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Neurocranial Measurements Strongly Associated with Cranial Length and Breadth: Toward the Solution of the Brachycephalization Problem

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Abstract The correlations between neurocranial measurements were examined by principal component analysis and Kaiser's normal varimax rotation methods to clarify which neurocranial substructures are the major source of the variations in maximum cranial length and breadth as a step toward elucidating the causes of brachycephalization. The results obtained from 30 male and 20 female modern Japanese show that cranial length is significantly associated with glabello-lambda and nasion-lambda lengths in both sexes and that cranial breadth is significantly associated with maximum frontal and biauricular breadths as well as with many cranial height measurements, but not with minimum frontal or biasterionic breadth across the sexes. Although the association between cranial length and the inion-opisthion chord, which was suggested to be strong in previous studies, was not significant at the 5% level, the present and previous findings still suggest that the variation in the occipital bone or the nuchal planum may be one of the causes for the variation in cranial length, and in turn, for brachycephalization or dolichocephalization.

Key words: Brachycephalization, Neurocranium, Inion-opisthion chord, Principal component analysis, Bootstrap method

The present author has conducted a series of multivariate analyses on the correlations between three basic neurocranial measurements, cranial length, cranial breadth, and basi-bregmatic height, and many postcranial measurements with the aim of clarifying the causes of brachycephalization (Mizoguchi, 1994, 1995, 1996, 1997, 1998a, b, 1999, 2000, 2001, 2002, 2003a, b, 2004, 2005). In addition to these, he has also examined the correlations between the above three neurocranial and eighty facial measurements (Mizoguchi, 2007b). Here, as the last analysis of this series, the correlations between the above three measurements and sixty-four other neurocranial measurements are examined. Such correlations within the cranial structure have been repeatedly analyzed for various samples and purposes. Therefore, the aim of the present paper is to confirm the results of previous analyses. In particular, a relatively strong association has been detected between cranial length and occipital subtense or the lower occipital arc by previous studies (Howells, 1957, 1972; Kanda, 1968), and on the basis of these results and his own analyses, Mizoguchi (2007a) proposed a hypothesis that brachycephalization or dolichocephalization is affected, at least in part, by diachronic changes in the degree of general development of skeletal muscles including the nuchal muscles, which in turn, may have occurred in accordance with diachronic changes in the quality and quantity of available nutrition, physical activity, etc. In the present paper, therefore, this point is more intensively examined.

Materials and Methods

The data used were the raw measurements of the neurocranium reported by Miyamoto (1924). These are of 30 male and 20 female modern

Table 1. Means and standard deviations for neurocranial measurements in Japanese males and females.1)

Variable2)		Males			Females		
		n	Mean	SD	n	Mean	SD
I1	Cranial index	30	79.1	3.3	20	81.5	4.2
1	Cranial length	30	178.4	5.6	20	169.4	4.9
8	Cranial breadth	30	141.0	4.7	20	137.8	4.1
17	Basi-bregmatic height	30	139.8	5.8	20	132.1	3.8
1a	Projective cranial length	30	177.6	6.1	20	169.2	4.9
3	Glabello-lambda length	30	174.0	5.9	20	165.7	4.5
2	Glabello-inion length	30	169.2	5.2	20	159.4	4.8
K8	Glabello-calotte base length (GLL)	30	91.1	9.4	20	81.7	7.8
K9	Glabello-calotte base length (GIL)	30	94.2	6.6	20	89.5	5.2
3a	Nasion-lambda length	30	172.9	5.6	20	165.9	4.4
2a	Nasion-inion length	30	163.6	5.1	20	155.5	4.7
K12	Nasion-calotte base length (NIL)	30	92.1	6.7	20	88.1	5.0
5	Cranial base length	30	102.3	3.5	20	94.8	3.6
7	Foramen magnum length	30	35.0	2.9	20	33.4	1.7
6	Basion-sphenobasion length	30	26.2	3.7	20	24.0	2.1
9	Minimum frontal breadth	30	93.1	5.2	20	89.8	3.0
10	Maximum frontal breadth	29	117.7	5.1	20	113.6	5.2
11	Biauricular breadth	30	123.6	4.9	20	118.3	3.3
12	Biasterionic breadth	30	107.5	5.0	20	104.6	4.0
13	Mastoidal breadth	30	102.4	4.9	20	96.7	4.2
16	Foramen magnum breadth	30	29.4	2.5	20	28.5	1.7
18	Total cranial height	30	141.4	5.8	20	133.1	3.9
20	Auriculo-bregmatic height	30	117.0	4.5	20	112.3	4.4
21	Auricular height	30	118.7	4.6	20	113.3	4.8
22b	Calotte height (GLL)	30	66.8	4.6	20	62.9	3.9
22a	Calotte height (GIL)	30	107.1	5.4	20	100.9	4.3
22	Calotte height (NIL)	30	111.5	5.4	20	105.6	4.3
23	Horizontal circumference (through glabella)	30	512.1	13.9	19	492.6	7.8
23a	Horizontal circumference (through ophryon)	30	508.5	13.6	20	490.8	8.5
23(1)	Anterior horizontal arc	30	241.5	8.1	20	226.3	7.2
23(2)	Posterior horizontal arc	30	267.4	11.7	20	264.5	7.3
24	Transverse arc	30	320.9	11.1	20	307.0	10.4
24b	Vertical transverse arc	30	324.9	11.9	20	311.5	12.1
25	Nasion-opisthion arc	30	372.7	11.9	20	358.8	8.2
25a	Nasion-inion arc	30	331.4	12.4	20	316.0	8.4
K39	Glabello-inion arc	30	321.1	12.2	20	304.7	9.0
38	Endocranial capacity	30	1498.3	114.1	20	1327.9	90.2
	Cubic root of endocranial capacity3)	30	11.436	0.290	20	10.986	0.251
K2	Weight of skull	30	727.1	82.9	20	665.2	68.2
	Cubic root of skull weight3)	30	8.980	0.337	20	8.720	0.294
26	Frontal arc	30	127.0	6.0	20	122.0	5.0
27	Parietal arc	30	127.2	9.1	20	121.5	5.3
28	Occipital arc	30	118.6	7.9	20	115.3	5.7
28(1)	Lambda-inion arc	30	76.9	8.3	20	72.6	7.5
27(2)	Bregma-sphenion arc	23	118.7	5.5	19	111.8	4.2
27(3)	Lambda-asterion arc	29	92.3	7.1	20	90.5	4.3
29	Frontal chord	30	111.4	5.4	20	107.0	3.9
30	Parietal chord	30	113.0	6.4	20	109.4	5.1
31	Occipital chord	30	100.2	5.7	20	97.5	3.8
31(1)	Lambda-inion chord	30	71.1	7.3	20	67.1	6.4
31(2)	Inion-opisthion chord	30	40.5	4.6	20	41.0	4.7
30(2)	Bregma-sphenion chord	22	97.5	4.1	18	92.4	3.5
30(3)	Lambda-asterion chord	29	84.2	5.9	20	82.7	3.3
30(1)	Sphenion-asterion chord	23	98.4	4.7	18	93.9	2.7
37a	Glabello-inion angle	30	15.6	2.3	20	15.4	3.2

Table 1. (Continued)

Variable[2]		Males			Females		
		n	Mean	SD	*n*	Mean	SD
K127	Nasion-lambda angle	29	12.6	3.1	20	12.2	3.0
37	Nasion-inion angle	30	11.9	2.0	20	11.4	3.1
33(1b)	Lambda-inion-glabella angle	30	81.9	2.8	20	83.1	3.1
32(1)	Frontal inclination (NIL)	30	64.1	3.0	20	63.5	2.7
32(2)	Glabello-bregma angle (GIL)	30	62.4	2.9	20	62.6	2.8
32(5)	Frontal curvature angle	30	129.3	2.7	20	128.4	3.0
32	Frontal profile angle	30	86.2	4.2	20	87.5	3.8
K134	Glabello-metopion angle	30	79.4	3.9	20	83.1	4.0
K137	Bregma-lambda angle	30	26.8	4.1	20	26.7	3.6
33	Occipital inclination	30	116.9	3.8	20	118.4	4.5
33(1)	Lambda-inion angle	30	96.9	3.9	20	98.3	5.0
33(2)	Opisthion-inion angle	30	152.2	6.3	20	153.2	7.5
33(4)	Lambda-inion-opisthion angle	29	124.5	5.6	20	126.2	6.0
34	Foramen magnum angle	30	4.4	5.5	20	7.2	4.6
37(2)	Cranial base angle	30	29.2	2.6	20	29.0	3.6

[1] The estimates of basic statistics listed here were recalculated by the present author on the basis of the raw data published by Miyamoto (1924). When measurements were available for both sides, only those from the right side were used.

