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Covariations of the Neurocranium with the Cervical, Thoracic and Lumbar Vertebrae and the Sacrum: Toward the Solution of the Brachycephalization Problem

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Abstract A series of analyses by the present author on the correlations between the neurocranium and individual vertebrae have shown that a few vertebral measurements are relatively highly correlated with cranial length or basi-bregmatic height. In this study, it was reconfirmed on the basis of male data that cranial length is associated with the sagittal and transverse diameters of the vertebral body throughout almost all vertebrae; and that basi-bregmatic height is also generally associated with the transverse diameter of the vertebral foramen. In addition, both male and female data on some representative measurements suggested that cranial length is associated also with the total transverse diameter of the atlas and with the sacral breadths at the upper and middle levels. For the causes of these associations, the possibility of the contribution from some ontogenetic and biomechanical factors was discussed.
Key words: Brachycephalization, Neurocranium, Vertebrae, Principal component analysis, Bootstrap method.

Since Mizoguchi (1992) found that some vertebral measurements might be correlated with cranial length and breadth, he (Mizoguchi, 1994, 1995, 1996, 1997, n.d.) has intensively analyzed the correlations between the three main neurocranial measurements (Miyamoto, 1924) and almost all the vertebral measurements reported by Okamoto (1930). In many of these analyses for individual vertebrae and the neurocranium, he confirmed, first, that the size of the vertebral foramen, especially the transverse diameter, had significant association with basi-bregmatic height (Mizoguchi, 1994, 1995, 1997), though this may not be related with brachycephalization. Second, Mizoguchi (1997) found in most of the analyses for individual thoracic vertebrae and the neurocranium that the sagittal and/or transverse diameters of the vertebral body were significantly associated with cranial length and/or basi-bregmatic height. And, finally, Mizoguchi (n.d.) found the significant associations between cranial length and the sacral breadths at the upper and middle levels.

The present study was intended to ascertain whether or not the above associations are found again when the observed values for each measurement item from all available vertebrae are simultaneously dealt with.

Materials and Methods

The data used are the measurements of the neurocranium and the vertebrae published by Miyamoto (1924) and Okamoto (1930), respectively. These data are of the same individuals, *i.e.*, 30 male and 20 female Japanese from the Kinai district.

Table 1. Principal component analysis of the correlation matrix on the three main cranial measurements and the superior sagittal diameters of the vertebral bodies of the cervical, thoracic and lumbar vertebrae from Japanese males.[1)]

Variable[2)]	Factor loadings					Total variance (%)
	PC I	II	III	IV	V	
1 Cranial length	.49**	−.34	−.23	.08	.08	41.98
8 Cranial breadth	.22	.03	−.16	.63	.49	71.19
17 Basi-bregmatic height	.42	−.42	−.07	.12	.43	56.77
4 Sup. sag. d. of v. body:						
Cervical vertebra III	.56***	.43	−.14	.44	.05	71.84
IV	.34	.70**	.05	.37	−.27	81.59
V	.33	.61*	−.17	.36	−.38	78.73
VI	.58**	.65**	.16	−.13	−.09	80.45
VII	.77***	.28	.18	−.13	−.16	75.06
Thoracic vertebra I	.71***	.13	.60	−.05	.12	91.07
II	.69***	.23	.46	−.12	.32	84.89
III	.84***	−.01	.36	−.02	.01	83.87
IV	.87***	−.07	.27	.04	−.05	83.82
V	.85***	−.22	.36	−.02	−.08	91.25
VI	.88***	−.32*	.21	.09	−.13	94.89
VII	.80***	−.45*	.02	.17	−.17	90.10
VIII	76***	−.49*	−.06	.17	−.10	86.13
IX	.77***	−.56**	−.02	.14	−.09	92.98
X	.83***	−.36*	−.18	.06	−.18	88.60
XI	.84***	−.18	−.36	−.23	−.09	92.61
XII	.74***	.00	−.49	−.24	−.11	86.30
Lumbar vertebra I	.84***	.04	−.32	−.16	−.07	84.36
II	.70*	.19	−.15	−.29	.10	64.29
III	.71***	.45	−.32	−.10	.15	84.75
IV	.70***	.45	−.17	−.20	.29	84.57
V	.70***	.23	−.19	−.05	.30	67.91
Total contribution (%)	49.31	13.92	7.41	5.19	4.58	80.40
Cumulative proportion (%)	49.31	63.23	70.63	75.82	80.40	80.40

[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)] Variable number according to Martin and Saller (1957).

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

In the present study, the superior, middle and inferior sagittal and transverse diameters of the vertebral body, the sagittal and transverse diameters of the vertebral foramen, the maximum width between the transverse processes and, furthermore, the total sagittal and transverse diameters of the atlas as well as the anterior superior transverse arc, maximum breadth, and middle transverse arc of the sacrum were selected for analysis because they are suggested to be strongly correlated with cranial length or basi-bregmatic height (Mizoguchi, 1994, 1995, 1996, 1997, n.d.). For the

Table 2. Solution obtained through the normal varimax rotation of the first five principal components (Table 1) for the correlation matrix on the three main cranial measurements and the superior sagittal diameters of the vertebral bodies of Japanese males.[1)]

Variable[2)]		Factor loadings				
		Fac I	II	III	IV	V
1 Cranial length		.56	.24	−.00	−.09	.21
8 Cranial breadth		.12	.04	.00	.17	.82
17 Basi-bregmatic height		.45	.16	.14	−.32	.47
4 Sup. sag. d. of v. body:						
Cervical vertebra	III	.18	.32	.19	.63	.39
	IV	−.07	.14	.23	.86***	.06
	V	.03	.21	.01	.86***	.00
	VI	−.06	.48	.54	.52	−.13
	VII	.33	.42	.56	.36	−.15
Thoracic vertebra	I	.26	.14	.90	.12	.05
	II	.12	.32	.84	.05	.16
	III	.50	.24	.71	.15	.03
	IV	.60*	.25	.62	.18	.05
	V	.68*	.15	.65	.06	−.03
	VI	.81**	.15	.50	.10	.04
	VII	.90**	.11	.26	.06	.08
	VIII	.89**	.14	.18	.00	.14
	IX	.92**	.12	.22	−.06	.13
	X	.86**	.33	.15	.09	.03
	XI	.69	.66*	.10	.02	−.07
	XII	.53	.74**	−.02	.14	−.09
Lumbar vertebra	I	.56	.68**	.17	.19	−.02
	II	.26	.68	.32	.09	−.02
	III	.14	.79*	.22	.35	.16
	IV	.05	.79*	.39	.21	.17
	V	.23	.65	.30	.15	.29

1) The sample size is 28. The cumulative proportion of the variances of the five principal components is 80.40%.

2) Variable number according to Martin and Saller (1957).

$^{*}P<0.05$; $^{**}P<0.01$; $^{***}P<0.001$, by the two-tailed bootstrap test.

multivariate analyses on the measurements of the vertebral body, vertebral foramen and transverse processes, however, only the male sample was used because the size of the female sample was too small compared with the number of the variables.

To examine the overall relations between the cranial and vertebral measurements, the correlation matrices on them were analyzed by the method of principal

Table 3. Principal component analysis of the correlation matrix on the three main cranial measurements and the middle sagittal diameters of the vertebral bodies of the cervical, thoracic and lumbar vertebrae from Japanese males.[1)]

Variable[2)]		Factor loadings					Total variance (%)
		PC I	II	III	IV	V	
1 Cranial length		.50**	−.38	.22	.00	−.24	50.37
8 Cranial breadth		.20	−.20	.41	.47	.59	82.08
17 Basi-bregmatic height		.36	−.53	.23	.35	−.15	60.22
6 Mid. sag. d. of v. body:							
Cervical vertebra	III	.51*	.58	.01	−.01	.39	74.04
	IV	.35	.62	.07	−.38	.46	87.83
	V	.53*	.59	.17	−.38	.15	83.52
	VI	.62**	.54	−.06	−.21	−.33	83.72
	VII	.74***	.33	−.44	.15	.00	86.85
Thoracic vertebra	I	.73***	.24	−.49	.21	−.15	88.75
	II	.79***	.09	−.36	.21	.07	81.48
	III	.83***	.07	−.27	.13	−.05	79.11
	IV	.88***	−.19	−.21	−.02	.07	86.52
	V	.86***	−.19	−.38	−.02	.05	92.62
	VI	.85***	−.36	−.12	−.02	.15	87.81
	VII	.74***	−.53	−.13	−.10	.17	88.50
	VIII	.64***	−.58	−.08	−.22	.22	84.20
	IX	.59*	−.66	.13	−.00	.16	81.64
	X	.77***	−.35	.01	−.40	−.04	87.17
	XI	.78***	−.17	.17	−.37	−.26	87.63
	XII	.49	−.23	.51	−.36	−.10	69.45
Lumbar vertebra	I	.59**	.33	.45	.13	.01	67.08
	II	.77***	.24	.38	.20	−.18	86.95
	III	.76***	.34	.36	.19	−.03	85.50
	IV	.81***	.36	.15	.17	−.16	86.22
	V	.80***	.11	.20	.30	−.15	80.51
Total contribution (%)		46.61	15.51	8.05	6.00	5.02	81.19
Cumulative proportion (%)		46.61	62.12	70.17	76.17	81.19	81.19

[1)] The sample size is 27. 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)] Variable number according to Martin and Saller (1957).

