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Associations between the Neurocranium and the Leg Bones: Toward the Solution of the Brachycephalization Problem

Yuji Mizoguchi

Department of Anthropology, National Science Museum
3–23–1 Hyakunincho, Shinjuku-ku, Tokyo, 169–0073 Japan
E-mail: mzgch@kahaku.go.jp

Abstract As a step toward clarifying the causes and mechanism of brachycephalization, correlations between neurocranial and leg bone measurements were examined by principal component analysis and Kaiser's normal varimax rotation methods. The results based on modern Japanese skeletons show that, while cranial breadth has no systematic association with any measurements of the patella, tibia or fibula, cranial length is strongly associated with tibial length and thickness in both sexes and with fibular length and thickness only in males. These, together with previous findings, suggest that the general development of skeletal muscles such as nuchal muscles and those attached on the extremity bones is considerably concerned with the variation of cranial length, and that the affection of such muscle development on the associations between cranial length and limb bone measurements may be more definitely expressed in males than in females because muscles are generally more developed in males.
Key words: Brachycephalization, Neurocranium, Patella, Tibia, Fibula

Since 1992, the present author has analyzed correlations between the neurocranium and postcranial bones as a step toward elucidating the causes and mechanism of brachycephalization, and, up to the present, shown that, while cranial breadth has no consistent association with any measurements of the vertebrae, ribs, sternum, scapula, clavicle, humerus, ulna, radius, pelvis, or femur, cranial length is strongly associated with the sagittal and transverse diameters of the vertebral bodies, sacral breadths, costal chords, many humeral measurements, pelvic breadths and height, and femoral lengths and thiknesses (Mizoguchi, 1992, 1994, 1995, 1996, 1997, 1998a, b, 1999, 2000, 2001, 2002, 2003a, b).

In the present study, correlations between the measurements of the neurocranium and the leg bones are further examined toward solving the brachycephalization problem.

Materials and Methods

The raw data of neurocranial measurements reported by Miyamoto (1924) and those of patellar, tibial and fibular measuremets by Hirai and Tabata (1928) were used here. These are of the same skeletons of 30 male and 20 female modern Japanese who had lived in the Kinai district. The basic statistics for three main neurocranial measurements, i.e., cranial length, cranial breadth and basi-bregmatic height, are presented in Mizoguchi (1994), and those for leg bone measurements are listed in Tables 1 to 3.

For examining the overall relations between neurocranial and leg bone measurements, principal component analysis (Lawley and Maxwell, 1963; Okuno *et al.*, 1971, 1976; Takeuchi and Yanai, 1972) was applied to the correlation matrices on them. The number of principal components was so determined that the cumulative proportion of the variances of the principal components exceeded 80%. The principal components obtained in such a way were then transformed by Kaiser's normal varimax rotation method (Asano, 1971; Okuno *et al.*, 1971) into different factors because these may reveal some other associations

Table 1. Means and standard deviations for the measurements of the right patella in Japanese males and females.[1)]

Variable[2)]		Males			Females		
		n	Mean	SD	*n*	Mean	SD
1	Maximum height	30	41.2	2.4	20	36.2	2.2
2	Maximum breadth	30	43.6	2.9	20	37.8	3.4
3	Maximum thickness	30	19.4	1.6	20	17.5	1.7
4	Hight of articular surface	30	30.4	2.4	20	27.3	2.0
5	Breadth of medial articular surface	30	20.2	2.2	20	17.8	2.2
6	Breadth of lateral articular surface	30	25.7	2.0	20	22.8	2.1

[1)] The estimates of basic statistics listed here were recalculated by the present author on the basis of the raw data published by Hirai and Tabata (1928).

[2)] Numbers for variables are according to Martin and Saller (1957).

Table 2. Means and standard deviations for the measurements of the right tibia in Japanese males and females.[1)]

Variable[2)]		Males			Females		
		n	Mean	SD	*n*	Mean	SD
1	Total length	30	326.7	20.3	20	300.7	17.3
1a	Maximum length	30	331.9	20.5	20	305.1	17.2
1b	Medial condyle-malleolus length	30	321.6	20.7	20	298.2	18.7
K4	Distance between superior and inferior articular surfaces	30	313.5	19.3	19	287.3	16.5
3	Maximum breadth of proximal end	30	75.3	3.3	20	66.7	3.8
6	Maximum breadth of distal end	30	47.5	2.8	20	42.5	3.2
7	Sagittal diameter of distal end	30	36.1	2.6	20	31.3	2.0
8	Maximum diameter at midshaft	30	28.5	2.2	20	24.0	1.8
9	Transverse diameter at midshaft	30	21.0	2.1	20	18.7	1.5
8a	Sagittal diameter at nutrient foramen	30	32.8	2.3	20	27.2	1.9
9a	Transverse diameter at nutrient foramen	30	24.1	3.1	20	20.7	1.6
10	Circumference at midshaft	30	78.8	5.7	20	67.9	3.7
10a	Circumference at nutrient foramen	30	89.4	6.4	20	75.9	4.6
10b	Minimum circumference of shaft	30	71.8	4.8	20	61.9	3.0
K6	Chord of shaft curvature	30	165.3	16.4	20	151.4	13.0
K7	Height of shaft curvature	30	2.6	1.5	20	2.1	0.9
12	Angle of retroversion	30	13.6	3.8	20	16.4	3.7
13	Angle of inclination	30	9.6	3.3	20	12.5	3.5
K20	Difference between retroversion and inclination angles	30	3.9	1.0	20	3.9	0.7
14	Angle of torsion	30	12.3	8.3	20	13.6	7.7
HT21	Inclination angle of condyle	30	91.6	2.6	20	90.6	2.5

[1)] The estimates of basic statistics listed here were recalculated by the present author on the basis of the raw data published by Hirai and Tabata (1928).

