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Significant Associations between Cranial Length and Femoral Measurements: Toward the Solution of the Brachycephalization Problem

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Abstract The correlations between neurocranial and femoral measurements were examined by principal component analysis and Kaiser's normal varimax rotation methods as a step toward claryfying the causes and mechanism of brachycephalization. The results based on modern Japanese skeletons show that cranial length is significantly associated with femoral lengths and the cross-sectional size of the femoral shaft both in males and in females, and that cranial breadth has no systematic association with any femoral measurements. These and previous findings suggest that the general development of some skeletal muscles such as nuchal muscles and those attached on the "proximal" bones of the extremities may have some influence on cranial length, and that the similarity between the femur and the humerus in having strong associations with cranial length may partly be explained by the ontogenetic homology (or homodynamy) between the "proximal" limb bones.
Key words: Brachycephalization, Neurocranium, Femur, Principal component analysis, Bootstrap method

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

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

Materials and Methods

The raw data of neurocranial and femoral measurements reported by Miyamoto (1924) and Hirai and Tabata (1928), respectively, 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 femoral measurements are listed in Table 1.

For examining the overall relations between neurocranial and femoral 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

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

Variable[2)]		Males			Females	
	n	Mean	SD	*n*	Mean	SD
1 Maximum length	30	413.7	24.0	20	382.3	20.6
2 Bicondylar length	30	409.9	24.2	20	377.6	19.9
3 Maximum trochanteric length	30	397.8	23.9	20	367.4	19.0
4 Physiological trochanteric length	30	387.2	23.7	20	356.6	17.5
5 Diaphyseal length	30	324.8	21.9	20	302.4	16.3
5a Diaphyseal length	30	349.4	21.8	20	323.9	16.5
6 Sagittal diameter at midshaft	30	27.1	2.3	20	23.3	1.8
7 Transverse diameter at midshaft	30	25.3	2.1	20	23.2	2.1
8 Circumference at midshaft	30	83.2	5.8	20	74.2	4.7
10 Sagittal subtrochanteric diameter	30	25.2	2.1	20	22.3	1.7
9 Transverse subtrochanteric diameter	30	29.3	2.7	20	27.3	1.9
K14 Maximum subtrochanteric diameter	30	29.9	2.6	20	27.9	2.1
K15 Minimum subtrochanteric diameter	30	23.6	2.0	20	20.8	1.8
11 Dorso-ventral diameter of the shaft just above the condyles	30	28.1	2.6	20	24.1	2.2
12 Medio-lateral diameter of the shaft just above the condyles	30	56.5	4.4	20	49.9	4.4
13 Upper epiphyseal length	30	96.5	5.7	20	86.1	5.2
13a Proximal width	30	91.5	5.4	20	80.5	4.9
14 Anterior neck and head length	30	72.8	5.4	20	64.7	4.6
15 Vertical diameter of neck	30	32.7	2.2	20	28.4	2.3
16 Sagittal diameter of neck	30	25.4	1.7	20	23.0	2.1
17 Circumference of neck	30	94.7	5.3	20	83.5	6.3
18 Vertical diameter of head	30	45.6	2.2	20	41.2	2.8
19 Transverse diameter of head	30	44.7	2.1	20	40.7	2.6
20 Circumference of head	30	143.1	6.8	20	130.1	8.4
21 Epicondylar breadth	29	78.7	3.7	20	69.6	4.0
22 Anteroposterior diameter of lateral condyle	30	60.0	3.6	20	54.1	3.6
23 Maximum dorso-ventral length of lateral condyle	30	60.8	3.6	20	54.6	3.7
24 Maximum dorso-ventral length of medial condyle	30	59.2	3.5	20	53.7	3.3
K7 Chord of shaft curvature	30	273.8	19.1	20	254.6	13.7
K8 Height of shaft curvature	30	9.1	2.9	20	9.2	1.9
HT31 Maximum epicondylar breadth	29	79.3	3.7	20	70.4	4.0
29 Collo-diaphyseal angle	30	130.5	4.6	20	129.1	5.3
30 Condylo-diaphyseal angle	30	79.7	1.5	20	78.2	2.3
28 Angle of torsion	30	14.2	9.6	20	24.7	10.3

[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' and letters 'HT' preceding the number are measurements according to Kiyono (1929) and to Hirai and Tabata (1928), respectively.

