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Associations between Neurocranial and Ulnar/Radial Measurements: Toward the Solution of the Brachycephalization Problem

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Abstract As a step toward elucidating the causes and mechanism of brachycephalization, correlations between neurocranial and ulnar/radial measurements were examined by principal component analysis and Kaiser's normal varimax rotation methods. The results based on 30 male and 20 female skeletons of modern Japanese showed that cranial length was significantly associated with some measurements of the ulna and the radius only in males. This and previous findings suggest that, while cranial breadth has no or little association with any measurements of the upper limb bones, cranial length is differentially associated with them, i.e., 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. Although the causes for this differential association of cranial length with upper limb bone measurements are not determinable for the present, a possibility was discussed from the viewpoint of osteogenesis.
Key words: Brachycephalization, Neurocranium, Ulna, Radius, Principal component analysis

Since 1992, the present author has analyzed correlations between the neurocranium and postcranial bones with the aim of clarifying the causes and mechanism of brachycephalization and shown that, while cranial breadth has no consistent association with any measurements of the vertebrae, ribs, scapula, clavicle or humerus, cranial length is definitely associated with the sagittal and transverse diameters of the vertebral bodies, sacral breadths, costal chords, the size of the scapula, and many measurements of the humerus (Mizoguchi, 1992, 1994, 1995, 1996, 1997, 1998a, b, 1999, 2000, 2001).

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

Materials and Methods

The raw measurement data of the neurocranium and of the right ulna and radius reported by Miyamoto (1924, 1925) 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 ulnar and radial measurements are listed in Tables 1 and 2, respectively.

For examining the overall relations between neurocranial and forearm 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 hidden behind the measurements dealt with.

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

Variable[2)]		Males			Females		
		n	Mean	SD	*n*	Mean	SD
1	Maximum length	30	239.2	12.6	20	217.9	9.2
2	Physiological length	30	210.0	11.2	20	191.0	8.3
3	Minimum circumference	30	36.8	2.5	20	32.3	2.0
K4	Chord of shaft curvature	30	181.1	10.4	20	165.4	8.7
K5	Height of shaft curvature	29	2.3	1.7	20	2.3	1.3
6	Breadth of olecranon	30	25.6	1.5	20	21.6	1.5
8	Height of olecranon	30	20.4	1.2	20	18.0	1.5
7	Depth of olecranon	30	24.5	1.2	20	22.0	1.2
5	Height of olecranon top	30	3.6	1.2	20	3.1	0.7
K10	Breadth of coronoid process	30	25.9	2.1	20	22.4	1.3
K11	Breadth of lateral portion of trochlear notch on coronoid process	30	11.8	1.9	20	10.4	1.8
K12	Breadth of medial portion of trochlear notch on coronoid process	30	14.5	1.3	20	12.6	0.8
10	Posterior breadth of lateral portion of trochlear notch on coronoid process	30	12.1	1.9	20	10.4	1.8
9	Anterior breadth of lateral portion of trochlear notch on coronoid process	30	8.1	0.9	20	6.6	0.9
K15	Anterior depth of coronoid process	29	15.9	1.3	20	14.4	1.0
K16	Total depth of coronoid process	29	34.6	1.8	20	30.3	1.7
12	Transverse diameter	30	15.6	1.2	20	13.4	0.9
11	Dorso-volar diameter	30	12.8	1.2	20	10.5	0.8
K19	Maximum diameter of midshaft	30	16.1	1.1	20	13.9	1.0
K20	Minimum diameter of midshaft	30	12.0	0.9	20	10.0	0.7
14	Upper dorso-volar diameter	30	25.2	2.2	20	22.4	1.7
13	Upper transverse diameter	30	19.8	1.9	20	17.3	1.4
K23	Maximum diameter of head	30	19.8	1.2	20	17.6	1.0
K24	Transverse diameter of head	30	16.8	1.2	20	14.9	1.1
K25	Angle of upper side-curvature	30	169.6	3.0	20	170.9	2.2
K26	Angle of lower side-curvature	30	175.0	3.0	20	171.9	3.2
K27	Backward flection angle of joint to shaft	30	19.9	6.0	20	17.0	5.1
K28	Inward flection angle of joint to shaft	30	16.2	4.2	20	15.3	4.1
15	Ulnar joint angle	30	84.1	4.6	20	83.9	4.3
K30	Arm angle	30	166.9	4.9	20	164.9	5.2

[1)] The estimates of basic statistics listed here were recalculated by the present author on the basis of the raw data published by Miyamoto (1925).

[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's (1929) system.

The measurements of the ulna or radius 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.

