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Interrelationships between Cranial Length and Breadth, Endocranial Capacity, Postcranial Measurements, and Stature: Toward the Solution of the Brachycephalization Problem

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Abstract It was examined whether postcranial measurements already shown in separate analyses to be significantly associated with cranial length, cranial breadth, or basi-bregmatic height were separately or concurrently associated with the relevant neurocranial measurement. Principal component analyses for males and females showed that all representative measurements of the vertebral body, humerus, pelvis, femur, and tibia were significantly associated with one another and with cranial length. These findings support the present author's previous hypothesis that variation in cranial length is related to the degree of development of skeletal muscles or body size. The sex difference in the manner of connecting cranial breadth with facial breadth may be explained by the sex difference in the amount of masticatory muscle. Basi-bregmatic height was also found to be simultaneously associated with vertebral foramen size and talar size in both sexes, but this may be explained by a property common to these three measurements, i.e., not being under the direct control of skeletal muscles, e.g., by a set of genes controlling the inherent size of most organs. Furthermore, the relationships of endocranial capacity and stature with neurocranial and postcranial measurements were examined and discussed.

Key words: Brachycephalization, Cranial length, Postcranial measurements, Principal component analysis, Bootstrap method

To clarify the causes of brachycephalization, a series of multivariate analyses was conducted on within-group correlations between neurocranial and postcranial measurements (Mizoguchi, 1994, 1995, 1996, 1997, 1998a, b, 1999, 2000, 2001, 2002, 2003b, c, 2004a, 2005, 2007b, 2008) on the premise that population differences are extensions of individual differences, as stated by Howells (1973). The results show that, while cranial breadth has no consistent associations with any postcranial measurements, cranial length is significantly associated with many postcranial measurements, such as vertebral body size, costal chord, pelvic width, and limb bone length and thickness, but these associations were detected in separate analyses. It has not been confirmed whether postcranial measurements are correlated with one another or separately connected with cranial length. In the present study, therefore, it is mainly examined how such postcranial measurements are associated with cranial length in the network of characters. In addition, it was also investigated how brain size (endocranial capacity) and body size (stature) are associated with neurocranial and postcranial measurements because problems of the relationship between neurocranial shape and the brain (Macalister, 1898; Sullivan, 1978) or stature (Jantz *et al*., 1992; Kouchi, 2000; Buretic-Tomljanovic, 2004) have not completely been settled.

Materials and Methods

In the present study, two sets of cranial and postcranial measurements of the same adult individuals were used. One set was raw measurements of 30 male and 20 female modern Japanese who lived in the Kinai district, reported by Miyamoto (1924, 1925, 1927), Okamoto (1930), Kikitsu (1930), and Hirai and Tabata (1928a, b). The values of "stature" (Miyamoto, 1924) are, however, those of living stature, except for one individual. The basic statistics for these data are listed in Table 1. Incidentally, these samples are the same as those used in previous studies (Mizoguchi, 1994, 1995, 1996, 1997, 1998a, b, 1999, 2000, 2001, 2002, 2003b, c, 2004a, 2005, 2007b, 2008).

The other set was of 19 male and 21 female Australian Aborigines from Murray River Valley, which was uploaded to the Internet by Brown (2001). The basic statistics for these data are listed in Table 2.

Because of the statistical restriction on sample size given the number of variables, representative (or relatively frequently used) postcranial variables to be analyzed were selected for each of the examinations of cranial length, cranial breadth, and basi-bregmatic height from postcranial variables found to be significantly or relatively highly associated with the relevant neurocranial measurement in previous studies. As a result, five variable sets were created for the Japanese samples: 1) associated with cranial length, excluding costal chord (Tables 3 to 6); 2) associated with cranial length, including costal and upper limb bone measurements (Tables 7 and 8); 3) associated with cranial length, including costal and lower limb bone measurements (Tables 9 and 10); 4) associated with cranial breadth (Tables 11 to 14); and 5) associated with basi-bregmatic heigtht (Tables 15 to 18). For the Australian Aboriginal samples, only the variables common to those shown in Table 1 and those used by Brown (2001) were selected (Table 2).

To examine the overall relationships between neurocranial and postcranial measurements, principal component analysis (Lawley and Maxwell, 1963; Okuno *et al.*, 1971, 1976; Takeuchi and Yanai, 1972) was applied to their correlation matrices. The number of principal components was determined so that the cumulative proportion of the variances of the principal components exceeded 80%. The principal components obtained were then transformed by Kaiser's normal varimax rotation method (Asano, 1971; Okuno *et al.*, 1971) into different factors in an attempt to reveal other associations behind the measurements.

The significance of factor loadings was tested by the bootstrap method (Efron, 1979a, b, 1982; Diaconis and Efron, 1983; Mizoguchi, 1993). In order to estimate the bootstrap standard deviation of a factor loading, 1,000 bootstrap replications, including the observed sample, were used. The bootstrap standard deviation was estimated by directly counting the cumulative frequency for the standard deviation in the bootstrap distribution.

The presence of common factors, such as those represented by principal components or rotated factors, was further tested by evaluating the similarities between the factors obtained for males and females, i.e., by estimating Spearman's rank correlation coefficient, rho (Siegel, 1956), between the variation patterns of factor loadings.

Statistical calculations were executed using programs written by the author in FORTRAN: BSFMD for calculating basic statistics, BTPCA for principal component analysis and Kaiser's normal varimax rotation, and RKCNCT for rank correlation coefficients. The FORTRAN 77 compiler used is FTN77 for personal computers, provided by Salford Software Ltd. To increase efficiency during programming and calculation, a GUI for programming, CPad, provided by "kito," was used.

Results

The results of principal component analyses (PCAs) and their rotated solutions for Japanese samples are shown in Tables 3 to 18. Spearman's rank correlation coefficients between males and females for the variation patterns of factor loadings on the principal components (PCs) and/or rotated factors (Facs) are listed in Tables 19 to 21. Similarly, the results of PCAs and rotated solutions for Australian Aborigines are shown in

Table 1. Means and standard deviations for cranial and postcranial measurements of Japanese males and females.[1)]

Variable[2)]		Males			Females		
		n	Mean	SD	*n*	Mean	SD
	SKULL						
1	Cranial length	30	178.4	5.6	20	169.4	4.9
8	Cranial breadth	30	141.0	4.7	20	137.8	4.1
17	Basi-bregmatic height	30	139.8	5.8	20	132.1	3.8
3	Glabello-lambda length	30	174.0	5.9	20	165.7	4.5
31(2)	Inion-opisthion chord	30	40.5	4.6	20	41.0	4.7
	Cubic root of endocranial capacity[3)]	30	11.436	0.290	20	10.986	0.251
45	Bizygomatic breadth	30	133.4	5.3	20	125.9	3.8
65(1)	Bicoronoid breadth	30	97.7	4.5	20	92.5	3.7
66	Bigonial breadth	30	100.3	5.0	20	91.9	3.9
	ATLAS						
K1	Total sagittal diameter	30	44.2	2.6	20	40.9	2.6
K2	Total transverse diameter	–	–	–	20	70.4	2.8
	AXIS						
K6	Total breadth	30	58.0	3.9	20	50.8	3.0
	THORACIC VERTEBRA VIII						
4	Superior sagittal diameter of vertebral body	30	26.4	2.0	19	23.8	1.9
7	Superior transverse diameter of vertebral body	30	31.6	2.5	19	28.3	1.5
	LUMBAR VERTEBRA III						
10	Sagittal diameter of vertebral foramen	30	14.1	1.3	20	14.2	1.3
11	Transverse diameter of vertebral foramen	30	21.8	1.4	20	20.8	1.6
	LUMBAR VERTEBRA IV						
4	Superior sagittal diameter of vertebral body	–	–	–	19	30.2	2.3
7	Superior transverse diameter of vertebral body	–	–	–	20	44.5	3.5
	SACRUM						
4	Anterior superior transverse arc	–	–	–	20	105.7	7.7
	RIB IV						
4	Chord	–	–	–	20	142.3	9.0
KK-4C	Thickness at costal angle	–	–	–	20	6.8	0.9
	HUMERUS						
2	Total length	30	289.8	15.7	20	269.5	12.5
6	Minimum diameter of midshaft	30	17.4	1.5	20	14.6	0.9
	PELVIS						
1	Height of innominate	29	206.3	9.8	20	189.9	9.7
2	Maximum pelvic breadth	30	258.8	13.8	20	251.9	14.4
	FEMUR						
1	Maximum length	30	413.7	24.0	20	382.3	20.6
6	Sagittal diameter at midshaft	30	27.1	2.3	20	23.3	1.8
	TIBIA						
1a	Maximum length	30	331.9	20.5	20	305.1	17.2
8	Maximum diameter at midshaft	30	28.5	2.2	20	24.0	1.8
	TALUS						
1	Length	29	50.7	2.1	20	45.6	1.9
2	Breadth	29	40.2	2.4	20	35.9	2.3
	BODY SIZE						
	Stature	29	1577.1	72.0	19	1489.2	55.9

[1)] The estimates of basic statistics were recalculated here on the basis of raw data published by previous authors: Miyamoto (1924): skull and stature; Okamoto (1930): vertebrae; Kikitsu (1930): ribs; Miyamoto (1925): humerus; Miyamoto (1927): pelvis; Hirai and Tabata (1928a): femur and tibia; Hirai and Tabata (1928b): talus. When measurements were available for both sides, only those from the right side were used.

