Bull. Natl. Mus. Nat. Sci., Ser. D, 43, pp. 7–15, December 22, 2017

Allometric relationship between hand bone lengths and stature in a modern Japanese population

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Abstract Human proximal limb elements are known to scale with body size with smaller allometry coefficients than distal limb elements. In the present study, we tested if this allometric tendency is applicable to the human hand. Specifically, the allometric relationships between hand bone lengths and stature in a modern Japanese population were examined based on a total of 197 anteroposterior X-ray images of the adult hand. The lengths of 19 metacarpal and phalangeal elements were measured by digitizing the images. We regressed each log-transformed bone length against log-transformed stature using reduced major axis (RMA) regression, and compared the allometry coefficients. Our results demonstrated that, in all the examined hand bone elements, allometry coefficients were significantly larger than one, indicating positive allometry. It was also found that the allometry coefficients of the distal hand bones were generally larger than those of the proximal bones, indicating that the general allometric relationship previously reported for the main limb bones is also applicable to the hand bones. No statistical differences were observed in the allometric relationship between males and females for all the examined hand bones except the 5$^{\text{th}}$ middle phalanx, possibly owing to larger variabilities in female 5$^{\text{th}}$ middle phalanx length. These results contribute to the understanding of normal growth and developmental patterns as well as to secular change of human hand proportions. Our results also provide some new insights into grasping biomechanics of the hand.
Key words: Allometric relationships, Hand bone lengths and stature, Metacarpals and phalanges, Planar radiography, Modern Japanese

Introduction

Human limb elements are known to scale allometrically with body size. Previous studies investigated the allometric relationships of the lengths of the humerus, radius, femur and tibia (Holliday and Ruff, 2001; Sylvester *et al.*, 2008; Auerbach and Sylvester, 2011). These studies demonstrated that the scaling relationships of some of the limb elements were non-isometric and that the proximal limb elements scaled with comparatively smaller allometry coefficients than the distal elements. Therefore, as a general tendency in humans, if stature is higher, the lengths of the distal limb segments (radius and tibia) relative to the proximal limb segments (humerus and femur) tend to be greater. However, such allometric relationships have not been investigated in the other parts of the postcranium.

The present study aimed to investigate if this allometric tendency is also applicable to the human hand. Relationships between metacarpal length and stature have been analyzed for the purpose of stature estimation (Musgrave and Harneja, 1978; Kimura, 1992; Meadows and Jantz, 1992; Wilbur, 1998: Takai *et al.*, 2005). However, no studies have previously compared the allometric coefficients of all the metacarpals and phalanges of the hand to investigate their scaling relationships. Such information may contribute to our understanding of normal growth and development patterns of the human hand, secular changes of hand proportions, and aspects of grasping biomechanics.

Materials and Methods

In the present study, we used anteroposterior X-ray images of the right hands of a total of 197 adult participants (61 males and 136 females) who participated in the Ogi Growth Study performed by Saga University School of Medicine from 1979 to 1988 (Takai, 1990; Takai and Shinoda, 1991). This study is a longitudinal growth study of Japanese students who resided in Ogi city, Saga prefecture, Japan. Along with standard anthropometric measurements, an anteroposterior X-ray image of the right hand was taken every year from an age of 6 to a maximum age of 18 years (all the X-ray films are currently housed in the Department of Anthropology, National Museum of Nature and Science). However, in the present study, we selected only the X-ray images (anonymized in an unlinkable fashion) of the hand after epiphyseal fusion, since our focus was on the adult hand.