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

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

Japanese who lived in the Kinai district. Their basic statistics are listed in Table 1. This set of neurocranial measurements inludes most conventional measurements.

The measurements of the neurocranium were divided into six groups, each of which contained similar measurements, to carry out the following multivariate analyses. This was necessary because of the statistical restriction on sample size given the number of variables.

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

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

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

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

Results

The results of the principal component analyses (PCAs) and the rotated solutions of neurocranial measurements for six data sets are shown in Tables 2 to 25. The Spearman’s rank correlation

Table 2. Principal component analysis of the correlation matrix for the first set of neurocranial measurements from Japanese males.[1]

	Variable[2]	Factor loadings				Total variance (%)
		PC I	II	III	IV	
1	Cranial length	0.96***	0.06	−0.12	−0.01	93.72
8	Cranial breadth	0.25	−0.13	0.72	−0.11	61.26
17	Basi-bregmatic height	0.43*	0.65	0.43	−0.09	80.17
1a	Projective cranial length	0.94***	−0.03	−0.06	−0.06	89.85
3	Glabello-lambda length	0.96***	0.02	−0.13	−0.10	95.10
2	Glabello-inion length	0.87***	0.22	−0.26	0.13	88.12
K8	Glabello-calotte base length (GLL)	0.39	0.04	−0.48	−0.57	72.08
K9	Glabello-calotte base length (GIL)	0.48*	−0.71	0.14	0.05	75.07
3a	Nasion-lambda length	0.97***	−0.04	−0.08	−0.02	94.04
2a	Nasion-inion length	0.87***	0.09	−0.24	0.19	86.88
K12	Nasion-calotte base length (NIL)	0.57***	−0.62	0.22	0.18	79.95
5	Cranial base length	0.70***	0.05	0.60	−0.01	85.88
7	Foramen magnum length	0.11	0.43	−0.13	0.74	75.56
6	Basion-sphenobasion length	0.09	0.78	0.22	−0.19	70.30
	Total contribution (%)	47.54	15.60	11.47	7.38	82.00
	Cumulative proportion (%)	47.54	63.14	74.62	82.00	82.00

[1] The sample size is 30. The number of principal components shown here was determined so that the cumulative proportion of the variances of the principal components exceeded 80%.

[2] See the second footnote for Table 1.

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

Table 3. Solution obtained through normal varimax rotation of the first four principal components of the correlation matrix for the first set of neurocranial measurements from Japanese males.[1]

	Variable[2]	Factor loadings			
		Fac I	II	III	IV
1	Cranial length	0.95***	−0.01	0.18	−0.01
8	Cranial breadth	0.00	−0.03	0.78	−0.08
17	Basi-bregmatic height	0.34	0.66	0.48	0.11
1a	Projective cranial length	0.91***	−0.08	0.25	−0.08
3	Glabello-lambda length	0.95***	−0.03	0.18	−0.12
2	Glabello-inion length	0.92***	0.09	0.00	0.15
K8	Glabello-calotte base length (GLL)	0.51	0.11	−0.31	−0.59
K9	Glabello-calotte base length (GIL)	0.34*	−0.71	0.35	−0.13
3a	Nasion-lambda length	0.94***	−0.10	0.23	−0.05
2a	Nasion-inion length	0.91***	−0.05	0.02	0.18
K12	Nasion-calotte base length (NIL)	0.42**	−0.66	0.44	0.02
5	Cranial base length	0.49**	0.08	0.78	0.04
7	Foramen magnum length	0.20	0.19	−0.17	0.81
6	Basion-sphenobasion length	0.10	0.82	0.16	0.04

[1] The sample size is 30. The cumulative proportion of the variances of the four principal components is 82.00%.

[2] See the second footnote for Table 1.

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

Table 4. Principal component analysis of the correlation matrix for the first set of neurocranial measurements from Japanese females.[1)]

Variable[2)]		Factor loadings				Total variance (%)
		PC I	II	III	IV	
1	Cranial length	0.91***	−0.34	−0.10	0.08	96.80
8	Cranial breadth	−0.34*	0.75	−0.18	−0.35	83.48
17	Basi-bregmatic height	0.29	0.71	−0.31	−0.01	69.03
1a	Projective cranial length	0.92***	−0.33	−0.08	0.12	96.62
3	Glabello-lambda length	0.91***	−0.07	−0.18	0.06	86.68
2	Glabello-inion length	0.80**	−0.03	−0.21	−0.42	86.42
K8	Glabello-calotte base length (GLL)	0.46	0.22	−0.57	−0.03	58.54
K9	Glabello-calotte base length (GIL)	0.49*	0.10	0.75	−0.28	88.75
3a	Nasion-lambda length	0.92***	−0.11	−0.09	0.06	86.90
2a	Nasion-inion length	0.90***	0.11	0.05	−0.27	90.24
K12	Nasion-calotte base length (NIL)	0.44*	0.22	0.78	−0.07	85.93
5	Cranial base length	0.70**	0.43	0.02	0.06	67.97
7	Foramen magnum length	0.22	0.26	0.00	0.72	63.09
6	Basion-sphenobasion length	0.32	0.45	0.31	0.46	61.19
	Total contribution (%)	44.98	13.40	13.04	8.70	80.12
	Cumulative proportion (%)	44.98	58.38	71.42	80.12	80.12

[1)] The sample size is 20. The number of principal components shown here was determined so that the cumulative proportion of the variances of the principal components exceeded 80%.

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

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

Table 5. Solution obtained through normal varimax rotation of the first four principal components of the correlation matrix for the first set of neurocranial measurements from Japanese females.[1)]

Variable[2)]		Factor loadings			
		Fac I	II	III	IV
1	Cranial length	0.95***	−0.22	0.10	0.12
8	Cranial breadth	−0.41	0.81	−0.00	−0.13
17	Basi-bregmatic height	0.20	0.76	−0.03	0.27
1a	Projective cranial length	0.94***	−0.22	0.11	0.16
3	Glabello-lambda length	0.90***	0.06	0.09	0.19
2	Glabello-inion length	0.84*	0.25	0.17	−0.25
K8	Glabello-calotte base length (GLL)	0.54	0.44	−0.30	0.08
K9	Glabello-calotte base length (GIL)	0.23	−0.05	0.91*	−0.03
3a	Nasion-lambda length	0.90***	−0.01	0.17	0.19
2a	Nasion-inion length	0.82*	0.24	0.42	−0.02
K12	Nasion-calotte base length (NIL)	0.14	−0.03	0.90	0.20
5	Cranial base length	0.54	0.40	0.32	0.35
7	Foramen magnum length	0.09	0.01	−0.07	0.79
6	Basion-sphenobasion length	0.07	0.16	0.34	0.68

[1)] The sample size is 20. The cumulative proportion of the variances of the four principal components is 80.12%.

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

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

coefficients between males and females for the variation patterns of factor loadings on the principal components (PCs) and/or rotated factors (Facs) are shown in Tables 26 to 31.

Those PCs or Facs that are significantly correlated at the 5% level both with one or more of the three main neurocranial measurements and with one or more of the other neurocranial measurements are as follows. In the sixth data set, however, no such PCs or Facs were found.

Table 6. Principal component analysis of the correlation matrix for the second set of neurocranial measurements from Japanese males.[1]

Variable[2]		Factor loadings					Total variance (%)
		PC I	II	III	IV	V	
1	Cranial length	0.53**	0.10	−0.52	−0.30	0.09	65.52
8	Cranial breadth	0.55*	0.67	0.27	0.02	0.13	85.32
17	Basi-bregmatic height	0.82***	−0.23	−0.16	0.23	−0.07	81.63
9	Minimum frontal breadth	0.30	0.61	0.20	−0.39	0.05	65.12
10	Maximum frontal breadth	0.54*	0.62	0.27	−0.32	−0.06	85.79
11	Biauricular breadth	0.65**	0.48	−0.13	0.17	−0.39	85.35
12	Biasterionic breadth	0.33	0.25	−0.75	0.08	0.27	81.25
13	Mastoidal breadth	0.50*	0.53	−0.34	0.34	−0.24	81.23
16	Foramen magnum breadth	0.30	0.16	0.43	0.65	0.45	93.15
18	Total cranial height	0.85***	−0.25	−0.19	0.22	−0.06	87.32
20	Auriculo-bregmatic height	0.72**	−0.23	0.54	−0.04	−0.13	87.30
21	Auricular height	0.73**	−0.26	0.51	−0.03	−0.09	85.76
22b	Calotte height (GLL)	0.59**	−0.61	−0.11	−0.03	−0.30	82.16
22a	Calotte height (GIL)	0.83***	−0.31	−0.06	−0.22	0.34	94.75
22	Calotte height (NIL)	0.85***	−0.33	−0.07	−0.22	0.25	94.12
	Total contribution (%)	40.24	17.49	13.05	7.47	5.47	83.72
	Cumulative proportion (%)	40.24	57.73	70.78	78.25	83.72	83.72

[1] The sample size is 29. The number of principal components shown here was determined so that the cumulative proportion of the variances of the principal components exceeded 80%.