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

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

Variable[2)]		Males			Females		
		n	Mean	SD	*n*	Mean	SD
1	Maximum length	30	223.1	11.6	20	201.3	8.8
2	Physiological length	30	207.2	11.0	20	187.7	8.5
3	Minimum circumference of shaft	30	42.1	3.2	20	35.4	1.7
K4	Circumference of shaft below radial tuberosity	30	42.7	3.2	20	35.8	2.1
K5	Chord of shaft curvature	30	157.0	9.3	20	142.9	10.0
K6	Height of shaft curvature	30	4.5	0.9	20	4.0	1.0
K7	Maximum diameter of head	30	22.4	1.2	20	19.5	1.2
K8	Minimum diameter of head	30	21.2	1.2	20	18.7	1.2
K9	Maximum diameter of neck	30	14.6	1.2	20	12.4	1.1
K10	Minimum diameter of neck	30	12.6	1.1	20	10.7	1.0
4	Transverse diameter of shaft	30	16.6	1.4	20	14.5	1.3
5	Sagittal diameter of shaft	30	11.6	0.9	20	9.6	0.9
K13	Transverse diameter of distal end	30	31.7	1.9	20	27.5	1.6
K14	Shaft-curvature angle from inside to outside	30	171.9	1.7	20	172.1	2.1
K15	Angle between proximal surface of head and axis of neck	30	89.8	3.4	20	89.1	2.9
7	Neck-shaft angle	30	169.5	3.5	20	168.4	2.7
8	Tuberosity-position angle	30	46.0	10.3	20	44.2	9.7

[1)] The estimates of basic statistics listed here were recalculated by the present author on the basis of the raw data published by Miyamoto (1925).

[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's (1929) system.

correlation coefficient (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 forearm bones are shown in Tables 3 to 18. In Tables 19 to 22, Spearman's rank correlation coefficients are listed to show similarities between males and females in the variation patterns of factor loadings on principal components (PCs) or rotated factors.

In the results of the PCAs and the rotated solutions (Tables 3 to 18), only three factors are found to have significant correlations both with one or more of the three main neurocranial measurements and with some of the ulnar or radial measurements: rotated factor V in Table 4, PC I in Table 7, and PC I in Table 11. All these three are those from the male data. In the results for females, there is no corresponding factor which has significant correlations with both cranial and ulnar/radial measurements simultaneously.

Spearman's rank correlation coefficients between males and females (Tables 19 to 22) show that there are several factors whose factor loading variation patterns are highly significantly similar to each other ($P<0.01$). Among them, however, there is no couple of factors both of which are significantly correlated with both cranial and ulnar/radial measurements.

Table 3. Principal component analysis of the correlation matrix on the first set of measurements of the neurocranium and the ulna from Japanese males.[1)]

	Variable[2)]	Factor loadings							Total variance (%)
		PC I	II	III	IV	V	VI	VII	
1	Cranial length	.23	−.39	−.10	.56	−.52	.15	−.23	87.51
8	Cranial breadth	.23	−.04	−.47	.50	.59	−.02	−.05	86.87
17	Basi-bregm. height	.16	−.53	−.30	.35	−.17	−.30	−.16	66.20
1	Maximum length	.89***	−.07	.31	−.01	.03	−.13	−.17	93.95
2	Physiol. length	.86***	−.12	.36	.01	.07	−.10	−.19	93.67
3	Minimum circumf.	.39	−.39	−.05	−.24	−.19	.50	.35	77.62
K4	Chord of shaft cur.	.84***	−.15	.40	.14	.06	−.15	−.10	94.77
K5	Ht. of shaft cur.	.18	−.10	.59	.44	−.03	.12	.44	79.36
6	Br. of olecranon	.72***	−.26	−.32	−.08	−.00	.17	.05	72.90
8	Ht. of olecranon	.54**	−.40	−.28	−.47	−.10	−.02	.19	80.21
7	Dep. of olecranon	.57**	−.10	.47	−.35	.19	.03	−.15	73.31
5	Ht. of olecr. top	.24	.26	−.14	−.28	−.23	−.75*	.23	90.03
K10	Br. of coro. proc.	.72***	.51	−.23	.20	.05	.15	.19	93.24
K11	Br. of lat. port.	.40	.82	.05	.09	−.26	.05	.08	92.20
K12	Br. of med. port.	.65***	−.12	−.30	.19	.35	−.18	.34	83.42
10	Post. br. of l.p.	.43	.71	−.11	.20	−.39	.03	−.04	89.75
9	Ant. br. of l. p.	.41	.53	−.21	−.23	.30	.27	−.30	80.48
K15	Ant. dep. of c. p.	.51*	−.18	−.40	−.25	−.30	.07	−.19	64.74
Total contribution (%)		30.32	15.07	10.22	9.02	7.37	6.48	4.87	83.35
Cumulative proportion (%)		30.32	45.38	55.60	64.63	71.99	78.48	83.35	83.35

[1)] The sample size is 28. 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 4. Solution obtained through the normal varimax rotation of the first seven principal components for the correlation matrix on the first set of measurements of the neurocranium and the ulna from Japanese males.[1)]

