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Structural Covariation between the Neurocranium and the Cervical Vertebrae: Toward the Solution of the Brachycephalization Problem

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Abstract As an attempt to elucidate the causes of brachycephalization, principal component analyses for the neurocranium and the cervical vertebrae were carried out on the basis of the metric data from 30 male and 20 female Japanese. The results show that cranial length or breadth is not consistently correlated with any of the measurements dealt with of the cervical vertebrae, suggesting no involvement of the cervical vertebrae in brachycephalization. Basi-bregmatic height was, however, found to have relatively high correlations with the ventral and central heights of the vertebral body and with the transverse diameter of the vertebral foramen. From these and previous studies, it is inferred that, in the course of the craniocervical development, the morphology of the braincase and the cervical vertebrae is determined, at least in part, by some common morphogenetic and/or biomechanical factors associated with the size and shape of the brain and spinal cord, the posture of the head and neck, *etc.*

With the ultimate aim of clarifying the causes of brachycephalization, MIZOGUCHI (1992) preliminarily examined the metric data of male Japanese skeletons from a viewpoint of biomechanical coordination among morphological characters, and found that cranial length might be relatively highly correlated not only with the size of jaws but also with the body diameters of the third lumbar vertebra, the size of pelvis, *etc.* MIZOGUCHI (1994), therefore, further attempted to investigate the interrelations between the measurements of the neurocranium and of all the lumbar vertebrae in more depth. In result, he showed that, although basi-bregmatic height was considerably associated with the vertebral foramen size of the lumbars, neither cranial length nor cranial breadth consistently had high correlations with any measurements of the lumbar vertebrae.

In the present study, a similar attempt was furthermore made to analyze the correlations between the measurements of the neurocranium and the cervical vertebrae in order to confirm whether the cervical vertebrae behave in the same way as the lumbar vertebrae in relation to the neurocranium.

Materials and Methods

The data used are the measurements of the neurocranium and the cervical 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. The basic statistics for the measurements of the cervical vertebrae are listed in Tables 1 to 4. Those for the neurocranium are presented in MIZOGUCHI (1994).

For examining the overall relationships between the measurements of the neurocranium and the cervical vertebrae, the principal component analysis (LAWLEY and MAXWELL, 1963; OKUNO *et al.*, 1971, 1976; TAKEUCHI and YANAI, 1972) was applied to the correlation matrices. 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 reality of

Table 1. Means and standard deviations for the measurements of the atlas in Japanese.[1)]

Variable[2)]		Male			Female		
		n	Mean	SD	*n*	Mean	SD
K1	Total sagittal diameter	30	44.2	2.6	20	40.9	2.6
K2	Total transverse diameter	30	79.5	3.3	20	70.4	2.8
10	Sagittal diameter of vertebral foramen	30	29.1	2.2	20	27.4	1.4
11	Transverse diameter of vertebral foramen	30	27.5	1.8	20	26.1	1.7

[1)] The estimates of basic statistics listed here were recalculated by the present author on the basis of the raw data published by OKAMOTO (1930).

[2)] Variable number according to MARTIN and SALLER (1957) except for K1 and K2, which are Nos. 1 and 2, respectively, of KIYONO's (1929) measurement system.

Table 2. Means and standard deviations for the measurements of the axis in Japanese.[1)]

Variable[2)]		Male			Female		
		n	Mean	SD	*n*	Mean	SD
1a	Total height	30	36.9	2.6	20	33.3	2.6
1b	Height of vertebral body	30	22.4	1.5	20	20.4	1.7
K1	Ventral vertical diameter	30	34.8	2.4	20	31.0	2.0
K6	Total breadth	30	58.0	3.9	20	50.8	3.0
K9	Max. width between sup. articular proc.	30	46.5	2.5	20	42.8	1.7
5	Inferior sagittal diam. of vert. body	30	15.7	1.4	18	14.1	1.0
8	Inferior transverse diam. of vert. body	30	19.2	2.1	18	18.1	1.7
10	Sagittal diameter of vertebral foramen	30	15.0	1.5	20	14.7	1.3
11	Transverse diameter of vertebral foramen	30	21.7	1.5	20	20.9	1.1

[1)] See the footnote to Table 1.

[2)] Variable number according to MARTIN and SALLER (1957) except for K1, K6 and K9, which are Nos. 1, 6 and 9, respectively, of KIYONO's (1929) measurement system.