[2] See the second footnote for Table 1.

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

Table 7. Solution obtained through normal varimax rotation of the first five principal components of the correlation matrix for the second set of neurocranial measurements from Japanese males.[1]

Variable[2]		Factor loadings				
		Fac I	II	III	IV	V
1	Cranial length	0.32	0.22	−0.64	−0.25	−0.16
8	Cranial breadth	0.11	0.77	−0.09	0.37	−0.31
17	Basi-bregmatic height	0.76	−0.04	−0.24	0.14	−0.41
9	Minimum frontal breadth	−0.03	0.80	−0.08	−0.04	−0.06
10	Maximum frontal breadth	0.17	0.88	−0.01	0.01	−0.23
11	Biauricular breadth	0.24	0.41	−0.12	0.01	−0.78**
12	Biasterionic breadth	0.00	0.00	−0.85	0.04	−0.30
13	Mastoidal breadth	0.04	0.25	−0.31	0.12	−0.80*
16	Foramen magnum breadth	0.15	0.10	0.09	0.94*	−0.10
18	Total cranial height	0.79	−0.05	−0.27	0.13	−0.40
20	Auriculo-bregmatic height	0.80*	0.30	0.35	0.15	−0.07
21	Auricular height	0.81*	0.27	0.31	0.16	−0.05
22b	Calotte height (GLL)	0.81*	−0.27	0.01	−0.25	−0.17
22a	Calotte height (GIL)	0.85	0.20	−0.41*	0.09	0.13
22	Calotte height (NIL)	0.87*	0.18	−0.37	0.04	0.07

[1] The sample size is 29. The cumulative proportion of the variances of the five principal components is 83.72%.

[2] See the second footnote for Table 1.

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

Table 8. Principal component analysis of the correlation matrix for the second set of neurocranial measurements from Japanese females.[1]

Variable[2]		Factor loadings				Total variance (%)
		PC I	II	III	IV	
1	Cranial length	−0.16	0.37	0.69	−0.34	75.41
8	Cranial breadth	0.70**	−0.08	−0.59	0.16	87.52
17	Basi-bregmatic height	0.80***	0.20	0.18	0.18	74.82
9	Minimum frontal breadth	0.45	0.06	−0.02	0.00	20.80
10	Maximum frontal breadth	0.72***	−0.15	−0.41	0.37	84.85
11	Biauricular breadth	0.54*	0.69	−0.20	0.01	80.02
12	Biasterionic breadth	0.37	0.68	−0.11	−0.49	84.81
13	Mastoidal breadth	0.06	0.88	−0.31	0.04	88.01
16	Foramen magnum breadth	−0.05	0.83	0.21	0.39	88.50
18	Total cranial height	0.88***	0.17	0.13	0.06	82.31
20	Auriculo-bregmatic height	0.86***	−0.20	−0.13	−0.39	95.43
21	Auricular height	0.84***	−0.17	−0.15	−0.45	95.65
22b	Calotte height (GLL)	0.77***	−0.47	0.22	0.07	87.16
22a	Calotte height (GIL)	0.67**	−0.03	0.58	0.16	82.03
22	Calotte height (NIL)	0.68**	−0.07	0.61	0.15	86.46
	Total contribution (%)	40.33	19.58	13.57	7.44	80.92
	Cumulative proportion (%)	40.33	59.91	73.48	80.92	80.92

[1] The sample size is 20. The number of principal components shown here was determined so that the cumulative proportion of the variances of the principal components exceeded 80%.

[2] See the second footnote for Table 1.

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

Table 9. Solution obtained through normal varimax rotation of the first four principal components of the correlation matrix for the second set of neurocranial measurements from Japanese females.[1]

Variable[2]		Factor loadings			
		Fac I	II	III	IV
1	Cranial length	0.20	0.18	0.83	0.03
8	Cranial breadth	0.21	0.20	−0.81	−0.38
17	Basi-bregmatic height	0.75	0.32	−0.23	−0.18
9	Minimum frontal breadth	0.32	0.16	−0.18	−0.22
10	Maximum frontal breadth	0.39	0.09	−0.81	−0.19
11	Biauricular breadth	0.26	0.81	−0.20	−0.18
12	Biasterionic breadth	0.04	0.77	0.18	−0.48
13	Mastoidal breadth	−0.15	0.92	−0.06	0.11
16	Foramen magnum breadth	0.19	0.72	0.17	0.54
18	Total cranial height	0.74	0.32	−0.24	−0.33
20	Auriculo-bregmatic height	0.44	0.03	−0.28	−0.82*
21	Auricular height	0.39	0.07	−0.25	−0.86*
22b	Calotte height (GLL)	0.73**	−0.33	−0.28	−0.38
22a	Calotte height (GIL)	0.90	−0.01	0.07	−0.09
22	Calotte height (NIL)	0.92	−0.05	0.08	−0.10

[1] The sample size is 20. The cumulative proportion of the variances of the four principal components is 80.92%.

[2] See the second footnote for Table 1.

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

Table 10. Principal component analysis of the correlation matrix for the third set of neurocranial measurements from Japanese males.[1)]

Variable[2)]		Factor loadings				Total variance (%)
		PC I	II	III	IV	
1	Cranial length	0.80***	−0.43	0.27	0.19	93.61
8	Cranial breadth	0.53***	0.70	0.23	0.15	84.84
17	Basi-bregmatic height	0.62***	−0.12	−0.49	−0.06	63.97
23	Horizontal circumference (through glabella)	0.84***	−0.12	0.45	0.20	96.06
23a	Horizontal circumference (through ophryon)	0.87***	−0.03	0.44	0.16	96.62
23(1)	Anterior horizontal arc	0.53**	0.30	−0.13	0.67	84.35
23(2)	Posterior horizontal arc	0.65***	−0.26	0.56	−0.33	91.88
24	Transverse arc	0.64***	0.68	−0.24	−0.13	95.20
24b	Vertical transverse arc	0.63***	0.70	−0.19	−0.16	94.20
25	Nasion-opisthion arc	0.81***	−0.39	−0.26	−0.11	88.46
25a	Nasion-inion arc	0.84***	−0.23	−0.37	−0.21	93.79
K39	Glabello-inion arc	0.84***	−0.28	−0.32	−0.19	92.68
	Cubic root of endocranial capacity[3)]	0.78***	0.24	0.17	−0.28	76.47
	Cubic root of skull weight[3)]	0.37	−0.36	−0.38	0.48	63.53
	Total contribution (%)	50.51	16.27	11.95	8.10	86.83
	Cumulative proportion (%)	50.51	66.78	78.73	86.83	86.83

[1)] The sample size is 30. The number of principal components shown here was determined so that the cumulative proportion of the variances of the principal components exceeded 80%.

[2),3)] See the second and third footnotes for Table 1.

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

Table 11. Solution obtained through normal varimax rotation of the first four principal components of the correlation matrix for the third set of neurocranial measurements from Japanese males.[1)]

Variable[2)]		Factor loadings			
		Fac I	II	III	IV
1	Cranial length	0.42	−0.05	0.82	0.29
8	Cranial breadth	−0.15	0.83	0.31	0.20
17	Basi-bregmatic height	0.74	0.22	0.05	0.19
23	Horizontal circumference (through glabella)	0.21	0.23	0.89	0.27
23a	Horizontal circumference (through ophryon)	0.21	0.32	0.88	0.23
23(1)	Anterior horizontal arc	0.09	0.44	0.18	0.78
23(2)	Posterior horizontal arc	0.23	0.07	0.88	−0.30
24	Transverse arc	0.31	0.92	0.04	0.07
24b	Vertical transverse arc	0.27*	0.93	0.06	0.02
25	Nasion-opisthion arc	0.83*	0.05	0.41	0.13
25a	Nasion-inion arc	0.89*	0.23	0.30	0.06
K39	Glabello-inion arc	0.87*	0.18	0.35	0.07
	Cubic root of endocranial capacity[3)]	0.34	0.58	0.54	−0.14
	Cubic root of skull weight[3)]	0.46	−0.17	0.07	0.62

[1)] The sample size is 30. The cumulative proportion of the variances of the four principal components is 86.83%.

