.9	plausible alternative
2-parameter power function with lognormal, heteroscedastic error	1878.8	4.6	plausible alternative
Straight line, intercept, with normal, heteroscedastic error Failed to converge. Convergence criterion changed to 0.014	1877.8	3.6	plausible alternative
3-parameter power function with normal, homoscedastic error Failed to converge. Equation rearranged and converged	1876.3	2.1	plausible alternative
2-parameter power function with normal, homoscedastic error	1874.3	0.1	essentially equivalent
Straight line, intercept, with normal, homoscedastic error	1874.2	0	Best

AIC = Akaike's information criterion;  $\Delta$ AIC = Akaike difference