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

component analysis (Lawley and Maxwell, 1963; Okuno *et al.*, 1971, 1976; Takeuchi and Yanai, 1972). In the present study, the number of principal components was so determined that the cumulative proportion of the variances of the principal components exceeded 80%. The principal components obtaind in such a way were then transformed by Kaiser's normal varimax rotation method (Asano, 1971; Okuno *et al.*, 1971) into different factors, which may suggest some other associations hidden behind the measurements dealt with.

Table 4. Solution obtained through the normal varimax rotation of the first five principal components (Table 3) for the correlation matrix on the three main cranial measurements and the middle sagittal diameters of the vertebral bodies of Japanese males.[1)]

Variable[2)]		Factor loadings				
		Fac I	II	III	IV	V
1 Cranial length		.37	−.55	−.06	.25	−.03
8 Cranial breadth		.22	−.15	.05	−.02	.86*
17 Basi-bregmatic height		.30	−.43	−.07	.50	.26
6 Mid. sag. d. of v. body:						
Cervical vertebra	III	.33	.04	−.38	−.67*	.18
	IV	.18	−.01	−.13	−.91**	.03
	V	.44*	−.11	−.15	−.76*	−.17
	VI	.54	−.06	−.42	−.37	−.48
	VII	.26	−.11	−.85*	−.25	−.08
Thoracic vertebra	I	.26	−.13	−.88**	−.07	−.15
	II	.25	−.29	−.80*	−.12	.09
	III	.34	−.36	−.73*	−.10	−.02
	IV	.23	−.65	−.61	−.11	.05
	V	.12	−.62	−.72**	−.08	−.01
	VI	.19	−.75	−.50	−.04	.16
	VII	.04	−.84*	−.38	.03	.16
	VIII	−.05	−.87*	−.24	−.02	.15
	IX	.11	−.82	−.12	.18	.30
	X	.20	−.86*	−.23	−.13	−.17
	XI	.46	−.73	−.16	−.11	−.31
	XII	.45	−.64	.25	−.12	−.10
Lumbar vertebra	I	.74*	−.12	−.12	−.27	.15
	II	.85**	−.22	−.28	−.10	.05
	III	.80*	−.17	−.31	−.25	.13
	IV	.75*	−.17	−.48	−.20	−.03
	V	.72**	−.28	−.44	.01	.11

[1)] The sample size is 27. The cumulative proportion of the variances of the five principal components is 81.19%.

[2)] Variable number according to Martin and Saller (1957).

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

The significance of factor loadings was tested by the bootstrap method (Efron, 1979 a, 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 estimation of a bootstrap standard devia-

Table 5. Principal component analysis of the correlation matrix on the three main cranial measurements and the inferior sagittal diameters of the vertebral bodies of the cervical, thoracic and lumbar vertebrae from Japanese males.[1)]

Variable[2)]		Factor loadings					Total variance (%)
		PC I	II	III	IV	V	
1 Cranial length		.54**	−.32	−.07	.20	.00	43.90
8 Cranial breadth		.24	.02	−.35	.66	.54	90.72
17 Basi-bregmatic height		.39	−.35	.14	.44	−.13	51.04
5 Inf. sag. d. of v. body:							
Cervical vertebra	II	.25	−.38	.36	−.00	.08	34.23
	III	.62*	.54	−.14	−.21	.27	81.41
	IV	.17	.57	−.46	−.24	.46	83.16
	V	.37	.73	−.06	−.35	.16	82.64
	VI	.78***	.35	.14	−.20	−.01	78.30
	VII	.60**	.03	.63	−.11	.27	85.12
Thoracic vertebra	I	.65**	.18	.58	−.23	−.05	84.68
	II	.77***	−.21	.35	−.05	.33	87.75
	III	.85***	−.13	.10	.05	.14	77.59
	IV	.79***	−.34	.18	−.12	.06	79.81
	V	.82***	−.44	−.07	−.16	.04	90.14
	VI	.86***	−.42*	−.05	−.12	.06	93.98
	VII	.81***	−.44*	−.27	−.05	.06	93.00
	VIII	.73***	−.57*	−.21	−.04	.14	91.36
	IX	.79***	−.47*	−.31	−.08	−.04	94.71
	X	.82***	−.07	−.37	−.13	−.26	89.84
	XI	.76***	.05	−.29	−.19	−.34	81.53
	XII	.74***	.29	−.30	−.07	−.36	86.41
Lumbar vertebra	I	.83***	.29	−.13	.23	−.07	83.89
	II	.72***	.50	−.07	.32	−.04	88.05
	III	.70***	.53	.14	.33	.04	90.13
	IV	.71***	.47	.18	.23	−.15	82.74
	V	.70***	.31	.28	.26	−.35	85.99
Total contribution (%)		46.87	15.28	8.08	5.82	5.18	81.23
Cumulative proportion (%)		46.87	62.15	70.24	76.06	81.23	81.23

[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)] Variable number according to Martin and Saller (1957).

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

tion was made by directly counting the cumulative frequency for the standard deviation in the bootstrap distribution.

Further, the reality of a common factor such as a principal component or rotated factor was indirectly examined by finding similarities between those factors obtained from the different samples of the same kind, *i.e.*, by estimating a Spearman's rank correlation coefficient (Siegel, 1956) between the variation patterns of the factor

Table 6. Solution obtained through the normal varimax rotation of the first five principal components (Table 5) for the correlation matrix on the three main cranial measurements and the inferior sagittal diameters of the vertebral bodies of Japanese males.[1)]

Variable[2)]		Factor loadings				
		Fac I	II	III	IV	V
1 Cranial length		.55	.20	.15	.19	.20
8 Cranial breadth		.16	.15	−.07	−.07	.92*
17 Basi-bregmatic height		.34	.26	.16	.50	.23
5 Inf. sag. d. of v. body:						
Cervical vertebra	II	.24	−.07	.45	.27	−.00
	III	.22	.49	.20	−.69	.08
	IV	.02	.12	−.13	−.86	.23
	V	−.07	.45	.14	−.76	−.13
	VI	.33	.61	.39	−.36	−.15
	VII	.16	.29	.86	−.07	−.01
Thoracic vertebra	I	.16	.48	.70	−.08	−.30
	II	.51	.22	.74	−.05	.15
	III	.61*	.40	.46	−.05	.16
	IV	.69	.21	.52	.05	−.03
	V	.87*	.15	.34	.01	−.01
	VI	.88*	.19	.37	.01	.03
	VII	.93*	.15	.17	−.01	.12
	VIII	.91*	.01	.23	.06	.17
	IX	.96*	.15	.09	.03	.05
	X	.80**	.46	−.08	−.14	−.13
	XI	.68**	.51	−.07	−.18	−.25
	XII	.52	.70	−.14	−.23	−.18
Lumbar vertebra	I	.44	.76	.09	−.17	.19
	II	.21	.85*	.08	−.22	.25
	III	.08	.85	.27	−.19	.25
	IV	.13	.86	.25	−.11	.05
	V	.17	.86	.25	.13	−.08

[1)] The sample size is 28. The cumulative proportion of the variances of the five principal components is 81.23%.

[2)] Variable number according to Martin and Saller (1957).

$^{*}P<0.05$; $^{**}P<0.01$; $^{***}P<0.001$, by the two-tailed bootstrap test.

loadings.