Table 3. Means and standard deviations for the measurements of the third to seventh cervical vertebrae in Japanese males.[1)]

	Variable[2)]	Cer. vert. III			Cer. vert. IV			Cer. vert. V			Cer. vert. VI			Cer. vert. VII		
		n	Mean	SD	*n*	Mean	SD	*n*	Mean	SD	*n*	Mean	SD	*n*	Mean	SD
1	Ventral height of vertebral body	30	13.8	1.0	30	12.9	1.4	30	12.0	1.4	30	12.0	1.5	29	13.9	1.3
3	Central height of vertebral body	30	10.3	1.0	30	9.7	1.1	30	9.4	1.1	30	9.4	1.2	29	11.4	1.3
2	Dorsal height of vertebral body	30	13.3	0.9	30	12.7	1.2	30	12.4	1.0	30	12.6	1.0	30	14.2	1.3
4	Superior sagittal diam. of vert. body	30	15.0	1.1	30	15.3	1.0	30	15.4	1.1	30	15.9	1.0	29	16.7	1.2
6	Middle sagittal diam. of vert. body	30	15.9	1.1	30	15.7	1.1	30	15.3	1.2	30	15.9	1.0	29	16.1	1.1
5	Inferior sagittal diam. of vert. body	30	16.1	1.1	30	16.4	0.9	30	16.4	1.1	30	17.3	1.2	30	16.7	1.1
7	Superior transverse diam. of vert. body	30	21.6	1.5	30	22.9	1.5	30	24.4	1.5	30	26.5	1.5	—	—	—
9	Middle transverse diam. of vert. body	—	—	—	—	—	—	—	—	—	—	—	—	29	28.9	2.0
8	Inferior transverse diam. of vert. body	30	20.9	1.5	30	22.0	1.9	30	23.0	1.6	30	25.4	2.1	30	28.8	2.0
10	Sagittal diameter of vertebral foramen	30	13.3	1.6	30	12.6	1.3	30	12.9	1.3	30	13.3	1.4	30	13.3	1.4
11	Transverse diameter of vertebral foramen	30	21.4	1.2	30	22.7	1.0	30	23.6	1.5	30	24.2	1.2	30	23.1	1.3
K12	Max. width between transverse processes	30	56.1	2.5	30	56.6	2.6	30	57.9	3.6	30	61.3	4.2	30	70.3	4.3
K13	Max. width between sup. articular proc.	30	45.7	2.6	30	48.2	2.4	30	49.4	2.6	30	51.2	2.6	30	50.9	2.7

1) See the footnote to Table 1.

2) Variable number according to MARTIN and SALLER (1957) except for K12 and K13, which are Nos. 12 and 13, respectively, of KIYONO's (1929) measurement system.

Table 4. Means and standard deviations for the measurements of the third to seventh cervical vertebrae in Japanese females.[1)]

	Variable[2)]	Cer. vert. III			Cer. vert. IV			Cer. vert. V			Cer. vert. VI			Cer. vert. VII		
		n	Mean	SD	*n*	Mean	SD	*n*	Mean	SD	*n*	Mean	SD	*n*	Mean	SD
1	Ventral height of vertebral body	20	12.3	1.3	20	11.7	1.3	20	10.9	1.4	20	11.0	1.6	19	13.0	0.9
3	Central height of vertebral body	18	9.1	1.1	20	8.8	1.1	20	8.8	1.1	20	8.8	1.1	19	9.9	1.3
2	Dorsal height of vertebral body	18	11.7	1.2	20	11.4	1.3	20	11.6	1.1	20	11.9	1.3	18	12.9	1.0
4	Superior sagittal diam. of vert. body	18	13.9	1.2	20	14.0	1.2	20	14.0	0.9	20	14.6	1.0	19	14.9	1.0
6	Middle sagittal diam. of vert. body	19	14.5	1.4	20	14.3	1.3	20	14.0	1.0	20	14.6	0.9	20	14.8	1.1
5	Inferior sagittal diam. of vert. body	20	14.6	0.9	20	14.7	1.1	20	15.0	1.1	20	15.5	1.1	19	15.0	1.3
7	Superior transverse diam. of vert. body	18	21.1	2.0	20	21.8	1.2	20	23.3	1.5	20	25.0	1.3	—	—	—
9	Middle transverse diam. of vert. body	—	—	—	—	—	—	—	—	—	—	—	—	20	27.2	1.6
8	Inferior transverse diam. of vert. body	20	19.5	1.4	20	20.6	1.7	20	21.6	1.5	20	23.8	1.5	20	26.3	2.1
10	Sagittal diameter of vertebral foramen	20	12.8	0.7	20	12.4	1.1	20	12.4	0.9	20	12.4	1.1	20	12.7	0.9
11	Transverse diameter of vertebral foramen	20	20.5	1.4	20	21.9	1.0	20	22.2	2.3	20	22.9	0.9	20	22.1	0.8
K12	Max. width between transverse processes	20	49.1	1.9	20	50.8	2.9	20	51.7	2.5	19	54.7	2.7	19	63.1	3.7
K13	Max. width between sup. articular proc.	20	42.9	2.5	20	45.4	2.2	20	46.0	2.3	20	46.7	2.6	20	46.6	2.6

1) See the footnote to Table 1.