[2)] Variable number according to Martin and Saller (1957) except for those with 'K' preceding the number, which are measurement item nos. of Kiyono's (1929) measurement system, and for those with 'KK,' which are measurement item nos. in Kikitsu (1930).

[3)] Cubic roots were calculated by the present author.

Table 2. Means and standard deviations for cranial and postcranial measurements of Australian Aboriginal males and females from Murray River Valley.[1)]

Variable[2)]		Males			Females		
		n	Mean	SD	*n*	Mean	SD
	SKULL						
V8	Glabella-opisthocranion	19	188.5	5.0	21	181.2	4.1
V7	Bi-parietal (= maximum cranial breadth)	19	130.7	4.8	21	126.8	3.9
V10	Basion-bregma	19	133.4	3.6	21	126.0	3.9
V9	Glabella-lambda	19	183.8	4.6	21	174.4	4.1
V33	Opisthion-inion	19	47.9	5.4	21	44.4	4.8
V29	Bi-zygion	19	137.4	4.7	21	125.6	4.3
V119	Mandibular bi-gonial breadth	19	99.2	7.4	21	91.3	5.7
	HUMERUS						
V186	R humerus length	19	335.2	17.9	21	310.1	18.9
	FEMUR						
V151	R femur length	19	460.5	26.7	21	426.4	21.5
V152	R femur midshaft AP	19	29.6	2.0	21	23.9	2.5

[1)] Estimates of basic statistics were recalculated here on the basis of raw data uploaded to the internet by Brown (2001). The individuals all include the variables listed here.
[2)] Variable number according to Brown (2001).

Table 3. Principal component analysis of correlations between postcranial measurements found to be strongly associated with cranial length (males).[1)]

Variable[2)]		Factor loadings						Total variance (%)
		PC I	II	III	IV	V	VI	
	SKULL							
1	Cranial length	0.71***	−0.55	0.10	0.09	0.12	0.25	89.83
8	Cranial breadth	0.38	0.24	0.73	−0.33	−0.05	0.12	86.79
17	Basi-bregmatic height	0.66***	−0.01	0.03	0.53	0.26	−0.30	86.78
3	Glabello-lambda length	0.76***	−0.53	0.05	0.15	0.17	0.11	91.87
31(2)	Inion-opisthion chord	0.11	−0.59	−0.57	−0.40	0.11	0.05	86.05
	Cubic root of endocranial capacity	0.55**	−0.30	0.61	−0.14	0.11	−0.21	83.31
	THORACIC VERTEBRA VIII							
4	Superior sagittal diameter of vertebral body	0.71***	−0.39	−0.06	−0.14	0.09	−0.20	72.46
7	Superior transverse diameter of vertebral body	0.60***	−0.36	0.17	0.18	−0.21	−0.02	59.31
	HUMERUS							
2	Total length	0.84***	0.29	−0.11	−0.11	0.08	−0.24	87.64
6	Minimum diameter of midshaft	0.50*	0.01	−0.07	0.45	−0.46	0.35	78.42
	PELVIS							
1	Height of innominate	0.86***	0.16	−0.21	−0.09	−0.11	0.03	83.50
2	Maximum pelvic breadth	0.73***	−0.03	−0.04	−0.26	−0.10	0.35	73.68
	FEMUR							
1	Maximum length	0.87***	0.36	−0.19	−0.06	0.11	−0.04	94.70
6	Sagittal diameter at midshaft	0.77***	0.26	0.03	−0.07	−0.27	0.03	74.96
	TIBIA							
1a	Maximum length	0.81***	0.33	−0.15	−0.25	−0.04	−0.04	84.50
8	Maximum diameter at midshaft	0.73***	0.12	−0.18	0.14	−0.21	−0.28	72.02
	BODY SIZE							
	Stature	0.39	0.47	−0.03	0.17	0.63	0.37	93.86
	Total contribution (%)	45.64	11.83	8.41	6.23	5.59	4.63	82.34
	Cumulative proportion (%)	45.64	57.47	65.89	72.11	77.71	82.34	82.34

[1)] Sample size is 28. Number of principal components was determined so that the cumulative proportion of the variances of the principal components exceeded 80%.
[2)] See the second footnote for Table 1.
* $P<0.05$; ** $P<0.01$; *** $P<0.001$, according to a two-tailed bootstrap test.

Table 4. Rotated solution of the first six principal components extracted from correlations between postcranial measurements found to be strongly associated with cranial length (males).[1)]

	Variable[2)]	Factor loadings					
		Fac I	II	III	IV	V	VI
	SKULL						
1	Cranial length	0.18	−0.89	0.06	0.23	0.15	0.07
8	Cranial breadth	0.22	−0.10	0.89	0.00	0.08	0.08
17	Basi-bregmatic height	0.39	−0.46	−0.05	0.10	0.23	−0.67*
3	Glabello-lambda length	0.25*	−0.90	0.00	0.16	0.13	−0.06
31(2)	Inion-opisthion chord	0.09	−0.45	−0.54	−0.26	−0.15	0.52**
	Cubic root of endocranial capacity	0.17	−0.63	0.58	−0.16	−0.10	−0.17
	THORACIC VERTEBRA VIII						
4	Superior sagittal diameter of vertebral body	0.47***	−0.70	−0.01	−0.11	−0.10	−0.01
7	Superior transverse diameter of vertebral body	0.24	−0.60	0.14	0.32	−0.17	−0.14
	HUMERUS						
2	Total length	0.87***	−0.23	0.11	−0.05	0.14	−0.17
6	Minimum diameter of midshaft	0.27	−0.21	−0.02	0.81	0.02	−0.07
	PELVIS						
1	Height of innominate	0.82***	−0.30	0.03	0.22	0.12	0.05
2	Maximum pelvic breadth	0.55*	−0.41	0.19	0.26	0.17	0.37
	FEMUR						
1	Maximum length	0.89***	−0.20	0.07	0.08	0.31	−0.10
6	Sagittal diameter at midshaft	0.74**	−0.17	0.27	0.31	0.01	−0.01
	TIBIA						
1a	Maximum length	0.88***	−0.15	0.15	0.05	0.15	0.07
8	Maximum diameter at midshaft	0.73*	−0.24	−0.05	0.21	−0.11	−0.27
	BODY SIZE						
	Stature	0.29	−0.02	0.08	0.01	0.92*	−0.10

1) Sample size is 28. Cumulative proportion of the variances of the six principal components is 82.34%.
2) See the second footnote for Table 1.
* $P<0.05$; ** $P<0.01$; *** $P<0.001$, according to a two-tailed bootstrap test.

Tables 22 to 25, and Spearman's rank correlation coefficients are listed in Table 26.

First, Tables 3 to 6 show the results of analyses of postcranial measurements found to be strongly associated with cranial length in previous separate analyses (Mizoguchi, 1994, 1995, 1996, 1997, 1998a, b, 2000, 2001, 2002, 2003b, c, 2004a, 2005). Among PCs and Facs, PC Is of both males (Table 3) and females (Table 5) were most highly significantly correlated with cranial length and, simultaneously, significantly correlated with the sagittal and transverse diameters of the vertebral body, humeral length and thickness, pelvic height and breadth, femoral length and thickness, and tibial length and thickness. It should be noted here that these PC Is are not significantly correlated with inion-opisthion chord or with stature at the 5% level.

The rotated factors which are significantly correlated with inion-opisthion chord (Fac VI for males in Table 4 and Fac IV for females in Table 6) have no significant correlation with any of the postcranial measurements or cranial length. Similarly, the rotated factors most strongly correlated with stature (Fac V for males in Table 4 and Fac IV for females in Table 6) have no significant correlation with any of the postcranial measurements or cranial length.