The X-ray films were scanned with a resolution of 150 dpi (a pixel size of 0.169 mm) using a film scanner (EPSON GT-X980). On each digital image, the most proximal and distal ends of the metacarpals (MC), proximal phalanges (PP), middle phalanges (MP), and distal phalanges (DP) along the shaft axis were manually digitized. This was done using a custom-made software named Dicom&16Tiff Viewer Ver.2.2 (Ogihara Lab., Dept. Mech. Eng., Keio University), and the distances between the proximal and distal ends of the bones were calculated (Figure 1). The measurement was conducted by one of the authors (S.A.), twice on a different day. The mean of the two values was used as the length of each MC or phalanx. The intra-observer error of the length measurement was approximately 0.3 mm for all the bones, corresponding to $<1\%$ of the length of the MCs and PPs, and $<2\%$ of the MPs and DPs, indicating that the measurements were made in a highly reproducible fashion.

To explore the scaling relationships of the 19 metacarpal and phalangeal bones with stature, we regressed each of the log-transformed bone length against log-transformed stature using reduced major axis (RMA) regression (Hofman, 1988; Sjøvold, 1990), a model II linear regression (R version 3.2.4, The R Project for Statistical Computing) with custom packages. We used RMA regression because both bone lengths and

Fig. 1. Anteroposterior X-ray image of the hand (left) and enlargement of the MP3 part (right) showing two digitized points connected by a line segment representing the MP3 length.

stature were measured with errors. All regression analyses were performed separately for males and females. The allometry coefficients (slopes) and intercepts of the male and female regression lines were computed and statistically tested by Student's t-test. Using the same software, we also tested if the regression line significantly deviates from one, i.e., geometric similarity.

The present study was approved by the Ethics Committee of the National Museum of Nature and Science.

Results and Discussion

Bivariate plots with RMA regression lines of the log-transformed 19 hand bones relative to log-transformed stature are shown in Figure 2. Table 1 lists the allometry coefficients and intercepts of the RMA regression lines of all 19 hand bones. For all hand bones, the allometry coefficients and intercepts of the male regression lines were not statistically different from those of the female regression lines except for the regression lines for the MP5 ($p < 0.001$). All regression lines significantly deviated from one, indicating that all the hand bones scale with positive allometry.

Figure 3 compares the allometry coefficients of the hand bones from the 1st to 5th rays. As the figure shows, the allometry coefficients for the MCs and PPs were smaller than those for the MPs and DPs in both males and females, indicating that the two proximal elements scale with comparatively smaller allometry coefficients than the distal bones. We also observed that the allometry coefficients tended to increase with distance from the 3rd ray, particularly in females.

In the present study, we found that the proximal bones scaled with comparatively smaller allometry coefficients than the distal bones in the human hand, as previously demonstrated for the four major limb bones (Holliday and Ruff, 2001; Sylvester *et al.*, 2008; Auerbach and Sylverster, 2011). Furthermore, Auerbach and Sylvester (2011) reported that the allometry coefficients of humerus, radius, femur and tibia are 1.03, 1.25, 1.12 and 1.28, respectively, for males and 1.03, 1.21, 1.17, and 1.35, respectively, for females, showing that the allometry coefficients of these proximal bones are smaller than those of hand bones. Therefore, there seems to exist a general tendency that distal elements grow faster in relation to proximal element in human limbs. The mechanism underlying the emergence of this allometric relationship is beyond the scope of the present study, but it should be related to differential skeletal growth defined by the expression of Hox genes (Reno *et al.*, 2008) or differences in timing of epiphyseal fusion between proximal and distal elements. In addition, it was noted that the allometry coefficients tended to increase with distance from the 3rd ray, particularly in females. The functional significances of these extracted allometric patterns are currently obscure. However, it might be related to change in mechanical requirement of the human hand with increasing size. How the human hand proportion emerges in development and how changes in skeletal proportion of the hand affect manipulative capability should be investigated in future studies. It must be noted, however, Auerbach and Sylvester (2011) used a model I regression analysis to calculate the allometry coefficients and their samples were of a mixed population from different geographical origins, indicating that direct comparisons of the allometry coefficients were actually impossible. To confidently conclude that there exists a general tendency that distal elements grow faster in relation to proximal element in human forelimbs, the allometric relationships of the humerus, radius, metacarpals and phalanges should be more rigorously investigated using the same method and samples from the same population.