2) See the footnote to Table 3.

such a common factor as represented by a principal component was tested by finding the similarity between the principal components extracted from the data of different cervical vertebrae, *i.e.*, by comparing the variation patterns of their factor loadings with one another. For carrying this out, in practice, SPEARMAN's rank correlation coefficient (SIEGEL, 1956) was used.

All the statistical calculations were executed with the mainframe, HITAC M880 (VOS3) System, of the Computer Centre, the University of Tokyo. The programs used are BSFMD for calculating basic statistics, PCAFPP for principal component analyses, and RKCNCT for rank correlation coefficients, which all had been written in FORTRAN by the present author.

Results

The results of the principal component analyses (PCAs) for males are shown in Tables 5 to 11, and those for females are in Tables 12 to 18. Glancing over these tables, it is discernible that the first principal components (PCs) are not necessarily those which can be interpreted as general size factors.

On the assumption that the reality of a factor common to some variables can be confirmed by finding significant similarity between the PCs extracted from different data sets, such a factor tightly associated with each cranial measurement was sought among the PCs for different cervical vertebrae using the SPEARMAN's rank correlation coefficient on the basis of their factor loadings. Table 19 shows the two PCs from the PCA for each cervical vertebra having the variation patterns of the factor loadings similar to that of the PC which is derived from the PCA for another cervical vertebra and is most highly correlated with cranial length. In the same way, Tables 20 and 21 show those for cranial breadth and basi-bregmatic height, respectively. The PCs compared are, however, only those from the PCAs for the third to the sixth cervical vertebrae of both sexes (Tables 7 to 10 and Tables 14 to 17) because the measurement items for the other vertebrae are not common to these cervical vertebrae.

As seen in Tables 19 to 21, it was found that many rank correlations between the PCs from different PCAs were statistically significant. Of the two PCs having the highest correlations with each cranial measurement, the one that had a greater number of significant rank correlations with the PCs from the PCAs for other cervical vertebrae was firstly selected as a common factor with higher possibility of existence, and, then, the variation patterns in the factor loadings of such PCs were compared with one another. Through these comparisons, three PCs having relatively high correlations (of greater than 0.30 in absolute value) with cranial length from different PCAs were found to have relatively high correlations with the transverse diameter of the vertebral foramen as well (Fig. 1). This is also true of cranial breadth (Fig. 2). On the other hand, with respect to basi-bregmatic

Table 5. Principal component analysis of the correlation matrix on the measurements of the neurocranium and the atlas of Japanese males.[1)]

Variable[2)]	Factor loadings				Total variance (%)
	PC I	II	III	IV	
1 Cranial length	.66*	−.63*	−.03	.08	83.54
8 Cranial breadth	.29	−.06	.88*	−.36*	98.61
17 Basi-bregmatic height	.72*	.00	−.14	−.28	61.04
K1 Total sagit. diameter	.74*	.35*	−.34*	−.25	84.49
K2 Total trans. diameter	.79*	−.27	−.15	−.08	72.85
10 sagit. d. of v. foramen	.57*	.68*	.17	.13	82.83
11 Trans. d. of v. foramen	.60*	.01	.23	.69*	90.25
Total contribution (%)	41.28	15.08	14.42	11.17	81.95
Cumulative proportion (%)	41.28	56.36	70.78	81.95	81.95

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%. The BARTLETT's approximate significance test (LAWLEY and MAXWELL, 1963) does not reject the null hypothesis that all the variances for the rest of the principal components listed here are equal to one another ($\chi^2=4.9$, d.f.$=5$, $P=0.431$).

2) See the footnote to Table 1.

* Greater than 0.30 in absolute value.

Table 6. Principal component analysis of the correlation matrix on the measurements of the neurocranium and the axis of Japanese males.[1)]

Variable[2)]	Factor loadings						Total variance (%)
	PC I	II	III	IV	V	VI	
1 Cranial length	.40*	−.18	−.11	.56*	.65*	−.01	94.15
8 Cranial breadth	.49*	−.34*	.06	−.39*	.28	−.44*	78.05
17 Basi-bregmatic height	.58*	.22	−.12	.59*	−.15	−.19	81.35
1a Total height	.88*	−.04	−.17	.04	−.29	.14	91.57
1b Height of vert. body	.77*	−.05	−.37*	−.22	.03	−.02	78.87
K1 Ventral vertical diam.	.85*	.18	−.29	.03	−.24	−.01	88.81
K6 Total breadth	.51*	−.72*	.05	−.26	−.14	.14	88.51
K9 Max. wid. s. art. proc.	.61*	−.31*	.40*	−.01	.24	.08	69.24
5 Inf. sag. d. of v. body	.25	.47*	−.11	−.29	.36*	.63*	90.43
8 Inf. trans. d. of v. b.	−.17	.35*	−.63*	−.32*	.23	−.37*	84.33
10 Sagit. d. of v. foramen	.32*	.44*	.75*	−.14	.04	−.23	92.40
11 Trans. d. of v. foramen	.66*	.60*	.26	−.10	−.03	−.06	87.30
Total contribution (%)	34.16	14.41	12.31	9.65	7.66	7.24	85.42
Cumulative proportion (%)	34.16	48.56	60.87	70.52	78.18	85.42	85.42