The factor significantly correlated with endocranial capacity is PC I for males (Table 3), which is also significantly correlated with cranial length, basi-bregmatic height, and many postcranial measurements; however, the female factor most strongly correlated with endocranial capacity is PC II (Table 5) or Fac II (Table 6), which seems to be relatively highly correlated with cranial breadth and basi-bregmatic height, but not with any of the postcranial measurements or cra-

Table 5. Principal component analysis of correlations between postcranial measurements found to be strongly associated with cranial length (females).[1)]

	Variable[2)]	Factor loadings PC I	II	III	IV	V	Total variance (%)
	SKULL						
1	Cranial length	0.61***	−0.27	0.65	0.12	−0.24	93.23
8	Cranial breadth	−0.08	0.78	−0.34	0.02	0.15	76.06
17	Basi-bregmatic height	0.31	0.77	0.33	−0.11	−0.01	80.36
3	Glabello-lambda length	0.58***	0.17	0.68	0.20	−0.30	96.12
31(2)	Inion-opisthion chord	0.16	0.10	−0.20	0.92*	−0.08	92.84
	Cubic root of endocranial capacity	0.21	0.82	0.31	0.06	0.07	82.34
	THORACIC VERTEBRA VIII						
4	Superior sagittal diameter of vertebral body	0.58**	−0.29	0.42	0.09	0.50	85.25
7	Superior transverse diameter of vertebral body	0.60**	0.15	−0.04	−0.35	0.43	68.38
	HUMERUS						
2	Total length	0.94***	−0.04	0.02	−0.13	−0.15	92.66
6	Minimum diameter of midshaft	0.73***	−0.31	−0.29	−0.14	−0.14	76.00
	PELVIS						
1	Height of innominate	0.93***	0.04	0.09	−0.05	0.09	87.90
2	Maximum pelvic breadth	0.83***	0.02	0.07	−0.11	0.24	75.63
	FEMUR						
1	Maximum length	0.88***	0.08	−0.29	−0.11	−0.20	90.45
6	Sagittal diameter at midshaft	0.70**	0.16	−0.49	−0.21	−0.33	90.98
	TIBIA						
1a	Maximum length	0.82***	0.07	−0.31	0.14	−0.24	85.80
8	Maximum diameter at midshaft	0.67***	−0.42	−0.03	0.11	0.19	67.88
	BODY SIZE						
	Stature	0.59	0.06	−0.40	0.43	0.40	85.57
	Total contribution (%)	42.81	14.19	12.30	8.02	6.65	83.97
	Cumulative proportion (%)	42.81	57.00	69.30	77.32	83.97	83.97

[1)] Sample size is 18. Number of principal components was determined so that the cumulative proportion of the variances of the principal components exceeded 80%.
[2)] See the second footnote for Table 1.
* $P<0.05$; ** $P<0.01$; *** $P<0.001$, according to a two-tailed bootstrap test.

nial length.

Tables 7 to 10 are the results of analyses on the interrelationships of costal chord and other postcranial measurements with cranial length. Although they are only for females because the sample sizes for costal measurements were too small in males (Mizoguchi, 1999), PC Is (Tables 7 and 9) indicate that costal chord is also significantly associated with cranial length together with many other postcranial measurements.

Tables 11 to 14 show the results of analyses of the correlations between measurements found to be significantly or relatively strongly associated with cranial breadth in previous separate analyses (Mizoguchi, 1995, 1996, 2007b). The factor most strongly correlated with cranial breadth is PC I in males (Table 11) and PC II in females (Table 13), but the variation patterns of factor loadings for these PCs are not similar (Table 20).

Tables 15 to 18 show the results of analyses of the correlations between measurements found to be significantly or relatively strongly associated with basi-bregmatic height in previous separate analyses (Mizoguchi, 1994, 1995, 1996, 1997, 1998a, 2004a, 2007b). The factor most highly significantly correlated with basi-bregmatic height is PC I both for males (Table 15) and for females (Table 17). PC Is are also significantly associated with the transverse diameter of the vertebral foramen and talar length and breadth, but not with stature.

Finally, Tables 22 to 25 show the results of

Table 6. Rotated solution of the first five principal components extracted from correlations between postcranial measurements found to be strongly associated with cranial length (females).[1)]

Variable[2)]		Factor loadings				
		Fac I	II	III	IV	V
	SKULL					
1	Cranial length	0.21	−0.04	0.91	0.00	0.25
8	Cranial breadth	0.06	0.67	−0.52	0.16	−0.10
17	Basi-bregmatic height	0.13	0.86	0.19	−0.09	0.07
3	Glabello-lambda length	0.20	0.38	0.87	0.10	0.11
31(2)	Inion-opisthion chord	0.06	0.04	0.08	0.95*	−0.08
	Cubic root of endocranial capacity	−0.00	0.89	0.13	0.07	0.07
	THORACIC VERTEBRA VIII					
4	Superior sagittal diameter of vertebral body	0.02	−0.07	0.42	0.06	0.82
7	Superior transverse diameter of vertebral body	0.38	0.26	−0.09	−0.21	0.65
	HUMERUS					
2	Total length	0.79***	0.09	0.39	−0.01	0.38
6	Minimum diameter of midshaft	0.77*	−0.27	0.12	0.00	0.27
	PELVIS					
1	Height of innominate	0.64*	0.19	0.35	0.06	0.56*
2	Maximum pelvic breadth	0.53	0.16	0.22	−0.01	0.64*
	FEMUR					
1	Maximum length	0.90*	0.12	0.12	0.08	0.24
6	Sagittal diameter at midshaft	0.94*	0.11	−0.08	0.01	0.00
	TIBIA					
1a	Maximum length	0.84*	0.09	0.15	0.31	0.15
8	Maximum diameter at midshaft	0.41	−0.31	0.24	0.17	0.57
	BODY SIZE					
	Stature	0.40	0.05	−0.19	0.61	0.54

[1)] Sample size is 18. Cumulative proportion of the variances of the five principal components is 83.97%.
[2)] See the second footnote for Table 1.
* $P<0.05$; ** $P<0.01$; *** $P<0.001$, according to a two-tailed bootstrap test.

analyses of the correlations between neurocranial and postcranial measurements of Australian Aborigines. From these results, it was found that the factor significantly associated with both neurocranial and postcranial measurements was only PC I for the male sample (Table 22), which shows that cranial length is significantly associated with humeral length as well as femoral length and thickness, but not with opisthion-inion chord. These findings are consistent with those from Japanese male and female samples (Tables 3 and 5).

Discussion

Previous separate analyses have revealed that cranial length is significantly associated with many postcranial measurements, such as vertebral body size, costal chord, pelvic width, and limb bone length and thickness (Mizoguchi, 1994, 1995, 1996, 1997, 1998a, b, 1999, 2000, 2001, 2002, 2003b, c, 2004a, 2005); that cranial breadth is significantly or relatively strongly associated with some cervical vertebral measurements and facial breadth at least in males (Mizoguchi, 1995, 1996, 2007b); and that basi-bregmatic height is significantly or relatively strongly associated with the diameters of the vertebral foramen and talar size (Mizoguchi, 1994, 1995, 1996, 1997, 1998a, 2004a); however, it has not been ascertained whether these measurements are separately or jointly associated with neurocranial measurements in the network of characters within the whole body. Furthermore, in previous studies by the present author, the role of brain and body size in such a character network was not examined. To clarify these points, the present analyses were carried out.

Table 7. Principal component analysis of correlations between postcranial measurements, including vertebral, costal and humeral, found to be strongly associated with cranial length (females).[1)]

	Variable[2)]	Factor loadings PC I	II	III	IV	V	VI	Total variance (%)
	SKULL							
1	Cranial length	0.66***	−0.04	−0.59	−0.35	−0.04	−0.16	94.31
8	Cranial breadth	−0.25	0.73	0.38	0.26	−0.20	0.01	84.84
17	Basi-bregmatic height	0.33	0.79	−0.14	0.15	0.25	0.13	85.22
3	Glabello-lambda length	0.63**	0.37	−0.57	−0.32	−0.09	−0.03	95.94
31(2)	Inion-opisthion chord	0.11	0.23	0.46	−0.75*	−0.10	0.03	85.89
	Cubic root of endocranial capacity	0.17	0.85	−0.17	0.17	−0.31	0.13	91.79
	ATLAS							
K2	Total transverse diameter	0.82***	−0.22	0.19	0.28	0.03	0.26	90.80
	THORACIC VERTEBRA VIII							
4	Superior sagittal diameter of vertebral body	0.79***	−0.18	−0.07	−0.01	0.02	0.38	79.96
7	Superior transverse diameter of vertebral body	0.61**	0.14	0.17	0.46	0.14	−0.41	80.95
	LUMBAR VERTEBRA IV							
4	Superior sagittal diameter of vertebral body	0.69***	−0.03	0.20	−0.21	0.33	0.40	82.61
7	Superior transverse diameter of vertebral body	0.68***	0.01	0.13	0.23	0.60	−0.15	91.66
	RIB IV							
4	Chord	0.64*	0.08	0.13	−0.37	−0.13	−0.08	59.72
KK-4C	Thickness at costal angle	0.49*	−0.27	−0.17	0.46	−0.47	0.32	87.82
	HUMERUS							
2	Total length	0.85***	0.04	−0.03	0.02	0.01	−0.36	84.98
6	Minimum diameter of midshaft	0.62**	−0.31	0.11	0.10	−0.51	−0.26	83.16
	BODY SIZE							
	Stature	0.57	0.07	0.68	−0.13	−0.22	−0.03	86.03
	Total contribution (%)	35.71	14.65	10.84	10.47	7.83	5.86	85.35
	Cumulative proportion (%)	35.71	50.36	61.20	71.67	79.50	85.35	85.35

[1)] Sample size is 18. Number of principal components was determined so that the cumulative proportion of the variances of the principal components exceeded 80%.