The present study also found that there is basically no statistical difference in the allometric relationship between males and females except for the MP5. This is owing to the fact that the variance of the MP5 length was much larger in females than in males. There were a certain number of female participants who had shorter-than-expected MP5 as shown in Figure 2. The same

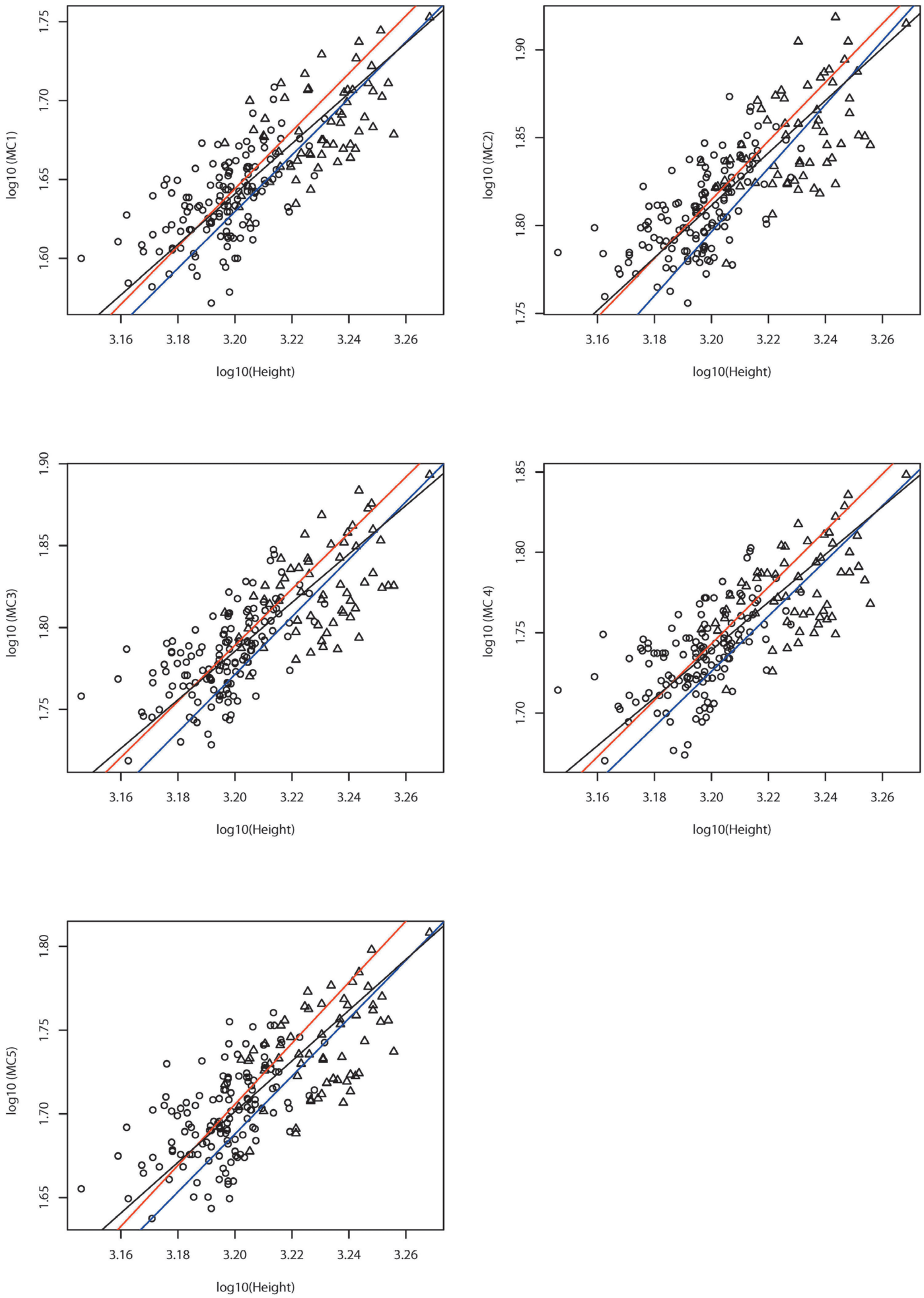

Fig. 2. Bivariate plots with RMA regression lines of log-transformed hand bones relative to log-transformed stature. Red circle, female; blue triangle, male. Red line, female regression line; blue line, male regression line.