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 hidden behind the measurements dealt with.

The measurements of the femur were, in practice, arbitrarily divided into three 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.

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 femur are shown in Tables 2 to 13. In Tables 14 to 16, 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 principal components (PCs) and/or rotated factors.

The PCAs and the rotated solutions show that only the first PCs from the first data sets of males and females have significant correlations both with one or more of the three main neurocranial measurements and with some femoral measurements in a similar way (Tables 2 and 4; Fig. 1). Namely, these first PCs suggest that cranial length is strongly associated with maximum length, bicondylar length, maximum trochanteric length, physiological trochanteric length, diaphy-

Table 2. Principal component analysis of the correlation matrix on the first set of measurements of the neurocranium and the femur from Japanese males.[1)]

Variable[2)]		Factor loadings				Total variance (%)
		PC I	II	III	IV	
1	Cranial length	.42***	−.20	.61	.22	64.19
8	Cranial breadth	.19	−.66	.29	−.07	56.00
17	Basi-bregmatic height	.45	−.11	.33	.70	80.90
1	Maximum length	.95***	−.07	−.23	.10	97.86
2	Bicondylar length	.95***	−.06	−.23	.12	98.23
3	Max. trochant. length	.96***	−.00	−.23	.10	98.87
4	Physiol. troch. length	.96***	.01	−.25*	.12	98.88
5	Diaphyseal length	.94***	.03	−.25	.16	97.23
5a	Diaphyseal length	.95***	.01	−.24	.13	98.10
6	Sagit. diam. at midshaft	.86***	−.28	−.03	−.28	89.28
7	Trans. diam. at midshaft	.72***	.41	.24	−.19	78.18
8	Circumf. at midshaft	.91***	−.01	.15	−.25	91.57
10	Sagit. subtroch. diam.	.78***	−.20	.10	−.32	75.54
9	Trans. subtroch. diam.	.65***	.50	.24	−.04	73.55
K14	Max. subtroch. diameter	.63**	.56	.32	−.04	81.55
K15	Min. subtroch. diameter	.87***	−.26	.22	−.21	90.98
Total contribution (%)		63.27	8.88	7.56	5.98	85.68
Cumulative proportion (%)		63.27	72.15	79.70	85.68	85.68

[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 3. 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 femur from Japanese males.[1)]

Variable[2)]		Factor loadings			
		Fac I	II	III	IV
1	Cranial length	.04	.27	.45	.60
8	Cranial breadth	.04	−.23	.68	.22
17	Basi-bregmatic height	.29	.10	.05	.84*
1	Maximum length	.92***	.26	.22	.15
2	Bicondylar length	.92***	.26	.20	.17
3	Max. trochant. length	.92***	.31	.18	.14
4	Physiol. troch. length	.92***	.30	.15	.15
5	Diaphyseal length	.92***	.29	.10	.18
5a	Diaphyseal length	.92***	.30	.14	.15
6	Sagit. diam. at midshaft	.69*	.25	.59*	−.05
7	Trans. diam. at midshaft	.38*	.78	.16	.04
8	Circumf. at midshaft	.60*	.55	.50	.04
10	Sagit. subtroch. diam.	.54	.35	.59*	−.04
9	Trans. subtroch. diam.	.33**	.78	.00	.14
K14	Max. subtroch. diameter	.27	.85	−.01	.17
K15	Min. subtroch. diameter	.56*	.37	.67*	.14

1) The sample size is 30. The cumulative proportion of the variances of the four principal components is 85.68%.
2) See the second footnote to Table 1.
* $P<0.05$; ** $P<0.01$; *** $P<0.001$, by a two-tailed bootstrap test.