[2),3)] See the second and third footnotes for Table 1.

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

Table 12. Principal component analysis of the correlation matrix for the third set of neurocranial measurements from Japanese females.[1]

	Variable[2]	Factor loadings				Total variance (%)
		PC I	II	III	IV	
1	Cranial length	0.60	−0.73	0.08	0.19	93.08
8	Cranial breadth	0.19	0.91	−0.03	0.02	86.64
17	Basi-bregmatic height	0.58*	0.40	0.34	−0.26	67.81
23	Horizontal circumference (through glabella)	0.85***	−0.27	0.15	0.29	90.79
23a	Horizontal circumference (through ophryon)	0.89***	−0.22	0.11	0.28	93.67
23(1)	Anterior horizontal arc	0.33	−0.25	0.88	0.19	98.04
23(2)	Posterior horizontal arc	0.61*	0.01	−0.72	0.11	90.29
24	Transverse arc	0.39	0.89	0.11	0.05	95.71
24b	Vertical transverse arc	0.34	0.90	0.06	0.12	93.44
25	Nasion-opisthion arc	0.83***	−0.20	−0.17	−0.18	79.64
25a	Nasion-inion arc	0.83***	−0.28	−0.15	−0.36	91.72
K39	Glabello-inion arc	0.82***	−0.22	−0.09	−0.38	86.82
	Cubic root of endocranial capacity[3]	0.70*	0.49	0.14	−0.28	82.13
	Cubic root of skull weight[3]	0.47	0.25	−0.29	0.63	76.58
	Total contribution (%)	41.19	26.84	11.62	7.95	87.60
	Cumulative proportion (%)	41.19	68.03	79.65	87.60	87.60

[1] The sample size is 19. The number of principal components shown here was determined so that the cumulative proportion of the variances of the principal components exceeded 80%.

[2,3] See the second and third footnotes for Table 1.

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

Table 13. Solution obtained through normal varimax rotation of the first four principal components of the correlation matrix for the third set of neurocranial measurements from Japanese females.[1]

	Variable[2]	Factor loadings			
		Fac I	II	III	IV
1	Cranial length	0.62	−0.49	0.44	0.34
8	Cranial breadth	−0.12	0.90	−0.17	0.12
17	Basi-bregmatic height	0.41	0.64	0.29	−0.12
23	Horizontal circumference (through glabella)	0.64	0.03	0.49	0.51
23a	Horizontal circumference (through ophryon)	0.67	0.08	0.46	0.52
23(1)	Anterior horizontal arc	0.11	0.01	0.98	−0.04
23(2)	Posterior horizontal arc	0.59	0.08	−0.46	0.58
24	Transverse arc	0.02	0.96	0.02	0.17
24b	Vertical transverse arc	−0.05	0.94	−0.03	0.23
25	Nasion-opisthion arc	0.86*	0.07	0.05	0.21
25a	Nasion-inion arc	0.96*	0.01	0.04	0.05
K39	Glabello-inion arc	0.93*	0.08	0.08	0.01
	Cubic root of endocranial capacity[3]	0.53	0.72	0.11	−0.01
	Cubic root of skull weight[3]	0.09	0.28	−0.02	0.82

[1] The sample size is 19. The cumulative proportion of the variances of the four principal components is 87.60%.

[2,3] See the second and third footnotes for Table 1.

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

1) PC I's from the first data sets of males and females (Tables 2 and 4)

These PCs from males and females are significantly correlated both with cranial length and with eight neurocranial measurements: projective cranial length, glabello-lambda length, glabello-inion length, glabello-calotte base length (GIL), nasion-lambda length, nasion-inion length, nasion-calotte base length (NIL), and cranial base length.

The factor loading variation patterns for these two PCs are significantly similar to each other, with the Spearman's rho value being 0.93 ($P<0.001$) (Table 26).

2) Fac I's from the first data sets of males and females (Tables 3 and 5)

These Facs are nearly identical to the above-mentioned PC I's. The neurocranial measurements that are significantly correlated with these Facs in both sexes are cranial length, projective cranial length, glabello-lambda length, gabello-inion length, nasion-lambda length, and nasion-inion length.

The factor loading variation patterns for these two Facs are significantly similar to each other, with the Spearman's rho value being 0.94 ($P<0.001$) (Table 26).

3) PC I's from the second data sets of males and females (Tables 6 and 8)

The neurocranial measurements that are significantly correlated with these PCs in both sexes are cranial breadth, basi-bregmatic height, maximum frontal breadth, biauricular breadth, total cranial height, auriculo-bregmatic height, auricular height, calotte height (GLL), calotte height (GIL), and calotte height (NIL). As shown in Table 27, the Spearman's rho value between these two PCs is 0.71 ($P<0.01$).

4) PC I's from the third data sets of males and females (Tables 10 and 12)

The neurocranial measurements that are significantly correlated with these PCs in both sexes are basi-bregmatic height, horizontal circumference (through glabella), horizontal circumference (through ophryon), posterior horizontal arc, nasion-opisthion arc, nasion-inion arc, glabello-inion arc, and the cubic root of endocranial capacity. The Spearman's rho value between these two PCs is 0.89 ($P<0.001$) (Table 28).

In passing, the above PC I's are so-called general size factors for males and females, and are significantly correlated with the cubic root of endocranial capacity. After the rotation of the PC axes, however, the factor that is most highly, though not significantly, correlated with the cubic root of endocranial capacity is Fac II, i.e. one of local factors, both in males and in females (Tables 11 and 13), and it is most highly correlated with cranial breadth among the three main neurocranial measurements across the sexes.

5) PC II and Fac II from the fourth data set of males (Tables 14 and 15)

In the case of the fourth data set, only male data showed a PC and a Fac that were significantly correlated with both one or more of the three main neurocranial measurements and one or more of the other neurocranial measurements. They are PC II and Fac II, and are correlated with cranial breadth, basi-bregmatic height, bregma-sphenion arc, frontal chord, and bregma-sphenion chord.

6) PC III from the fifth data set of males (Table 18)

Also in the case of the fifth data set, only male data showed a PC that was significantly correlated with both one or more of the three main neurocranial measurements and one or more of the other neurocranial measurements. It is PC III and is correlated with cranial breadth, glabello-bregma angle (GIL), and frontal curvature angle.

In addition to the above, there are one PC and one Fac to be noted. As mentioned in the introductory section, Mizoguchi (2007a) proposed a hypothesis that brachycephalization or dolichocephalization is affected, at least in part, by the diachronic changes in the degree of general de-

Table 14. Principal component analysis of the correlation matrix for the fourth set of neurocranial measurements from Japanese males.1)

Variable2)		Factor loadings				Total variance (%)
		PC I	II	III	IV	
1	Cranial length	0.61	0.39	0.56	0.12	85.17
8	Cranial breadth	0.40	0.57*	−0.23	−0.44	74.37
17	Basi-bregmatic height	0.27	0.70**	−0.18	−0.25	65.52
26	Frontal arc	0.37	0.52	−0.41	0.40	73.64
27	Parietal arc	−0.38	0.57	0.60	−0.32	92.85
28	Occipital arc	0.88***	−0.32	0.21	0.03	93.44
28(1)	Lambda-inion arc	0.78***	−0.47	0.08	−0.25	90.10
27(2)	Bregma-sphenion arc	0.36	0.75**	−0.22	−0.28	81.80
27(3)	Lambda-asterion arc	0.87***	−0.24	0.14	−0.14	85.72
29	Frontal chord	0.53	0.64*	−0.36	0.31	90.78
30	Parietal chord	−0.26	0.52	0.76	−0.24	96.99
31	Occipital chord	0.91***	−0.27	−0.03	−0.12	91.29
31(1)	Lambda-inion chord	0.78***	−0.45	−0.02	−0.24	86.78
31(2)	Inion-opisthion chord	0.51	0.16	0.32	0.64	78.98
30(2)	Bregma-sphenion chord	0.42	0.75**	−0.30	−0.10	83.85
30(3)	Lambda-asterion chord	0.90***	−0.25	0.13	−0.02	88.60
30(1)	Sphenion-asterion chord	0.34	0.52	0.47	0.35	73.08
	Total contribution (%)	37.12	25.71	12.83	8.63	84.29
	Cumulative proportion (%)	37.12	62.83	75.66	84.29	84.29

1) The sample size is 22. The number of principal components shown here was determined so that the cumulative proportion of the variances of the principal components exceeded 80%.