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

Table 7. Principal component analysis of the correlation matrix on the three main cranial measurements and the superior transverse diameters of the vertebral bodies of the cervical, thoracic and lumbar vertebrae from Japanese males.[1)]

Variable[2)]		Factor loadings						Total variance (%)
		PC I	II	III	IV	V	VI	
1 Cranial length		.37*	.11	−.50	−.38	.38	−.11	70.16
8 Cranial breadth		.20	.38	−.44	−.04	−.55	−.43	86.06
17 Basi-bregmatic height		.35	.15	−.45	−.21	.36	.14	54.31
7 Sup. trans. d. of v. b.:								
Cervical vertebra	III	.37*	.47	−.08	.39	−.04	.62*	89.92
	IV	.50	.64*	.15	.07	−.14	.24	76.45
	V	.40**	.74*	−.19	−.23	−.07	.02	80.60
	VI	.62***	.57*	.14	−.36	.03	−.05	85.48
Thoracic vertebra	I	.49**	.24	.36	.26	−.32	−.34	70.97
	II	.71**	−.06	.30	−.24	−.05	.02	65.51
	III	.55*	.18	.53	−.16	.42	−.21	86.52
	IV	.72**	.15	.33	.22	.35	−.29	89.83
	V	.88***	.07	.07	.21	.18	.09	86.37
	VI	78*	.01	−.04	.37	.10	−.02	76.21
	VII	.81***	−.14	−.26	.35	.03	−.05	86.70
	VIII	.84***	−.16	−.27	.22	.19	−.04	89.36
	IX	.84***	−.13	−.33	.19	.06	−.12	89.01
	X	.86***	−.10	−.28	.02	−.01	−.15	85.72
	XI	.89***	−.12	.04	−.02	−.09	−.06	82.97
	XII	.91***	−.08	.09	.01	−.16	−.03	86.69
Lumbar vertebra	I	.86***	−.31	−.03	−.09	−.21	.07	88.89
	II	.86***	−.25	−.04	−.22	−.22	.07	91.23
	III	.78**	−.30	.08	−.18	−.22	.27	85.57
	IV	.81**	−.27	.12	−.31	−.13	.16	89.08
	V	.85**	−.11	.21	−.15	.06	.12	81.70
Total contribution (%)		50.36	9.22	7.28	5.56	5.38	4.51	82.31
Cumulative proportion (%)		50.36	59.58	66.86	72.42	77.80	82.31	82.31

[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)] Variable number according to Martin and Saller (1957).

$^{*}P<0.05$; $^{**}P<0.01$; $^{***}P<0.001$, by the two-tailed bootstrap test.

Table 8. Solution obtained through the normal varimax rotation of the first six principal components (Table 7) for the correlation matrix on the three main cranial measurements and the superior transverse diameters of the vertebral bodies of Japanese males.[1)]

Variable[2)]		Factor loadings					
		Fac I	II	III	IV	V	VI
1 Cranial length		.13	.11	−.79**	.18	−.13	−.06
8 Cranial breadth		.02	−.12	−.06	.14	−.90***	.06
17 Basi-bregmatic height		.10	.01	−.68*	.22	.02	.16
7 Sup. trans. d. of v. b.:							
Cervical vertebra	III	.05	−.09	−.01	.28	.09	.89***
	IV	.19	.32	−.01	.10	−.25	.74**
	V	.08	.27	−.40	−.02	−.50*	.56**
	VI	.35*	.57	−.32	−.02	−.35	.42
Thoracic vertebra	I	.22	.45	.42	.30	−.40	.17
	II	.68	.41	−.03	.14	−.03	.10
	III	.26	.87*	−.09	.13	.13	.05
	IV	.19	.74*	−.01	.55	.02	.10
	V	.44	.38	−.12	.63*	.06	.34
	VI	.32	.24	−.03	.74***	−.03	.24
	VII	.39	.05	−.11	.82***	−.09	.13
	VIII	.41	.13	−.27	.79***	−.01	.08
	IX	.43	.08	−.26	.77***	−.17	.05
	X	.54	.14	−.28	.64***	−.25	.03
	XI	.68	.28	−.07	.50**	−.15	.09
	XII	.70**	.28	−.00	.49*	−.17	.16
Lumbar vertebra	I	.83	.06	−.06	.44**	−.09	.03
	II	.86*	.09	−.13	.34*	−.15	.05
	III	.88*	.02	−.03	.25	.04	.14
	IV	.89*	.18	−.13	.20	.01	.06
	V	.73	.37	−.12	.32	.08	.16

[1)] The sample size is 29. The cumulative proportion of the variances of the six principal components is 82.31%.

[2)] Variable number according to Martin and Saller (1957).

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

Results

The direct results of the principal component analyses (PCAs) and the rotated solutions on the measurements of the vertebral body and foramen are shown in Tables 1 to 20. From Tables 1, 3 and 5, it is clear that the principal components (PCs) correlated with cranial length also have significant correlations ($P<0.05$) with the superior, middle and inferior sagittal diameters of the vertebral body in about half of

Table 9. Principal component analysis of the correlation matrix on the three main cranial measurements and the middle transverse diameters of the vertebral bodies of the cervical, thoracic and lumbar vertebrae from Japanese males.[1)]

Variable[2)]		Factor loadings					Total variance (%)
		PC I	II	III	IV	V	
1 Cranial length		.38*	−.12	.68	−.12	−.46	85.31
8 Cranial breadth		.20	.46	.45	−.46	.49	90.45
17 Basi-bregmatic height		.30	−.07	.69	.50	.03	81.97
9 Mid. trans. d. of v. b.:							
Cervical vertebra	VII	.55*	.53	−.14	.23	.11	66.27
Thoracic vertebra	I	.51***	.46	.37	−.12	.14	63.50
	II	.73***	.35	−.17	.06	−.08	69.89
	III	.80***	.08	.02	.34	.06	76.31
	IV	.81***	−.32	−.05	.20	.19	83.12
	V	.69*	−.37	.05	.23	.32	77.51
	VI	.86***	−.30	−.04	.01	.23	89.16
	VII	.88***	−.34	−.07	−.13	−.10	91.73
	VIII	.82***	−.43	.06	−.23	−.10	93.04
	IX	.82***	−.36	.05	−.23	.13	87.28
	X	.90***	−.10	−.08	−.14	.05	85.48
	XI	.87***	−.03	−.07	−.14	.12	78.96
	XII	.82***	.25	−.24	.16	.08	82.14
Lumbar vertebra	I	.80**	.13	−.03	−.08	−.07	67.31
	II	.82***	.23	−.12	−.24	−.23	85.22
	III	.90***	.17	−.07	−.12	−.22	91.36
	IV	.88***	.16	−.06	−.02	−.20	84.88
	V	.78***	.21	.04	.38	−.19	83.26
Total contribution (%)		56.00	8.78	6.82	5.58	4.45	81.63
Cumulative proportion (%)		56.00	64.79	71.60	77.18	81.63	81.63

[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)] Variable number according to Martin and Saller (1957).

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

the cervical vertebrae and nearly all thoracic and lumbar vertebrae. Similar associations are also found in the analyses on the superior and middle transverse diameters of the vertebral body (Tables 7 and 9). It is further ascertained that the PCs correlated with basi-bregmatic height also have significant correlations with the transverse diameter of the vertebral foramen in all cervical and almost all thoracic and lumbar vertebrae (Tables 17 and 19). On the other hand, the rotated factors from the data on the vertebral body or foramen do not consistently show significant correlations with both cranial and vertebral measurements (Tables 2, 4, 6, 8, 10, 12, 14, 16, 18 and 20).

Table 10. Solution obtained through the normal varimax rotation of the first five principal components (Table 9) for the correlation matrix on the three main cranial measurements and the middle transverse diameters of the vertebral bodies of Japanese males.[1]

Variable[2]		Factor loadings				
		Fac I	II	III	IV	V
1 Cranial length		.18	.06	.31	−.13	−.84***
8 Cranial breadth		.03	.07	.00	−.95**	−.03
17 Basi-bregmatic height		.12	.07	.85	−.10	−.25
9 Mid. trans. d. of v. b.:						
Cervical vertebra	VII	.06	.75	.14	−.20	.18
Thoracic vertebra	I	.11	.45	.19	−.59	−.18
	II	.28	.78*	.00	−.11	−.04
	III	.47*	.63	.37	−.02	.01
	IV	.79*	.35	.28	.06	.06
	V	.76	.19	.38	−.00	.12
	VI	.86*	.34	.16	−.08	.02
	VII	.83**	.38	−.02	.06	−.26
	VIII	.86*	.23	−.02	−.00	−.38
	IX	.87*	.22	.01	−.15	−.19
	X	.75**	.51	−.03	−.13	−.14
	XI	.69**	.51	−.01	−.20	−.08
	XII	.44	.78	.08	−.08	.12
Lumbar vertebra	I	.48	.62	−.00	−.15	−.19
	II	.43	.72	−.20	−.15	−.30
	III	.50	.74	−.07	−.10	−.31
	IV	.48	.74	.01	−.06	−.26
	V	.30	.76*	.37	.07	−.16

[1] The sample size is 29. The cumulative proportion of the variances of the five principal components is 81.63%.