Table 4. Principal component analysis of the correlation matrix on the first set of measurements of the neurocranium and the femur from Japanese females.[1)]

Variable[2)]		Factor loadings			Total variance (%)
		PC I	II	III	
1	Cranial length	.42*	.51	−.42	60.77
8	Cranial breadth	−.04	−.60	.73	89.76
17	Basi-bregmatic height	.28	−.43	.35	38.90
1	Maximum length	.92***	−.33	−.09	96.97
2	Bicondylar length	.91***	−.32	−.15	96.02
3	Max. trochant. length	.94***	−.29	−.09	98.40
4	Physiol. troch. length	.92***	−.31	−.18	96.57
5	Diaphyseal length	.88***	−.40	−.16	95.53
5a	Diaphyseal length	.90***	−.37	−.17	96.96
6	Sagit. diam. at midshaft	.79***	−.30	.06	72.03
7	Trans. diam. at midshaft	.69***	.66	.23	96.73
8	Circumf. at midshaft	.88***	.38	.16	94.03
10	Sagit. subtroch. diam.	.82***	.22	.08	72.95
9	Trans. subtroch. diam.	.68***	.56	.24	83.61
K14	Max. subtroch. diameter	.62***	.62	.19	79.70
K15	Min. subtroch. diameter	.82***	.26	.23	79.08
	Total contribution (%)	58.28	18.52	7.45	84.25
	Cumulative proportion (%)	58.28	76.81	84.25	84.25

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

Variable[2)]	Factor loadings		
	Fac I	II	III
1 Cranial length	.20	.42	−.63
8 Cranial breadth	.06	−.12	.94*
17 Basi-bregmatic height	.34	.02	.52
1 Maximum length	.94***	.28	.07
2 Bicondylar length	.95***	.26	.02
3 Max. trochant. length	.94***	.32	.05
4 Physiol. troch. length	.95***	.25	−.02
5 Diaphyseal length	.96***	.18	.05
5a Diaphyseal length	.96***	.21	.03
6 Sagit. diam. at midshaft	.78***	.29	.19
7 Trans. diam. at midshaft	.15	.96	−.16
8 Circumf. at midshaft	.47***	.85	−.08
10 Sagit. subtroch. diam.	.53*	.67	−.06
9 Trans. subtroch. diam.	.19	.89	−.10
K14 Max. subtroch. diameter	.13	.87	−.17
K15 Min. subtroch. diameter	.46**	.76	.04

1) The sample size is 20. The cumulative proportion of the variances of the three principal components is 84.25%.
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 second set of measurements of the neurocranium and the femur from Japanese males.[1)]

Variable[2)]	Factor loadings					Total variance (%)
	PC I	II	III	IV	V	
1 Cranial length	.41*	−.27	.61	−.26	.32	78.47
8 Cranial breadth	.34	.10	.28	.75	.42	94.13
17 Basi-bregmatic height	.42*	−.19	.67	−.07	−.23	72.06
11 Dorso-vent. diam. of shaft just above the condyles	.66**	−.18	.03	.02	−.12	47.94
12 Medio-lat. diam. of shaft just above the condyles	.69***	−.10	.06	.09	−.51*	74.91
13 Upper epiphyseal length	.75***	.57	.12	−.23	.07	96.02
13a Proximal width	.85***	.45	.03	−.08	.11	94.32
14 Ant. neck and head length	.72***	.61	.01	−.16	−.04	91.97
15 Vertical diameter of neck	.82***	−.35	−.07	−.08	−.06	80.93
16 Sagittal diameter of neck	.54***	−.27	−.29	−.31	.52	81.77
17 Circumference of neck	.85***	−.38	−.18	−.10	.05	91.05
18 Vert. diameter of head	.91***	−.08	−.13	.19	−.03	89.94
19 Trans. diameter of head	.90***	−.05	−.16	.19	−.07	88.33
20 Circumference of head	.92***	−.03	−.18	.15	−.04	91.41
Total contribution (%)	52.45	10.13	8.04	6.72	6.46	83.80
Cumulative proportion (%)	52.45	62.58	70.62	77.35	83.80	83.80