2) See the second footnote for Table 1.

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

Table 15. Solution obtained through normal varimax rotation of the first four principal components of the correlation matrix for the fourth set of neurocranial measurements from Japanese males.1)

Variable2)		Factor loadings			
		Fac I	II	III	IV
1	Cranial length	0.42	0.26	0.44	0.64
8	Cranial breadth	0.20	0.82*	0.15	−0.12
17	Basi-bregmatic height	−0.01	0.79*	0.16	0.05
26	Frontal arc	−0.08	0.60	−0.39	0.47
27	Parietal arc	−0.37	0.15	0.88	0.03
28	Occipital arc	0.91***	−0.03	−0.08	0.30
28(1)	Lambda-inion arc	0.94***	−0.04	−0.09	−0.06
27(2)	Bregma-sphenion arc	0.05	0.89*	0.15	0.06
27(3)	Lambda-asterion arc	0.90***	0.12	−0.03	0.16
29	Frontal chord	0.04	0.76*	−0.29	0.50
30	Parietal chord	−0.24	0.06	0.94	0.18
31	Occipital chord	0.91***	0.16	−0.19	0.11
31(1)	Lambda-inion chord	0.91***	0.01	−0.17	−0.08
31(2)	Inion-opisthion chord	0.24	−0.01	−0.05	0.85
30(2)	Bregma-sphenion chord	0.03	0.89*	−0.00	0.20
30(3)	Lambda-asterion chord	0.90***	0.08	−0.10	0.26
30(1)	Sphenion-asterion chord	0.06	0.24	0.35	0.74

1) The sample size is 22. The cumulative proportion of the variances of the four principal components is 84.29%.

2) See the second footnote for Table 1.

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

Table 16. Principal component analysis of the correlation matrix for the fourth set of neurocranial measurements from Japanese females.[1]

Variable[2]		Factor loadings					Total variance (%)
		PC I	II	III	IV	V	
1	Cranial length	0.68	0.33	0.09	−0.48	0.39	95.98
8	Cranial breadth	−0.57	0.40	−0.30	0.25	−0.36	76.89
17	Basi-bregmatic height	−0.07	0.77*	0.29	0.26	0.06	75.52
26	Frontal arc	−0.49	0.65	−0.08	−0.44	−0.04	87.38
27	Parietal arc	0.08	0.41	0.71	−0.36	−0.31	90.57
28	Occipital arc	0.84	0.07	−0.31	−0.11	0.07	82.12
28(1)	Lambda-inion arc	0.94	0.07	0.11	0.23	−0.02	96.03
27(2)	Bregma-sphenion arc	−0.28	0.68	−0.13	0.56	0.06	86.24
27(3)	Lambda-asterion arc	0.62	0.18	−0.62	−0.14	−0.13	82.95
29	Frontal chord	−0.36	0.81	−0.03	−0.37	0.02	91.74
30	Parietal chord	0.34	0.45	0.69	−0.36	−0.20	96.53
31	Occipital chord	0.51	0.47	−0.40	0.13	−0.12	66.87
31(1)	Lambda-inion chord	0.82	0.18	0.15	0.37	−0.20	90.33
31(2)	Inion-opisthion chord	−0.27	0.14	−0.70	−0.46	0.29	88.44
30(2)	Bregma-sphenion chord	−0.25	0.77	−0.07	0.37	0.12	80.94
30(3)	Lambda-asterion chord	0.43	0.37	−0.56	−0.15	−0.41	83.03
30(1)	Sphenion-asterion chord	0.29	0.45	0.16	0.23	0.64	77.09
	Total contribution (%)	27.50	23.59	15.89	11.29	6.95	85.21
	Cumulative proportion (%)	27.50	51.08	66.98	78.27	85.21	85.21

[1] The sample size is 18. The number of principal components shown here was determined so that the cumulative proportion of the variances of the principal components exceeded 80%.

[2] See the second footnote for Table 1.

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

Table 17. Solution obtained through normal varimax rotation of the first five principal components of the correlation matrix for the fourth set of neurocranial measurements from Japanese females.[1]

Variable[2]		Factor loadings				
		Fac I	II	III	IV	V
1	Cranial length	0.43	−0.14	0.36	−0.11	0.78
8	Cranial breadth	0.01	0.56	−0.11	−0.30	−0.60
17	Basi-bregmatic height	−0.02	0.77	0.38	−0.00	0.14
26	Frontal arc	−0.01	0.37	0.34	−0.78**	−0.11
27	Parietal arc	−0.10	0.05	0.95*	−0.01	0.01
28	Occipital arc	0.75	−0.20	−0.03	0.21	0.42
28(1)	Lambda-inion arc	0.56	−0.05	0.17	0.67	0.41
27(2)	Bregma-sphenion arc	0.03	0.92	−0.11	−0.04	−0.09
27(3)	Lambda-asterion arc	0.89	−0.10	−0.14	−0.04	0.11
29	Frontal chord	0.07	0.51	0.40	−0.70*	0.02
30	Parietal chord	0.07	0.04	0.95	0.09	0.23
31	Occipital chord	0.75	0.30	−0.00	0.08	0.11
31(1)	Lambda-inion chord	0.53	0.14	0.23	0.72*	0.20
31(2)	Inion-opisthion chord	0.24	−0.05	−0.39	−0.82*	0.09
30(2)	Bregma-sphenion chord	0.05	0.88	0.03	−0.17	0.03
30(3)	Lambda-asterion chord	0.88*	0.06	0.05	−0.13	−0.18
30(1)	Sphenion-asterion chord	0.01	0.48	0.01	0.11	0.73

[1] The sample size is 18. The cumulative proportion of the variances of the five principal components is 85.21%.

[2] See the second footnote for Table 1.

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

Table 18. Principal component analysis of the correlation matrix for the fifth set of neurocranial measurements from Japanese males.[1]

Variable[2]		Factor loadings				Total variance (%)
		PC I	II	III	IV	
1	Cranial length	−0.10	0.46	0.41	0.30	47.66
8	Cranial breadth	−0.18	−0.17	0.79**	−0.24	74.01
17	Basi-bregmatic height	0.36	0.47	0.53	0.22	67.87
37a	Glabello-inion angle	0.51	0.75	0.03	−0.24	87.95
K127	Nasion-lambda angle	−0.03	−0.80	0.29	−0.13	75.02
37	Nasion-inion angle	0.42	0.78	−0.09	−0.39	93.67
33(1b)	Lambda-inion-glabella angle	0.01	0.44	0.04	0.75	76.14
32(1)	Frontal inclination (NIL)	0.95***	−0.09	0.22	−0.07	97.07
32(2)	Glabello-bregma angle (GIL)	0.91***	−0.04	0.29*	−0.11	92.10
32(5)	Frontal curvature angle	−0.55*	−0.09	0.66*	−0.00	75.32
32	Frontal profile angle	0.74	−0.55	0.01	0.28	93.51
K134	Glabello-metopion angle	0.78*	−0.52	−0.12	0.18	92.60
	Total contribution (%)	31.78	25.41	14.60	9.29	81.08
	Cumulative proportion (%)	31.78	57.19	71.78	81.08	81.08

[1] The sample size is 29. The number of principal components shown here was determined so that the cumulative proportion of the variances of the principal components exceeded 80%.

[2] See the second footnote for Table 1.

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

Table 19. Solution obtained through normal varimax rotation of the first four principal components of the correlation matrix for the fifth set of neurocranial measurements from Japanese males.[1]

Variable[2]		Factor loadings			
		Fac I	II	III	IV
1	Cranial length	−0.15	0.18	0.26	0.60
8	Cranial breadth	0.02	−0.06	0.86	−0.03
17	Basi-bregmatic height	0.27	0.42	0.30	0.59
37a	Glabello-inion angle	0.15	0.90	−0.09	0.19
K127	Nasion-lambda angle	0.32	−0.56	0.41	−0.40
37	Nasion-inion angle	0.01	0.96	−0.14	0.05
33(1b)	Lambda-inion-glabella angle	−0.05	−0.02	−0.23	0.84
32(1)	Frontal inclination (NIL)	0.92*	0.35	0.04	−0.01
32(2)	Glabello-bregma angle (GIL)	0.87**	0.39	0.13	0.00
32(5)	Frontal curvature angle	−0.34	−0.27	0.74	0.15
32	Frontal profile angle	0.92	−0.27	−0.15	−0.02
K134	Glabello-metopion angle	0.90	−0.18	−0.26	−0.13

[1] The sample size is 29. The cumulative proportion of the variances of the four principal components is 81.08%.