[2)] Bare-numbered variables are measurements according to Martin and Saller (1957), and those with the letter 'K' and letters 'HT' preceding the number are measurements according to Kiyono (1929) and to Hirai and Tabata (1928), respectively.

hidden behind the measurements dealt with.

The measurements of the tibia were, in practice, arbitrarily divided into two groups in carrying out the above multivariate analyses because of a statistical restriction on sample size and the number of variables, namely, because the number of individuals was too small, particularly in females, compared with the total number of variables to obtain the solutions. As for the patella and fibula, such treatment was not made because

Table 3. Means and standard deviations for the measurements of the right fibula in Japanese males and females.[1)]

Variable[2)]		Males			Females		
		n	Mean	SD	n	Mean	SD
1	Maximum length	30	326.9	19.2	20	299.4	16.1
2	Maximum diameter at midshaft	30	14.1	1.6	20	13.1	1.6
3	Minimum diameter at midshaft	30	10.3	1.2	20	9.0	1.2
4	Circumference at midshaft	30	41.5	3.3	20	38.6	3.6
4a	Min. circumference below proximal end	30	35.0	3.2	20	32.9	2.7
K6	Min. circumference above distal end	30	36.8	2.8	20	33.2	2.3

[1)] The estimates of basic statistics listed here were recalculated by the present author on the basis of the raw data published by Hirai and Tabata (1928).

[2)] Bare-numbered variables are measurements according to Martin and Saller (1957), and those with the letter 'K' preceding the number are measurements according to Kiyono (1929).

the number of variables was smaller than the number of individuals observed.

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

Statistical calculations were executed with the mainframe, HITACHI MP5800 System, of the Computer Centre, the University of Tokyo. The programs used are BSFMD for calculating basic statistics, BTPCA for principal component analysis and Kaiser's normal varimax rotation, and RKCNCT for rank correlation coefficients. All of these programs were written in FORTRAN by the present author.

Results

The direct results of the principal component analyses (PCAs) and the rotated solutions for the neurocranium and the patella are shown in Tables 4 to 7, and, in Table 8, Spearman's rank correlation coefficients are listed to show the degree of similarity between males and females in the variation patterns of factor loadings on the principal components (PCs) and/or rotated factors. Similarly, the results for the tibia are shown in Tables 9 to 18, and those for the fibula, in Tables 19 to 23.

First of all, the PCAs and the rotated solutions for the patella show that there is no PC or rotated factor common to males and females which is significantly correlated both with a cranial measurement and with one or more patellar measurements (Tables 4 to 8).

In the analyses for the tibia, it was found that the male and female PC I's from the first data sets had significant correlations both with cranial length and with the total length, maximum length, medial condyle-malleolus length, distance between the superior and inferior articular surfaces, maximum breadth of the proximal end, maximum breadth of the distal end, sagittal diameter of the distal end, maximum diameter at midshaft, transverse diameter at midshaft, sagittal diameter at the nutrient foramen, and transverse diameter at the nutrient foramen (Tables 9 and 11; Fig. 1). The Spearman's rho between these PC I's from males and females is 0.90, which is significant at the 0.1% level (Table 17). As for cranial breadth, no evidence was found for

Table 4. Principal component analysis of the correlation matrix on the measurements of the neurocranium and the patella from Japanese males.[1)]

Variable[2)]	Factor loadings				Total variance (%)
	PC I	II	III	IV	
1 Cranial length	.56**	.50	−.15	−.42	75.36
8 Cranial breadth	.26	.58	.45	.61	97.19
17 Basi-bregmatic height	.35	.61	−.57	.03	82.74
1 Maximum height	.86***	.01	.06	.11	75.86
2 Maximum breadth	.91***	−.14	.09	−.05	86.33
3 Maximum thickness	.87***	−.24	.08	−.05	82.09
4 Hight of art. surface	.82***	−.26	−.01	.20	77.57
5 Br. of med. art. surface	.77***	.12	.40	−.39	91.46
6 Br. of lat. art. surface	.65***	−.28	−.52	.31	85.80
Total contribution (%)	50.05	13.30	11.14	9.33	83.82
Cumulative proportion (%)	50.05	63.35	74.49	83.82	83.82

1) The sample size is 30. The number of the principal components shown here was so determined that the cumulative proportion of the variances of the principal components exceeded 80%.
2) See the second footnote to Table 1.
* $P<0.05$; ** $P<0.01$; *** $P<0.001$, by a two-tailed bootstrap test.

Table 5. Solution obtained through the normal varimax rotation of the first four principal components for the correlation matrix on the measurements of the neurocranium and the patella from Japanese males.[1)]

Variable[2)]	Factor loadings			
	Fac I	II	III	IV
1 Cranial length	.09	.63	−.01	−.59
8 Cranial breadth	.05	.10	.98*	−.09
17 Basi-bregmatic height	.14	.89	.11	.00
1 Maximum height	.69**	.17	.23	−.45
2 Maximum breadth	.73*	.07	.07	−.57
3 Maximum thickness	.74*	.00	.00	−.52
4 Hight of art. surface	.82*	.01	.11	−.29
5 Br. of med. art. surface	.29	.05	.12	−.90***
6 Br. of lat. art. surface	.87*	.28	−.11	.13

1) The sample size is 30. The cumulative proportion of the variances of the four principal components is 83.82%.
2) See the second footnote to Table 1.
* $P<0.05$; ** $P<0.01$; *** $P<0.001$, by a two-tailed bootstrap test.