	Variable[2)]	Factor loadings						
		Fac I	II	III	IV	V	VI	VII
1	Cranial length	.08	.10	−.14	.88*	−.03	.23	.13
8	Cranial breadth	−.00	.02	.09	.13	.90***	.16	−.11
17	Basi-bregm. height	.06	−.26	−.08	.70**	.26	−.17	−.06
1	Maximum length	.90*	.22	−.20	.12	.12	−.10	.02
2	Physiol. length	.92*	.16	−.17	.12	.12	−.04	.05
3	Minimum circumf.	.10	−.03	−.82***	.01	−.07	.20	.21
K4	Chord of shaft cur.	.90*	.14	−.13	.18	.17	−.07	.20
K5	Ht. of shaft cur.	.26	.07	.04	.05	.01	.13	.84**
6	Br. of olecranon	.35	.14	−.66	.18	.33	.01	−.13
8	Ht. of olecranon	.26	−.13	−.78*	.03	.07	−.28	−.17
7	Dep. of olecranon	.78*	−.04	−.19	−.26	−.10	.04	−.02
5	Ht. of olecr. top	.09	.20	−.02	−.05	−.02	−.92***	−.10
K10	Br. of coro. proc.	.24	.78	−.25	−.07	.44*	−.03	.04
K11	Br. of lat. port.	.12	.93	.08	−.15	−.06	−.12	.05
K12	Br. of med. port.	.28	.11	−.34	.03	.74**	−.25	.13
10	Post. br. of l. p.	.08	.93	.04	.12	−.03	−.12	−.05
9	Ant. br. of l. p.	.24	.50	−.07	−.38	.22	.22	−.50
K15	Ant. dep. of c. p.	.19	.17	−.56	.30	.00	−.10	−.41

[1)] The sample size is 28. The cumulative proportion of the variances of the seven principal components is 83.35%.
[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. Principal component analysis of the correlation matrix on the first set of measurements of the neurocranium and the ulna from Japanese females.[1)]

	Variable[2)]	Factor loadings						Total variance (%)
		PC I	II	III	IV	V	VI	
1	Cranial length	.56	.12	.09	−.12	−.68*	−.14	84.02
8	Cranial breadth	−.29	−.07	.38	.59	.42	.04	75.86
17	Basi-bregm. height	.22	.18	.31	.70	.12	.39	82.89
1	Maximum length	.88*	.08	−.33	.18	.21	.01	97.30
2	Physiol. length	.74*	.13	−.52	.28	.23	−.01	96.72
3	Minimum circumf.	.37	.42	.50	−.26	.00	−.14	64.91
K4	Chord of shaft cur.	.84	−.17	−.46	.05	.07	.00	95.16
K5	Ht. of shaft cur.	.57	−.36	−.32	.06	−.31	.22	71.03
6	Br. of olecranon	.65	−.22	.46	−.04	.22	−.05	73.56
8	Ht. of olecranon	.61	.03	.55	.11	−.17	.02	70.86
7	Dep. of olecranon	.61	.03	.39	−.08	−.18	−.29	65.18
5	Ht. of olecr. top	.29	.51	−.11	−.39	.02	.58	83.36
K10	Br. of coro. proc.	.15	.81	.04	−.27	.38	−.26	96.86
K11	Br. of lat. port.	−.05	.97*	−.07	−.07	.06	.07	96.81
K12	Br. of med. port.	.23	−.48	−.18	−.35	.63	−.28	90.99
10	Post. br. of l. p.	−.05	.97*	−.07	−.07	.06	.07	96.81
9	Ant. br. of l. p.	.14	.48	−.07	.67	−.12	−.39	87.87
K15	Ant. dep. of c. p.	.46	−.28	.55	−.23	.27	.28	79.46
	Total contribution (%)	25.07	21.18	12.28	10.63	8.90	5.82	83.87
	Cumulative proportion (%)	25.07	46.24	58.52	69.15	78.05	83.87	83.87

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

	Variable[2)]	Factor loadings					
		Fac I	II	III	IV	V	VI
1	Cranial length	.25	−.02	.53	−.48	−.49	−.12
8	Cranial breadth	−.25	−.09	−.03	.80	.12	−.19
17	Basi-bregm. height	.21	.05	.19	.78	−.36	−.01
1	Maximum length	.93	.13	.27	.05	.09	−.02
2	Physiol. length	.95	.17	.03	.08	.08	−.12
3	Minimum circumf.	−.09	.45	.66*	−.08	−.00	.04
K4	Chord of shaft cur.	.93	−.11	.18	−.17	.11	.04
K5	Ht. of shaft cur.	.63	−.41	.11	−.21	−.24	.17
6	Br. of olecranon	.24	−.14	.74	.16	.25	.13
8	Ht. of olecranon	.16	−.03	.78	.14	−.22	.02
7	Dep. of olecranon	.17	.01	.76	−.16	−.03	−.15
5	Ht. of olecr. top	.25	.56	.03	−.12	−.23	.62
K10	Br. of coro. proc.	.03	.92	.17	−.06	.26	−.11
K11	Br. of lat. port.	−.01	.95	−.09	.02	−.24	−.03
K12	Br. of med. port.	.25	−.21	.05	−.12	.88***	.12
10	Post. br. of l. p.	−.01	.95	−.09	.02	−.24	−.03
9	Ant. br. of l. p.	.24	.31	.04	.27	−.31	−.75**
K15	Ant. dep. of c. p.	.06	−.16	.64	.21	.23	.51*