[2] See the second footnote for Table 1.

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

velopment of skeletal muscles including the nuchal ones. If this hypothesis is correct, it is expected that there is an association between the size of the nuchal planum and cranial length. This can be assessed in the results of the fourth data set (Tables 14 to 17). Among the PCs and Facs shown in Tables 14 to 17, the first two PCs/Facs, which are most strongly, though not significantly, correlated with cranial length are as follows: PC I and Fac IV in males and PC I and Fac V in females. Conveniently, if you regard factor loadings of greater than 0.60 as meaning-

Table 20. Principal component analysis of the correlation matrix for the fifth set of neurocranial measurements from Japanese females.[1]

Variable[2]		Factor loadings				Total variance (%)
		PC I	II	III	IV	
1	Cranial length	0.44	−0.34	0.51	−0.06	56.97
8	Cranial breadth	−0.64	0.14	−0.43	0.44	79.93
17	Basi-bregmatic height	0.04	0.14	−0.08	0.90**	83.78
37a	Glabello-inion angle	0.79	0.41	−0.19	−0.27	89.42
K127	Nasion-lambda angle	−0.78	0.01	0.54	0.01	89.64
37	Nasion-inion angle	0.86	0.36	−0.15	−0.11	91.07
33(1b)	Lambda-inion-glabella angle	0.43	0.13	−0.51	0.20	50.04
32(1)	Frontal inclination (NIL)	0.04	0.95**	0.29	−0.01	98.41
32(2)	Glabello-bregma angle (GIL)	0.07	0.97***	0.20	0.03	98.18
32(5)	Frontal curvature angle	0.47	0.04	0.60	0.47	79.84
32	Frontal profile angle	−0.88	0.29	0.05	−0.12	87.99
K134	Glabello-metopion angle	−0.80	0.39	−0.21	−0.22	88.78
	Total contribution (%)	36.67	21.17	13.27	11.73	82.84
	Cumulative proportion (%)	36.67	57.83	71.11	82.84	82.84

[1] The sample size is 20. The number of principal components shown here was determined so that the cumulative proportion of the variances of the principal components exceeded 80%.

[2] See the second footnote for Table 1.

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

Table 21. Solution obtained through normal varimax rotation of the first four principal components of the correlation matrix for the fifth set of neurocranial measurements from Japanese females.[1]

Variable[2]		Factor loadings			
		Fac I	II	III	IV
1	Cranial length	−0.02	−0.11	0.73	−0.17
8	Cranial breadth	−0.23	−0.07	−0.68	0.52
17	Basi-bregmatic height	0.07	0.08	0.04	0.91
37a	Glabello-inion angle	0.80	0.38	0.20	−0.25
K127	Nasion-lambda angle	−0.93	0.14	−0.11	−0.00
37	Nasion-inion angle	0.82	0.35	0.31	−0.12
33(1b)	Lambda-inion-glabella angle	0.66	−0.03	−0.11	0.23
32(1)	Frontal inclination (NIL)	0.00	0.99*	−0.05	0.03
32(2)	Glabello-bregma angle (GIL)	0.08	0.98*	−0.09	0.08
32(5)	Frontal curvature angle	−0.01	0.26	0.77	0.38
32	Frontal profile angle	−0.67	0.24	−0.61	−0.05
K134	Glabello-metopion angle	−0.42	0.25	−0.79	−0.13

[1] The sample size is 20. The cumulative proportion of the variances of the four principal components is 82.84%.

[2] See the second footnote for Table 1.

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

ful, both male and female PC I's have meaningful correlations with occipital arc, lambda-inion arc, lambda-asterion arc, and lambda-inion chord. But neither PC I has a significant correlation with inion-opisthion chord. On the other hand, male Fac IV is relatively strongly correlated with inion-opisthion chord and sphenion-asterion chord. In females, however, Fac V, which corresponds to male Fac IV, has a strong correlation only with the sphenion-asterion chord. In any case, the Spearman's rank correlation coefficients between males and females are not so high. The

Table 22. Principal component analysis of the correlation matrix for the sixth set of neurocranial measurements from Japanese males.[1]

Variable[2]		Factor loadings				Total variance (%)
		PC I	II	III	IV	
1	Cranial length	0.33	−0.40	0.62	0.35	78.32
8	Cranial breadth	−0.36	0.01	0.67	0.14	59.47
17	Basi-bregmatic height	0.44	0.45	0.60	0.28	83.78
K137	Bregma-lambda angle	0.73	0.37	−0.22	0.24	78.35
33	Occipital inclination	0.76	−0.43	−0.22	−0.11	81.85
33(1)	Lambda-inion angle	0.87	−0.02	0.08	−0.17	80.14
33(2)	Opisthion-inion angle	0.50	−0.82	0.08	−0.07	93.00
33(4)	Lambda-inion-opisthion angle	0.05	0.92	−0.03	−0.04	84.95
34	Foramen magnum angle	−0.10	−0.18	−0.58	0.75*	95.25
37(2)	Cranial base angle	0.67	0.53	−0.10	−0.03	73.94
	Total contribution (%)	30.13	25.17	16.57	9.03	80.90
	Cumulative proportion (%)	30.13	55.30	71.88	80.90	80.90

[1] The sample size is 29. The number of principal components shown here was determined so that the cumulative proportion of the variances of the principal components exceeded 80%.

[2] See the second footnote for Table 1.

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

Table 23. Solution obtained through normal varimax rotation of the first four principal components of the correlation matrix for the sixth set of neurocranial measurements from Japanese males.[1]

Variable[2]		Factor loadings			
		Fac I	II	III	IV
1	Cranial length	0.02	−0.49	0.74	0.03
8	Cranial breadth	−0.38	0.20	0.61	−0.18
17	Basi-bregmatic height	0.53	0.18	0.70	−0.16
K137	Bregma-lambda angle	0.86	−0.04	0.00	0.20
33	Occipital inclination	0.45	−0.77	−0.18	0.02
33(1)	Lambda-inion angle	0.70	−0.49	0.06	−0.26
33(2)	Opisthion-inion angle	−0.01	−0.96	0.07	−0.02
33(4)	Lambda-inion-opisthion angle	0.51	0.75	−0.03	−0.16
34	Foramen magnum angle	−0.02	−0.03	−0.13	0.97*
37(2)	Cranial base angle	0.85*	0.11	−0.04	−0.11

[1] The sample size is 29. The cumulative proportion of the variances of the four principal components is 80.90%.

[2] See the second footnote for Table 1.

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

rho for PC I's is 0.56 ($P<0.05$), and the rho for male Fac IV and female Fac V is not significant at the 5% level (Table 29).

Finally, the degree of contribution of cranial length and breadth to the cranial index was confirmed (Tables 32 and 33). The PCs (Table 32) suggest that there is a between-sex difference in the degree of their contribution (PC I), or in the ratio of the variation element independent of cranial index to the total variation of cranial length and breadth (PC II). The Facs (Table 33) also seem to show a slight sex difference in their contribution.

Discussion

The main purpose of the present paper is to confirm the relationship between various neuro-

Table 24. Principal component analysis of the correlation matrix for the sixth set of neurocranial measurements from Japanese females.[1)]

Variable[2)]		Factor loadings				Total variance (%)
		PC I	II	III	IV	
1	Cranial length	0.06	−0.79	0.28	−0.27	76.94
8	Cranial breadth	−0.24	0.73	0.24	0.51	91.11
17	Basi-bregmatic height	0.13	0.35	0.85	−0.05	85.63
K137	Bregma-lambda angle	0.82**	0.32	0.15	0.20	84.22
33	Occipital inclination	0.92***	−0.23	0.02	0.10	90.60
33(1)	Lambda-inion angle	0.94***	−0.09	−0.08	−0.09	90.67
33(2)	Opisthion-inion angle	0.42	−0.76	0.10	0.43	94.20
33(4)	Lambda-inion-opisthion angle	0.41	0.78	−0.14	−0.39	94.19
34	Foramen magnum angle	0.50	0.23	−0.68	0.14	78.77
37(2)	Cranial base angle	0.77***	0.12	0.28	−0.14	70.77
	Total contribution (%)	36.77	26.76	14.48	7.70	85.71
	Cumulative proportion (%)	36.77	63.53	78.01	85.71	85.71

[1)] The sample size is 20. The number of principal components shown here was determined so that the cumulative proportion of the variances of the principal components exceeded 80%.