Table 6. Principal component analysis of the correlation matrix on the measurements of the neurocranium and the patella from Japanese females.[1)]

Variable[2)]	Factor loadings			Total variance (%)
	PC I	II	III	
1 Cranial length	−.02	.87	.32	85.33
8 Cranial breadth	.40	−.82	.12	84.79
17 Basi-bregmatic height	.49*	−.21	.79	90.87
1 Maximum height	.83***	−.03	−.24	75.12
2 Maximum breadth	.90***	.16	−.03	83.45
3 Maximum thickness	.93***	.04	.08	87.67
4 Hight of art. surface	.80*	.12	−.32	75.36
5 Br. of med. art. surface	.79***	.15	.26	71.75
6 Br. of lat. art. surface	.82***	.08	−.27	75.64
Total contribution (%)	52.23	17.14	11.73	81.11
Cumulative proportion (%)	52.23	69.37	81.11	81.11

1) The sample size is 20. The number of the principal components shown here was so determined that the cumulative proportion of the variances of the principal components exceeded 80%.
2) See the second footnote to Table 1.
* $P<0.05$; ** $P<0.01$; *** $P<0.001$, by a two-tailed bootstrap test.

Table 7. Solution obtained through the normal varimax rotation of the first three principal components for the correlation matrix on the measurements of the neurocranium and the patella from Japanese females.[1)]

Variable[2)]	Factor loadings		
	Fac I	II	III
1 Cranial length	.03	.91	.16
8 Cranial breadth	.17	−.82	.38
17 Basi-bregmatic height	.14	−.10	.94
1 Maximum height	.84*	−.18	.09
2 Maximum breadth	.87***	.05	.29
3 Maximum thickness	.84***	−.05	.42
4 Hight of art. surface	.87	−.04	−.02
5 Br. of med. art. surface	.67	.11	.51
6 Br. of lat. art. surface	.87**	−.07	.05

[1)] The sample size is 20. The cumulative proportion of the variances of the three principal components is 81.11%.
[2)] See the second footnote to Table 1.
* $P<0.05$; ** $P<0.01$; *** $P<0.001$, by a two-tailed bootstrap test.

Table 8. Spearman's rank correlation coefficients between males and females in the variation pattern of factor loadings on the principal components and/or rotated factors obtained from neurocranial and patellar measurements.[1)]

	Male PC I	II	III	IV	Fac I	II	III	IV
Female PC I	.88**	.68*	—	—	.73*	—	—	—
II	—	—	—	—	—	—	—	.68*
III	—	.87**	—	—	.80**	—	—	—
Fac I	.68*	.83**	—	—	.83**	—	—	—
II	—	—	—	.78*	—	—	—	.75*
III	—	.67*	—	—	—	—	—	—

[1)] Only those rank correlations 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 4, 5, 6 and 7.
* $P<0.05$; ** $P<0.01$; *** $P<0.001$, by a two-tailed test.

Table 9. Principal component analysis of the correlation matrix on the first set of measurements of the neurocranium and the tibia from Japanese males.[1)]

Variable[2)]	Factor loadings					Total variance (%)
	PC I	II	III	IV	V	
1 Cranial length	.41*	.41	−.14	.22	.60	76.80
8 Cranial breadth	.27	.15	.52	−.54	.50	89.86
17 Basi-bregmatic height	.43	.62	.04	.35	.13	71.00
1 Total length	.89***	−.42	−.04	.03	.08	98.71
1a Maximum length	.91***	−.40	−.06	.02	.09	99.16
1b Med. cond.-mal. length	.90***	−.41	−.08	−.01	.08	98.55
K4 Dist. between sup. and inf. articular surfaces	.90***	−.40	−.05	.05	.10	98.49
3 Max. br. of proximal end	.81***	.16	.36	.09	−.20	87.22
6 Max. br. of distal end	.72***	.14	.52	.03	−.28	89.09
7 Sagit. diam. of distal end	.62***	.18	.44	.02	−.21	65.99
8 Max. diam. at midshaft	.76***	.09	−.30	.27	.00	74.91
9 Trans. diam. at midshaft	.74***	.13	−.21	−.38	−.02	75.21
8a Sagit. d. at nut. foramen	.78***	.38	−.28	.02	−.17	86.24
9a Trans. d. at nut. foramen	.46*	.39	−.50	−.50	−.21	90.31
Total contribution (%)	51.27	11.70	9.73	6.70	6.44	85.82
Cumulative proportion (%)	51.27	62.96	72.69	79.38	85.82	85.82

[1)] The sample size is 30. The number of the principal components shown here was so determined that the cumulative proportion of the variances of the principal components exceeded 80%.
[2)] See the second footnote to Table 2.
* $P<0.05$; ** $P<0.01$; *** $P<0.001$, by a two-tailed bootstrap test.

Table 10. Solution obtained through the normal varimax rotation of the first five principal components for the correlation matrix on the first set of measurements of the neurocranium and the tibia from Japanese males.[1)]

Variable[2)]		Factor loadings				
		Fac I	II	III	IV	V
1	Cranial length	.19	.82**	−.04	−.09	.21
8	Cranial breadth	.07	.10	.21	−.05	.92***
17	Basi-bregmatic height	−.04	.73	.39	−.15	−.05
1	Total length	.94***	.07	.26*	−.14	.05
1a	Maximum length	.94***	.10	.26*	−.17	.05
1b	Med. cond.-mal. length	.94***	.07	.24	−.18	.05
K4	Dist. between sup. and inf. articular surfaces	.94***	.12	.26*	−.13	.05
3	Max. br. of proximal end	.40*	.21	.79*	−.17	.07
6	Max. br. of distal end	.30	.07	.88*	−.10	.12
7	Sagit. diam. of distal end	.23	.11	.75*	−.11	.13
8	Max. diam. at midshaft	.57**	.46	.24	−.32	−.24
9	Trans. diam. at midshaft	.46**	.13	.22	−.66**	.20
8a	Sagit. d. at nut. foramen	.34**	.41	.39	−.63*	−.17
9a	Trans. d. at nut. foramen	.09	.09	.05	−.94**	.02

[1)] The sample size is 30. The cumulative proportion of the variances of the five principal components is 85.82%.
[2)] See the second footnote to Table 2.
* $P<0.05$; ** $P<0.01$; *** $P<0.001$, by a two-tailed bootstrap test.