[1)] The sample size is 20. The cumulative proportion of the variances of the six principal components is 83.87%.
[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. Principal component analysis of the correlation matrix on the second set of measurements of the neurocranium and the ulna from Japanese males.[1)]

	Variable[2)]	Factor loadings						Total variance (%)
		PC I	II	III	IV	V	VI	
1	Cranial length	.43*	.30	−.03	.13	.63	−.31	77.64
8	Cranial breadth	.19	.15	.38	.38	.33	.65	88.38
17	Basi-bregm. height	.27	.39	.31	.31	.35	−.50	78.15
K16	Total dep. of c. p.	.77***	.13	.23	.11	−.34	.00	79.84
12	Transverse diameter	.75***	−.23	−.42	.01	.19	.18	85.09
11	Dorso-volar diam.	.84***	−.27	−.12	.04	−.06	−.09	81.31
K19	Max. d. of midshaft	.72***	−.22	−.34	.04	.23	−.09	73.96
K20	Min. d. of midshaft	.83***	−.22	−.13	−.08	−.18	.05	80.53
14	Up. dorso-volar d.	.81***	.18	.17	−.12	−.25	.18	82.28
13	Up. trans. diameter	.83***	.03	.24	.03	.10	.03	76.73
K23	Max. diam. of head	.39	−.25	.54	−.57	−.11	−.18	88.29
K24	Trans. d. of head	.42	−.46	.46	−.24	.09	−.11	67.64
K25	Angle of up. s.-c.	.16	−.44	−.52	.43	−.33	−.21	83.30
K26	Angle of low. s.-c.	−.32	.45	.42	.20	−.36	−.26	71.83
K27	Back. flec. angle	.46	.21	.33	.59	−.31	.03	80.01
K28	Inward flec. angle	−.33	−.67	.51	.10	.18	.14	87.19
15	Ulnar joint angle	.21	.87*	−.17	−.18	−.05	.13	88.83
K30	Arm angle	.27	.84*	−.15	−.31	.01	.07	90.23
	Total contribution (%)	31.15	17.61	11.51	7.75	7.34	5.81	81.18
	Cumulative proportion (%)	31.15	48.77	60.28	68.03	75.37	81.18	81.18

[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 8. Solution obtained through the normal varimax rotation of the first six principal components for the correlation matrix on the second set of measurements of the neurocranium and the ulna from Japanese males.[1)]

	Variable[2)]	Factor loadings					
		Fac I	II	III	IV	V	VI
1	Cranial length	.31	.21	.02	−.04	.79*	.12
8	Cranial breadth	.04	−.04	−.08	.25	.09	.90***
17	Basi-bregm. height	−.12	.10	.05	.26	.83*	.01
K16	Total dep. of c. p.	.30	.21	.30	.75*	.06	.02
12	Transverse diameter	.91*	.08	.00	.13	.03	.06
11	Dorso-volar diam.	.74*	−.03	.24	.43	.11	−.13
K19	Max. d. of midshaft	.81	.02	.05	.13	.24	−.09
K20	Min. d. of midshaft	.71*	.08	.29	.43*	−.07	−.10
14	Up. dorso-volar d.	.40	.38	.40	.58*	−.04	.13
13	Up. trans. diameter	.49	.13	.40	.48	.29	.21
K23	Max. diam. of head	.07	−.06	.92*	.11	−.02	−.10
K24	Trans. d. of head	.25	−.34	.68	.13	.10	.05
K25	Angle of up. s.-c.	.41	−.36	−.45	.27	−.15	−.49
K26	Angle of low. s.-c.	−.75	.12	−.03	.34	.12	−.11
K27	Back. flec. angle	−.02	−.00	−.08	.86*	.18	.17
K28	Inward flec. angle	−.19	−.81	.24	−.16	−.11	.30
15	Ulnar joint angle	−.07	.92	−.10	.10	.10	.11
K30	Arm angle	−.01	.93*	.04	.04	.14	.07

[1)] The sample size is 29. The cumulative proportion of the variances of the six principal components is 81.18%.
[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. Principal component analysis of the correlation matrix on the second set of measurements of the neurocranium and the ulna from Japanese females.[1)]