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 7. 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 femur from Japanese males.[1)]

Variable[2)]	Factor loadings				
	Fac I	II	III	IV	V
1 Cranial length	.08	.11	.80	.12	.33
8 Cranial breadth	.14	.11	.10	.95*	−.00
17 Basi-bregmatic height	.30	.10	.76	.03	−.20
11 Dorso-vent. diam. of shaft just above the condyles	.62*	.19	.22	.05	.11
12 Medio-lat. diam. of shaft just above the condyles	.77*	.23	.20	−.07	−.24
13 Upper epiphyseal length	.24	.93	.18	.04	.11
13a Proximal width	.41	.84	.11	.17	.18
14 Ant. neck and head length	.29	.91	.04	.03	.02
15 Vertical diameter of neck	.78*	.16	.25	−.02	.32
16 Sagittal diameter of neck	.31	.16	.05	.00	.83*
17 Circumference of neck	.80*	.15	.18	.00	.47
18 Vert. diameter of head	.82*	.36	.07	.25	.20
19 Trans. diameter of head	.81*	.37	.03	.22	.17
20 Circumference of head	.81*	.41	.02	.20	.21

[1)] The sample size is 30. The cumulative proportion of the variances of the five principal components is 83.80%.
[2)] See the second footnote to Table 1.
* $P<0.05$; ** $P<0.01$; *** $P<0.001$, by a two-tailed bootstrap test.

Table 8. Principal component analysis of the correlation matrix on the second set of measurements of the neurocranium and the femur from Japanese females.[1)]

Variable[2)]	Factor loadings			Total variance (%)
	PC I	II	III	
1 Cranial length	.25	−.51	−.73	85.17
8 Cranial breadth	.13	.88	.29	87.34
17 Basi-bregmatic height	.21	.54	−.50	59.00
11 Dorso-vent. diam. of shaft just above the condyles	.79**	−.16	−.22	70.00
12 Medio-lat. diam. of shaft just above the condyles	.86***	.21	−.15	80.71
13 Upper epiphyseal length	.79**	−.40	.26	84.57
13a Proximal width	.80**	−.43	.15	85.83
14 Ant. neck and head length	.72**	−.42	.44	88.89
15 Vertical diameter of neck	.84***	.15	.09	73.38
16 Sagittal diameter of neck	.83***	.11	−.16	73.36
17 Circumference of neck	.89***	.21	.03	84.22
18 Vert. diameter of head	.95***	.15	−.02	93.22
19 Trans. diameter of head	.96***	.12	−.04	94.32
20 Circumference of head	.96***	.16	.01	95.42
Total contribution (%)	58.84	14.67	9.01	82.53
Cumulative proportion (%)	58.84	73.52	82.53	82.53

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

Variable[2)]		Factor loadings		
		Fac I	II	III
1	Cranial length	.20	−.89	−.12
8	Cranial breadth	.27	.81	−.37
17	Basi-bregmatic height	.35	.00	−.68
11	Dorso-vent. diam. of shaft just above the condyles	.76*	−.34	.11
12	Medio-lat. diam. of shaft just above the condyles	.89***	−.03	−.09
13	Upper epiphyseal length	.68	−.16	.60*
13a	Proximal width	.69	−.26	.56*
14	Ant. neck and head length	.59	−.05	.73***
15	Vertical diameter of neck	.84***	.09	.12
16	Sagittal diameter of neck	.85***	−.11	−.03
17	Circumference of neck	.91**	.10	.05
18	Vert. diameter of head	.96***	.01	.07
19	Trans. diameter of head	.97***	−.03	.07
20	Circumference of head	.97***	.03	.08

[1)] The sample size is 20. The cumulative proportion of the variances of the three principal components is 82.53%.
[2)] See the second footnote to Table 1.
* $P<0.05$; ** $P<0.01$; *** $P<0.001$, by a two-tailed bootstrap test.