[2)] See the second footnote for Table 1.

* $P<0.05$; ** $P<0.01$; *** $P<0.001$, according to a two-tailed bootstrap test.

Concurrent relationships of postcranial measurements

PC Is in Japanese males and females (Tables 3 and 5) indicate that many postcranial measurements are concurrently associated with cranial length. Strong associations between humeral, femoral, and tibial thickness met our expectations from the fact that body weight or mechanical loading has a strong influence on the diaphyseal cross-sectional size of the femur (Ruff *et al.*, 1991). The significant associations of the vertebral body size with the limb bone thickness are also compatible with the same expectations.

Among the above findings, the strong associations of cranial length with, at least, humeral and femoral length and femoral thickness are supported by the results obtained from the Australian Aboriginal male sample (PC I in Table 22).

As regards pelvic measurements, however, Mizoguchi (1998b, 2003a, 2005) considered that the shapes of the neurocranium and maternal pelvis have been formed, mutually affecting each other, through the human evolutionary process and, in modern human populations, the close correspondence between neurocranial and pelvic forms is fixed as a population characteristic. Therefore, it was anticipated here that the manner of association of pelvic measurements with cranial length may differ from that for limb bone measurements; however, the results (PC Is in Tables 3 and 5) revealed that pelvic measurements

Table 8. Rotated solution of the first six principal components extracted from correlations between postcranial measurements, including vertebral, costal and humeral, found to be strongly associated with cranial length (females).[1)]

	Variable[2)]	Factor loadings					
		Fac I	II	III	IV	V	VI
	SKULL						
1	Cranial length	0.14	−0.08	−0.93***	−0.03	−0.13	0.15
8	Cranial breadth	0.03	0.74	0.43	−0.19	0.07	−0.26
17	Basi-bregmatic height	0.25	0.79	−0.21	0.07	0.21	0.27
3	Glabello-lambda length	0.07	0.34	−0.90**	−0.08	−0.06	0.17
31(2)	Inion-opisthion chord	−0.20	0.04	−0.09	−0.85**	0.28	0.07
	Cubic root of endocranial capacity	−0.02	0.93	−0.20	−0.03	−0.12	−0.07
	ATLAS						
K2	Total transverse diameter	0.41	−0.03	−0.06	−0.11	−0.52	0.67*
	THORACIC VERTEBRA VIII						
4	Superior sagittal diameter of vertebral body	0.14	−0.03	−0.34	−0.11	−0.40	0.70*
7	Superior transverse diameter of vertebral body	0.85*	0.17	−0.05	−0.02	−0.22	0.08
	LUMBAR VERTEBRA IV						
4	Superior sagittal diameter of vertebral body	0.18	−0.01	−0.18	−0.30	0.00	0.82***
7	Superior transverse diameter of vertebral body	0.78	−0.01	−0.12	0.02	0.10	0.53
	RIB IV						
4	Chord	0.21	0.03	−0.42	−0.55	−0.15	0.23
KK-4C	Thickness at costal angle	0.03	0.06	−0.09	0.20	−0.87**	0.27
	HUMERUS						
2	Total length	0.67*	0.03	−0.49	−0.25	−0.27	0.18
6	Minimum diameter of midshaft	0.34	−0.19	−0.24	−0.32	−0.72	−0.05
	BODY SIZE						
	Stature	0.33	0.07	0.12	−0.76*	−0.30	0.24

[1)] Sample size is 18. Cumulative proportion of the variances of the six principal components is 85.35%.
[2)] See the second footnote for Table 1.
* $P<0.05$; ** $P<0.01$; *** $P<0.001$, according to a two-tailed bootstrap test.

also had strong associations with cranial length together with many limb bone measurements. This suggests that bearing body weight may be a more important function of the pelvis than obstetric function, i.e., compatibility with the neurocranium in shape.

Furthermore, PC Is extracted from female data (Tables 7 and 9) show that the costal chord is also significantly associated with cranial length together with many other postcranial measurements. This finding again suggests a strong association between cranial length and body weight because the size of the thorax must be related with the amount of inspiration sustaining body mass or weight (Mizoguchi, 2004b).

The above findings support the present author's previous hypothesis that the variation in cranial length is related to the degree of development of skeletal muscles or body size (Mizoguchi, 2001, 2003b, c, 2004b).

Reappraisal of inion-opisthion chord

In Mizoguchi's (2001, 2003b, c, 2004b) hypothesis, the nuchal planum plays an important role as an intermediate between cranial length and postcranial measurements.

Howells (1957), using European male skulls, obtained a correlation coefficient of 0.579 for cranial length and the greatest depth of the curve of the occipital bone on the sagittal contour (Sag Op-lambda/Max subtense), which was higher than that of 0.311 between cranial length and the greatest depth of the curve of the frontal bone (Sag Nas-bregma/Max subtense). Kanda (1968) carried out factor analyses and the rotation for two samples of Japanese male skulls, and showed that cranial length is highly associated with the lower occipital arc (inion-opisthion) in a sample

Table 9. Principal component analysis of correlations between postcranial measurements, including costal, sacral, pelvic and lower limb bone, found to be strongly associated with cranial length (females).[1)]

	Variable[2)]	Factor loadings					Total variance (%)
		PC I	II	III	IV	V	
	SKULL						
1	Cranial length	0.60***	−0.57	0.32	0.31	−0.08	89.33
8	Cranial breadth	−0.13	0.86	0.16	−0.21	0.24	87.99
17	Basi-bregmatic height	0.31	0.48	0.68	0.01	−0.17	82.25
3	Glabello-lambda length	0.58**	−0.32	0.60	0.35	−0.09	93.45
31(2)	Inion-opisthion chord	0.18	0.45	−0.27	0.66	0.24	80.28
	Cubic root of endocranial capacity	0.20	0.53	0.71	−0.06	0.26	89.65
	RIB IV						
4	Chord	0.61*	−0.10	0.02	0.47	0.10	61.21
KK-4C	Thickness at costal angle	0.49*	−0.41	0.09	−0.53	0.37	82.93
	SACRUM						
4	Anterior superior transverse arc	0.74***	−0.55	0.01	−0.12	−0.00	85.75
	PELVIS						
1	Height of innominate	0.91***	0.11	0.03	−0.18	0.04	87.47
2	Maximum pelvic breadth	0.84***	0.04	0.02	−0.25	0.20	81.80
	FEMUR						
1	Maximum length	0.82***	0.33	−0.21	−0.11	−0.36	96.48
6	Sagittal diameter at midshaft	0.67**	0.35	−0.24	−0.28	−0.34	81.35
	TIBIA						
1a	Maximum length	0.75***	0.40	−0.24	0.11	−0.29	87.68
8	Maximum diameter at midshaft	0.66***	−0.27	−0.31	−0.04	0.26	66.64
	BODY SIZE						
	Stature	0.58	0.36	−0.39	0.22	0.36	79.86
	Total contribution (%)	37.70	18.51	12.21	9.11	5.86	83.38
	Cumulative proportion (%)	37.70	56.21	68.42	77.52	83.38	83.38

[1)] Sample size is 19. Number of principal components was determined so that the cumulative proportion of the variances of the principal components exceeded 80%.

[2)] See the second footnote for Table 1.

* $P<0.05$; ** $P<0.01$; *** $P<0.001$, according to a two-tailed bootstrap test.

from the Kinai district (factor loadings of 0.701 and 0.950, respectively), but not in another sample from the Tohoku district. Further, Howells (1972) conducted a factor analysis of the pooled within-group variance/covariance matrix based on 17 different populations, and obtained a rotated factor called "simple factor of occipital angulation," which indicated that occipital subtense was relatively highly associated with glabello-occipital length, with factor loadings of 0.91 and 0.47, respectively.

From these findings and his own results of postcranial measurements, Mizoguchi (2001, 2003b, c, 2004b) considered that the degree of general development of skeletal muscles, including nuchal muscles, was a cause of the strong association between cranial length and limb bone measurements. Later, Mizoguchi (2008) examined direct relationships between cranial length and occipital measurements to confirm Howell's and Kanda's findings; however, the results did not show any significant associations. The rotated factor IV from male data on the occipital bone has a factor loading of 0.64 for cranial length and 0.85 for the inion-opisthion chord. For females, factor loadings for a corresponding factor, PC IV, are 0.48 and 0.46, respectively. These factor loadings are not significant at the 5% level.