1) The sample size is 30. For the way of determination of the principal component number, see the first footnote to Table 5. The result of the BARTLETT's approximate significance test is as follows: $\chi^2=42.5$, d.f.$=20$, $P=0.002$ (for details, also see the first footnote to Table 5).

2) See the footnote to Table 2.

* Greater than 0.30 in absolute value.

Table 7. Principal component analysis of the correlation matrix on the measurements of the neurocranium and the third cervical vertebra of Japanese males.[1)]

Variable[2)]	Factor loadings PC I	II	III	IV	V	VI	Total variance (%)
1 Cranial length	.34*	.03	−.03	.47*	−.65*	.40*	92.36
8 Cranial breadth	.51*	.09	−.08	.32*	.47*	.46*	79.84
17 Basi-bregmatic height	.24	.39*	.03	.67*	−.24	−.30*	80.13
1 Vent. height of v. body	.26	.69*	−.06	−.47*	.06	−.30	85.29
3 Cent. height of v. body	.27	.68*	−.12	−.46*	−.24	.10	83.36
2 Dors. height of v. body	.36*	.71*	−.08	−.29	−.25	.27	86.16
4 Sup. sag. d. of v. body	.79*	−.23	.12	−.05	−.10	−.24	75.80
6 Mid. sag. d. of v. body	.66*	−.64*	.08	−.26	−.04	−.06	92.42
5 Inf. sag. d. of v. body	.72*	−.47*	.20	−.23	−.12	−.06	85.40
7 Sup. trans. d. of v. b.	.10	.26	.77*	.28	.03	−.02	75.13
8 Inf. trans. d. of v. b.	.13	.54*	.56*	.09	.43*	.11	82.14
10 Sagit. d. of v. foramen	−.17	.08	−.86*	.17	.15	.05	82.89
11 Trans. d. of v. foramen	.45*	.31*	−.29	.43*	.08	−.51*	82.94
K12 Max. wid. trans. proc.	.75*	.00	−.18	−.12	.21	.07	65.45
K13 Max. wid. s. art. proc.	.79*	−.05	−.24	.17	.19	.12	77.40
Total contribution (%)	24.87	18.25	12.78	11.67	7.67	6.54	81.78
Cumulative proportion (%)	24.87	43.12	55.90	67.57	75.24	81.78	81.78

[1)] The sample size is 30. For the way of determination of the principal component number, see the first footnote to Table 5. The result of the BARTLETT's approximate significance test is as follows: $\chi^2=66.1$, d.f.$=44$, $P=0.015$ (for details, also see the first footnote to Table 5).

[2)] See the footnote to Table 3.

* Greater than 0.30 in absolute value.

Table 8. Principal component analysis of the correlation matrix on the measurements of the neurocranium and the fourth cervical vertebra of Japanese males.[1)]

Variable[2)]	Factor loadings PC I	II	III	IV	V	VI	Total variance (%)
1 Cranial length	.53*	.24	.24	−.16	−.45*	.34*	74.70
8 Cranial breadth	.23	.49*	.23	−.33*	.60*	−.13	81.90
17 Basi-bregmatic height	.76*	.08	−.02	−.11	.14	.45*	80.78
1 Vent. height of v. body	.49*	−.18	−.56*	.29	−.11	−.33*	79.28
3 Cent. height of v. body	.44*	.12	−.77*	.23	.09	−.14	88.38
2 Dors. height of v. body	.71*	.11	−.43*	.20	.06	.32*	85.42
4 Sup. sag. d. of v. body	−.41*	.72*	−.39*	.08	−.00	−.02	84.47
6 Mid. sag. d. of v. body	−.60*	.59*	−.32*	−.13	−.06	.01	83.58
5 Inf. sag. d. of v. body	−.53*	.48*	−.37*	−.26	.19	.30*	84.06
7 Sup. trans. d. of v. b.	.16	.38*	.61*	.54*	.10	−.15	86.22
8 Inf. trans. d. of v. b.	.41*	.58*	.22	.45*	.25	.02	82.72
10 Sagit. d. of v. foramen	.47*	−.53*	−.14	−.48*	.11	−.22	80.34
11 Trans. d. of v. foramen	.57*	.28	.12	−.47*	−.02	−.19	67.13
K12 Max. wid. trans. proc.	.19	.69*	.08	−.02	−.46*	−.14	75.01
K13 Max. wid. s. art. proc.	.31*	.69*	.00	−.32*	−.13	−.27	77.37
Total contribution (%)	23.50	21.66	13.78	9.70	6.39	5.72	80.76
Cumulative proportion (%)	23.50	45.16	58.95	68.65	75.04	80.76	80.76