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

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

Table 25. Solution obtained through normal varimax rotation of the first four principal components of the correlation matrix for the sixth set of neurocranial measurements from Japanese females.[1)]

Variable[2)]		Factor loadings			
		Fac I	II	III	IV
1	Cranial length	0.02	−0.43	0.24	−0.73
8	Cranial breadth	−0.13	0.13	0.25	0.90
17	Basi-bregmatic height	0.26	0.14	0.85	0.23
K137	Bregma-lambda angle	0.87**	0.06	0.04	0.29
33	Occipital inclination	0.90***	−0.23	−0.13	−0.17
33(1)	Lambda-inion angle	0.91***	0.02	−0.19	−0.23
33(2)	Opisthion-inion angle	0.39	−0.85	−0.09	−0.26
33(4)	Lambda-inion-opisthion angle	0.43	0.84	−0.05	0.21
34	Foramen magnum angle	0.44	0.19	−0.73	0.18
37(2)	Cranial base angle	0.80	0.13	0.21	−0.09

[1)] The sample size is 20. The cumulative proportion of the variances of the four principal components is 85.71%.

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

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

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

	Male	PC I	II	III	IV	Fac I	II	III	IV
Female PC	I	.93***	—	—	—	.88***	—	—	—
	II	.83***	—	—	—	.83***	—	—	—
	III	—	—	—	—	—	—	—	—
	IV	—	—	—	—	—	—	—	—
Fac	I	.89***	—	—	—	.94***	—	—	—
	II	—	—	—	—	—	—	—	—
	III	—	—	—	—	—	—	—	—
	IV	—	—	—	—	—	—	—	—

[1)] Only those rank correlation coefficients that are 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.

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

Table 27. Spearman's rank correlation coefficients between males and females for the variation patterns of factor loadings of the principal components and/or rotated factors obtained from the second sets of neurocranial measurements.[1)]

	Male	PC I	II	III	IV	V	Fac I	II	III	IV	V
Female PC	I	.71**	—	—	—	—	.53*	—	—	—	—
	II	—	—	.58*	.55*	—	.53*	—	—	—	—
	III	—	.71**	—	—	—	—	.63*	—	—	—
	IV	—	—	—	—	—	—	—	—	—	—
Fac	I	.82***	.67**	—	—	—	.79***	—	—	—	—
	II	—	.58*	—	.68**	—	.70**	—	—	—	.76**
	III	—	—	—	—	.54*	—	—	.65**	—	—
	IV	—	—	—	—	—	—	—	—	—	—

[1)] Only those rank correlation coefficients that are 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.

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

Table 28. Spearman's rank correlation coefficients between males and females for the variation patterns of factor loadings of the principal components and/or rotated factors obtained from the third sets of neurocranial measurements.[1)]

	Male	PC I	II	III	IV	Fac I	II	III	IV
Female PC	I	.89***	—	—	—	—	—	.66*	—
	II	.58*	.64*	—	—	—	—	—	—
	III	—	—	—	—	—	—	—	—
	IV	—	—	—	.72**	.54*	—	—	.62*
Fac	I	.86***	.65*	—	—	.53*	—	.54*	—
	II	—	.61*	—	—	—	.56*	—	—
	III	—	—	—	—	—	—	—	.56*
	IV	—	—	—	—	—	—	—	—

[1)] Only those rank correlation coefficients that are 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.

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

Table 29. Spearman's rank correlation coefficients between males and females for the variation patterns of factor loadings of the principal components and/or rotated factors obtained from the fourth sets of neurocranial measurements.[1)]

	Male	PC I	II	III	IV	Fac I	II	III	IV
Female PC	I	.56*	.79***	.53*	—	.69**	.71**	—	—
	II	—	.79***	.53*	—	.70**	.80***	—	—
	III	.66**	—	—	—	.50*	—	.50*	—
	IV	—	—	—	.57*	—	—	—	.61**
	V	—	—	—	.54*	—	—	—	.63**
Fac	I	.91***	.75***	—	—	.83***	.58*	—	—
	II	—	.75***	.70**	—	—	.81***	—	—
	III	—	—	—	—	.52*	—	—	—
	IV	—	—	—	—	—	—	—	—
	V	—	—	.56*	—	—	—	—	—

[1)] Only those rank correlation coefficients that are 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 14, 15, 16, and 17.

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

Table 30. Spearman's rank correlation coefficients between males and females for the variation patterns of factor loadings of the principal components and/or rotated factors obtained from the fifth sets of neurocranial measurements.[1)]

Male	PC I	II	III	IV	Fac I	II	III	IV
Female PC I	—	.83***	—	—	.67*	.65*	—	.67*
II	.88***	—	—	—	.64*	—	—	—
III	—	—	—	—	—	—	—	—
IV	—	—	.80**	—	—	—	.66*	—
Fac I	—	.89***	—	—	—	.87***	—	.66*
II	.69*	—	—	—	—	—	—	—
III	—	.66*	—	—	—	—	—	.59*
IV	—	—	.66*	—	—	—	—	—

[1)] Only those rank correlation coefficients that are 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 18, 19, 20, and 21.

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

Table 31. Spearman's rank correlation coefficients between males and females for the variation patterns of factor loadings of the principal components and/or rotated factors obtained from the sixth sets of neurocranial measurements.[1)]

Male	PC I	II	III	IV	Fac I	II	III	IV
Female PC I	.84**	—	.65*	—	—	—	.66*	—
II	—	.78**	—	—	—	.88***	—	—
III	—	—	—	—	—	—	—	—
IV	—	—	—	—	—	—	—	—
Fac I	.81**	—	.66*	—	—	—	.70*	—
II	—	.78**	—	—	—	.85**	—	—
III	—	—	.64*	—	—	—	.67*	—
IV	—	—	—	—	—	.73*	—	—

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

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

Table 32. Principal component analyses of the correlations between cranial length and breadth and cranial index in Japanese male and female samples.[1)]

Variable[2)]	Male			Female		
	Factor loadings		Total variance (%)	Factor loadings		Total variance (%)
	PC I	II		PC I	II	
1 Cranial length	−0.63*	0.77***	99.99	0.88***	0.47***	99.99
8 Cranial breadth	0.66	0.75*	99.99	−0.88**	0.48***	99.99
I1 Cranial index	1.00**	−0.01	99.98	−1.00***	−0.00	99.97
Total contribution (%)	61.29	38.69	99.98	84.89	15.09	99.98
Cumulative proportion (%)	61.29	99.98	99.98	84.89	99.98	99.98

[1)] The sample size is 30 and 20 for males and females, respectively. The numbers of principal components shown here were determined so that the cumulative proportions of the variances of the principal components exceeded 80%.

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

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

Table 33. Solutions obtained through normal varimax rotation of the first two principal components extracted from the correlation matrices for cranial length and breadth and cranial index of Japanese males and females.[1)]

Variable[2)]	Male		Female	
	Factor loadings		Factor loadings	
	Fac I	II	Fac I	II
1 Cranial length	0.07	1.00	0.96*	−0.28
8 Cranial breadth	1.00	0.09	−0.29	0.96
I1 Cranial index	0.72***	−0.69	−0.71***	0.70

[1)] The sample size is 30 and 20 for males and females, respectively. The cumulative proportion of the variances of the two principal components is 99.98% in both sexes.

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

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

cranial measurements found by previous authors, particularly, the relatively strong associations between cranial length and occipital measurements (Howells, 1957, 1972; Kanda and Kurisu, 1968; Kanda, 1968).

Cranial length and the other neurocranial measurements

As shown by the PC I's and Fac I's of both sexes from the first data set (Tables 2 to 5), glabello-lambda and nasion-lambda lengths are highly significantly associated with cranial length. This means that the total variation of the frontal and parietal portions in the anteroposterior direction clearly contributes to the variation in maximum cranial length, and this is supported by one of the factors extracted by Howells (1973), FACT 1. He carried out a "principal factor analysis" of the within-group correlations of 70 craniofacial measurements and angles using 834 male skulls from 17 different populations. In his results, FACT 1 is most highly correlated with glabello-occipital length, and at the same time, is relatively highly correlated with basion-nasion length and nasion radius (the perpendicular to the transmeatal axis from nasion).