Table 11. Principal component analysis of the correlation matrix on the first set of measurements of the neurocranium and the tibia from Japanese females.[1)]

Variable[2)]		Factor loadings				Total variance (%)
		PC I	II	III	IV	
1	Cranial length	.45*	.44	−.52	.43	84.42
8	Cranial breadth	.02	−.57	.72	.06	84.57
17	Basi-bregmatic height	.30*	−.73	−.05	.50	86.50
1	Total length	.88***	−.22	−.15	−.36*	98.03
1a	Maximum length	.90***	−.17	−.15	−.33*	97.60
1b	Med. cond.-mal. length	.88***	−.27	−.19	−.25	93.54
K4	Dist. between sup. and inf. articular surfaces	.89***	−.21	−.15	−.36*	98.36
3	Max. br. of proximal end	.82***	−.30	.08	.21	81.45
6	Max. br. of distal end	.75***	−.04	−.02	.30	65.48
7	Sagit. diam. of distal end	.82***	−.11	−.15	.41	87.19
8	Max. diam. at midshaft	.62**	.61	.20	.11	81.38
9	Trans. diam. at midshaft	.70***	.30	.45	.09	79.52
8a	Sagit. d. at nut. foramen	.76***	.52	.24	−.10	91.83
9a	Trans. d. at nut. foramen	.74***	.24	.34	.03	73.10
Total contribution (%)		52.56	15.28	9.57	8.51	85.93
Cumulative proportion (%)		52.56	67.84	77.42	85.93	85.93

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

Table 12. Solution obtained through the normal varimax rotation of the first four principal components for the correlation matrix on the first set of measurements of the neurocranium and the tibia from Japanese females.[1)]

Variable[2)]	Factor loadings Fac I	II	III	IV
1 Cranial length	.07	.30	−.81	.31
8 Cranial breadth	−.04	.07	.87	.30
17 Basi-bregmatic height	.17	−.22	.20	.86
1 Total length	.94***	.25	−.03	.19
1a Maximum length	.92***	.30	−.07	.18
1b Med. cond.-mal. length	.89***	.22	−.06	.29
K4 Dist. between sup. and inf. articular surfaces	.94***	.26	−.04	.18
3 Max. br. of proximal end	.53*	.37	.08	.63
6 Max. br. of distal end	.37	.45	−.16	.54
7 Sagit. diam. of distal end	.41*	.39	−.26	.69
8 Max. diam. at midshaft	.13	.85	−.28	.01
9 Trans. diam. at midshaft	.23	.84	.09	.16
8a Sagit. d. at nut. foramen	.37	.87	−.17	−.06
9a Trans. d. at nut. foramen	.34	.77	.04	.17

[1)] The sample size is 19. The cumulative proportion of the variances of the four principal components is 85.93%.
[2)] See the second footnote to Table 2.
* $P<0.05$; ** $P<0.01$; *** $P<0.001$, by a two-tailed bootstrap test.

Table 13. Principal component analysis of the correlation matrix on the second set of measurements of the neurocranium and the tibia from Japanese males.[1)]

Variable[2)]	Factor loadings PC I	II	III	IV	V	Total variance (%)
1 Cranial length	.53	.17	.34	.50	−.00	68.14
8 Cranial breadth	.33	−.13	−.43	.37	−.45	65.36
17 Basi-bregmatic height	.52	.09	.12	.53	.38	71.08
10 Circumf. at midshaft	.84*	.45	.01	−.20	.07	94.80
10a Circumf. at nut. foramen	.79*	.48	.00	−.06	.09	86.27
10b Min. circumf. of shaft	.89*	.33	.01	−.14	−.11	92.53
K6 Chord of shaft curvature	.17	.73*	−.14	−.30	.04	67.07
K7 Height of shaft curvature	−.41	.68**	.11	−.19	.18	70.55
12 Angle of retroversion	−.55	.73*	−.02	.34	−.12	96.31
13 Angle of inclination	−.49	.68*	.11	.43	−.18	93.47
K20 Difference between retr. and incl. angles	−.50	.56*	−.43	−.09	.15	79.07
14 Angle of torsion	−.01	.23	.67	−.27	−.56	89.19
HT21 Incl. angle of condyle	−.33	−.11	.69	.00	.29	68.11
Total contribution (%)	29.67	22.83	11.37	9.50	6.77	80.15
Cumulative proportion (%)	29.67	52.50	63.87	73.38	80.15	80.15

[1)] The sample size is 30. The number of the principal components shown here was so determined that the cumulative proportion of the variances of the principal components exceeded 80%.
[2)] See the second footnote to Table 2.
* $P<0.05$; ** $P<0.01$; *** $P<0.001$, by a two-tailed bootstrap test.