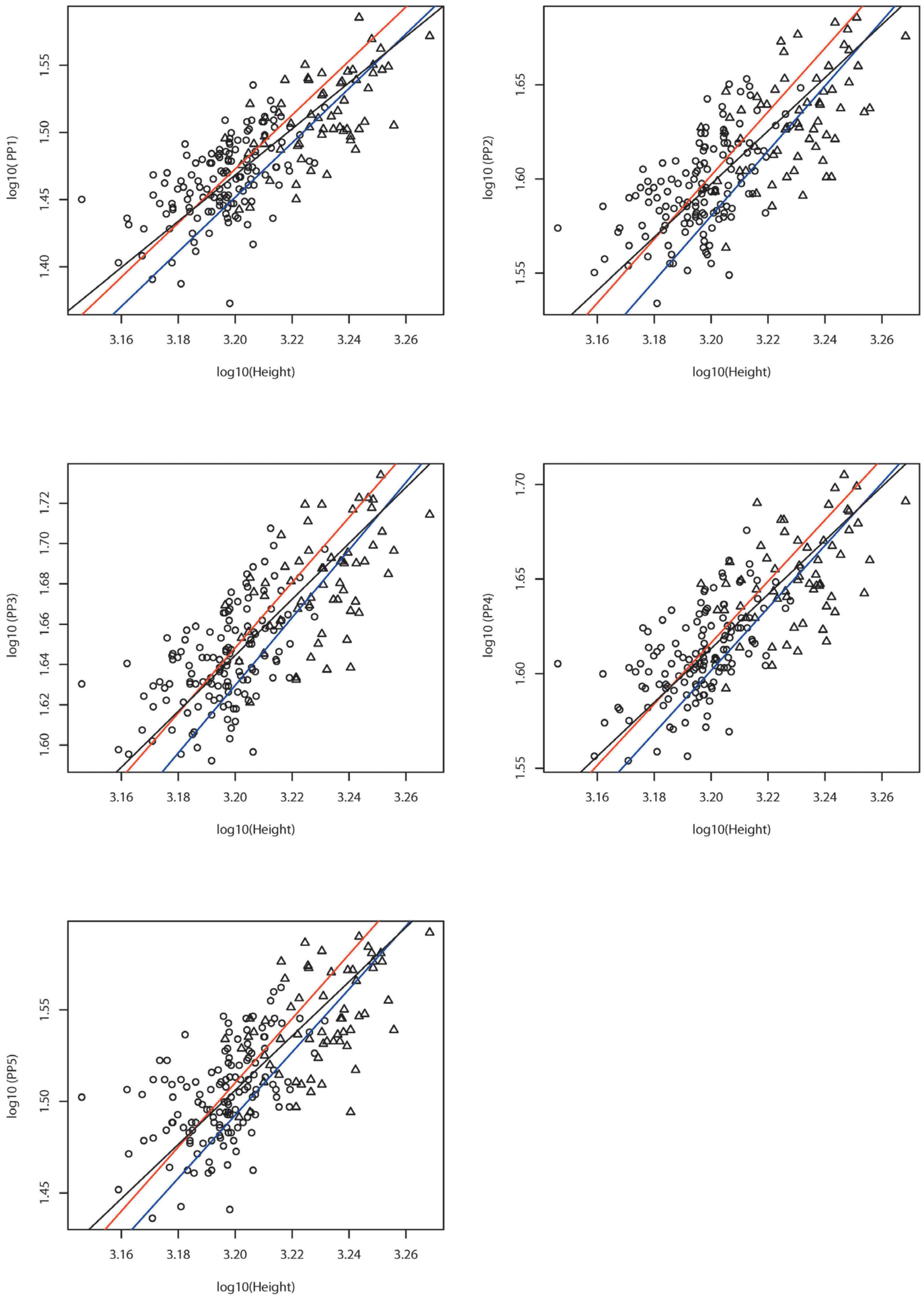

Fig. 2. Continued.