[1)] The sample size is 30. For the way of determination of the principal component number, see the first footnote to Table 5. The result of the BARTLETT's approximate significance test is as follows: $\chi^2=64.6$, d.f.$=44$, $P=0.021$ (for details, also see the first footnote to Table 5).

[2)] See the footnote to Table 3.

* Greater than 0.30 in absolute value.

Table 9. Principal component analysis of the correlation matrix on the measurements of the neurocranium and the fifth cervical vertebra of Japanese males.[1]

Variable[2]	Factor loadings						Total variance (%)
	PC I	II	III	IV	V	VI	
1 Cranial length	.38*	.23	−.21	−.14	−.52*	.61*	89.99
8 Cranial breadth	.25	.33*	−.47*	.08	.60*	.29	84.39
17 Basi-bregmatic height	.74*	.14*	.01	.02	−.08	.24	63.93
1 Vent. height of v. body	.45*	−.34*	.54*	.17	−.02	.42*	82.00
3 Cent. height of v. body	.33*	.19	.80*	−.05	.16	.19	85.79
2 Dors. height of v. body	.54*	.15	.44*	.11	−.17	−.47*	76.80
4 Sup. sag. d. of v. body	−.52*	.64*	.15	−.33*	.19	.14	86.32
6 Mid. sag. d. of v. body	−.56*	.73*	.06	−.23	−.07	.12	91.47
5 Inf. sag. d. of v. body	−.48*	.64*	.43*	−.00	.07	.02	83.53
7 Sup. trans. d. of v. b.	.32*	.63*	−.31*	.46*	−.01	−.02	80.82
8 Inf. trans. d. of v. b.	.34*	.65*	−.04	.50*	−.09	−.12	81.43
10 Sagit. d. of v. foramen	.44*	−.64*	−.10	−.37*	.21	.01	79.60
11 Trans. d. of v. foramen	.68*	.30*	−.07	−.38*	.06	−.31*	80.42
K12 Max. wid. trans. proc.	.42*	.51*	−.16	−.48*	−.39*	−.15	86.96
K13 Max. wid. s. art. proc.	.61*	.37*	.05	−.15	.50*	−.03	79.14
Total contribution (%)	24.00	22.77	11.69	8.23	8.02	7.46	82.17
Cumulative proportion (%)	24.00	46.77	58.46	66.69	74.72	82.17	82.17

[1] The sample size is 30. For the way of determination of the principal component number, see the first footnote to Table 5. The result of the BARTLETT's approximate significance test is as follows: $\chi^2=54.6$, d.f.$=44$, $P=0.130$ (for details, also see the first footnote to Table 5).

[2] See the footnote to Table 3.

* Greater than 0.30 in absolute value.

Table 10. Principal component analysis of the correlation matrix on the measurements of the neurocranium and the sixth cervical vertebra of Japanese males.[1]

Variable[2]	Factor loadings						Total variance (%)
	PC I	II	III	IV	V	VI	
1 Cranial length	.35*	.26	.34*	.49*	−.38*	.41*	85.02
8 Cranial breadth	.25	.20	.55*	−.21	.46*	.41*	83.58
17 Basi-bregmatic height	.31*	.57*	−.01	.56*	.10	.02	75.15
1 Vent. height of v. body	.14	.57*	−.57*	.22	.25	−.24	83.97
3 Cent. height of v. body	.17	.38*	−.72*	.00	.22	.29	82.13
2 Dors. height of v. body	.45*	.13	−.78*	−.11	−.00	.04	84.59
4 Sup. sag. d. of v. body	.63*	−.61*	−.17	.01	.03	.01	80.23
6 Mid. sag. d. of v. body	.58*	−.64*	−.22	−.02	−.34*	−.01	90.53
5 Inf. sag. d. of v. body	.78*	−.28	−.20	.12	−.24	.07	79.68
7 Sup. trans. d. of v. b.	.68*	−.14	.39*	.31*	.21	−.04	77.65
8 Inf. trans. d. of v. b.	.43*	−.43*	.16	.30*	.50*	−.32*	83.68
10 Sagit. d. of v. foramen	.02	.63*	.18	.15	−.41*	−.28	69.57
11 Trans. d. of v. foramen	.55*	.42*	.33*	−.27	−.06	−.43*	85.07
K12 Max. wid. trans. proc.	.80*	.24	.15	−.33*	−.05	.02	82.71
K13 Max. wid. s. art. proc.	.63*	.48*	.08	−.46*	−.00	.08	85.27
Total contribution (%)	25.63	18.97	15.58	8.53	7.47	5.74	81.92
Cumulative proportion (%)	25.63	44.60	60.18	68.71	76.18	81.92	81.92

[1] The sample size is 30. For the way of determination of the principal component number, see the first footnote to Table 5. The result of the BARTLETT's approximate significance test is as follows: $\chi^2=53.4$, d.f.$=44$, $P=0.158$ (for details, also see the first footnote to Table 5).