Table 14. Solution obtained through the normal varimax rotation of the first five principal components for the correlation matrix on the second set of measurements of the neurocranium and the tibia from Japanese males.[1]

Variable[2]		Factor loadings				
		Fac I	II	III	IV	V
1	Cranial length	.25	−.01	−.08	.76*	−.17
8	Cranial breadth	.01	−.09	−.79	.16	.02
17	Basi-bregmatic height	.24	−.06	.01	.76	.26
10	Circumf. at midshaft	.94	−.12	−.06	.23*	−.04
10a	Circumf. at nut. foramen	.87	−.02	−.08	.32*	.00
10b	Min. circumf. of shaft	.87	−.21	−.22	.25	−.15
K6	Chord of shaft curvature	.67*	.43	.06	−.19	.01
K7	Height of shaft curvature	.18	.67	.42	−.22	−.02
12	Angle of retroversion	−.11	.97*	.00	.03	−.07
13	Angle of inclination	−.15	.92	−.01	.16	−.18
K20	Difference between retr. and incl. angles	.05	.71	.04	−.41	.34
14	Angle of torsion	.12	.09	.17	−.05	−.92*
HT21	Incl. angle of condyle	−.33	−.01	.70	.19	−.23

[1] The sample size is 30. The cumulative proportion of the variances of the five principal components is 80.15%.
[2] See the second footnote to Table 2.
* $P<0.05$; ** $P<0.01$; *** $P<0.001$, by a two-tailed bootstrap test.

Table 15. Principal component analysis of the correlation matrix on the second set of measurements of the neurocranium and the tibia from Japanese females.[1]

Variable[2]		Factor loadings					Total variance (%)
		PC I	II	III	IV	V	
1	Cranial length	.62	−.24	−.56	−.00	−.22	80.92
8	Cranial breadth	−.18	−.10	.81	−.41	.17	89.12
17	Basi-bregmatic height	−.08	−.72	.32	−.23	.12	68.84
10	Circumf. at midshaft	.91***	.01	.31	.18	.09	96.45
10a	Circumf. at nut. foramen	.81***	.10	.42	.33	.02	95.24
10b	Min. circumf. of shaft	.89***	−.01	.20	.22	.16	91.25
K6	Chord of shaft curvature	.72*	.09	.07	−.21	−.17	61.36
K7	Height of shaft curvature	.56*	.24	−.28	−.45	.08	65.67
12	Angle of retroversion	−.07	.92**	.17	−.10	−.25	96.13
13	Angle of inclination	−.07	.86**	.26	−.16	−.36	96.23
K20	Difference between retr. and incl. angles	.00	.56	−.35	.26	.43	69.28
14	Angle of torsion	−.44	−.13	.28	.67	−.35	86.47
HT21	Incl. angle of condyle	−.29	.47	.09	.12	.63	72.94
Total contribution (%)		29.44	21.57	13.69	9.49	8.11	82.30
Cumulative proportion (%)		29.44	51.01	64.70	74.19	82.30	82.30

[1] The sample size is 20. The number of the principal components shown here was so determined that the cumulative proportion of the variances of the principal components exceeded 80%.
[2] See the second footnote to Table 2.
* $P<0.05$; ** $P<0.01$; *** $P<0.001$, by a two-tailed bootstrap test.

Table 16. Solution obtained through the normal varimax rotation of the first five principal components for the correlation matrix on the second set of measurements of the neurocranium and the tibia from Japanese females.[1)]

Variable[2)]		Factor loadings				
		Fac I	II	III	IV	V
1	Cranial length	.28	−.24	−.64	−.38	−.35
8	Cranial breadth	.04	.03	.94*	.01	−.07
17	Basi-bregmatic height	−.05	−.59	.49	.03	−.32
10	Circumf. at midshaft	.96*	−.04	−.00	−.17	−.05
10a	Circumf. at nut. foramen	.97*	.08	.01	.03	−.02
10b	Min. circumf. of shaft	.93*	−.11	−.09	−.19	.02
K6	Chord of shaft curvature	.57	.16	−.07	−.43	−.29
K7	Height of shaft curvature	.23	.14	−.16	−.75	−.02
12	Angle of retroversion	−.00	.96	.04	−.05	.19
13	Angle of inclination	−.01	.97	.12	−.03	.05
K20	Difference between retr. and incl. angles	.01	.20	−.36	−.11	.72
14	Angle of torsion	−.07	.05	−.03	.92	−.10
HT21	Incl. angle of condyle	−.10	.15	.20	.04	.81

[1)] The sample size is 20. The cumulative proportion of the variances of the five principal components is 82.30%.
[2)] See the second footnote to Table 2.
* $P<0.05$; ** $P<0.01$; *** $P<0.001$, by a two-tailed bootstrap test.

Table 17. Spearman's rank correlation coefficients between males and females in the variation pattern of factor loadings on the principal components and/or rotated factors obtained from the first data sets on neurocranial and tibial measurements.[1)]

	Male PC I	II	III	IV	V	Fac I	II	III	IV	V
Female PC I	.90***	.64*	—	—	—	.78**	—	—	—	—
II	—	—	.66*	—	—	—	—	—	—	—
III	—	—	—	—	—	—	—	—	—	—
IV	.71**	.74**	—	—	—	.71**	.53*	—	—	—
Fac I	.85***	.63*	—	—	—	.72**	—	—	—	—
II	—	—	—	—	.67**	—	—	—	.53*	—
III	—	—	—	—	—	—	—	—	—	—
IV	—	—	.78***	—	—	—	—	—	.63*	—

[1)] Only those rank correlations 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 9, 10, 11 and 12.
* $P<0.05$; ** $P<0.01$; *** $P<0.001$, by a two-tailed test.