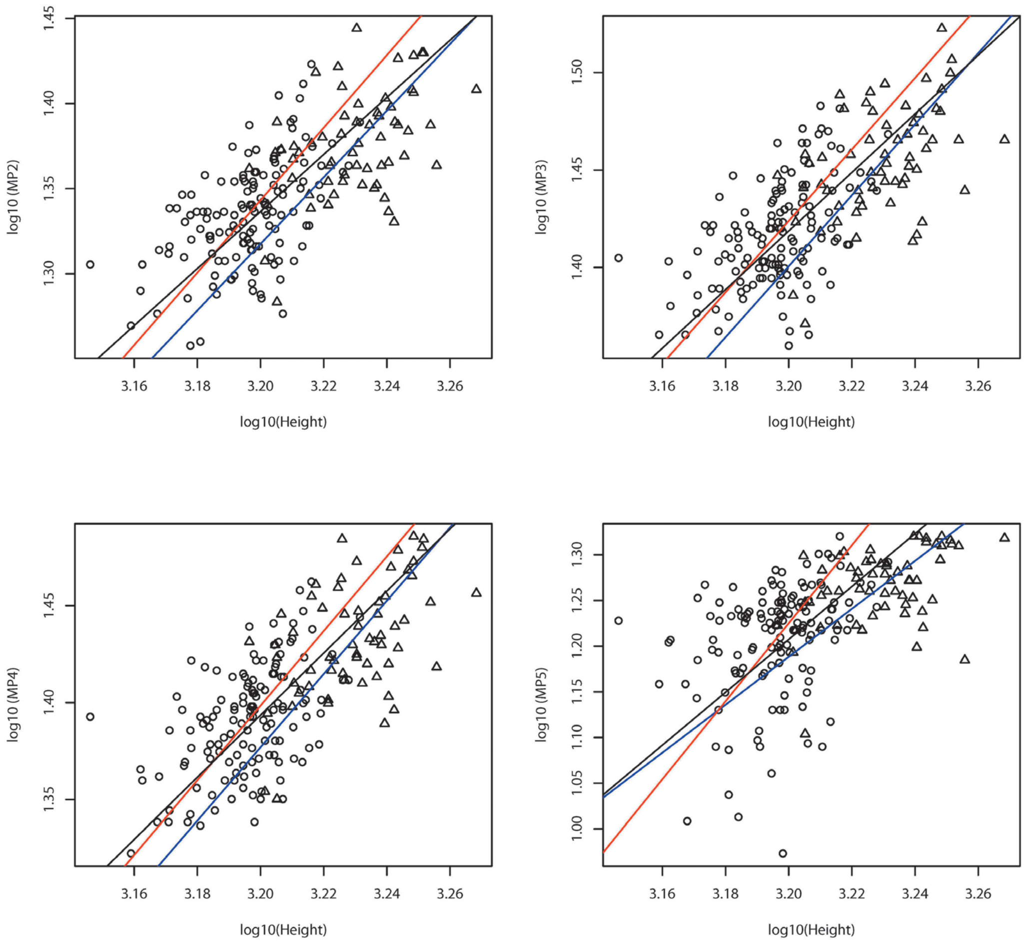

Fig. 2. Continued.

tendency, although not significant, can be observed in DP1. We can offer no explanations as to why this occurs, but distal hand bones distant from the 3rd ray, i.e. the center of the hand, may be developmentally more variable than other hand bones.