In the present study, it was further confirmed that the inion-opisthion chord is not significantly associated with cranial length or with any post-

Table 10. Rotated solution of the first five principal components extracted from correlations between postcranial measurements, including costal, sacral, pelvic and lower limb bone, found to be strongly associated with cranial length (females).[1)]

Variable[2)]		Factor loadings				
		Fac I	II	III	IV	V
	SKULL					
1	Cranial length	0.07	−0.90	−0.04	0.00	0.26
8	Cranial breadth	0.10	0.61	0.67	0.20	−0.09
17	Basi-bregmatic height	0.29	−0.22	0.82	−0.07	−0.13
3	Glabello-lambda length	0.07	−0.90	0.31	0.01	0.13
31(2)	Inion-opisthion chord	0.10	−0.00	0.06	0.85	−0.24
	Cubic root of endocranial capacity	−0.00	−0.03	0.94*	0.07	0.09
	RIB IV					
4	Chord	0.22	−0.56	0.01	0.47	0.15
KK-4C	Thickness at costal angle	0.04	−0.15	−0.00	−0.20	0.87*
	SACRUM					
4	Anterior superior transverse arc	0.30	−0.59	−0.21	−0.08	0.61*
	PELVIS					
1	Height of innominate	0.64	−0.28	0.23	0.18	0.55*
2	Maximum pelvic breadth	0.50	−0.21	0.20	0.17	0.67*
	FEMUR					
1	Maximum length	0.94*	−0.13	0.08	0.15	0.16
6	Sagittal diameter at midshaft	0.88	0.05	0.07	0.03	0.19
	TIBIA					
1a	Maximum length	0.85	−0.15	0.08	0.35	0.05
8	Maximum diameter at midshaft	0.28	−0.25	−0.26	0.30	0.61
	BODY SIZE					
	Stature	0.38	0.06	0.03	0.74	0.31

[1)] Sample size is 19. Cumulative proportion of the variances of the five principal components is 83.38%.
[2)] See the second footnote for Table 1.
* $P<0.05$; ** $P<0.01$; *** $P<0.001$, according to a two-tailed bootstrap test.

Table 11. Principal component analysis of correlations between measurements found to be strongly associated with cranial breadth (males).[1)]

Variable[2)]		Factor loadings				Total variance (%)
		PC I	II	III	IV	
	SKULL					
1	Cranial length	0.64***	0.51	0.08	−0.19	70.57
8	Cranial breadth	0.69***	−0.27	−0.44	−0.15	75.94
17	Basi-bregmatic height	0.52**	0.57	0.32	0.29	78.27
45	Bizygomatic breadth	0.85***	−0.07	−0.05	0.28	80.24
65(1)	Bicoronoid breadth	0.76***	−0.24	0.15	0.45	86.58
	Cubic root of endocranial capacity	0.65***	0.39	−0.36	−0.42	88.72
	AXIS					
K6	Total breadth	0.60***	−0.64	0.01	−0.14	78.86
	BODY SIZE					
	Stature	0.32	−0.21	0.77	−0.45	94.75
Total contribution (%)		41.73	16.52	13.13	10.36	81.74
Cumulative proportion (%)		41.73	58.25	71.38	81.74	81.74

[1)] Sample size is 29. Number of principal components was determined so that the cumulative proportion of the variances of the principal components exceeded 80%.
[2)] See the second footnote for Table 1.
* $P<0.05$; ** $P<0.01$; *** $P<0.001$, according to a two-tailed bootstrap test.

Table 12. Rotated solution of the first four principal components extracted from correlations between measurements found to be strongly associated with cranial breadth (males).[1)]

Variable[2)]		Factor loadings			
		Fac I	II	III	IV
	SKULL				
1	Cranial length	0.09	0.61	0.17	0.54
8	Cranial breadth	0.68	0.53	−0.07	−0.13
17	Basi-bregmatic height	0.07	0.17	0.06	0.86*
45	Bizygomatic breadth	0.75*	0.25	−0.01	0.43
65(1)	Bicoronoid breadth	0.81	−0.06	0.07	0.45
	Cubic root of endocranial capacity	0.16	0.91*	−0.01	0.18
	AXIS				
K6	Total breadth	0.78	0.13	0.34	−0.23
	BODY SIZE				
	Stature	0.11	0.02	0.96	0.11

[1)] Sample size is 29. Cumulative proportion of the variances of the four principal components is 81.74%.
[2)] See the second footnote for Table 1.
* $P<0.05$; ** $P<0.01$; *** $P<0.001$, according to a two-tailed bootstrap test.

Table 13. Principal component analysis of correlations between measurements found to be strongly associated with cranial breadth (females).[1)]

Variable[2)]		Factor loadings				Total variance (%)
		PC I	II	III	IV	
	SKULL					
1	Cranial length	0.03	0.80	−0.34	−0.42	93.42
8	Cranial breadth	0.53	−0.79	0.02	−0.02	90.15
17	Basi-bregmatic height	0.82***	−0.06	−0.30	−0.03	76.32
45	Bizygomatic breadth	0.58	0.35	0.29	0.26	61.96
65(1)	Bicoronoid breadth	0.76***	0.27	−0.06	−0.01	65.46
	Cubic root of endocranial capacity	0.79***	−0.25	−0.26	−0.32	85.10
	AXIS					
K6	Total breadth	0.58	0.37	0.18	0.50	74.57
	BODY SIZE					
	Stature	0.28	0.07	0.80	−0.50	96.86
Total contribution (%)		36.18	20.85	12.84	10.61	80.48
Cumulative proportion (%)		36.18	57.03	69.87	80.48	80.48

[1)] Sample size is 19. Number of principal components was determined so that the cumulative proportion of the variances of the principal components exceeded 80%.
[2)] See the second footnote for Table 1.
* $P<0.05$; ** $P<0.01$; *** $P<0.001$, according to a two-tailed bootstrap test.

cranial measurements (PC I in Table 3, Fac VI in Table 4, PC I in Table 5, and Fac IV in Table 6). This is also clear in the results of analyses of Australian Aboriginal data (PC I in Table 22, Fac III in Table 23, PC I in Table 24, and Fac IV in Table 25).

It is considered that inion-opisthion chord at least is not an appropriate measure for the size of the nuchal planum, presumably because of the difficulty in determining a landmark, *inion*. Although the importance of nuchal planum size should be examined in the future, other possible causal factors of the strong associations between cranial length and limb bone measurements may be considered.

Masticatory muscles are also skeletal muscles,

Table 14. Rotated solution of the first four principal components extracted from correlations between measurements found to be strongly associated with cranial breadth (females).[1)]

	Variable[2)]	Factor loadings			
		Fac I	II	III	IV
	SKULL				
1	Cranial length	0.10	0.96	0.02	0.04
8	Cranial breadth	0.62	−0.71	0.09	−0.07
17	Basi-bregmatic height	0.80*	−0.01	−0.08	0.34
45	Bizygomatic breadth	0.15	0.04	0.19	0.75
65(1)	Bicoronoid breadth	0.55	0.19	0.10	0.55
	Cubic root of endocranial capacity	0.91*	−0.06	0.10	0.08
	AXIS				
K6	Total breadth	0.10	−0.01	−0.04	0.86
	BODY SIZE				
	Stature	0.05	−0.02	0.98*	0.12

[1)] Sample size is 19. Cumulative proportion of the variances of the four principal components is 80.48%.
[2)] See the second footnote for Table 1.
* $P<0.05$; ** $P<0.01$; *** $P<0.001$, according to a two-tailed bootstrap test.

Table 15. Principal component analysis of correlations between postcranial measurements found to be strongly associated with basi-bregmatic height (males).[1)]

	Variable[2)]	Factor loadings					Total variance (%)
		PC I	II	III	IV	V	
	SKULL						
1	Cranial length	0.64***	0.15	0.11	0.26	0.52	77.99
8	Cranial breadth	0.38	0.36	0.57	0.31	−0.45	89.28
17	Basi-bregmatic height	0.70***	−0.00	−0.32	0.39	0.07	74.19
66	Bigonial breadth	0.62**	−0.49	−0.19	−0.06	−0.28	73.79
	Cubic root of endocranial capacity	0.71***	0.13	0.54	0.18	0.12	85.93
	ATLAS						
K1	Total sagittal diameter	0.53*	−0.15	−0.55	0.34	0.06	72.58
	LUMBAR VERTEBRA III						
10	Sagittal diameter of vertebral foramen	0.54**	−0.57	0.20	−0.36	0.18	81.51
11	Transverse diameter of vertebral foramen	0.74***	−0.34	0.36	−0.27	−0.01	86.74
	TALUS						
1	Length	0.77***	0.29	−0.21	−0.22	−0.07	77.88
2	Breadth	0.67***	0.29	−0.32	−0.20	−0.38	82.00
	BODY SIZE						
	Stature	0.28	0.70	−0.12	−0.46	0.24	85.48
	Total contribution (%)	37.90	13.93	12.67	8.84	7.34	80.67
	Cumulative proportion (%)	37.90	51.83	64.49	73.33	80.67	80.67