Table 18. Spearman's rank correlation coefficients between males and females in the variation pattern of factor loadings on the principal components and/or rotated factors obtained from the second data sets on neurocranial and tibial measurements.[1)]

	Male PC I	II	III	IV	V	Fac I	II	III	IV	V
Female PC I	—	—	—	—	—	.81***	—	—	—	—
II	.70**	.64*	—	—	—	—	.71**	—	.55*	—
III	—	—	—	—	—	—	—	—	—	—
IV	—	—	—	—	—	—	—	—	—	—
V	—	—	—	—	—	—	—	—	—	—
Fac I	.63*	—	—	—	—	.83***	—	.55*	—	—
II	.81***	.69**	—	—	—	.57*	.85***	—	.72**	—
III	—	—	—	—	—	—	—	—	—	—
IV	—	—	—	—	—	—	—	—	—	—
V	—	—	—	—	—	—	—	—	—	—

[1)] Only those rank correlations 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 13, 14, 15 and 16.
* $P<0.05$; ** $P<0.01$; *** $P<0.001$, by a two-tailed test.

Table 19. Principal component analysis of the correlation matrix on the measurements of the neurocranium and the fibula from Japanese males.[1)]

Variable[2)]	Factor loadings					Total variance (%)
	PC I	II	III	IV	V	
1 Cranial length	.55**	.46	−.19	.30	−.18	66.70
8 Cranial breadth	.18	.47	.81	.19	.19	98.83
17 Basi-bregmatic height	.34	.68	−.34	.11	.30	79.16
1 Maximum length	.58**	.01	.09	−.68	.31	90.25
2 Max. diameter at midshaft	.83***	.14	−.21	−.05	−.01	75.28
3 Min. diameter at midshaft	.71***	−.26	.24	.05	−.39	78.58
4 Circumference at midshaft	.93***	.03	.03	−.11	−.18	90.46
4a Min. cir. below prox. end	.43	−.60	−.05	.39	.50	95.15
K6 Min. cir. above dist. end	.82***	−.33	.01	.11	.03	79.48
Total contribution (%)	40.90	16.14	10.27	8.76	7.69	83.77
Cumulative proportion (%)	40.90	57.04	67.31	76.07	83.77	83.77

[1)] The sample size is 30. The number of the principal components shown here was so determined that the cumulative proportion of the variances of the principal components exceeded 80%.
[2)] See the second footnote to Table 3.
* $P<0.05$; ** $P<0.01$; *** $P<0.001$, by a two-tailed bootstrap test.

Table 20. Solution obtained through the normal varimax rotation of the first five principal components for the correlation matrix on the measurements of the neurocranium and the fibula from Japanese males.[1)]

Variable[2)]	Factor loadings				
	Fac I	II	III	IV	V
1 Cranial length	.42*	.68	.09	.13	−.05
8 Cranial breadth	.07	.11	.98*	−.05	−.04
17 Basi-bregmatic height	−.09	.87	.09	−.16	−.01
1 Maximum length	.25	.07	.05	−.91*	.06
2 Max. diameter at midshaft	.59	.51*	−.07	−.33	.16
3 Min. diameter at midshaft	.87*	−.08	.09	−.05	.12
4 Circumference at midshaft	.82*	.31	.05	−.36	.10
4a Min. cir. below prox. end	.19	−.04	−.04	−.03	.96***
K6 Min. cir. above dist. end	.70*	.12	−.02	−.21	.50

[1)] The sample size is 30. The cumulative proportion of the variances of the five principal components is 83.77%.
[2)] See the second footnote to Table 3.
* $P<0.05$; ** $P<0.01$; *** $P<0.001$, by a two-tailed bootstrap test.

Table 21. Principal component analysis of the correlation matrix on the measurements of the neurocranium and the fibula from Japanese females.[1)]

Variable[2)]	Factor loadings				Total variance (%)
	PC I	II	III	IV	
1 Cranial length	.36	−.31	−.81	−.07	89.19
8 Cranial breadth	−.20	.79	.41	−.24	88.82
17 Basi-bregmatic height	−.09	.72	−.39	−.34	79.36
1 Maximum length	.38	.58	−.29	.39	71.10
2 Max. diameter at midshaft	.78***	.35	.16	.22	80.38
3 Min. diameter at midshaft	.72*	.18	−.38	−.26	75.08
4 Circumference at midshaft	.86***	−.04	.24	.19	84.10
4a Min. cir. below prox. end	.53*	−.25	.24	−.64	80.86
K6 Min. cir. above dist. end	.83***	−.15	.32	−.01	81.24
Total contribution (%)	35.04	20.17	16.06	9.86	81.13
Cumulative proportion (%)	35.04	55.20	71.27	81.13	81.13

[1)] The sample size is 20. The number of the principal components shown here was so determined that the cumulative proportion of the variances of the principal components exceeded 80%.
[2)] See the second footnote to Table 3.
* $P<0.05$; ** $P<0.01$; *** $P<0.001$, by a two-tailed bootstrap test.

Table 22. Solution obtained through the normal varimax rotation of the first four principal components for the correlation matrix on the measurements of the neurocranium and the fibula from Japanese females.[1)]

Variable[2)]		Factor loadings			
		Fac I	II	III	IV
1	Cranial length	.05	.13	−.93	−.04
8	Cranial breadth	.01	.56	.76	−.01
17	Basi-bregmatic height	−.11	.88	.02	.08
1	Maximum length	.53	.44	−.10	.48
2	Max. diameter at midshaft	.88**	.17	.04	.02
3	Min. diameter at midshaft	.52	.44	−.46	−.27
4	Circumference at midshaft	.88***	−.17	−.10	−.18
4a	Min. cir. below prox. end	.28	−.01	−.08	−.85
K6	Min. cir. above dist. end	.78*	−.21	−.06	−.40

[1)] The sample size is 20. The cumulative proportion of the variances of the four principal components is 81.13%.
[2)] See the second footnote to Table 3.
* $P<0.05$; ** $P<0.01$; *** $P<0.001$, by a two-tailed bootstrap test.