Table 10. Principal component analysis of the correlation matrix on the third set of measurements of the neurocranium and the femur from Japanese males.[1)]

Variable[2)]		Factor loadings					Total variance (%)
		PC I	II	III	IV	V	
1	Cranial length	.38*	−.27	.74	.16	−.15	80.88
8	Cranial breadth	.32	−.32	.11	.03	.74	77.05
17	Basi-bregmatic height	.48	.01	.34	.45	.28	63.13
21	Epicondylar breadth	.91***	.07	−.20	.17	.03	90.05
22	Anteroposterior diameter of lateral condyle	.93***	−.07	−.20	−.15	−.11	94.99
23	Max. dorso-ventral length of lateral condyle	.88***	−.13	−.18	−.10	−.17	85.79
24	Max. dorso-ventral length of medial condyle	.92***	−.17	−.17	−.07	−.09	90.99
K7	Chord of shaft curv.	.73***	.22	.29	−.46	−.03	87.79
K8	Height of shaft curv.	.11	.64	.52	−.38	−.01	84.70
HT31	Max. epicondylar breadth	.91***	.11	−.20	.15	.05	90.18
29	Collo-diaphyseal angle	−.18	−.69	.03	.16	−.34	65.93
30	Condylo-diaphyseal angle	.28	.54	.21	.54	−.29	78.78
28	Angle of torsion	−.18	.84	−.35	.18	.09	89.81
Total contribution (%)		40.78	16.83	10.58	7.86	7.03	83.08
Cumulative proportion (%)		40.78	57.61	68.19	76.06	83.08	83.08

[1)] The sample size is 29. 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 11. Solution obtained through the normal varimax rotation of the first five principal components for the correlation matrix on the third set of measurements of the neurocranium and the femur from Japanese males.[1)]

Variable[2)]		Factor loadings				
		Fac I	II	III	IV	V
1	Cranial length	.13	.24	.74	.40	.17
8	Cranial breadth	.17	−.03	.10	−.13	.85
17	Basi-bregmatic height	.24	.06	.16	.54	.50
21	Epicondylar breadth	.88***	.01	−.08	.28	.20
22	Anteroposterior diameter of lateral condyle	.96***	.11	.08	−.00	.06
23	Max. dorso-ventral length of lateral condyle	.91***	.04	.15	.02	.02
24	Max. dorso-ventral length of medial condyle	.93***	.02	.16	.03	.11
K7	Chord of shaft curv.	.62**	.69*	.15	−.01	.07
K8	Height of shaft curv.	−.07	.90*	−.08	.16	−.08
HT31	Max. epicondylar breadth	.88***	.05	−.12	.27	.21
29	Collo-diaphyseal angle	−.10	−.52	.58*	−.11	−.17
30	Condylo-diaphyseal angle	.14	.15	−.14	.83	−.19
28	Angle of torsion	−.13	.14	−.86*	.29	−.17

[1)] The sample size is 29. The cumulative proportion of the variances of the five principal components is 83.08%.
[2)] See the second footnote to Table 1.
* $P<0.05$; ** $P<0.01$; *** $P<0.001$, by a two-tailed bootstrap test.

Table 12. Principal component analysis of the correlation matrix on the third set of measurements of the neurocranium and the femur from Japanese females.[1)]

Variable[2)]		Factor loadings					Total variance (%)
		PC I	II	III	IV	V	
1	Cranial length	.28	.85	−.14	−.20	.06	86.64
8	Cranial breadth	.26	−.80	.25	−.20	−.08	81.44
17	Basi-bregmatic height	.50**	−.22	.28	−.58	.10	71.59
21	Epicondylar breadth	.94***	−.01	−.04	.07	.19	92.32
22	Anteroposterior diameter of lateral condyle	.95***	−.10	−.13	.19	−.07	97.45
23	Max. dorso-ventral length of lateral condyle	.96***	−.05	−.11	.19	−.03	97.28
24	Max. dorso-ventral length of medial condyle	.92***	−.00	−.13	.22	.01	91.82
K7	Chord of shaft curv.	.50*	.34	.54	.37	−.08	80.09
K8	Height of shaft curv.	−.45	.31	.51	.25	.50	87.81
HT31	Max. epicondylar breadth	.93***	.03	−.04	.06	.16	89.43
29	Collo-diaphyseal angle	.17	.02	.73	.06	−.47	78.84
30	Condylo-diaphyseal angle	−.43	−.04	−.25	.52	−.48	75.74
28	Angle of torsion	−.30	−.52	.03	.51	.47	83.98
	Total contribution (%)	42.90	14.73	10.40	9.87	7.83	85.73
	Cumulative proportion (%)	42.90	57.63	68.03	77.90	85.73	85.73