As mentioned before, the length of metacarpals has been used to estimate the stature (Musgrave and Harneja, 1978; Kimura, 1992; Meadows and Jantz, 1992; Wilbur, 1998; Takai *et al.*, 2005). The regression equations derived in the present study can also be used for stature estimation. In the previous studies, however, the length of metacarpals was directly regressed with stature without logarithmic transformation, assuming that the allometric relationship between the metacarpal length and the stature was relatively minor. Furthermore, the previous studies used ordinary least square regression (model I) whereas the present study used RMA regression (geometric mean regression of model II). When the two variables both contain error as in the present case, a model I (Y on X) regression tends to underestimates the slope, thus resulting in overestimation of the shortest individuals and underestimation of the tallest (Sjøvold, 1990). Therefore, the present approach might have provided theoretically better equations for stature estimation based on the length of metacarpals. However, this must also be confirmed in future studies.

Here we have focused on the adult hand using

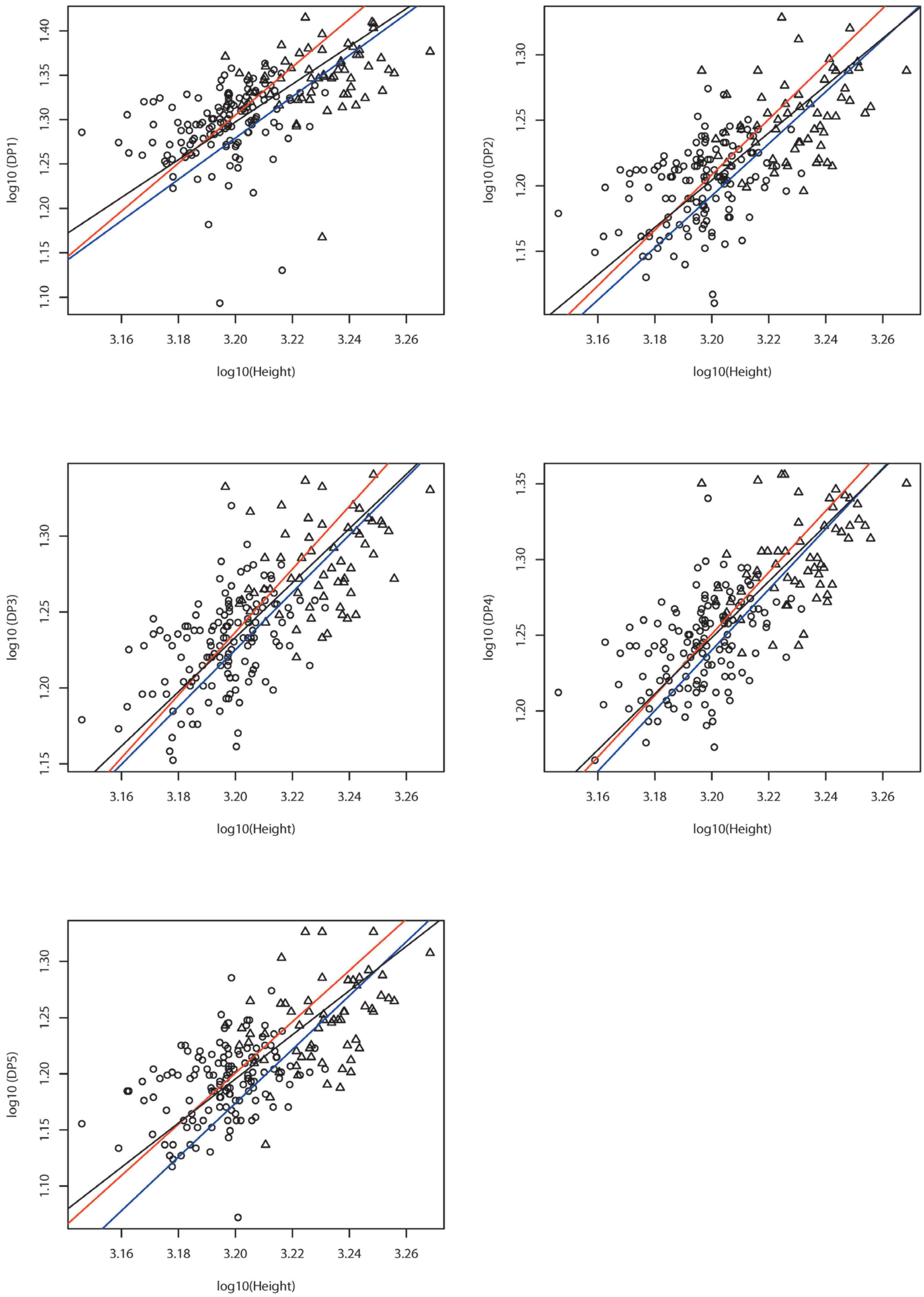

Fig. 2. Continued.

Table 1. Allometry coefficients and intercepts of the RMA regression lines

		Slope	95% confidence interval		Intercept	95% confidence interval	
MC1	Male	1.79	1.45	2.22	−4.11	−5.48	−3.00
	Female	1.83	1.59	2.10	−4.20	−5.07	−3.45
	Combined	1.60	1.46	1.75	−3.46	−3.95	−3.02
MC2	Male	1.81	1.45	2.26	−4.00	−5.45	−2.85
	Female	1.67	1.46	1.91	−3.53	−4.29	−2.86
	Combined	1.49	1.36	1.64	−2.96	−3.42	−2.55
MC3	Male	1.76	1.41	2.20	−3.85	−5.27	−2.72
	Female	1.71	1.49	1.96	−3.69	−4.49	−2.99
	Combined	1.48	1.35	1.63	−2.96	−3.43	−2.54
MC4	Male	1.72	1.37	2.15	−3.77	−5.17	−2.66
	Female	1.76	1.53	2.03	−3.89	−4.75	−3.14
	Combined	1.49	1.35	1.64	−3.02	−3.51	−2.58