[2] Variable number according to Martin and Saller (1957).

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

Regarding the maximum width between the transverse processes, there is no PC nor rotated factor which is significantly correlated simultaneously with this and any of the cranial measurements (Tables 21 and 22).

In Tables 23 to 26, the direct results of the PCAs and the rotated solutions for the three main cranial measurements and some representative vertebral ones are shown. The representative measurement items were selected as follows. That is, from each set of the cervical, thoracic and lumbar vertebrae, one vertebra around the middle level of each set whose measurements were more highly correlated with cranial length or basi-bregmatic height was selected as a representative. The direct result of the PCA for males (Table 23) shows that the first PC correlated with cranial length

Table 11. Principal component analysis of the correlation matrix on the three main cranial measurements and the inferior transverse diameters of the vertebral bodies of the cervical, thoracic and lumbar vertebrae from Japanese males.[1]

Variable[2]		Factor loadings PC I	II	III	IV	V	VI	Total variance (%)
1 Cranial length		.28	.25	−.31	.59	.23	−.19	66.68
8 Cranial breadth		.24	.33	.20	.03	.54	−.39	63.69
17 Basi-bregmatic height		.30	.22	.06	.76	−.08	−.09	72.81
8 Inf. trans. d. of v. b.:								
Cervical vertebra	II	−.10	.46	−.02	−.32	−.27	−.45	60.04
	III	.27	.80	.23	−.22	−.19	−.02	84.95
	IV	.49	.67	.31	.14	.06	−.07	82.20
	V	.57	.18	.65	.22	−.06	.12	84.58
	VI	.59*	−.17	.66	−.22	−.05	.06	86.46
	VII	.68**	−.18	.58	−.08	−.03	.15	85.98
Thoracic vertebra	I	.66**	−.24	.10	−.08	.50	.08	76.10
	II	.61	−.28	.20	.30	.21	−.04	62.40
	III	.76***	−.12	−.12	−.14	.31	.21	77.33
	IV	.87***	.05	−.18	.15	−.03	.08	82.55
	V	.82***	.14	−.30	−.02	−.05	.30	87.81
	VI	.79***	.32	−.29	−.08	−.16	.28	91.52
	VII	.90***	.26	−.14	−.05	−.00	.17	92.02
	VIII	.81***	.29	−.29	−.08	.14	.17	88.79
	IX	.87***	.32	−.13	−.17	.00	−.05	90.47
	X	.90***	.02	.04	−.18	.02	−.02	83.81
	XI	.86***	−.12	−.06	−.13	.06	−.02	77.94
	XII	.89***	−.26	−.11	−.16	−.02	−.11	90.39
Lumbar vertebra	I	.89***	−.23	−.18	.05	−.06	−.22	92.45
	II	.81***	−.31	−.05	−.14	−.08	−.41*	93.60
	III	.84***	−.24	−.06	.01	−.20	−.36*	93.25
	IV	.88***	−.25	−.03	.04	−.24	−.17	93.25
	V	.58	−.24	.08	.41	−.47	.16	81.10
Total contribution (%)		49.66	9.82	7.51	6.32	4.73	4.36	82.39
Cumulative proportion (%)		49.66	59.48	66.99	73.30	78.03	82.39	82.39

[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] Variable number according to Martin and Saller (1957).
$*P<0.05$; $**P<0.01$; $***P<0.001$, by the two-tailed bootstrap test.

and basi-bregmatic height also has significant correlations with most of the vertebral measurements dealt with. Although the first PC for the female data has no significant factor loadings (Table 25), it shows a similar tendency in the variation pattern of the factor loadings to that for the male data (Table 27). The measurement items which

Table 12. Solution obtained through the normal varimax rotation of the first six principal components (Table 11) for the correlation matrix on the three main cranial measurements and the inferior transverse diameters of the vertebral bodies of Japanese males.[1)]

Variable[2)]		Factor loadings					
		Fac I	II	III	IV	V	VI
1 Cranial length		.10	−.07	−23	.70*	.25	.22
8 Cranial breadth		.08	.14	.14	.19	.74	.06
17 Basi-bregmatic height		.08	.00	.16	.83*	−.03	.07
8 Inf. trans. d. of v. b.:							
Cervical vertebra	II	.06	.74	−.15	−.10	.10	−.07
	III	−.17	.74	.31	.08	.13	.40
	IV	−.03	.45	.45	.40	.32	.40
	V	.12	.07	.83	.31	.06	.20
	VI	.37	−.02	.82	−.19	.06	.13
	VII	.36	−.12	.81	−.06	.02	.24
Thoracic vertebra	I	37	−.42*	.31	−.06	.41	.41
	II	.44	−.37	.38	.29	.17	.17
	III	.37	−.32	.20	−.07	.21	.67**
	IV	.48	−.08	.18	.31	−.02	.68***
	V	.32	−.06	.11	.14	−.10	.86***
	VI	.24	.14	.11	.13	−.14	.89***
	VII	.35	.09	.25	.17	.06	.83***
	VIII	.28	.04	.07	.14	.16	.87***
	IX	.44	.26	.19	.10	.18	.75***
	X	.56	.04	.35	−.00	.14	.61***
	XI	.61	−.10	.25	−.00	.11	.57**
	XII	.77	−.12	.20	−.05	.05	.51**
Lumbar vertebra	I	.81*	−.10	.12	.19	.03	.45*
	II	.91*	.00	.16	−.01	.11	.26
	III	.89	.04	.18	.16	−.02	.30
	IV	.81	−.04	.27	.15	−.13	.39*
	V	.43	−.15	.36	.40	−.51	.22

[1)] The sample size is 29. The cumulative proportion of the variances of the six principal components is 82.39%.

[2)] Variable number according to Martin and Saller (1957).

$^{*}P<0.05$; $^{**}P<0.01$; $^{***}P<0.001$, by the two-tailed bootstrap test.

are relatively highly correlated with both the first PCs from the male and female data in the same direction are cranial length, the total transverse diameter of the atlas, the sagittal diameter of the vertebral body of the thoracic vertebra VII, and the anterior superior transverse arc, maximum breadth, and middle transverse arc of the sacrum.

In the rotated solutions for the same data, it is discernible that the sixth factor from the male data is significantly correlated with both cranial length and the total

Table 13. Principal component analysis of the correlation matrix on the three main cranial measurements and the sagittal diameters of the vertebral foramina of the cervical and thoracic vertebrae from Japanese males.[1)]

Variable[2)]		Factor loadings					Total variance (%)
		PC I	II	III	IV	V	
1 Cranial length		.09	.39	−.73	.09	−.06	69.85
8 Cranial breadth		.26	−.04	−.43	−.29	.57	66.18
17 Basi-bregmatic height		.29	.32	−.59	.37	.07	67.57
10 Sagit. d. of v. foramen:							
Cervical vertebra	I	.48*	−.23	−.09	−.02	.50	53.74
	II	.80***	.06	.28	.10	.32	83.48
	III	.65**	.33	.42	.05	.33	82.15
	IV	.72***	.42	.26	.18	−.06	79.25
	V	.64***	.51	.35	.16	.02	82.74
	VI	.52*	.70	.07	−.16	−.03	78.32
	VII	.78***	.39	−.00	−.11	−.27	85.26
Thoracic vertebra	I	.88***	.14	−.08	−.22	−.08	84.73
	II	.91***	−.04	−.04	−.31	−.08	92.41
	III	.79***	−.18	−.21	−.29	−.25	85.19
	IV	.87***	−.14	−.04	−.27	−.22	90.67
	V	.86***	−.29	.08	−.31	.02	92.32
	VI	.89***	−.28	.05	−.20	.06	91.44
	VII	.77***	−.35	−.10	.04	−.01	72.64
	VIII	.87***	−.05	−.10	.20	−.05	80.75
	IX	.74***	−.34	−.30	.35	−.10	87.95
	X	.76***	.06	−.16	.39	.05	76.68
	XI	.81***	−.15	.00	.25	−.05	74.12
	XII	.46**	−.57	.31	.45	−.10	84.01
Total contribution (%)		50.47	10.55	8.21	6.17	4.67	80.06
Cumulative proportion (%)		50.47	61.02	69.23	75.40	80.06	80.06

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) Variable number according to Martin and Saller (1957).

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

transverse diameter of the atlas (Table 24); that the fifth factor from the male data is significantly correlated not only with basi-bregmatic height but also with the total sagittal and transverse diameters of the atlas and the transverse diameter of the vertebral foramen of the cervical vertebra III (Table 24); and that the seventh factor from the male data (Table 24) and the fourth factor from the female data (Table 26) are significantly correlated with both basi-bregmatic height and the transverse diameter of the vertebral foramen of the thoracic vertebra VII, though these factors are not necessarily similar to each other in the variation pattern of factor loadings (Table 28).