[1)] Sample size is 28. Number of principal components was determined so that the cumulative proportion of the variances of the principal components exceeded 80%.
[2)] See the second footnote for Table 1.
* $P<0.05$; ** $P<0.01$; *** $P<0.001$, according to a two-tailed bootstrap test.

but according to Korfage *et al.* (2005a, b), fine control or the composition of muscle fibers greatly differs between masticatory and other skeletal muscles. Further, Weijs and Hillen (1986) have showed that, although head width has a significant correlation with the cross-sectional area of the masseter muscle, cranial base length, which is significantly associated with cranial length in both sexes (Mizoguchi, 2008), is not significantly correlated with any of the four masticatory mus-

Table 16. Rotated solution of the first five principal components extracted from correlations between postcranial measurements found to be strongly associated with basi-bregmatic height (males).[1)]

	Variable[2)]	Factor loadings				
		Fac I	II	III	IV	V
	SKULL					
1	Cranial length	0.17	−0.16	0.13	0.31	0.78
8	Cranial breadth	0.08	−0.00	0.94*	−0.01	0.09
17	Basi-bregmatic height	0.14	−0.12	0.14	0.77*	0.32
66	Bigonial breadth	0.02	−0.63	0.08	0.55	−0.18
	Cubic root of endocranial capacity	0.14	−0.37	0.60	0.09	0.58
	ATLAS					
K1	Total sagittal diameter	0.06	−0.07	−0.11	0.83*	0.14
	LUMBAR VERTEBRA III					
10	Sagittal diameter of vertebral foramen	0.00	−0.88	−0.11	0.06	0.17
11	Transverse diameter of vertebral foramen	0.15	−0.85	0.27	0.10	0.21
	TALUS					
1	Length	0.69*	−0.28	0.18	0.41	0.13
2	Breadth	0.67	−0.20	0.27	0.48	−0.18
	BODY SIZE					
	Stature	0.87***	0.12	−0.05	−0.14	0.25

[1)] Sample size is 28. Cumulative proportion of the variances of the five principal components is 80.67%.
[2)] See the second footnote for Table 1.
* $P<0.05$; ** $P<0.01$; *** $P<0.001$, according to a two-tailed bootstrap test.

Table 17. Principal component analysis of correlations between postcranial measurements found to be strongly associated with basi-bregmatic height (females).[1)]

	Variable[2)]	Factor loadings					Total variance (%)
		PC I	II	III	IV	V	
	SKULL						
1	Cranial length	0.30	0.74	0.21	−0.01	−0.45	88.80
8	Cranial breadth	0.28	−0.85	0.27	−0.07	0.19	90.81
17	Basi-bregmatic height	0.71***	−0.28	0.35	0.35	−0.06	82.42
66	Bigonial breadth	0.36	0.77	0.31	0.13	0.01	83.61
	Cubic root of endocranial capacity	0.48	−0.53	0.36	0.31	−0.41	90.87
	ATLAS						
K1	Total sagittal diameter	0.54	0.24	0.25	−0.23	0.61	84.39
	LUMBAR VERTEBRA III						
10	Sagittal diameter of vertebral foramen	0.41	0.19	−0.43	0.66	0.16	85.26
11	Transverse diameter of vertebral foramen	0.65*	0.01	−0.46	0.24	0.23	74.65
	TALUS						
1	Length	0.85***	0.06	−0.07	−0.30	−0.05	82.49
2	Breadth	0.81**	0.02	0.02	−0.44	−0.06	85.17
	BODY SIZE						
	Stature	0.42	−0.22	−0.68	−0.27	−0.34	87.22
	Total contribution (%)	31.38	21.52	12.67	10.53	8.96	85.06
	Cumulative proportion (%)	31.38	52.90	65.57	76.10	85.06	85.06

[1)] Sample size is 19. Number of principal components was determined so that the cumulative proportion of the variances of the principal components exceeded 80%.
[2)] See the second footnote for Table 1.
* $P<0.05$; ** $P<0.01$; *** $P<0.001$, according to a two-tailed bootstrap test.

Table 18. Rotated solution of the first five principal components extracted from correlations between postcranial measurements found to be strongly associated with basi-bregmatic height (females).[1)]

	Variable[2)]	Factor loadings				
		Fac I	II	III	IV	V
	SKULL					
1	Cranial length	0.04	0.93	0.04	−0.15	0.02
8	Cranial breadth	0.61	−0.67	0.15	−0.09	0.23
17	Basi-bregmatic height	0.82*	0.06	−0.26	−0.09	0.25
66	Bigonial breadth	0.02	0.81	−0.16	0.11	0.38
	Cubic root of endocranial capacity	0.93*	−0.05	−0.01	−0.13	−0.14
	ATLAS					
K1	Total sagittal diameter	0.02	0.10	−0.11	−0.07	0.90**
	LUMBAR VERTEBRA III					
10	Sagittal diameter of vertebral foramen	0.08	0.14	−0.91*	−0.01	−0.01
11	Transverse diameter of vertebral foramen	0.10	−0.05	−0.73	−0.39	0.24
	TALUS					
1	Length	0.28	0.20	−0.15	−0.69**	0.45
2	Breadth	0.28	0.17	0.03	−0.71**	0.50*
	BODY SIZE					
	Stature	−0.03	−0.16	−0.22	−0.87	−0.23

[1)] Sample size is 19. Cumulative proportion of the variances of the five principal components is 85.06%.
[2)] See the second footnote for Table 1.
* $P<0.05$; ** $P<0.01$; *** $P<0.001$, according to a two-tailed bootstrap test.

Table 19. Spearman's rank correlation coefficients between males and females for the variation patterns of factor loadings of the principal components and/or rotated factors obtained from the data set on cranial length and other cranial and postcranial measurements.[1)]

		Male	PC I	II	III	IV	V	VI	Fac I	II	III	IV	V	VI
Female	PC	I	.78***	.49*	.52*	–	–	–	.79***	–	–	–	–	–
		II	–	–	.52*	–	–	–	–	–	–	–	–	–
		III	–	.67**	–	–	–	–	–	.90***	–	–	–	–
		IV	–	–	–	–	.66**	–	–	–	–	.56*	–	–
		V	–	–	–	–	–	–	–	–	–	–	–	–
	Fac	I	.66**	.65**	–	–	–	–	.78***	.56*	–	.49*	–	–
		II	–	–	.53*	–	–	–	–	–	.50*	–	–	–
		III	.51*	–	–	–	–	–	–	.63**	–	–	–	–
		IV	–	–	–	–	–	–	–	–	–	.54*	–	–
		V	–	–	–	–	–	–	–	–	–	–	–	–

[1)] Only rank correlation coefficients significant at the 5% level are listed here. The signs of rank correlation coefficients are removed because the signs of factor loadings are reversible. The original factor loadings are listed in Tables 3, 4, 5, and 6.
* $P<0.05$; ** $P<0.01$; *** $P<0.001$, according to a two-tailed test.

cles (masseter, temporal, and medial and lateral pterygoid muscles). Therefore, it seems unlikely that the strong associations between cranial length and postcranial measurements are caused by common factors controlling masticatory and other skeletal muscles. Presumably, we should seek other causes for the strong associations using better measures for the nuchal planum.

Associations with body size

In the present study, stature was used as a measure of body size, but body weight or the amount of skeletal muscle may be a better measure. According to Ruff *et al.* (1991), body weight or mechanical loading has a strong influence on the diaphyseal cross-sectional size of the femur in adults after initial skeletal maturity (18 years). In

Table 20. Spearman's rank correlation coefficients between males and females for the variation patterns of factor loadings of the principal components and/or rotated factors obtained from the data set on cranial breadth and other cranial and postcranial measurements.[1)]

	Male	PC I	II	III	IV	Fac I	II	III	IV
Female PC	I	–	–	–	–	–	–	–	–
	II	–	–	–	–	–	–	–	–
	III	–	–	–	–	–	–	–	–
	IV	–	–	–	–	.76*	–	–	–
Fac	I	–	–	–	–	–	–	.71*	–
	II	–	–	–	–	–	–	–	–
	III	–	–	–	–	–	–	–	–
	IV	–	–	–	–	–	–	–	–

[1)] Only rank correlation coefficients significant at the 5% level are listed here. The signs of rank correlation coefficients are removed because the signs of factor loadings are reversible. The original factor loadings are listed in Tables 11, 12, 13, and 14.
* $P<0.05$; ** $P<0.01$; *** $P<0.001$, according to a two-tailed test.