On the other hand, the PC I's of both sexes from the fourth data set (Tables 14 and 16) suggest that cranial length is relatively strongly correlated with occipital and lambda-inion arcs/chords, but not with the frontal or parietal arc/chord. This finding is consistent with the result suggested by one of Kanda and Kurisu's (1968) rotated factors, F_3', which is highly correlated with maximum cranial length and the occipital arc, but not with the frontal or parietal arc. The sample used by Kanda and Kurisu was, however, a pooled one composed of 37 plus 30 male Kinai Japanese skulls reported by Kanda (1959) and by Miyamoto (1924), respectively, with the latter being the same as the present data. Therefore, it may not be surprising that their result is similar to the present one. However, Howells' (1972) Factor 14, which was obtained through an "image-covariance common factor analysis" and the rotations probably based on the same data as those of Howells (1973), is relatively highly correlated with the frontal chord, but not with glabello-occipital length (nor with frontal subtense or glabella projection) and his Factor 16 is relatively highly correlated with the parietal subtense and chord, but not with glabello-occipital length. The associations suggested by these two factors are completely consistent with the present findings, but Howells' Factor 18, which is strongly correlated with the occipital chord and basion-bregma height, is not highly correlated with glabello-occipital length (nor with occipital subtense or the frontal chord). On the other hand, Howells' Factor 17, which has a high correlation with the occipital subtense, shows the highest correlation with glabello-occipital length among the above-mentioned Factors (14, 16, 17, and 18). In summary, Howells' (1972) Factor 18 can be interpreted as a factor relating to the neurocranial height, and Factor 17 may partly correspond to the present PC I's from the fourth data sets of males and females. The strong association between occipital subtense and maximum cranial length is furthermore supported by Key's (1983) rotated factor 7, which was extracted from a pooled within-group correlation matrix, corrected for sex-differences, of 80 craniofacial measurements of 732 or fewer prehistoric and historic Native Americans from the Plains area of the United States. This factor is most highly correlated with glabello-occipital length among the 21 rotated factors listed, and at the same time, is strongly correlated with occipital subtense (positively) and occipital angle (inversely).

In addition, Pearson and Davin (1924) have presented numerous correlation coefficients between cranial measurements based on some 700 to 900 male and 400 to 600 female Egyptian skulls from the period of 600 to 200 B.C. Although a correlation coefficient can generally be decomposed into smaller elements or components from a viewpoint of factor analysis, or, in other words, may only superficially show combined information from a variety of sources, it may sometimes be suggestive. In Pearson and Davin's correlation matrices, the maximum length (glabella to occipital point) has the highest correlation with the occipital arc among the three sub-sagittal arcs, i.e. frontal, parietal, and occipital arcs, in both sexes. The same tendency was also confirmed in the present study (Table 34). Further, using just 100 male or probably male skulls of European derivation, Howells (1957) obtained correlation coefficients of 0.311 and 0.579 between the maximum length and the greatest depths of the curves of the frontal and occipital bones, respectively. This again implies the greater contribution of the occipital depth in the anteroposterior direction to maximum cranial length than the frontal.

From the above comparisons, two points can be inferred. First, the variation in the upper parts of the frontal and parietal bones is not so strongly associated with the variation of maximum cranial length; in other words, the portion that co-varies with maximum cranial length relates to the basal parts of the frontal and parietal bones as represented by the glabello-lambda or nasion-lambda length. Second, it is most likely that the protrusion of the occipital bone in the anteroposterior direction is considerably associated with maximum cranial length independently of the anterior basal part of the neurocranium.

Table 34. Correlation coefficients between cranial length and sagittal arcs and chords in Japanese males and females.[1]

Variable[2]		1 Cranial length	
		Male	Female
26	Frontal arc	0.37	0.05
27	Parietal arc	0.27	0.29
28	Occipital arc	0.53*	0.60**
28(1)	Lambda-inion arc	0.36	0.54*
29	Frontal chord	0.42	0.19
30	Parietal chord	0.46*	0.54*
31	Occipital chord	0.39	0.28
31(1)	Lambda-inion chord	0.23	0.37
31(2)	Inion-opisthion chord	0.51*	0.10

[1] The sample size is 22 and 18 for males and females, respectively.

[2] See the second footnote for Table 1.

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

Cranial length and the nuchal planum

A considerable contribution of the occipital bone to maximum cranial length may also be inferred from the rotated solutions (Tables 15 and 17) of the fourth data set (Tables 14 and 16). First, male Fac IV and female Fac V are most strongly, though not significantly, correlated with cranial length and with sphenion-asterion chord. This is consistent with the above-mentioned idea that cranial length co-varies with the anterior basal part of the neurocranium. It is interesting that the same rotated factor, though only of males, is also strongly correlated with inion-opisthion chord. Kanda (1968) carried out two factor analyses using two data sets of male Japanese skulls: 67 skulls from the Kinai district, originally reported by Kanda (1959) and Miyamoto (1924), and 57 skulls from the Tohoku district. His rotated factor from the Kinai skulls (partly overlapped with the present sample), F'_{K3}, similarly suggests that cranial length is strongly associated with the inion-opisthion arc. But a rotated factor, F'_{T1}, from the Tohoku skulls, which is strongly correlated with occipital and inion-opisthion arcs, does not have a high correlation with maximum cranial length. From the present and Kanda's (1968) findings, therefore, this intercharacter connection between cranial length and inion-opisthion chord/arc may not be so strong.

There is, however, a point to be examined before a conclusion is drawn. As suggested in the preceding section, the occipital arc, which is considered to contain information relating to occipital subtense, seems to have strong associations with cranial length. If the variation in occipital subtense is caused by both brain size and the amount of nuchal muscles and if the variation in the inion-opisthion chord/arc is due to the amount of nuchal muscles, then these two metric characters must share common information about nuchal muscles. As there are no reports that deal with both the inion-opisthion chord/arc and occipital subtense, as far as the present author knows, we cannot strictly discuss the association between these two characters. However, male PC I (Table 14) and Fac IV (Table 15) suggest that the association between the inion-opisthion chord and occipital arc is reasonably high, with all the relevant factor loadings being equal to or greater than 0.30. Therefore, the possibility that the degree of development of nuchal muscles is one of the causes of the variation in cranial length cannot be rejected. If the variation in the nuchal planum to which nuchal muscles attach influences the variation in cranial length, they must have played a role in the occurrence of brachycephalization or dolichocephalization.

Cranial breadth and the other neurocranial beadths

As for cranial breadth, male and female PC I's from the second data set (Tables 6 and 8) show that cranial breadth and height are significantly associated with maximum frontal breadth and biauricular breadth as well as many cranial height measurements, but not with minimum frontal breadth or biasterionic breadth nor with foramen magnum breadth. Howells' (1972) Factor 2 also tends to have relatively high correlations with maximum breadth, biauricular breadth, and maximum frontal breadth, but not with asterionic breadth or minimum cranial breadth. It is interesting here that, while the minimum frontal and biasterionic breadths located in the front and rear ends of the braincase are not significantly associated with maximum cranial breadth, some representative measurements of basal braincase breadth such as biauricular breadth covary with maximum cranial breadth. It is not known whether this finding suggests more than the possibility that some peripheral regions of the braincase vary according to other constraints, more or less independently of the variation in the main region.

Sex difference in cranial index

It is widely known that cranial index tends to be lower in males than in females in almost all human populations (Pearson and Davin, 1924; Cameron, 1929) including the present sample (Table 1). According to Matsumura's (1925) detailed investigation of 6000 male and 2000 female Japanese, the cephalic index also has the same tendency, with the male index being lower than the female index in 47 of the 53 local populations studied.

In the present study, some between-sex differences were found in the way or degree of contribution of cranial length and breadth to cranial index (Tables 32 and 33). In Table 32, it is shown that the two PCs extracted explain nearly 100% of the total variation. This is reasonable because the sources of variation are originally only two metric characters, i.e. cranial length and breadth. The variation element expressed by PC II is considered to represent the information itself lost when a cranial index is obtained by dividing cranial breadth by cranial length. The sex difference detected between these PC II's may be explained by the finding that the association between cranial length and inion-opisthion chord tends to be stronger in males than in females (Tables 15 and

17). Namely, it may be considered that males who have stronger skeletal muscles including nuchal ones have an extra or additional factor that influences maximum cranial length and breadth compared with females.

Summary and Conclusions

Principal component analyses of neurocranial measurements and the rotated solutions showed that cranial length is significantly associated with glabello-lambda and nasion-lambda lengths in both sexes and that cranial breadth is significantly associated with maximum frontal and biauricular breadths but not with minimum frontal breadth or biasterionic breadth across the sexes. Although the association between cranial length and inion-opisthion chord was not significant at the 5% level, the present and previous findings still suggest that the variation in the occipital bone or the nuchal planum may be one of the causes for the variation of cranial length, and in turn, for brachycephalization or dolichocephalization.

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