[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 13. Solution obtained through the normal varimax rotation of the first five principal components for the correlation matrix on the third set of measurements of the neurocranium and the femur from Japanese females.[1]

Variable[2]		Factor loadings				
		Fac I	II	III	IV	V
1	Cranial length	.19	.90	.00	−.13	.00
8	Cranial breadth	.15	−.76	.14	−.37	−.25
17	Basi-bregmatic height	.22	−.12	.14	−.77**	−.22
21	Epicondylar breadth	.91***	.05	.03	−.31*	−.02
22	Anteroposterior diameter of lateral condyle	.96***	−.04	.10	−.09	−.21
23	Max. dorso-ventral length of lateral condyle	.96***	.00	.11	−.11	−.16
24	Max. dorso-ventral length of medial condyle	.94***	.05	.07	−.08	−.11
K7	Chord of shaft curv.	.47	.21	.66	.01	.31
K8	Height of shaft curv.	−.37	.12	.15	−.02	.84**
HT31	Max. epicondylar breadth	.89***	.10	.04	−.29	−.04
29	Collo-diaphyseal angle	.01	−.09	.88	−.07	−.05
30	Condylo-diaphyseal angle	−.22	−.12	.05	.82**	−.14
28	Angle of torsion	−.03	−.63	−.28	.24	.55*

[1] The sample size is 20. The cumulative proportion of the variances of the five principal components is 85.73%.
[2] See the second footnote to Table 1.
* $P<0.05$; ** $P<0.01$; *** $P<0.001$, by a two-tailed bootstrap test.

Table 14. 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.[1]

	Male PC I	II	III	IV	Fac I	II	III	IV
Female PC I	.98***	—	.87***	—	.90***	—	—	—
II	—	—	—	—	—	.82***	—	—
III	.58*	—	.60*	—	.64**	—	—	—
Fac I	.84***	—	.91***	—	.93***	—	—	—
II	—	—	—	.54*	—	.85***	—	.57*
III	—	.52*	—	—	—	.73**	—	—

[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 2, 3, 4 and 5.
* $P<0.05$; ** $P<0.01$; *** $P<0.001$, by a two-tailed test.

Table 15. 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.[1]

	Male PC I	II	III	IV	V	Fac I	II	III	IV	V
Female PC I	.84***	—	.79***	—	—	.92***	—	—	—	—
II	—	—	—	.58*	—	—	—	—	—	—
III	—	.62*	—	—	—	—	—	—	—	—
Fac I	.79***	—	.81***	—	—	.93***	—	—	—	—
II	—	—	—	—	—	—	—	—	—	—
III	.54*	—	—	—	—	—	.85***	—	—	—

[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 6, 7, 8 and 9.
* $P<0.05$; ** $P<0.01$; *** $P<0.001$, by a two-tailed test.

Table 16. 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 third data sets.[1)]

	Male PC I	II	III	IV	V	Fac I	II	III	IV	V
Female PC I	.87***	—	—	—	—	.88***	—	—	—	—
II	—	—	—	—	—	—	—	—	—	—
III	—	—	—	—	—	—	—	—	—	—
IV	—	.65*	—	—	—	—	—	—	—	.73**
V	—	—	—	—	—	—	—	—	—	—
Fac I	.89***	—	—	—	—	.91***	—	—	—	—
II	—	—	—	—	—	—	—	—	—	—
III	—	—	—	—	—	—	—	—	.60*	—
IV	—	—	—	—	—	—	—	—	—	.88***
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 10, 11, 12 and 13.