Table 21. Spearman's rank correlation coefficients between males and females for the variation patterns of factor loadings of the principal components and/or rotated factors obtained from the data set on basi-bregmatic height and other cranial and postcranial measurements.[1)]

	Male	PC I	II	III	IV	V	Fac I	II	III	IV	V
Female PC	I	.65*	–	–	–	–	–	–	–	–	–
	II	–	–	–	–	–	–	–	.67*	–	–
	III	–	–	–	.81**	–	–	–	–	–	–
	IV	–	.69*	–	–	–	.62*	–	–	–	–
	V	–	–	–	–	–	–	–	–	–	–
Fac	I	–	–	–	–	–	–	–	.75**	–	–
	II	–	–	–	–	–	–	–	–	–	–
	III	–	–	–	–	–	–	–	–	–	–
	IV	–	.69*	–	–	–	.96***	–	–	–	–
	V	–	–	.71*	–	.63*	–	–	–	.84**	.61*

[1)] Only rank correlation coefficients significant at the 5% level are listed here. The signs of rank correlation coefficients are removed because the signs of factor loadings are reversible. The original factor loadings are listed in Tables 15, 16, 17, and 18.
* $P<0.05$; ** $P<0.01$; *** $P<0.001$, according to a two-tailed test.

the present analyses (Tables 3 and 5), stature was not significantly correlated with PC Is, which are significantly correlated with the length and thickness of limb bones, vertebral body size, and pelvic size, as well as with cranial length. On the other hand, the factors most highly correlated with stature (Fac V in Table 4 and Fac IV in Table 6) had no significant correlations with any postcranial measurements or cranial length. How should these findings be interpreted?

As observed in practice, stature includes many elements, such as the cranium, vertebral bodies, lower limb bones, etc. It is natural that variation in the length of one limb bone does not explain all variations in stature if there are many different factors, genetic and environmental, influencing each component bone separately. As already stated above, therefore, the strong associations found between postcranial bone measurements, especially limb bone thickness and vertebral body size, seem to be explained reasonably by body weight rather than stature.

In the future, however, the relationships between cranial length and stature should be examined in more depth because, as discussed by Mizoguchi (2007a), there are two opposite views based on inter-group data, one of which maintains that head or cranial length is not significant-

Table 22. Principal component analysis of correlations between cranial and postcranial measurements of Australian Aboriginal males.[1)]

Variable[2)]		Factor loadings					Total variance (%)
		PC I	II	III	IV	V	
	SKULL						
V8	Glabella-opisthocranion	0.84***	0.27	−0.15	−0.04	−0.29	89.37
V7	Bi-parietal (=maximum cranial breadth)	0.10	0.73	−0.30	0.54	−0.13	94.38
V10	Basion-bregma	0.64***	−0.33	−0.41	−0.13	0.24	76.56
V9	Glabella-lambda	0.89***	0.20	−0.20	−0.08	−0.16	91.00
V33	Opisthion-inion	0.35	0.28	0.75	0.17	0.05	79.58
V29	Bi-zygion	0.48*	0.41	−0.17	−0.19	0.61	84.18
V119	Mandibular bi-gonial breadth	0.53*	−0.26	0.18	0.49	0.47	83.85
	HUMERUS						
V186	R humerus length	0.78***	−0.42	0.07	0.18	−0.21	85.96
	FEMUR						
V151	R femur length	0.84***	−0.34	0.08	0.05	−0.18	85.66
V152	R femur midshaft AP	0.57***	0.34	0.37	−0.49	−0.01	80.61
Total contribution (%)		41.93	14.87	10.90	8.92	8.50	85.12
Cumulative proportion (%)		41.93	56.80	67.70	76.62	85.12	85.12

[1)] Sample size is 19. Number of principal components was determined so that the cumulative proportion of the variances of the principal components exceeded 80%.
[2)] Variable number according to Brown (2001).
* $P<0.05$; ** $P<0.01$; *** $P<0.001$, according to a two-tailed bootstrap test.

Table 23. Rotated solution of the first five principal components extracted from correlations between cranial and postcranial measurements of Australian Aboriginal males.[1)]

Variable[2)]		Factor loadings				
		Fac I	II	III	IV	V
	SKULL					
V8	Glabella-opisthocranion	0.83**	0.28	0.19	0.30	−0.09
V7	Bi-parietal (=maximum cranial breadth)	0.02	0.09	0.03	0.97**	−0.01
V10	Basion-bregma	0.59	0.42	−0.35	−0.21	0.28
V9	Glabella-lambda	0.84***	0.38	0.12	0.22	−0.01
V33	Opisthion-inion	0.08	0.01	0.85	0.08	0.25
V29	Bi-zygion	0.11	0.88**	0.10	0.14	0.15
V119	Mandibular bi-gonial breadth	0.24	0.16	0.14	−0.00	0.86***
	HUMERUS					
V186	R humerus length	0.82	−0.12	0.09	−0.14	0.39*
	FEMUR					
V151	R femur length	0.84	0.00	0.14	−0.17	0.31
V152	R femur midshaft AP	0.39	0.44	0.61	−0.14	−0.25

[1)] Sample size is 19. Cumulative proportion of the variances of the five principal components is 85.12%.
[2)] Variable number according to Brown (2001).
* $P<0.05$; ** $P<0.01$; *** $P<0.001$, according to a two-tailed bootstrap test.

ly correlated with stature (Kouchi, 2000; four results obtained by Mizoguchi [2007a] using Ivanovsky's [1923], Angel's [1944], Kurisu's [1970], and Kouchi's [2004] data) and the other suggests that head or cranial length is relatively highly associated with stature (Jantz *et al*., 1992; Buretic-Tomljanovic, 2004). Furthermore, preliminary analysis on inter-population correlations between cranial and limb bone measurements (Mizoguchi, 2007a) has shown that cranial length

Table 24. Principal component analysis of correlations between cranial and postcranial measurements of Australian Aboriginal females.[1)]

	Variable[2)]	Factor loadings				Total variance (%)
		PC I	II	III	IV	
	SKULL					
V8	Glabella-opisthocranion	0.47	0.80*	−0.07	−0.07	88.12
V7	Bi-parietal (= maximum cranial breadth)	0.08	0.71	−0.16	−0.28	61.26
V10	Basion-bregma	0.51	−0.24	0.45	0.02	51.85
V9	Glabella-lambda	0.34	0.81*	−0.24	0.13	84.23
V33	Opisthion-inion	−0.01	0.62	0.25	0.68	90.15
V29	Bi-zygion	0.52	0.21	0.46	−0.56	83.63
V119	Mandibular bi-gonial breadth	0.53*	0.06	0.64*	0.08	70.20
	HUMERUS					
V186	R humerus length	0.84**	−0.28	−0.40*	−0.01	94.78
	FEMUR					
V151	R femur length	0.85**	−0.20	−0.42*	0.01	94.87
V152	R femur midshaft AP	0.73	−0.43	0.03	0.35	83.40
Total contribution (%)		31.19	25.93	13.15	9.99	80.25
Cumulative proportion (%)		31.19	57.11	70.26	80.25	80.25

1) Sample size is 21. Number of principal components was determined so that the cumulative proportion of the variances of the principal components exceeded 80%.
2) Variable number according to Brown (2001).
* $P<0.05$; ** $P<0.01$; *** $P<0.001$, according to a two-tailed bootstrap test.

Table 25. Rotated solution of the first four principal components extracted from correlations between cranial and postcranial measurements of Australian Aboriginal females.[1)]

	Variable[2)]	Factor loadings			
		Fac I	II	III	IV
	SKULL				
V8	Glabella-opisthocranion	0.14	0.89*	0.19	0.18
V7	Bi-parietal (=maximum cranial breadth)	−0.15	0.76	−0.05	−0.06
V10	Basion-bregma	0.28	−0.18	0.64	0.03
V9	Glabella-lambda	0.15	0.84	−0.06	0.33
V33	Opisthion-inion	−0.18	0.31	0.08	0.87*
V29	Bi-zygion	0.01	0.38*	0.75	−0.36
V119	Mandibular bi-gonial breadth	0.13	0.04	0.80	0.22
	HUMERUS				
V186	R humerus length	0.95	0.10	0.12	−0.18
	FEMUR				
V151	R femur length	0.95*	0.16	0.10	−0.14
V152	R femur midshaft AP	0.78	−0.27	0.35	0.19

1) Sample size is 21. Cumulative proportion of the variances of the four principal components is 80.25%.
2) Variable number according to Brown (2001).
* $P<0.05$; ** $P<0.01$; *** $P<0.001$, according to a two-tailed bootstrap test.

is not significantly correlated with humeral, radial, ulnar, femoral, tibial, or fibular length. These are not compatible with the present results based on intra-group data and this is also a future task to be solved.

Associations with brain size

Mizoguchi (2008) showed that the cubic root of endocranial capacity is significantly associated with the three main neurocanial measurements, especially with cranial length and basi-bregmatic

Table 26. Spearman's rank correlation coefficients between males and females for the variation patterns of factor loadings of the principal components and/or rotated factors obtained from the Australian Aboriginal data sets.[1)]

		Male	PC I	II	III	IV	V	Fac I	II	III	IV	V
Female	PC	I	–	–	–	–	–	–	–	–	0.66*	–
		II	–	–	–	–	–	–	–	–	0.84**	–
		III	–	–	–	–	0.85**	–	–	–	–	–
		IV	–	–	–	–	–	–	–	–	–	–
	Fac	I	0.68*	.71*	–	–	–	0.79**	–	–	0.67*	–
		II	–	–	–	–	–	–	–	–	0.85**	–
		III	–	–	–	–	–	–	–	–	–	–
		IV	–	–	–	–	–	–	–	–	–	–

[1)] Only rank correlation coefficients significant at the 5% level are listed here. The signs of rank correlation coefficients are removed because the signs of factor loadings are reversible. The original factor loadings are listed in Tables 22, 23, 24, and 25.