	Variable[2)]	Factor loadings						Total variance (%)
		PC I	II	III	IV	V	VI	
1	Cranial length	.19	−.17	−.54	−.50	−.24	−.16	69.49
8	Cranial breadth	−.04	.35	.28	.78	.13	−.05	82.31
17	Basi-bregm. height	.37	.47	−.26	.32	.46	−.18	77.27
K16	Total dep. of c. p.	.63	−.15	−.03	.50	−.48	−.17	93.57
12	Transverse diameter	.63	−.37	.22	−.15	.22	−.13	67.43
11	Dorso-volar diam.	.63	−.19	.29	−.21	.04	−.49*	79.96
K19	Max. d. of midshaft	.77	−.23	.05	−.18	.21	.07	72.10
K20	Min. d. of midshaft	.81	−.20	.04	−.27	−.25	−.12	84.35
14	Up. dorso-volar d.	.81	−.15	−.06	.43	−.00	.03	87.11
13	Up. trans. diameter	.30	−.33	.32	−.10	−.13	.75**	88.35
K23	Max. diam. of head	.45	−.02	−.76	.18	−.06	.21	85.88
K24	Trans. d. of head	.68	.32	−.24	−.04	.06	.34	73.25
K25	Angle of up. s.-c.	.03	.27	.69	−.35	−.09	−.04	67.44
K26	Angle of low. s.-c.	−.39	−.33	−.06	.27	−.69	−.12	82.88
K27	Back. flec. angle	.42	.22	.65	.26	−.19	.06	75.07
K28	Inward flec. angle	.19	.87	−.21	−.08	−.22	−.12	90.59
15	Ulnar joint angle	−.19	−.91	−.05	.27	.12	.04	96.01
K30	Arm angle	−.12	−.86	−.03	.16	.26	−.17	87.36
Total contribution (%)		24.66	19.21	12.52	10.92	7.46	6.37	81.13
Cumulative proportion (%)		24.66	43.87	56.38	67.31	74.77	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 1.
* $P<0.05$; ** $P<0.01$; *** $P<0.001$, by a two-tailed bootstrap test.

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

	Variable[2)]	Factor loadings					
		Fac I	II	III	IV	V	VI
1	Cranial length	.18	.09	−.24	−.76*	−.11	−.11
8	Cranial breadth	−.12	.09	−.08	.87*	−.04	−.17
17	Basi-bregm. height	.15	.30	−.43	.35	.46	−.39
K16	Total dep. of c. p.	.61	.06	−.42	.30	−.54*	.03
12	Transverse diameter	.74	−.24	.03	−.05	.24	.11
11	Dorso-volar diam.	.85	−.02	.20	−.06	.06	−.18
K19	Max. d. of midshaft	.72	−.05	−.18	−.10	.32	.25
K20	Min. d. of midshaft	.84*	.14	−.12	−.25	−.08	.19
14	Up. dorso-volar d.	.67	−.02	−.54	.33	−.02	.14
13	Up. trans. diameter	.18	−.14	.01	.02	.02	.91***
K23	Max. diam. of head	.12	.11	−.89*	−.20	.02	.06
K24	Trans. d. of head	.34	.46	−.48	.00	.31	.30
K25	Angle of up. s.-c.	.18	.31	.71	.10	.06	.17
K26	Angle of low. s.-c.	−.22	−.22	.00	−.04	−.85*	−.03
K27	Back. flec. angle	.44	.28	.25	.57	−.13	.28
K28	Inward flec. angle	−.04	.91	−.13	.02	.03	−.24
15	Ulnar joint angle	−.01	−.95	−.14	−.02	−.18	.10
K30	Arm angle	.13	−.92	−.05	−.07	−.05	−.10

[1)] The sample size is 20. The cumulative proportion of the variances of the six principal components is 81.13%.
[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. Principal component analysis of the correlation matrix on the first set of measurements of the neurocranium and the radius from Japanese males.[1)]

	Variable[2)]	Factor loadings					Total variance (%)
		PC I	II	III	IV	V	
1	Cranial length	.41*	.25	.49	.15	−.26	56.75
8	Cranial breadth	.21	−.36	.47	.28	.70	95.70
17	Basi-bregm. height	.34	.20	.56	.47	−.30	77.63
1	Maximum length	.84***	.08	.18	−.45	.10	96.56
2	Physiol. length	.81***	.08	.18	−.49	.14	95.98
3	Min. cir. of shaft	.79***	−.37	−.16	−.03	−.15	80.99
K4	Cir. below rad. t.	.72***	−.54	−.16	.18	−.19	89.40
K5	Chord of shaft cur.	.82***	−.13	.16	−.33	−.18	86.44
K6	Ht. of shaft cur.	.43*	−.69	.15	.19	−.09	73.26
K7	Max. diam. of head	.78***	.43	−.03	.23	.18	89.15
K8	Min. diam. of head	.79***	.45	−.07	.18	.13	87.55
K9	Max. diam. of neck	.71***	.30	−.46	.20	−.04	84.63
K10	Min. diam. of neck	.54***	−.10	−.62	.21	.15	75.77
Total contribution (%)		44.13	12.73	11.89	8.56	6.53	83.83
Cumulative proportion (%)		44.13	56.86	68.75	77.31	83.83	83.83