[2] See the footnote to Table 3.

* Greater than 0.30 in absolute value.

Table 11. Principal component analysis of the correlation matrix on the measurements of the neurocranium and the seventh cervical vertebra of Japanese males.[1)]

Variable[2)]		Factor loadings						Total variance
		PC I	II	III	IV	V	VI	(%)
1	Cranial length	.33*	−.17	.61*	−.23	−.30	.31*	74.80
8	Cranial breadth	.18	−.29	.20	.18	.55*	.66*	91.92
17	Basi-bregmatic height	.38*	−.08	.66*	−.24	.16	−.15	69.43
1	Vent. height of v. body	.27	.70*	.30*	−.21	.35*	−.16	84.31
3	Cent. height of v. body	.09	.80*	−.22	.16	.27	.27	87.03
2	Dors. height of v. body	.34*	.79*	−.14	.01	.09	−.14	78.17
4	Sup. sag. d. of v. body	.87*	.03	−.19	−.07	−.15	.03	82.35
6	Mid. sag. d. of v. body	.88*	.15	−.18	−.15	−.20	.02	88.71
5	Inf. sag. d. of v. body	.74*	.12	.05	.01	−.47*	.17	81.22
9	Mid. trans. d. of v. b.	.54*	−.55*	−.27	−.27	.34*	−.10	87.42
8	Inf. trans. d. of v. b.	.62*	−.36*	−.36*	−.19	.33*	−.21	83.14
10	Sagit. d. of v. foramen	.03	.15	.74*	.12	.07	−.16	61.31
11	Trans. d. of v. foramen	.26	−.27	.28	.72*	.09	−.38*	88.77
K12	Max. wid. trans. proc.	.78*	−.05	.14	.17	.08	.01	67.25
K13	Max. wid. s. art. proc.	.35*	−.01	−.16	.82*	−.08	.08	83.57
Total contribution (%)		26.96	16.24	12.97	10.49	7.72	6.25	80.63
Cumulative proportion (%)		26.96	43.19	56.16	66.65	74.37	80.63	80.63

[1)] The sample size is 29. For the way of determination of the principal component number, see the first footnote to Table 5. The result of the BARTLETT's approximate significance test is as follows: $\chi^2=58.9$, d.f. $=44$, $P=0.064$ (for details, also see the first footnote to Table 5).

[2)] See the footnote to Table 3.

* Greater than 0.30 in absolute value.

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

Variable[2)]		Factor loadings				Total variance
		PC I	II	III	IV	(%)
1	Cranial length	.64*	−.17	−.64*	−.26	91.67
8	Cranial breadth	−.60*	.69*	.20	.05	87.40
17	Basi-bregmatic height	−.00	.75*	−.08	−.63*	96.67
K1	Total sagit. diameter	.25	.59*	−.51*	.43*	84.81
K2	Total trans. diameter	.88*	.06	.25	−.03	84.29
10	Sagit. d. of v. foramen	.66*	.44*	.19	.34*	78.99
11	Trans. d. of v. foramen	.68*	.03	.45*	−.15	69.14
Total contribution (%)		35.71	22.98	14.63	11.39	84.71
Cumulative proportion (%)		35.71	58.69	73.32	84.71	84.71

[1)] The sample size is 20. For the way of determination of the principal component number, see the first footnote to Table 5. The result of the BARTLETT's approximate significance test is as follows: $\chi^2=7.7$, d.f. $=5$, $P=0.172$ (for details, also see the first footnote to Table 5).

[2)] See the footnote to Table 1.

* Greater than 0.30 in absolute value.