MC5	Male	1.73	1.38	2.16	−3.84	−5.24	−2.72
	Female	1.82	1.58	2.10	−4.12	−5.02	−3.35
	Combined	1.51	1.37	1.67	−3.14	−3.64	−2.69
PP1	Male	2.03	1.65	2.49	−5.03	−6.54	−3.81
	Female	2.01	1.74	2.32	−4.96	−5.94	−4.11
	Combined	1.72	1.56	1.89	−4.03	−4.58	−3.54
PP2	Male	1.73	1.38	2.16	−3.94	−5.35	−2.82
	Female	1.69	1.47	1.95	−3.81	−4.63	−3.10
	Combined	1.41	1.28	1.56	−2.92	−3.39	−2.49
PP3	Male	1.68	1.35	2.09	−3.74	−5.08	−2.67
	Female	1.62	1.40	1.87	−3.53	−4.33	−2.83
	Combined	1.39	1.26	1.53	−2.80	−3.26	−2.38
PP4	Male	1.65	1.32	2.07	−3.68	−5.04	−2.60
	Female	1.62	1.41	1.87	−3.57	−4.36	−2.89
	Combined	1.43	1.30	1.57	−2.95	−3.41	−2.53
PP5	Male	1.72	1.37	2.16	−4.01	−5.42	−2.89
	Female	1.75	1.51	2.03	−4.10	−5.00	−3.32
	Combined	1.48	1.34	1.64	−3.23	−3.74	−2.78
MP2	Male	1.96	1.55	2.47	−4.95	−6.59	−3.64
	Female	2.13	1.84	2.46	−5.47	−6.54	−4.55
	Combined	1.68	1.51	1.86	−4.03	−4.62	−3.50
MP3	Male	1.82	1.45	2.28	−4.42	−5.92	−3.23
	Female	1.83	1.58	2.13	−4.44	−5.38	−3.63
	Combined	1.50	1.35	1.67	−3.39	−3.91	−2.91
MP4	Male	1.89	1.51	2.37	−4.67	−6.22	−3.44
	Female	1.92	1.66	2.23	−4.76	−5.74	−3.91
	Combined	1.60	1.45	1.77	−3.73	−4.28	−3.23
MP5	Male	**2.63**	2.08	3.32	**−7.21**	−9.45	−5.44
	Female	**4.27**	3.63	5.02	**−12.44**	−14.82	−10.41
	Combined	2.89	2.57	3.26	−8.06	−9.24	−7.01
DP1	Male	2.33	1.81	3.00	−6.18	−8.33	−4.51
	Female	2.71	2.30	3.19	−7.36	−8.89	−6.06
	Combined	2.13	1.89	2.39	−5.51	−6.36	−4.76
DP2	Male	1.98	1.56	2.52	−5.16	−6.90	−3.78
	Female	2.11	1.81	2.47	−5.56	−6.71	−4.57
	Combined	1.80	1.62	2.01	−4.57	−5.22	−3.98
DP3	Male	1.89	1.48	2.42	−4.82	−6.53	−3.48
	Female	2.07	1.78	2.41	−5.39	−6.47	−4.46
	Combined	1.79	1.61	1.99	−4.50	−5.13	−3.93
DP4	Male	2.00	1.58	2.53	−5.17	−6.88	−3.81
	Female	2.03	1.75	2.37	−5.25	−6.32	−4.34
	Combined	1.85	1.68	2.05	−4.69	−5.31	−4.12
DP5	Male	2.40	1.89	3.04	−6.49	−8.57	−4.86
	Female	2.28	1.95	2.67	−6.11	−7.35	−5.05
	Combined	1.97	1.77	2.19	−5.10	−5.83	−4.45