* $P<0.05$; ** $P<0.01$; *** $P<0.001$, according to a two-tailed test.

height, in males, and, in females, only with basi-bregmatic height. This can be confirmed in the results of the present analyses (PC Is in Tables 3, 11, and 15 for males; and PC I in Table 13 or Fac I in Table 14, and Fac I in Table 18 for females), but the relationship of endocranial capacity with postcranial measurements tends to be different in males and females. In males, endocranial capacity has significant associations with postcranial measurements along with cranial length and basi-bregmatic height while, in females, no such tendency is found. This sex difference may be due merely to the sex difference in the amount of skeletal muscle primarily originating from the sexual dimorphism in body size. Namely, the sex difference in the manner of association of endocranial capacity with postcranial measurements may be an aspect of the phenomenon that stronger associations between neurocranial size, including brain size, and postcranial measurements occur only in males whose skeletal muscles generally tend to develop better and whose body size tends to be larger than in females, as reported by Mizoguchi (2003c, 2004b) to explain the fact that significant associations between cranial length and the measurements of relatively small or thin extremity bones, like the scapula, ulna, radius, patella, and fibula, are found only in males, while significant associations with relatively large or thick limb bones, like the humerus, femur, and tibia, are found in both males and females.

Sex difference in the relationship between cranial and facial breadths

In addition, a sex difference is found in the manner of connecting cranial breadth with facial breadth. The PC or Fac most highly correlated with cranial breadth is also significantly correlated with bizygomatic and bicoronoid breadth as well as the total breadth of the axis in males (PC I in Table 11), but not with any of these in females (PC II in Table 13). Although masticatory muscles are qualitatively different from other skeletal muscles (Korfage *et al.*, 2005a, b), this between-sex difference may also be explained in the same way as the above-mentioned sex difference in the manner of association of endocranial capacity with postcranial measurements.

Basi-bregmatic height, vertebral foramen width, and talar size

In previous studies, it was found that basi-bregmatic height is strongly associated with the transverse diameters of the vertebral foramina of almost all vertebrae (Mizoguchi, 1994, 1995, 1996, 1997, 1998a), and also with many talar measurements (Mizoguchi, 2004a). In the present study, PC Is in Tables 15 and 17 indicate that basi-bregmatic height is simultaneously associated with the transverse diameter of the vertebral foramen (third lumbar vertebra) and talar length and breadth in both sexes. Furthermore, only in males, the same PC I shows that these measurements are significantly associated also with cranial length, bigonial breadth, endocranial capacity, the total sagittal diameter of the atlas, and the sagittal diameter of the vertebral foramen (third lumbar vertebra). As shown in Table 21, however, Spearman's rank correlation of 0.65 between male and female PC Is is significant at the 5% level, implying that these two PCs tend to have similar associations with the original variables.

Mizoguchi (1998a) stated that the associations between basi-bregmatic height and the transverse diameters of the vertebral foramina may partly be explained by supposing that the vertebral foramen is an extension of the cranial cavity, as already noted by Mizoguchi (1994, 1995, 1997). If so, however, it would not be strange that cranial length and cranial breadth are also associated with vertebral foramen size; however, in the PCA of the three main neurocranial measurements and the transverse diameters of vertebral foramina of all the vertebrae (Mizoguchi, 1998a), neither cranial length nor cranial breadth had any significant associations with basi-bregmatic height and the transverse diameters of the vertebral foramina; therefore, Mizoguchi could not find any clear explanation of these findings at that time.

As regards the strong association between basi-bregmatic height and talar size, Mizoguchi (2004a) stated that such a strong association may be only provisionally interpreted as a result of biomechanical adaptation and/or adjustment (or accomodation) to balancing the posture of the body, including the head, as already speculated by Mizoguchi (1992).

The most important finding in this context is the significant association of basi-bregmatic height with both the transverse diameter of the vertebral foramen and talar size in both sexes (PC Is in Tables 15 and 17). As already mentioned above, however, basi-begmatic height is further significantly associated with other measurements, such as cranial length, bigonial width and endocranial capacity, in males. In males, cranial length, basi-bregmatic height and endocranial capacity are furthermore associated with many limb bone measurements, as indicated by male PC I in Table 3, although not by female PC I in Table 5. Therefore, the between-sex difference in the manner of association of basi-bregmatic height with the other measurements suggested by PC Is in Tables 15 and 17 may also be caused by the sex difference in the amount of skeletal muscle primarily originating from the sexual dimorphism in body size, but, if so, what is the causal factor common to males and females that strongly connects both vertebral foramen size and talar size with basi-bregmatic height?

A possible property common to these three measurements may be not being under the direct control of skeletal muscles. No muscles attach to the talus (White, 1991); vertebral foramen size seems to be associated with the thickness of the spinal cord, but is relatively free from the influence of muscles; and basi-bregmatic height appears to be least influenced by muscles among the three main neurocranial measurements. If so, at least two size factors may have to be distinguished for body size: a set of genes associated with the amount of skeletal muscle or body weight, and a set of genes controlling the inherent size of most organs, with the former being more susceptible to environmental factors than the latter. If this is correct, the strong associations between basi-bregmatic height, the transverse diameter of the vertebral foramen, and talar size in females (PC I in Table 17) may be explained by the latter size factor alone, and the significant associations between basi-bregmatic height and many other measurements in males (PC I in Table 15) may be explained by a compound factor of these two size factors.

Incidentally, it is interesting that the male and female PC Is (Tables 15 and 17) are not significantly correlated with living stature, which is also true of PC Is in Tables 3 and 5. In addition, the rotated factors (Fac V in Table 4 and Fac IV in Table 6), which are most highly correlated with stature, also show that stature is not significantly associated with humeral, femoral, or tibial length. In the talus, however, there is another possibility that talar size is strongly associated with stature. This is suggested by Fac I from males (Table 16) and Fac IV from females (Table 18), the rank correlation coefficient between which is as high as 0.96 ($P<0.001$) (Table 21). Taking into account that the talus is bearing the whole body, this finding is also reasonable. From these results, it may be said that the variation in stature is caused by at least three factors: 1) associated with the inherent size of most organs, 2) associated with body weight or the amount of skeletal muscle, and 3) miscellaneous factors, e.g., relating to the intervertebral disks.

Summary and Conclusions

PCAs of Japanese male and female data indicated that many limb bone, pelvic, and vertebral body measurements are concurrently associated with cranial length. The strong associations between at least cranial length and limb bone measurements were also confirmed in Australian Aboriginal male data. These findings support the present author's previous hypothesis that the variation in cranial length is related to the degree of development of skeletal muscles or body size.

It was further confirmed in Japanese male and female samples that inion-opisthion chord is not significantly associated with cranial length or with any postcranial measurements. This is also clear in the results from Australian Aboriginal data. The inion-opisthion chord is, therefore, not considered an appropriate measure for the size of the nuchal planum, presumably because of the difficulty in determining a landmark, *inion*.

Stature was not shown to be significantly associated with cranial length or limb bone length or thickness, vertebral body size, or pelvic size. The strong associations found between cranial length and postcranial bone measurements, especially limb bone thicknesses and vertebral body size, seem to be explained by the amount of skeletal muscle or body weight rather than stature.

The cubic root of endocranial capacity was reconfirmed to be significantly associated with the three main neurocanial measurements, especially cranial length and basi-bregmatic height, in males, and, in females, only with basi-bregmatic height, but the relationship of endocranial capacity with postcranial measurements tends to differ in males and females. This sex difference may be an aspect of the phenomenon that stronger associations between neurocranial measurements, including brain size, and postcranial measurements occur only in males whose skeletal muscles generally tend to develop better and whose body size tends to be larger than in females.

A sex difference was found also in the manner of connecting cranial breadth with facial breadth. Cranial breadth is significantly associated with bizygomatic and bicoronoid breadth as well as the total breadth of the axis in males, but not with any of these in females. Although the masticatory muscles are qualitatively different from other skeletal muscles, this between-sex difference may also be explained in the same way as the sex difference in the manner of association of neurocranial measurements, including brain size, with postcranial measurements.

Basi-bregmatic height is also found to be simultaneously associated with vertebral foramen and talar sizes in both sexes. This may be due to a property common to these three measurements, i.e., not being under the direct control of skeletal muscles. A set of genes controlling the inherent size of most organs, for example, may be a factor relating to such a property.

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