Table 23. Spearman's rank correlation coefficients between males and females in the variation pattern of factor loadings on the principal components and/or rotated factors obtained from neurocranial and fibular measurements.[1)]

	Male PC I	II	III	IV	V	Fac I	II	III	IV	V
Female PC I	.93***	—	—	—	—	.82**	—	—	—	.68*
II	—	—	—	—	—	—	—	—	—	—
III	—	—	—	—	—	—	—	—	—	—
IV	—	—	—	.78*	—	—	—	—	.75*	—
Fac I	.93***	—	—	.68*	—	.72*	—	.67*	.67*	—
II	—	—	—	—	—	—	—	—	—	—
III	—	—	—	—	—	—	—	—	—	—
IV	—	.70*	—	—	—	—	—	—	—	—

[1)] Only those rank correlations 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 19, 20, 21 and 22.
* $P<0.05$; ** $P<0.01$; *** $P<0.001$, by a two-tailed test.

any consistent association between that breadth and tibial measurements.

Finally, in the case of the fibula, there are one PC and one rotated factor which are significantly correlated both with cranial length and with fibular measurements. They are PC I and the first rotated factor from the male data set (Tables 19 and 20). The former has a corresponding PC from females (PC I in Table 21), with the Spearman's rho between them being 0.93 ($P<0.001$), as shown in Table 23. But the factor loading of cranial length on that female PC I is not significant at the 5% level (Table 21; Fig. 2). On the other hand, the latter, the first rotated factor from males, has no corresponding PC or rotated factor from females. Regarding cranial breadth, there is neither PC nor rotated factor which suggests any constant associations of the breadth with certain fibular measurements.

Discussion

In the present study, cranial breadth was found not to be consistently associated with any leg bone measurements in the same way as shown in the analyses on other postcranial bones (Mizoguchi, 1994, 1995, 1996, 1997, 1998a, b, 1999, 2000, 2001, 2002, 2003a, b).

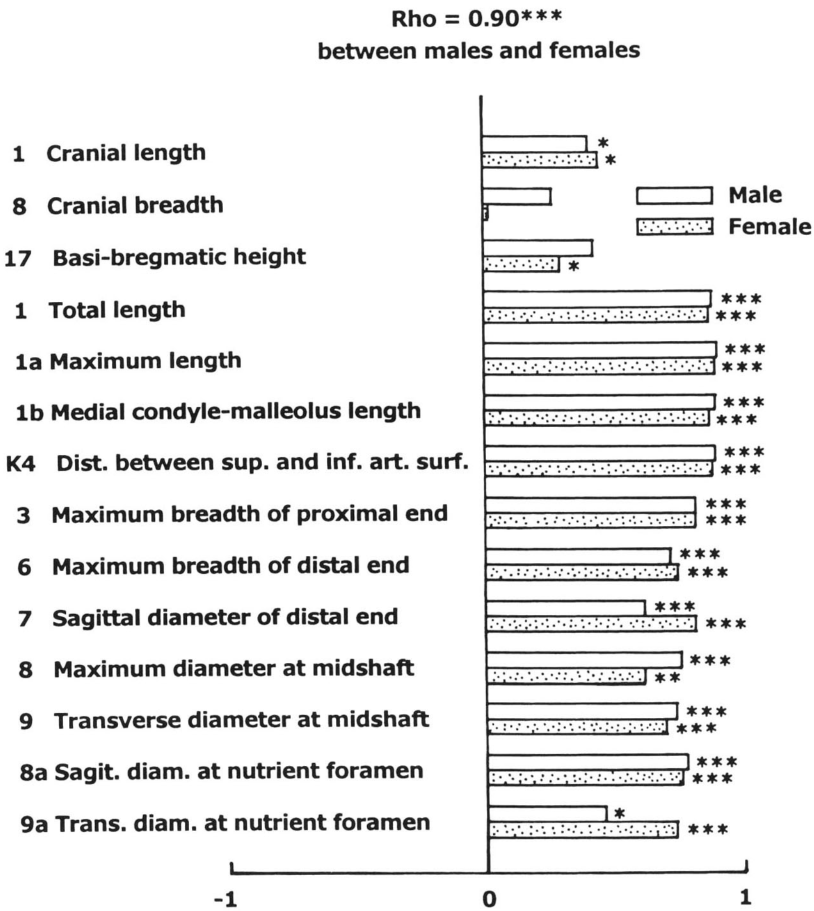

Fig. 1. Factor loadings on the first principal components obtained from the first data sets of the neurocranium and tibia for males and females. For the numbers preceding measurement items, see the second footnote to Table 2.

* $P<0.05$; ** $P<0.01$; *** $P<0.001$.

As for the associations with cranial length, significant ones were found in the male and female data sets on tibial measurements as well as in the male data set on fibular measurements (Figs. 1 and 2). When Mizoguchi (2003b) found the similarity between the humerus and the femur in having some strong associations with cranial length, he suggested that such a similarity may partly be explained by the ontogenetic homology (or homodynamy) between the "proximal" limb bones. This possibility should not be discarded yet. But, in the present study, one of the "distal" limb bones, the tibia, also showed strong associations with cranial length. Further, another "distal" lower limb bone, the fibula, also seems to have consistent associations with cranial length.