[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 12. 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 radius from Japanese males.[1)]

	Variable[2)]	Factor loadings				
		Fac I	II	III	IV	V
1	Cranial length	.09	−.04	.70*	−.27	.00
8	Cranial breadth	−.02	−.17	.09	−.08	.96**
17	Basi-bregm. height	.10	−.12	.86*	.00	.10
1	Maximum length	.28	−.18	.13	−.91*	.08
2	Physiol. length	.25	−.14	.09	−.93**	.10
3	Min. cir. of shaft	.34	−.72	.03	−.42	−.04
K4	Cir. below rad. t.	.30	−.87	.06	−.20	.03
K5	Chord of shaft cur.	.17	−.45	.21	−.76*	−.07
K6	Ht. of shaft cur.	−.08	−.80	.11	−.09	.26
K7	Max. diam. of head	.79	−.01	.34	−.36	.15
K8	Min. diam. of head	.78*	−.01	.32	−.39	.07
K9	Max. diam. of neck	.85***	−.20	.07	−.20	−.19
K10	Min. diam. of neck	.71***	−.41	−.28	−.03	−.01

[1)] The sample size is 30. The cumulative proportion of the variances of the five principal components is 83.83%.
[2)] See the second footnote to Table 2.
* $P<0.05$; ** $P<0.01$; *** $P<0.001$, by a two-tailed bootstrap test.

Discussion

Previous analyses on the neurocranium and the scapula, clavicle or humerus (Mizoguchi, 2000, 2001) suggested that cranial breadth had no consistent association with any measurements of these three upper limb bones. Also in the present study, this is the case: cranial breadth was found to have no consistent association with any of the ulnar or radial measurements dealt with. Therefore, it can be concluded that cranial breadth has

Table 13. Principal component analysis of the correlation matrix on the first set of measurements of the neurocranium and the radius from Japanese females.[1)]

Variable[2)]		Factor loadings					Total variance (%)
		PC I	II	III	IV	V	
1	Cranial length	.35	−.43	−.22	−.65	.28	86.14
8	Cranial breadth	−.20	.73	.49	.14	−.21	87.52
17	Basi-bregm. height	−.05	.25	.74	−.28	.28	77.51
1	Maximum length	.72***	−.38	.51	.01	−.09	92.68
2	Physiol. length	.64***	−.46	.53	−.02	−.15	93.24
3	Min. cir. of shaft	.67**	.36	−.07	−.50	−.14	86.00
K4	Cir. below rad. t.	.83***	.20	−.03	−.01	−.04	73.17
K5	Chord of shaft cur.	.72***	−.38	−.06	.08	−.43	86.00
K6	Ht. of shaft cur.	.55*	.27	−.22	.10	−.57	74.86
K7	Max. diam. of head	.70*	.43	−.06	−.12	.25	74.54
K8	Min. diam. of head	.67*	.46	−.25	−.12	.12	75.15
K9	Max. diam. of neck	.77***	.03	−.01	.42	.34	88.51
K10	Min. diam. of neck	.63*	−.06	−.08	.51	.43	84.96
Total contribution (%)		38.34	14.72	11.68	9.66	8.71	83.10
Cumulative proportion (%)		38.34	53.06	64.74	74.39	83.10	83.10

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 14. 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 radius from Japanese females.[1)]

Variable[2)]		Factor loadings				
		Fac I	II	III	IV	V
1	Cranial length	.26	−.17	−.87**	−.07	.09
8	Cranial breadth	.17	.11	.82	−.18	.37
17	Basi-bregm. height	.07	−.16	.17	−.09	.84
1	Maximum length	.16	−.90***	−.09	.25	.12
2	Physiol. length	.07	−.94***	−.12	.16	.11
3	Min. cir. of shaft	.89*	−.20	−.13	−.09	.03
K4	Cir. below rad. t.	.68*	−.36	−.00	.35	−.11
K5	Chord of shaft cur.	.26	−.71	−.14	.13	−.50
K6	Ht. of shaft cur.	.57	−.26	.28	−.01	−.52
K7	Max. diam. of head	.75	−.05	−.04	.39*	.14
K8	Min. diam. of head	.80	.03	−.03	.32	−.07
K9	Max. diam. of neck	.33	−.29	−.01	.83***	−.06
K10	Min. diam. of neck	.15	−.18	−.06	.88***	−.09

1) The sample size is 20. The cumulative proportion of the variances of the five principal components is 83.10%.
2) See the second footnote to Table 2.
* $P<0.05$; ** $P<0.01$; *** $P<0.001$, by a two-tailed bootstrap test.

no association with the size of any upper limb bones.