Table 14. Solution obtained through the normal varimax rotation of the first five principal components (Table 13) for the correlation matrix on the three main cranial measurements and the sagittal diameters of the vertebral foramina of Japanese males.[1]

Variable[2]	Factor loadings Fac I	II	III	IV	V
1 Cranial length	.07	−.02	−.82	−.14	.04
8 Cranial breadth	.20	−.05	−.25	−.12	.74
17 Basi-bregmatic height	−.01	.17	−.77	.20	.12
10 Sagit. d. of v. foramen:					
Cervical vertebra I	.22	.12	.01	.29	.62
II	.32	.65	.11	.40	.38
III	.16	.81	.15	.17	.29
IV	.29	.80	−.10	.25	−.07
V	.18	.88	−.04	.16	−.04
VI	.29	.75	−.26	−.25	−.02
VII	.62**	.62	−.26	.06	−.12
Thoracic vertebra I	.74**	.47	−.18	.14	.16
II	.84*	.37	−.04	.18	.21
III	.88*	.12	−.13	.21	.09
IV	.88**	.27	−.02	.24	.09
V	.81*	.24	.18	.29	.31
VI	.76*	.27	.11	.38	.33
VII	.61	.12	−.04	.53*	.24
VIII	.54	.39	−.23	.54*	.14
IX	.48	.05	−.31	.73**	.12
X	.31	.43	−.36	.57	.16
XI	.48	.34	−.10	.61*	.11
XII	.19	.03	.31	.84**	−.05

[1] The sample size is 29. The cumulative proportion of the variances of the five principal components is 80.06%.

[2] Variable number according to Martin and Saller (1957).

**P*<0.05; ***P*<0.01; ****P*<0.001, by the two-tailed bootstrap test.

Discussion

As was expected, the present results based on male data clearly showed that cranial length is associated with the sagittal and transverse diameters of the vertebral body in general; and that basi-bregmatic height is also generally associated with the transverse diameter of the vertebral foramen. In addition, both male and female data on some representative measurements suggested that cranial length is associated also with the total transverse diameter of the atlas and with the sacral breadths at the upper and middle levels.

Table 15. Principal component analysis of the correlation matrix on the three main cranial measurements and the sagittal diameters of the vertebral foramina of the thoracic and lumbar vertebrae from Japanese males.[1)]

Variable[2)]		Factor loadings					Total variance (%)
		PC I	II	III	IV	V	
1 Cranial length		.07	.38	.75	−.04	.04	71.29
8 Cranial breadth		.39	.01	.46	−.55	.18	69.26
17 Basi-bregmatic height		.35	.52	.51	.23	.13	71.58
10 Sagit. d. of v. foramen:							
Thoracic vertebra	I	.83***	.02	.11	−.31	−.19	84.04
	II	.88***	−.06	−.02	−.32	−.20	91.51
	III	.83***	−.03	.06	−.18	−.26	78.57
	IV	.90***	−.02	−.14	−.25	−.01	88.73
	V	.83***	−.32	−.14	−.31	−.07	92.08
	VI	.87***	−.25	−.12	−.21	.07	88.66
	VII	.78***	−.13	−.08	−.01	.45	84.48
	VIII	.84***	−.08	.16	.18	.17	80.01
	IX	.73***	−.26	.34	.35	.19	87.75
	X	.77***	.00	.30	.32	.10	78.57
	XI	.79***	−.15	.02	.17	.09	68.54
	XII	.41*	−.56	−.28	.42	.27	82.10
Lumbar vertebra	I	.72***	.12	.03	.38	−.43	86.36
	II	.70***	.15	−.13	.32	−.47	85.47
	III	.67***	.49	−.33	.14	−.09	83.69
	IV	.39	.66	−.43	−.00	.26	84.67
	V	.45*	.60	−.39	−.12	.30	82.59
Total contribution (%)		48.76	10.48	9.43	7.63	5.70	82.00
Cumulative proportion (%)		48.76	59.24	68.67	76.30	82.00	82.00

[1)] The sample size is 26. 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)] Variable number according to Martin and Saller (1957).
*$P<0.05$; **$P<0.01$; ***$P<0.001$, by the two-tailed bootstrap test.

The association between basi-bregmatic height and the transverse diameter of the vertebral foramen may partly be explained by supposing that the vertebral foramen is an extension of the cranial cavity, as already noted by Mizoguchi (1994, 1995, 1997). If so, it would be expected that cranial length and breadth are also associated with the vertebral foramen size. But, in fact, it is not the case. This problem should therefore be examined in more depth in the future.

Focusing on the matter of brachycephalization, it was found that there were no vertebral measurements which were consistently associated with cranial breadth. All

Table 16. Solution obtained through the normal varimax rotation of the first five principal components (Table 15) for the correlation matrix on the three main cranial measurements and the sagittal diameters of the vertebral foramina of Japanese males.[1)]

Variable[2)]		Factor loadings				
		Fac I	II	II	IV	V
1 Cranial length		.02	−.07	.84	−.05	−.00
8 Cranial breadth		.62*	−.03	.46	.04	.30
17 Basi-bregmatic height		−.02	.26	.75	.21	−.22
10 Sagit. d. of v. foramen:						
Thoracic vertebra	I	.82**	.15	.19	.17	−.30
	II	.87**	.16	.04	.20	−.31
	III	.74*	.11	.11	.21	−.41
	IV	.79*	.33	−.02	.32	−.23
	V	.86*	.08	−.18	.34	−.16
	VI	.78*	.17	−.11	.46	−.13
	VII	.50	.35	.01	.69*	.05
	VIII	.46	.17	.23	.66	−.27
	IX	.31	−.08	.28	.80*	−.25
	X	.31	.11	.36	.64	−.37
	XI	.45	.15	.05	.60	−.30
	XII	.06	−.05	−.44	.78	−.09
Lumbar vertebra	I	.30	.11	.13	.29	−.81
	II	.32	.20	.00	.21	−.82
	III	.27	.69	.04	.14	−.52
	IV	.07	.91	.04	.03	−.12
	V	.21	.88	.05	.05	−.03

[1)] The sample size is 26. The cumulative proportion of the variances of the five principal components is 82.00%.

[2)] Variable number according to Martin and Saller (1957).

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

the vertebral measurements which had strong possibility of contributing to the variaiton of cranial index were those associated with cranial length: the vertebral body size, especially the sagittal diameters of the thoracic vertebrae; the total transverse diameter of the atlas; and the sacral breadths at the upper and middle levels, as mentioned above.

Of these strong associations, those between cranial length and the sacral breadths were already interpreted by Mizoguchi (n.d.) as suggesting that the form of the maternal pelvic inlet has been and is still one of the most important determinants for the neurocranial form in modern human populations, and that the close correspondency in form between the neurocranium and the pelvis is now fixed as a population character.

Table 17. Principal component analysis of the correlation matrix on the three main cranial measurements and the transverse diameters of the vertebral foramina of the cervical and thoracic vertebrae from Japanese males.[1)]

Variable[2)]		Factor loadings						Total variance (%)
		PC I	II	III	IV	V	VI	
1 Cranial length		.32	−.07	.35	.73	.06	.29	84.40
8 Cranial breadth		.23	.27	.53	−.20	−.48	.42	86.24
17 Basi-bregmatic height		.54***	.19	.25	.37	.03	.07	53.48
11 Trans. d. of v. foramen:								
Cervical vertebra	I	.59***	.14	.25	.17	.07	−.32	56.32
	II	.72***	.20	.17	−.15	.29	−.22	73.80
	III	.69***	.46	−.02	−.11	.25	.19	79.82
	IV	.74***	.54	.05	.04	.05	.10	84.94
	V	.72***	.52	−.11	−.07	.16	.05	84.13
	VI	.72***	.42	−.22	−.11	.09	.08	77.35
	VII	.67***	.27	−.48	−.06	−.16	.07	77.87
Thoracic vertebra	I	.80***	−.02	−.30	.32	−.21	.02	87.37
	II	.79***	−.29	−.31	.23	−.11	.07	87.93
	III	.84***	−.21	−.30	.10	−.28	−.01	92.01
	IV	.79***	−.31	−.30	−.02	.06	.02	81.36
	V	.87***	−.23	.13	.07	−.04	−.08	84.35
	VI	.82***	−.41	.06	.01	−.08	−.22	89.76
	VII	.83***	−.31	.10	.04	.03	−.02	80.37
	VIII	.50	.04	.51	−.24	−.49	−.11	82.51
	IX	.76***	−.22	.29	−.35	.02	−.15	85.50
	X	.77***	−.14	.17	−.29	.20	−.16	80.11
	XI	.28	−.48	.38	−.03	.46	.42	84.83
	XII	.28	−.35	−.32	−.47	−.02	.48	75.60
Total contribution (%)		46.00	9.83	8.49	6.60	4.97	4.58	80.46
Cumulative proportion (%)		46.00	55.83	64.31	70.92	75.88	80.46	80.46

[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)] Variable number according to Martin and Saller (1957).