In fact, Mizoguchi (2002) had already noticed the fact that some measurements of the scapula, ulna, and radius are relatively strongly associated with cranial length only in males. But, till then, he had adopted the repeatability in two independent sets of data from males and females as a criterion for judging the reality of an association between two characters. Therefore, he had not regarded those associations found only in either of two data sets as rigidly real phenomena. In the present study, however, similar cases were further found in the lower limb bones, as was stated

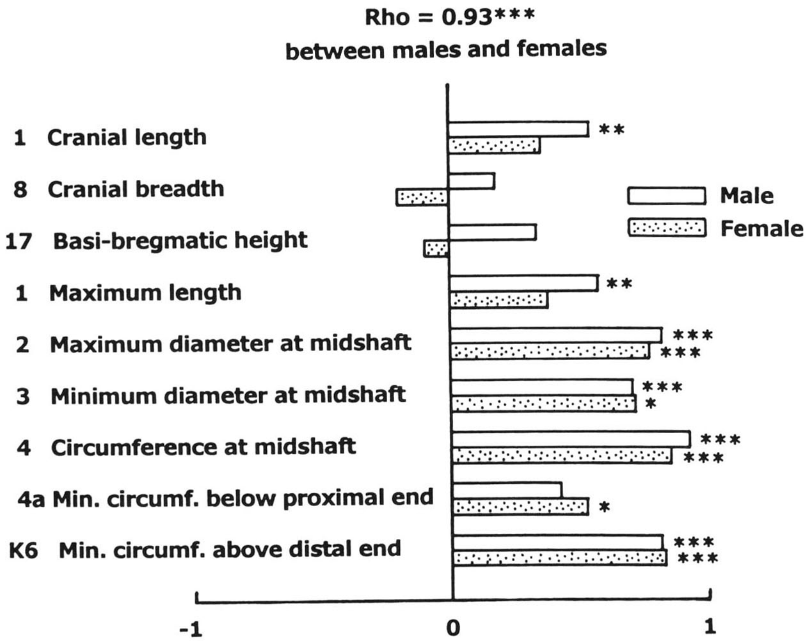

Fig. 2. Factor loadings on the first principal components obtained from the data sets of the neurocranium and fibula for males and females. For the numbers preceding measurement items, see the second footnote to Table 3.

* $P<0.05$; ** $P<0.01$; *** $P<0.001$.

above. Here, it is noticeable that, when an association with cranial length is found in either of sexes, it is always found in males. This means that a significant association is easy to find either because of the larger sample size for males (as seen in Tables 19 and 21, for example) or because skeletal muscles are generally more developed in males than in females. If the latter is the case, it is most likely that the general development of skeletal muscles including nuchal muscles and those attached to all limb bones is one of the major causes for the associations between cranial length and the measurements of limb bones. This is the same hypothesis as that proposed by Mizoguchi (2001) when he found strong associations between cranial length and many humeral measurements. If this hypothesis is correct, it may also explain the fact that stronger associations with cranial length are found in humeral, femoral and tibial measurements, while weaker ones are found in ulnar, radial and fibular measurements because the volume of muscles attached seems to be larger for the former limb bones than for the latter.

Associations found in somatometric data

Although there are few studies on correlations between cranial and postcranial bones, those based on somatometric data have frequently been conducted. Howells (1951), using somatometric data on 20 measurements of 152 Wisconsin students, obtained a centroid factor matrix. This shows that the first centroid (orthogonal) factor has relatively high correlations (of 0.5 or higher) with stature, sitting height, upper arm length, lower arm length (radius), lower leg length (tibia), biacromial breadth, head circumference, head length, bizygomatic breadth, and face height. This is compatible with a series of PCAs by the present author (Mizoguchi, 2001, 2002, present study) at least in the fact that head length is relatively highly associated with upper arm length, lower arm length (radius), and lower leg length (tibia).

Hoshi and Kouchi (1978) reported correlation matrices on anthropometric data of the head, face and body from 104 or more Japanese males. Mizoguchi (1992) carried out principal component analysis using their correlation coefficients. As a result, it was found that the first PC was particularly highly correlated with maximum hip breadth (factor loading=0.78), neck girth (0.77), forearm girth (0.75), thigh girth (0.74), foot length (0.72), calf girth (0.71), upper arm girth (0.69), etc. And, among the three main head measurements, cranial length is most highly correlated with this PC: the factor loading is 0.38 for head length, 0.18 for head breadth, and 0.17 for auricular height. As for the lengths of the extremities, this PC has correlations of 0.49 for upper arm length, of 0.59 for forearm length, of 0.36 for thigh length, and of 0.56 for tibial height. From these findings, it may be said that, among the three main head measurements, head length is most strongly associated with the thicknesses of the neck and extremities and considerably related with extremity lengths as well, as pointed out by Mizoguchi (2003b). This is again not inconsistent with a series of PCAs on osteological data by the present author (Mizoguchi, 2001, 2002, 2003b, present study).

After all, as was discussed by Mizoguchi (2001), it is expected that the strong associations between cranial length and some limb bone measurements are represented by those between the anteroposterior length of the occipital bone and the limb bone measurements, and that the degree of the associations is partly determined by the degree of general development in the nuchal muscles and those attached to all the limb bones. Of course, this hypothesis should further be confirmed in the future.

Summary and Conclusions

Principal component analyses on the neurocranium and the leg bones showed that, while cranial breadth was not consistently associated with any measurements of the patella, tibia or fibula, cranial length was significantly associated with tibial lengths and thicknesses in both males and females as well as with fibular lengths and thicknesses in males. From these and previous findings, it is concluded that the strong associations between cranial length and some limb bone measurements may partly be caused by the general development of skeletal muscles such as the nuchal muscles and those attached to the limb bones.

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