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

Variable[2)]		Factor loadings					Total variance (%)
		PC I	II	III	IV	V	
1	Cranial length	.29	−.61*	.30*	.55*	.12	86.60
8	Cranial breadth	−.23	.87*	−.08	.03	.24	87.03
17	Basi-bregmatic height	.21	.59*	−.32*	.30*	.47*	81.08
1a	Total height	.88*	.28	.26	.02	.10	92.21
1b	Height of vert. body	.79*	.01	.39*	−.31*	.03	88.37
K1	Ventral vertical diam.	.83*	.04	.42*	−.10	.10	89.40
K6	Total breadth	.62*	.33*	−.28	.26	−.48*	86.05
K9	Max. wid. s. art. proc.	.37*	−.49*	−.29	−.14	−.26	54.83
5	Inf. sag. d. of v. body	−.23	.06	.75*	−.28	.23	74.62
8	Inf. trans. d. of v. b.	.04	.65*	.43*	.29	−.45*	89.48
10	Sagit. d. of v. foramen	.57*	−.32*	−.48*	.16	.36*	80.99
11	Trans. d. of v. foramen	.36*	.29	−.61*	−.47*	−.05	81.34
Total contribution (%)		27.45	21.04	17.54	8.35	8.29	82.67
Cumulative proportion (%)		27.45	48.49	66.03	74.38	82.67	82.67

[1)] The sample size is 18. For the way of determination of the principal component number, see the first footnote to Table 5. The result of the BARTLETT's approximate significance test is as follows: $\chi^2=37.5$, d.f.$=27$, $P=0.086$ (for details, also see the first footnote to Table 5).

[2)] See the footnote to Table 2.

* Greater than 0.30 in absolute value.

Table 14. Principal component analysis of the correlation matrix on the measurements of the neurocranium and the third cervical vertebra of Japanese females.[1)]

Variable[2)]		Factor loadings					Total variance (%)
		PC I	II	III	IV	V	
1	Cranial length	−.22	−.01	−.78*	.28	−.28	81.42
8	Cranial breadth	−.09	.44*	.80*	.00	.10	85.01
17	Basi-bregmatic height	.18	.62*	.27	.31*	.37*	72.55
1	Vent. height of v. body	.60*	.28	−.36*	−.47*	−.15	80.91
3	Cent. height of v. body	.78*	.40*	−.16	−.22	−.11	85.59
2	Dors. height of v. body	.64*	.48*	−.39*	−.23	.16	86.07
4	Sup. sag. d. of v. body	−.89*	.05	−.10	.04	.11	82.24
6	Mid. sag. d. of v. body	−.77*	.47*	−.11	−.11	−.11	84.30
5	Inf. sag. d. of v. body	−.88*	.27	−.22	−.06	.04	90.45
7	Sup. trans. d. of v. b.	−.31*	.78*	.18	−.36*	−.19	90.35
8	Inf. trans. d. of v. b.	.07	.54*	−.42*	.19	.56*	82.34
10	Sagit. d. of v. foramen	.38*	.01	.61*	.50*	−.23	82.23
11	Trans. d. of v. foramen	−.17	.61*	.42*	−.47*	−.16	82.33
K12	Max. wid. trans. proc.	−.00	.72*	−.31*	.43*	−.23	85.80
K13	Max. wid. s. art. proc.	.16	.55*	−.02	.65*	−.22	79.74
Total contribution (%)		26.15	22.86	17.14	11.68	5.59	83.42
Cumulative proportion (%)		26.15	49.01	66.15	77.83	83.42	83.42

[1)] The sample size is 18. For the way of determination of the principal component number, see the first footnote to Table 5. The result of the BARTLETT's approximate significance test is as follows: $\chi^2=91.4$, d.f.$=54$, $P<0.001$ (for details, also see the first footnote to Table 5).

[2)] See the footnote to Table 3.

* Greater than 0.30 in absolute value.

Table 15. Principal component analysis of the correlation matrix on the measurements of the neurocranium and the fourth cervical vertebra of Japanese females.[1)]

Variable[2)]	Factor loadings					Total variance (%)
	PC I	II	III	IV	V	
1 Cranial length	−.00	.26	−.57*	−.58*	−.03	73.88
8 Cranial breadth	.13	.16	.71*	.52*	.26	88.35
17 Basi-bregmatic height	.61*	.14	.43*	−.17	.18	62.88
1 Vent. height of v. body	.62*	−.04	−.66*	.03	−.17	86.04
3 Cent. height of v. body	.66*	.22	−.47*	.35*	.25	89.37
2 Dors. height of v. body	.58*	.08	−.60*	.38*	.26	91.18
4 Sup. sag. d. of v. body	−.42*	.76*	.16	−.13	−.25	85.29
6 Mid. sag. d. of v. body	−.38*	.90*	−.05	−.09	.06	96.55
5 Inf. sag. d. of v. body	−.16	.89*	−.01	.02	.14	84.35
7 Sup. trans. d. of v. b.	.60*	.55*	.06	.31*	−.33*	87.06
8 Inf. trans. d. of v. b.	.68*	.58*	.08	−.12	−.12	83.10
10 Sagit. d. of v. foramen	.62*	−.40*	.20	−.45*	.24	83.17
11 Trans. d. of v. foramen	.70*	−.12	.49*	.01	−.37*	88.79
K12 Max. wid. trans. proc.	.86*	.02	.14	−.25	−.23	87.18
K13 Max. wid. s. art. proc.	.38*	.34*	.25	−.38*	.50*	70.84
Total contribution (%)	29.82	21.68	16.27	9.69	6.41	83.87
Cumulative proportion (%)	29.82	51.51	67.78	77.46	83.87	83.87

[1)] The sample size is 20. For the way of determination of the principal component number, see the first footnote to Table 5. The result of the BARTLETT's approximate significance test is as follows: $\chi^2 = 106.6$, d.f. $= 54$, $P < 0.001$ (for details, also see the first footnote to Table 5).