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

The problem is how to explain the associations of cranial length with the vertebral body size as well as with the total transverse diameter of the atlas. Although Mizoguchi (1995, 1997) who found these associations for the first time did not discuss the causes for them, they may be explained with J. W. von Goethe's "vertebral theory of the skull" (de Beer, 1937; Moore, 1981; Kardong, 1995). Moore (1981) states that, in some fish such as *Acipenser*, several spinal (occipitospinal) vertebrae are added to the occipital region. And Kardong (1995) notes that, although T. H. Huxley, who ar-

Table 18. Solution obtained through the normal varimax rotation of the first six principal components (Table 17) for the correlation matrix on the three main cranial measurements and the transverse diameters of the vertebral foramina of Japanese males.[1)]

Variable[2)]	Factor loadings					
	Fac I	II	III	IV	V	VI
1 Cranial length	.18	.02	.08	.89*	.01	.09
8 Cranial breadth	−.07	.19	.89*	.14	.00	.12
17 Basi-bregmatic height	.19	.36	.14	.54	.22	−.06
11 Trans. d. of v. foramen:						
Cervical vertebra I	.16	.32	.05	.31	.53	−.24
II	.10	.56	−.00	.09	.64**	.00
III	.14	.83	.08	.11	.22	.15
IV	.21	.81	.21	.23	.21	−.08
V	.22	.86	.06	.06	.22	−.03
VI	.33	.79	.06	−.02	.18	.02
VII	.61	.62	.05	−.14	−.00	−.07
Thoracic vertebra I	.80	.37	.04	.25	.15	−.10
II	.85*	.21	−.05	.20	.24	.12
III	.88*	.25	.11	.06	.28	.02
IV	.73*	.26	−.12	.01	.38	.25
V	.57*	.23	.15	.26	.61**	.11
VI	.64	.06	.07	.13	.67***	.08
VII	.56	.19	.09	.23	.58**	.22
VIII	.16	.08	.73	.02	.50	−.13
IX	.29	.21	.26	−.05	.79***	.20
X	.27	.34	.06	−.03	.75***	.21
XI	−.03	−.07	−.03	.36	.36	.77***
XII	.40*	.08	.11	−.38	−.03	.66*

1) The sample size is 29. The cumulative proportion of the variances of the six principal components is 80.46%.

2) Variable number according to Martin and Saller (1957).

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

gued that skull ossification showed no similarity with ossification of the following vertebrae, was probably right about this for most of the skull, the occipital region does ossify in a manner similar to vertebrae. That is to say, if the occipital region is really controlled in part by similar genes to those for vertebrae, it is likely that cranial length has some associations with vertebral measurements, but cranial breadth does not.

Regarding the peculiarity of the occipital region, Mizoguchi (1984) pointed out that it varied relatively independently of the frontal, parietal and temporal regions, and Sjøvold (1984) showed in his study based on father-son data, at least, that the

Table 19. Principal component analysis of the correlation matrix on the three main cranial measurements and the transverse diameters of the vertebral foramina of the thoracic and lumbar vertebrae from Japanese males.[1)]

Variable[2)]		Factor loadings						Total variance (%)
		PC I	II	III	IV	V	VI	
1 Cranial length		.34	.30	−.54	.45	−.09	.02	70.65
8 Cranial breadth		.21	.20	.37	.61	.17	−.46	83.32
17 Basi-bregmatic height		.52***	.06	−.16	.38	−.52	−.00	71.93
11 Trans. d. of v. foramen:								
Thoracic vertebra	I	.74***	−.30	−.38	.01	−.09	−.19	82.28
	II	.80***	−.26	−.38	−.15	.05	−.12	87.88
	III	.84***	−.35	−.20	−.09	−.02	−.19	91.35
	IV	.85***	−.15	−.12	−.30	−.05	−.01	84.23
	V	.88***	−.13	−.08	.16	.14	.16	87.29
	VI	.87***	−.17	−.09	.01	.25	.18	88.30
	VII	.88***	.02	−.07	.03	.18	.18	84.83
	VIII	.49	−.18	.39	.56	.17	−.17	79.99
	IX	.79***	−.06	.39	.09	.15	.24	87.29
	X	.79***	−.04	.37	−.02	−.06	.35	88.79
	XI	.42	.71	−.03	−.11	.37	.15	84.65
	XII	.37	−.00	.21	−.55	.23	−.52	81.08
Lumbar vertebra	I	.82***	−.01	.21	−.20	−.21	−.11	80.89
	II	.38	.19	.53	−.26	−.44	.04	72.79
	III	.71***	.43	.20	−.06	−.18	−.01	75.99
	IV	.21	.80	−.30	−.17	.07	−.05	81.21
	V	.56**	.44	−.08	.05	−.15	−.22	58.70
Total contribution (%)		44.04	10.38	8.78	8.24	4.94	4.78	81.17
Cumulative proportion (%)		44.04	54.42	63.21	71.45	76.39	81.17	81.17

[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)] Variable number according to Martin and Saller (1957).
*$P<0.05$; **$P<0.01$; ***$P<0.001$, by the two-tailed bootstrap test.

heritability estimates for occipital chord and subtense were higher than those for frontal and parietal chords and subtenses. Although the causes for these characteristics of the occipital region are unknown for the present, there is a possibility that this heterogeneity within the skull is caused by the difference in ontogenetic derivation between the occipital and the other regions of the skull.

In addition to such an ontogenetic problem, it is also necessary to take into consideration the posture of the head and the vertebral column. Can a sagittally elongated vertebral body, especially of a thoracic vertebra, be biomechanically produced in the process of its growth by having a long head? Although a few authors such as

Table 20. Solution obtained through the normal varimax rotation of the first six principal components (Table 19) for the correlation matrix on the three main cranial measurements and the transverse diameters of the vertebral foramina of Japanese males.[1)]

Variable[2)]	Factor loadings					
	Fac I	II	III	IV	V	VI
1 Cranial length	.30	.42	−.16	.15	−.62*	−.01
8 Cranial breadth	−.06	.13	.05	.90*	−.04	.03
17 Basi-bregmatic height	.38	.06	.36	.19	−.64*	.04
11 Trans. d. of v. foramen:						
Thoracic vertebra I	.88**	.01	.06	.08	−.17	.10
II	.90***	.12	.03	−.03	−.03	.22
III	.91***	−.03	.16	.11	.00	.23
IV	.77***	.15	.31	−.09	.07	.34
V	.64*	.14	.09	.19	−.18	.61***
VI	.67	.15	.03	.09	−.02	.64***
VII	.59	.29	.12	.11	−.09	.61**
VIII	.20	−.16	.08	.75*	−.07	.40
IX	.32	.05	.32	.27	.04	.77***
X	.32	.04	.48	.08	−.05	.74***
XI	.00	.84	.04	.04	.09	.37*
XII	.41**	.19	.26	.13	.72*	−.08
Lumbar vertebra I	.57**	.13	.59*	.13	.08	.30
II	−.00	.05	.83**	.00	.09	.18
III	.27	.48	.58	.18	−.08	.30
IV	.02	.89	.08	−.10	−.06	−.09
V	.34	.52	.34	.23	−.16	.01

1) The sample size is 29. The cumulative proportion of the variances of the six principal components is 81.17%.

2) Variable number according to Martin and Saller (1957).

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

Solow and Tallgren (1976), Solow *et al.* (1982) and Huggare (1992) have examined some relations between the measurements or morphology and posture of the cranium and cervical vertebrae, there are no quantitative analysis of the correlations between cranial measurements and the posture of the head or the vertebral column except the cervical one, as far as the present author knows.

Thus, the casuses for the variation in cranial length should further be examined in the future from at least three points of view: the ontogenetic relation of the occipital region with vertebrae, the biomechanical role of vertebrae in bearing elongated or shortened skulls, and the adjustment of the neurocranial form to the maternal pelvic inlet.