On the other hand, cranial length has been shown to be highly significantly associated with many humeral measurements ($P<0.01$) in both males and females (Mizoguchi, 2001), and with some scapular measurements ($P<0.001$) at least in males (Mizoguchi, 2000). As regards clavicular measurements, it has been found that they have no significant association ($P>0.05$) with

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

	Variable[2]	Factor loadings						Total variance (%)
		PC I	II	III	IV	V	VI	
1	Cranial length	.51	−.04	.19	.73	.06	−.18	86.31
8	Cranial breadth	.42	.29	.32	−.15	.58	−.12	72.72
17	Basi-bregm. height	.59	.09	−.47	.37	.29	−.04	80.39
4	Trans. d. of shaft	.50	.48	−.07	.06	−.62*	−.15	88.64
5	Sagit. d. of shaft	.48	.60	.45	−.13	−.21	.10	86.68
K13	Tr. d. of dist. end	.61	.24	−.00	−.44	.24	.12	70.20
K14	Shaft-curv. angle	−.31	−.19	.76	.11	.04	−.33	84.00
K15	Ang. b. head & neck	−.63	.64	−.12	.17	.22	.16	92.78
7	Neck-shaft angle	−.56	.73	.07	.24	.04	.14	92.49
8	Tub.-position angle	.24	−.32	.31	.22	−.04	.82**	97.55
Total contribution (%)		24.97	18.17	12.67	10.58	9.62	9.16	85.18
Cumulative proportion (%)		24.97	43.14	55.81	66.39	76.02	85.18	85.18

[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 16. Solution obtained through the normal varimax rotation of the first six principal components for the correlation matrix on the second set of measurements of the neurocranium and the radius from Japanese males.[1]

	Variable[2]	Factor loadings					
		Fac I	II	III	IV	V	VI
1	Cranial length	.05	−.12	.11	.89*	−.16	.12
8	Cranial breadth	.82***	.02	.09	.20	.00	−.05
17	Basi-bregm. height	.21	−.10	−.59	.63*	.02	−.07
4	Trans. d. of shaft	−.05	−.06	−.21	.16	−.89***	−.14
5	Sagit. d. of shaft	.48	.11	.11	.02	−.76***	.17
K13	Tr. d. of dist. end	.70	−.22	−.32	−.11	−.23	.05
K14	Shaft-curv. angle	.00	−.00	.91	.06	.11	−.02
K15	Ang. b. head & neck	−.04	.94	−.05	−.12	.11	−.11
7	Neck-shaft angle	−.06	.94*	.10	−.06	−.12	−.05
8	Tub.-position angle	−.01	−.13	−.01	.08	.03	.97**

[1] The sample size is 30. The cumulative proportion of the variances of the six principal components is 85.18%.
[2] See the second footnote to Table 2.
* $P<0.05$; ** $P<0.01$; *** $P<0.001$, by a two-tailed bootstrap test.

cranial length in males nor in females (Mizoguchi, 2000). In the present study, only male data (Tables 7 and 11) showed that cranial length was significantly associated with some ulnar and radial measurements.

Mizoguchi (2001) suggested, mainly on the basis of the analyses on the neurocranium and humerus, that the general development of skeletal muscles including nuchal muscles and the muscles of the upper limbs has more influence on the variation in cranial length than on the variation in cranial breadth. If so, it is expected that the same tendency can be found in all the analyses on the neurocranium and upper limb bones of both males and females. But, in fact, such a strong association with cranial length was found only in the results on the humerus. No such association was found in the analyses on the clavicle.

Table 17. Principal component analysis of the correlation matrix on the second set of measurements of the neurocranium and the radius from Japanese females.[1)]

	Variable[2)]	Factor loadings					Total variance (%)
		PC I	II	III	IV	V	
1	Cranial length	.53	.46	−.32	.55*	.01	89.96
8	Cranial breadth	−.27	−.54	.65	−.02	−.29	86.83
17	Basi-bregm. height	.01	−.35	.51	.73	.07	92.20
4	Trans. d. of shaft	.72*	−.32	−.46	−.04	−.02	84.59
5	Sagit. d. of shaft	.77***	−.25	.01	−.16	−.15	71.14
K13	Tr. d. of dist. end	.65*	−.34	.14	.11	.46	77.74
K14	Shaft-curv. angle	.10	.56	.47	−.15	.59	91.55
K15	Ang. b. head & neck	.85***	.09	.19	.03	−.32	87.13
7	Neck-shaft angle	.68*	.14	.53	−.35	−.03	89.18
8	Tub.-position angle	.04	.78	.28	.13	−.41	87.89
Total contribution (%)		30.93	18.66	16.33	10.50	9.40	85.82
Cumulative proportion (%)		30.93	49.59	65.92	76.42	85.82	85.82

[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 18. 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 radius from Japanese females.[1)]

	Variable[2)]	Factor loadings				
		Fac I	II	III	IV	V
1	Cranial length	.23	.17	−.89***	.16	−.01
8	Cranial breadth	.06	.06	.80	.45	−.13
17	Basi-bregm. height	−.01	−.05	.07	.96	−.00
4	Trans. d. of shaft	.58	−.49	−.37	−.15	−.34
5	Sagit. d. of shaft	.80	−.23	−.06	−.03	−.12
K13	Tr. d. of dist. end	.49	−.59**	−.17	.31	.26
K14	Shaft-curv. angle	.01	.11	−.08	−.01	.95**
K15	Ang. b. head & neck	.88*	.17	−.23	.11	−.02
7	Neck-shaft angle	.81	.11	.15	−.04	.44
8	Tub.-position angle	.12	.88**	−.21	.00	.21

[1)] The sample size is 20. 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.