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

seal length, sagittal diameter at midshaft, transverse diameter at midshaft, circumference at midshaft, sagittal subtrochanteric diameter, transverse subtrochanteric diameter, maximum subtrochanteric diameter, and minimum subtrochanteric diameter. The Spearman's rank correlation coefficient of 0.98 between these first PCs is highly significant (Table 14).

On the other hand, there is neither PC nor rotated factor which suggests that cranial breadth is constantly associated with certain femoral measurements.

Discussion

In the same way as in the analyses on the upper limb bones (Mizoguchi, 2000, 2001, 2002), cranial breadth was found not to be consistently associated with any femoral measurements also in the present study.

On the other hand, cranial length was revealed to be significantly associated with many femoral measurements, especially the total lengths and the cross-sectional size of the shaft, in both males and females. Previous multivariate analyses have shown that cranial length is differentially associated with the upper limb bones: strongly associated with many measurements of the humerus; considerably with some measurements of the male scapula, ulna and radius; and not with any measurements of the clavicle (Mizoguchi, 2000, 2001, 2002). When Mizoguchi (2001) found the strong associations between cranial length and many humeral measurements, he thought that the general development of skeletal muscles including nuchal ones and those of the upper limbs might partly be related with the variation of cranial length by increasing the attachment area of the nuchal muscles. But, later, not all upper limb bones were found to be strongly associated with cranial length, as noted above. Therefore, Mizoguchi (2002) could not totally support his previous hypothesis of general development of skeletal muscles (Mizoguchi, 2001). In the present study, however, another limb bone, the femur, was found to be strongly related with cranial length again (Tables 2 and 4; Fig. 1).

A few reports support this finding. Brown (1987) showed Spearman's rank correlation coefficients for cranial size and some femur dimensions in Australian Aboriginal males (n=29) and females (n=34): 0.23 (not significant at the 5% level) and 0.58 ($P<0.001$) between cranial length and "femur length" for males and females, respectively; 0.60 ($P<0.001$) and 0.21 (n.s.) between cranial length and "femur bicondylar breadth"; and 0.24 (n.s.) and 0.54 ($P<0.01$) between cranial length and "femur transverse mid-