Table 21. Principal component analysis of the correlation matrix on the three main cranial measurements and the maximum widths between the transverse processes of the cervical, thoracic and lumbar vertebrae from Japanese males.[1)]

Variable[2)]		Factor loadings							Total variance (%)
		PC I	II	III	IV	V	VI	VII	
1 Cranial length		.39	.26	.02	−.37	−.29	.56	−.13	76.93
8 Cranial breadth		.31	.26	−.15	.25	.50	.32	.45	79.62
17 Basi-bregmatic height		.34	.26	.42	−.36	−.10	.44	.31	79.14
K12 Max. wid. between trans. proc.:									
Cervical vertebra	III	.46	.43	−.28	.34	−.20	−.29	.37	84.63
	IV	.44	.61	−.24	.32	−.32	−.08	−.07	83.06
	V	.53*	.52	−.15	−.21	−.22	.00	−.34	78.43
	VI	.74***	.37	−.32	−.14	−.08	−.25	.15	89.80
	VII	.70***	.29	−.20	−.22	−.10	−.12	.20	73.31
Thoracic vertebra	I	.78***	−.12	−.24	−.26	.15	.14	.06	79.51
	II	.77***	.03	−.19	−.34	.21	.13	−.08	81.59
	III	.79***	−.18	−.12	−.30	.27	−.21	−.14	89.75
	IV	.75***	−.35	−.05	−.30	.19	−.18	.00	83.94
	V	.74***	−.41	−.13	−.13	−.04	−.25	−.16	84.56
	VI	.72***	−.50	−.20	.02	−.07	−.09	.07	82.36
	VII	.70***	−.45	−.03	.22	−.26	.18	.15	86.43
	VIII	.66***	−.58	−.10	.27	.04	.09	.06	86.40
	IX	.53**	−.55	.02	.33	−.11	.39	.03	85.81
	X	.45	.21	−.37	.48	−.43	.22	−.23	88.81
	XI	.48*	.16	.10	.24	.45	.25	−.35	71.74
	XII	.37*	.18	−.02	.64	.49	−.03	−.16	84.52
Lumbar vertebra	I	.18	.66	−.05	−.10	.37	.14	−.02	64.22
	II	.63*	.28	.47	.02	.12	−.29	.00	78.46
	III	.54**	.15	.72	.16	−.03	−.15	.06	89.20
	IV	.62**	.02	.69	.11	−.17	−.10	.02	91.18
	V	.67***	.02	.58	.07	−.15	.00	−.12	82.04
Total contribution (%)		35.43	13.27	9.52	8.01	6.59	5.59	3.79	82.22
Cumulative proportion (%)		35.43	48.71	58.23	66.24	72.83	78.42	82.22	82.22

[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)] Variable number according to Martin and Saller (1957) except for K12, which is No. 12 of Kiyono's (1929) measurement system.

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

Table 22. Solution obtained through the normal varimax rotation of the first seven principal components (Table 21) for the correlation matrix on the three main cranial measurements and the maximum widths between the transverse processes of Japanese males.[1)]

Variable[2)]		Factor loadings						
		Fac I	II	III	IV	V	VI	VII
1 Cranial length		.15	.18	.07	.07	.03	.84**	−.05
8 Cranial breadth		.09	.14	−.02	.09	.36	.06	.79***
17 Basi-bregmatic height		.06	−.05	.43	−.02	−.14	.68	.34
K12 Max. wid. between trans. proc.:								
Cervical vertebra	III	.13	.81	.16	.05	−.07	−.18	.33
	IV	.00	.87*	.14	−.02	.19	.11	−.00
	V	.35	.57	.14	−.20	.19	.42	−.23
	VI	.61	.67	.15	−.06	−.02	.10	.19
	VII	.57*	.51	.20	−.01	−.09	.22	.22
Thoracic vertebra	I	.75*	.14	.04	.29	.12	.28	.20
	II	.77*	.14	.08	.11	.23	.35	.13
	III	.90*	.05	.20	.12	.18	.02	−.02
	IV	.85*	−.05	.22	.26	.02	.00	.03
	V	.76*	.10	.18	.41*	.02	−.08	−.22
	VI	.64	.12	.10	.61***	−.04	−.08	−.01
	VII	.33	.17	.22	.81***	−.04	.10	.06
	VIII	.44	.00	.12	.78***	.15	−.11	.08
	IX	.16	−.04	.12	.88***	.16	.12	.05
	X	−.05	.74	−.08	.44	.28	.18	−.16
	XI	.21	.04	.21	.09	.77**	.14	.10
	XII	.05	.23	.19	.14	.76*	−.32	.24
Lumbar vertebra	I	.10	.24	.05	−.47	.40	.27	.34
	II	.33	.20	.76	−.11	.19	−.01	.10
	III	.07	.08	.92*	.08	.11	.03	.06
	IV	.14	.08	.90	.23	.03	.11	−.04
	V	.21	.10	.79	.25	.15	.22	−.11

1) The sample size is 29. The cumulative proportion of the variances of the seven principal components is 82.22%.

2) Variable number according to Martin and Saller (1957) except for K12, which is No. 12 of Kiyono's (1929) measurement system.

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

Table 23. Principal component analysis of the correlation matrix on the three main cranial measurements and some representative vertebral measurements of Japanese males.[1)]

Variable[2)]	Factor loadings							Total variance (%)
	PC I	II	III	IV	V	VI	VII	
SKULL								
1 Cranial length	.59***	.18	.07	.18	.11	.59*	.27	85.95
8 Cranial breadth	.25	.32	.48	−.06	−.51	.07	−.32	76.86
17 Basi-bregmatic ht.	.54*	.18	.53	.05	.42	−.24	.30	93.70
ATLAS								
K1 Total sagit. diam.	.55**	.31	−.08	−.07	.56*	−.17	−.11	76.50
K2 Total trans. diam.	.71***	.34	−.05	−.15	.29	.30	−.12	83.38
CERVICAL VERTEBRA III								
4 S. sag. d. v. b.[3)]	.46*	.49	−.13	−.36	−.36	−.14	.13	77.04
7 S. tr. d. v. b.[4)]	.31*	.10	.01	.75*	.05	−.31	−.29	84.56
11 Tr. d. of v. f.[5)]	.66***	−.08	.20	−.37	.11	−.35	−.15	77.62
THORACIC VERTEBRA VII								
4 S. sag. d. v. b.[3)]	.75***	−.07	.14	−.26	.04	.13	−.13	69.50
7 S. tr. d. v. b.[4)]	.75***	.02	−.17	.39	−.16	.07	.01	76.92
11 Tr. d. of v. f.[5)]	.39	−.54	.45	−.05	−.26	−.23	.30	86.38
LUMBAR VERTEBRA III								
4 S. sag. d. v. b.[3)]	.60*	.45	−.26	−.12	−.29	−.05	−.15	75.65
7 S. tr. d. v. b.[4)]	.50	.40	−.39	.23	−.20	−.28	.41	90.18
11 Tr. d. of v. f.[5)]	.51**	−.13	.50	.31	−.15	.18	−.08	68.74
SACRUM								
4 A. s. tr. arc[6)]	.54*	−.69	−.30	−.05	.03	−.08	−.14	89.28
OK Maximum breadth	.75***	−.47	−.28	−.00	.02	.01	−.19	89.02
8 Mid. trans. arc	.65*	−.51	−.22	−.07	−.13	.13	.22	82.23
Total contribution (%)	33.40	13.40	9.01	7.58	7.42	5.76	4.81	81.38
Cumulative proportion (%)	33.40	46.81	55.82	63.39	70.81	76.57	81.38	81.38

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) Variable number according to Martin and Saller (1957) except for K1, K2 and OK. K1 and K2 are Nos. 1 and 2, respectively, of Kiyono's (1929) measurement system. The measurements with the "OK" mark are listed in Okamoto (1930), but the definitions for them are not presented.

3) Superior sagittal diameter of the vertebral body.

4) Superior transverse diameter of the vertebral body.

5) Transverse diameter of the vertebral foramen.

6) Anterior superior transverse arc.