In the results on the scapula, ulna and radius, it was found only in males, as was stated above. These findings, therefore, imply that cranial length or the nuchal muscles may not necessarily be related to all the other skeletal muscles. It is unknown for the present how this differential association of cranial length with upper limb bone measurements is generated. But the lack of association of clavicular measurements with cranial length may be explained in part by the facts that this bone is intramembranous, i.e., ontogenetically different from the other limb bones which are cartilaginous, and that the lower part of the squama of the occipital bone, which is occupied by the areas of muscular attachments, is also cartilaginous (Warwick and Williams, 1973). Namely, it may be said that the associations between cranial length and some measurements of the upper

Table 19. Principal components from the measurements of the neurocranium and ulna which show significantly similar loading variation patterns at the 5% level.[1)]

First variable set				Second variable set			
Principal components compared			Spearman's rank corr.	Principal components compared			Spearman's rank corr.
Male		Female		Male		Female	
I	–	I	0.56*	I	–	I	0.74***
II	–	I	0.49*	III	–	II	0.56*
III	–	III	0.55*	III	–	IV	0.47*
III	–	V	0.56*	V	–	V	0.55*
V	–	VI	0.53*				
VII	–	IV	0.48*				

[1)] The similarity in the variation patterns of factor loadings between two PCs, one of which was from males and the other from females, was assessed by Spearman's rank correlation coefficient. 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, 5, 7 and 9.

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

Table 20. Rotated factors for the measurements of the neurocranium and ulna which show significantly similar loading variation patterns at the 5% level.[1)]

First variable set				Second variable set			
Rotated factors compared			Spearman's rank corr.	Rotated factors compared			Spearman's rank corr.
Male		Female		Male		Female	
I	–	I	0.66**	I	–	I	0.81***
II	–	II	0.53*	II	–	II	0.70**
II	–	III	0.58*	II	–	V	0.50*
III	–	III	0.78***	III	–	III	0.61**
III	–	V	0.49*				
IV	–	II	0.47*				
V	–	V	0.49*				
VI	–	VI	0.48*				
VII	–	IV	0.76***				

[1)] The similarity in the variation patterns of factor loadings between two rotated factors, one of which was from males and the other from females, was assessed by Spearman's rank correlation coefficient. 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, 6, 8 and 10.

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

limb bones except the clavicle are caused in part by some factors common to the bones formed through the cartilaginous ossification.

In order to confirm the above differential association of cranial length with upper limb bone measurements, further analyses should be done in the future by the simultaneous use of measurements of the neurocranium and two or more upper limb bones taking account of the interrelations between the upper limb bones as well.

Summary and Conclusions

Principal component analyses on the neurocranium and the forearm bones showed that cranial length was significantly associated with some

Table 21. Principal components from the measurements of the neurocranium and radius which show significantly similar loading variation patterns at the 5% level.[1)]

First variable set: Principal components compared, Male	Female	Spearman's rank corr.	Second variable set: Principal components compared, Male	Female	Spearman's rank corr.
I	I	0.68*	II	I	0.67*
II	V	0.62*	VI	V	0.65*
III	I	0.56*			
IV	II	0.63*			

[1)] The similarity in the variation patterns of factor loadings between two PCs, one of which was from males and the other from females, was assessed by Spearman's rank correlation coefficient. 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, 13, 15 and 17.

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

Table 22. Rotated factors for the measurements of the neurocranium and radius which show significantly similar loading variation patterns at the 5% level.[1)]

First variable set: Rotated factors compared, Male	Female	Spearman's rank corr.	Second variable set: Rotated factors compared, Male	Female	Spearman's rank corr.
I	IV	0.75**	I	IV	0.70*
II	V	0.66*	IV	I	0.67*
IV	III	0.68*	V	II	0.75*

[1)] The similarity in the variation patterns of factor loadings between two rotated factors, one of which was from males and the other from females, was assessed by Spearman's rank correlation coefficient. The signs of rank correlation coefficients are removed because the signs of factor loadings are reversible. The original factor loadings are listed in Tables 12, 14, 16 and 18.

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

measurements of the ulna and radius only in males, and that cranial breadth had no consistent association with any measurement of the two upper limb bones. From this and previous findings, it was suggested that cranial length was differentially associated with upper limb bone measurements. Although the causes for the differential association are not exactly determinable for the present, it was inferred, at least, that the difference between the clavicle and the other upper limb bones in the association with cranial length might be due partly to the difference in their ways of osteogenesis.

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