Bold text at MP5 indicates a statistically significant difference between male and female with a p-value less than 0.05.

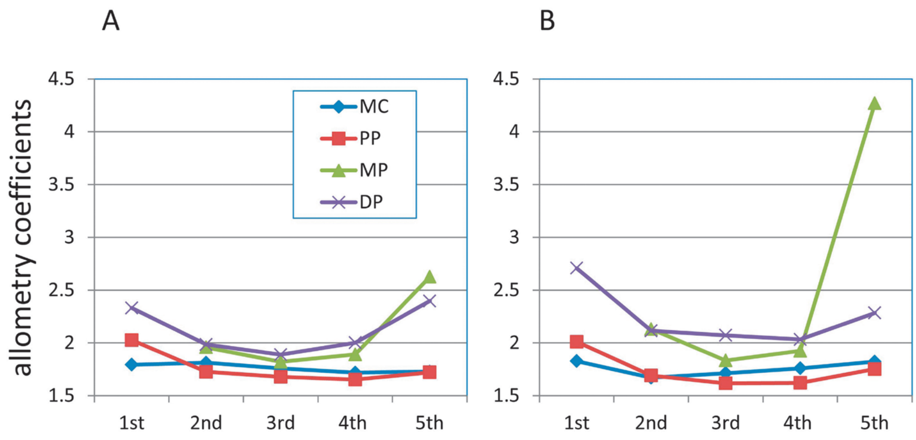

Fig. 3. Allometry coefficients of the metacarpals and phalanges from the 1st to 5th rays. A, male; B, female.

the X-ray images of hands taken after epiphyseal fusion, and thus did not study the ontogenetic changes of the hand bones. However, longitudinal-growth radiographs of the same participants are available, along with standard anthropometric measurements. Continued investigations of developmental change of hand bone lengths are necessary to further clarify some of the quesitons raised above.

Acknowledgement

We would like to extend our appreciation to the Editor of this journal, Dr. Kazuhiro Sakaue for his generous help. The manuscript was improved with valuable suggestions and comments from anonymous reviewers.

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