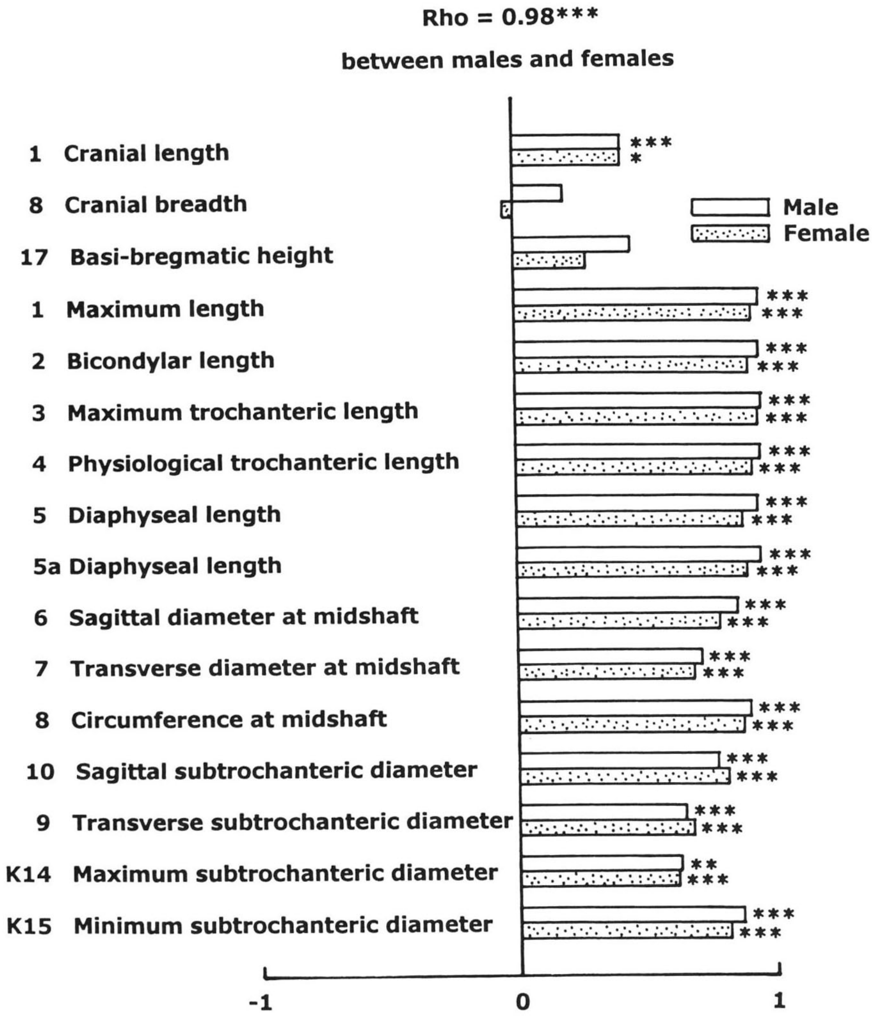

Fig. 1. Factor loadings on the first principal components obtained from the first data sets of the neurocranium and femur for males and females. For the numbers preceding measurement items, see the second footnote to Table 1.
* $P<0.05$; ** $P<0.01$; *** $P<0.001$.

shaft." These coefficients suggest that, at least in females, cranial length is strongly correlated with femoral length and the thickness at midshaft of the femur. This is compatible with the present findings (Tables 2 and 4; Fig. 1).

Although there are few studies on correlations between cranial and postcranial bones, those on somatometric data have frequently been conducted. But, even in such somatological studies, exhaustive investigations dealing with many measurement items are scarce. One of the exceptions is Hoshi and Kouchi (1978). Using their anthropometric data of the head, face and body from 104 or more Japanese males, Mizoguchi (1992) carried out principal component analysis. The results show that the first PC, which is considered a general size factor and 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., has the highest factor loading for cranial length among the three main head measurements: 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. It may be said from these findings that, of 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. It is interesting here that the factor loadings are higher for the distal segments than for the proximal segments both in girth and in length except for the combination of thigh and calf girths. In the case of the upper limb bones, however, humeral measurements are more strongly associated with cranial length than those of the forearm bones (Mizoguchi, 2001, 2002). Namely, the intensity of association with head or cranial length of proximal and distal limb segments seems reverse between somatometric and osteometric cases. The causes for this should be sought through further analyses. On the other hand, in the case of the lower limbs, nothing can be said about this tendency because there is no comparative data on the leg bones at present. But, at least, the above Mizoguchi's (1992) finding that the variation of thigh girth may be associated with those of head length is compatible with the present findings in the analyses of osteometric data (Tables 2 and 4; Fig. 1).

From the above, without doubt there are strong associations between cranial length and the lengths and thickness of the femur. And, as shown by Mizoguchi (2001), many humeral measurements are also strongly associated with cranial length. Although the causes for inconsistent relations between cranial length and the measurements of the upper limb bones except the humerus are unknown (Mizoguchi, 2002), the general development of some skeletal muscles such as nuchal muscles and those attached on the "proximal" limb bones may have some influence on cranial length, and the similarity between the femur and the humerus in having strong association with cranial length may partly be explained by ontogenetic homology (or homodynamy). But this is just a speculation. The causes for such strong associations remain still to be sought.

Summary and Conclusions

While cranial breadth has no systematic association with any femoral measurements, cranial length is significantly associated with femoral lengths and the cross-sectional size of the femoral shaft both in males and in females. The general development of some skeletal muscles such as nuchal muscles and those attached on the "proximal" limb bones may have some influence on cranial length, and the similarity between the femur and the humerus in having strong associations with cranial length may partly caused by the ontogenetic homology (or homodynamy) between the "proximal" bones.

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