**P*<0.05; ***P*<0.01; ****P*<0.001, by the two-tailed bootstrap test.

Table 24. Solution obtained through the normal varimax rotation of the first seven principal components (Table 23) for the correlation matrix on the three main cranial measurements and some repesentative vertebral measurements of Japanese males.[1)]

Variable[2)]	Factor loadings						
	Fac I	II	III	IV	V	VI	VII
SKULL							
1 Cranial length	.16	−.13	.07	.04	.18	.88***	.05
8 Cranial breadth	.19	.14	.83***	.06	.01	.06	.10
17 Basi-bregmatic ht.	.06	.12	−.00	.17	.71**	.26	.56**
ATLAS							
K1 Total sagit. diam.	.18	−.10	−.11	.17	.80***	.13	−.14
K2 Total trans. diam.	.26	−.22	.18	−.02	.61*	.51*	−.23
CERVICAL VERTEBRA III							
4 S. sag. d. v. b.[3)]	.79*	−.01	.27	−.19	.21	.03	.01
7 S. tr. d. v. b.[4)]	.06	−.05	.07	.91*	.11	.01	−.00
11 Tr. d. of v. f.[5)]	.19	−.41	.27	−.05	.63**	−.16	.28
THORACIC VERTEBRA VII							
4 S. sag. d. v. b.[3)]	.15	−.49	.35	−.09	.46	.28	.12
7 S. tr. d. v. b.[4)]	.39	−.44	.12	.47	.08	.41	.07
11 Tr. d. of v. f.[5)]	−.03	−.39	.18	−.03	−.03	−.02	.82***
LUMBAR VERTEBRA III							
4 S. sag. d. v. b.[3)]	.70*	−.20	.33	.10	.23	.12	−.22
7 S. tr. d. v. b.[4)]	.84***	−.05	−.22	.31	.07	.17	.11
11 Tr. d. of v. f.[5)]	−.11	−.20	.47	.32	.09	.40	.38
SACRUM							
4 A. s. tr. arc[6)]	−.05	−.93	−.10	.08	.08	−.05	.09
OK Maximum breadth	.10	−.89	.04	.17	.21	.13	.02
8 Mid. trans. arc	.18	−.79	−.08	−.07	−.01	.28	.27

[1)] The sample size is 30. The cumulative proportion of the variances of the seven principal components is 81.38%.

[2)–6)] See the footnotes to Table 23.

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

Summary and Conclusions

It was confirmed in the present PCAs based on male data that cranial length is significantly associated with the superior, middle and inferior sagittal diameters of the vertebral body as well as with the superior and middle transverse diameters of the vertebral body for about half of the cervical vertebrae and nearly all thoracic and lumbar vertebrae; and that basi-bregmatic height is significantly associated with the transverse diameter of the vertebral foramen for all cervical vertebrae and almost all thoracic and lumbar vertebrae. Moreover, the PCAs for both male and female data on

Table 25. Principal component analysis of the correlation matrix on the three main cranial measurements and some representative vertebral measurements of Japanese females.[1)]

Variable[2)]	Factor loadings						Total variance (%)
	PC I	II	III	IV	V	VI	
SKULL							
1 Cranial length	.58	−.21	.21	−.20	−.39	−.09	62.09
8 Cranial breadth	−.67	.54	−.12	.04	−.21	−.41*	95.92
17 Basi-bregmatic ht.	−.20	.59	−.07	.53	−.48	−.04	91.39
ATLAS							
K1 Total sagit. diam.	−.21	.02	.53	−.17	.30	−.40	60.46
K2 Total trans. diam.	.66	.40	−.06	.06	.39	−.27	82.93
CERVICAL VERTEBRA III							
4 S. sag. d. v. b.[3)]	.14	.04	.75	−.22	−.10	−.19	68.54
7 S. tr. d. v. b.[4)]	−.42	.64	.19	−.46	−.29	.01	91.42
11 Tr. d. of v. f.[5)]	−.42	.63	.06	−.45	.11	.10	80.78
THORACIC VERTEBRA VII							
4 S. sag. d. v. b.[3)]	.51	.24	.38	.46	.07	.36	79.79
7 S. tr. d. v. b.[4)]	.09	.70*	−.10	−.04	.07	.48	74.43
11 Tr. d. of v. f.[5)]	−.23	.73	−.30	.10	.01	−.03	69.33
LUMBAR VERTEBRA III							
4 S. sag. d. v. b.[3)]	.36	.37	.65	.40	−.20	−.15	92.01
7 S. tr. d. v. b.[4)]	.38	.52	.34	−.24	.21	.37	77.67
11 Tr. d. of v. f.[5)]	.23	.52	−.18	.23	.50	−.38	80.36
SACRUM							
4 A. s. tr. arc[6)]	.92	.10	−.14	−.22	−.09	−.04	93.44
OK Maximum breadth	.82	.17	−.26	−.16	−.30	−.21	93.13
8 Mid. trans. arc	.74	.23	−.40	−.23	−.13	−.11	84.66
Total contribution (%)	25.84	20.61	11.91	8.47	7.29	6.97	81.08
Cumulative proportion (%)	25.84	46.45	58.35	66.82	74.11	81.08	81.08

[1)] The sample size is 17. 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)–6)] See the footnotes to Table 23.

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

some representative measurements suggested that cranial length is relatively highly associated with the total transverse diameter of the atlas, the sagittal diameter of the vertebral body of the thoracic vertebra VII, and the anterior superior transverse arc, maximum breadth, and middle transverse arc of the sacrum. On the other hand, the two rotated factors from the PCs for the same representative measurements of males and females, respectively, showed that basi-bregmatic height is significantly associated with the transverse diameter of the vertebral foramen of the thoracic vertebra VII.

For these results, it was particularly noted that the variation of cranial length

Table 26. Solution obtained through the normal varimax rotation of the first six principal components (Table 25) for the correlation matrix on the three main cranial measurements and some representative vertebral measurements of Japanese females.[1]

Variable[2]	Factor loadings					
	Fac I	II	III	IV	V	VI
SKULL						
1 Cranial length	.62	−.21	.28	−.10	−.29	.12
8 Cranial breadth	−.31	.40	.09	.69*	.16	−.44
17 Basi-bregmatic ht.	−.05	.14	−.14	.91***	.01	.21
ATLAS						
K1 Total sagit. diam.	−.28	.07	.67*	−.12	.21	−.12
K2 Total trans. diam.	.48	.01	.08	−.08	.72**	.27
CERVICAL VERTEBRA III						
4 S. sag. d. v. b.[3]	.09	.08	.78	−.06	−.15	.20
7 S. tr. d. v. b.[4]	−.05	.83	.25	.33	−.17	−.15
11 Tr. d. of v. f.[5]	−.20	.86	.09	.07	.09	−.12
THORACIC VERTEBRA VII						
4 S. sag. d. v. b.[3]	.12	−.11	.04	.06	.12	.87***
7 S. tr. d. v. b.[4]	.08	.64*	−.32	.12	.14	.44
11 Tr. d. of v. f.[5]	−.05	.51	−.26	.49*	.36	−.02
LUMBAR VERTEBRA III						
4 S. sag. d. v. b.[3]	.16	−.09	.55	.43	.10	.63**
7 S. tr. d. v. b.[4]	.22	.54*	.15	−.22	.15	.59*
11 Tr. d. of v. f.[5]	.10	.08	−.00	.14	.87***	.07
SACRUM						
4 A. s. tr. arc[6]	.90	−.05	−.02	−.20	.16	.22
OK Maximum breadth	.95*	−.07	−.04	.07	.13	.06
8 Mid. trans. arc	.86	.06	−.20	−.04	.23	.02

[1] The sample size is 17. The cumulative proportion of the variances of the six principal components is 81.08%.

[2]–[6] See the footnotes to Table 23.

**P*<0.05; ***P*<0.01; ****P*<0.001, by the two-tailed bootstrap test.

should further be examined at least from the viewpoints of the ontogenetic relation of the occipital region with vertebrae, the biomechanical role of vertebrae in bearing the skull, and the adjustment of the neurocranial form to the maternal pelvic inlet.

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Table 27. Principal components from the cranial and vertebral measurements which show significantly similar loading variation patterns at the 5% level.[1)]

Principal components compared (Sex)	Spearman's rank correlation
I (M)—I (F)	0.50*
II (M)—III (F)	0.76***
III (M)—I (F)	0.60*
VI (M)—I (F)	0.52*
I (F) —II (F)	0.61**

[1)] The similarity in the variation patterns of factor loadings between two principal components (PC's) was assessed by using the Spearman's rank correlation coefficient. The signs of rank correlations are removed because the signs of factor loadings are reversible. The PC's compared are those from the principal component analyses for the cranial and vertebral measurements of both sexes (Tables 23 and 25).

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

Table 28. Rotated factors for the cranial and vertebral measurements which show significantly similar loading variation patterns at the 5% level.[1)]

Rotated factors compared (Sex)	Spearman's rank correlation
II (M)—I (F)	0.57*
II (M)—III (F)	0.57*
III (M)—IV (F)	0.52*
VII (M)—III (F)	0.60*
I (F) —II (F)	0.64**
I (F) —IV (F)	0.52*

[1)] The similarity in the variation patterns of factor loadings between two rotated factors was assessed by using the Spearman's rank correlation coefficient. The signs of rank correlations are removed because the signs of factor loadings are reversible. The rotated factors compared are those from the solutions for the cranial and vertebral measurements of both sexes (Tables 24 and 26).

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

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