[2)] See the footnote to Table 3.

* Greater than 0.30 in absolute value.

Table 16. Principal component analysis of the correlation matrix on the measurements of the neurocranium and the fifth cervical vertebra of Japanese females.[1)]

Variable[2)]	Factor loadings						Total variance (%)
	PC I	II	III	IV	V	VI	
1 Cranial length	.28	.42*	−.33*	.43*	−.00	−.60*	91.62
8 Cranial breadth	.01	−.41*	.79*	−.17	−.03	.21	86.80
17 Basi-bregmatic height	.51*	−.53*	.30*	.29	−.14	−.16	75.72
1 Vent. height of v. body	.77*	−.22	−.38*	−.37*	.05	.00	92.66
3 Cent. height of v. body	.83*	.07	−.20	−.40*	−.08	.14	92.64
2 Dors. height of v. body	.70*	−.02	−.29	−.47*	−.19	−.07	83.51
4 Sup. sag. d. of v. body	.19	.85*	.21	.16	−.30	.17	93.57
6 Mid. sag. d. of v. body	.30	.85*	.24	.12	.11	.06	89.22
5 Inf. sag. d. of v. body	.48*	.63*	.19	.09	−.22	.21	77.31
7 Sup. trans. d. of v. b.	.61*	.02	.50*	.02	.30	.04	70.91
8 Inf. trans. d. of v. b.	.72*	−.08	.33*	.23	.03	−.24	73.52
10 Sagit. d. of v. foramen	.37*	−.69*	−.17	.30	−.27	.10	80.83
11 Trans. d. of v. foramen	.07	−.05	−.53*	.54*	−.28	.47*	89.02
K12 Max. wid. trans. proc.	.18	.17	−.35*	.04	.80*	.24	87.58
K13 Max. wid. s. art. proc.	.43*	−.38*	.05	.56*	.31*	.13	75.72
Total contribution (%)	24.76	21.09	13.49	10.79	7.92	5.99	84.04
Cumulative proportion (%)	24.76	45.85	59.33	70.13	78.05	84.04	84.04

[1)] The sample size is 20. For the way of determination of the principal component number, see the first footnote to Table 5. The result of the BARTLETT's approximate significance test is as follows: $\chi^2 = 107.2$, d.f. $= 44$, $P < 0.001$ (for details, also see the first footnote to Table 5).

[2)] See the footnote to Table 3.

* Greater than 0.30 in absolute value.

Table 17. Principal component analysis of the correlation matrix on the measurements of the neurocranium and the sixth cervical vertebra of Japanese females.[1)]

Variable[2)]	Factor loadings PC I	II	III	IV	V	Total variance (%)
1 Cranial length	.48*	−.15	.57*	−.40*	−.21	77.59
8 Cranial breadth	−.15	.17	−.11	.90*	−.16	88.89
17 Basi-bregmatic height	.28	.55*	.28	.24	−.57*	83.32
1 Vent. height of v. body	.45*	.52*	−.40*	−.43*	.00	82.91
3 Cent. height of v. body	.41*	.54*	−.63*	.04	.03	85.96
2 Dors. height of v. body	.44*	.32*	−.74*	−.22	−.00	88.70
4 Sup. sag. d. of v. body	.72*	−.55*	.16	.20	.04	87.83
6 Mid. sag. d. of v. body	.77*	−.49*	.20	.03	−.06	87.92
5 Inf. sag. d. of v. body	.80*	−.36*	.16	−.01	−.03	78.78
7 Sup. trans. d. of v. b.	.67*	.14	.12	.42*	.08	67.15
8 Inf. trans. d. of v. b.	.60*	.43*	−.14	.30*	.47*	87.19
10 Sagit. d. of v. foramen	.05	.77*	.23	.03	−.42*	82.11
11 Trans. d. of v. foramen	−.16	.43*	.57*	.35*	.46*	86.10
K12 Max. wid. trans. proc.	.07	.54*	.65*	−.16	.03	75.30
K13 Max. wid. s. art. proc.	.07	.52*	.48*	−.42*	.32*	78.62
Total contribution (%)	23.21	21.55	17.83	12.58	7.38	82.56
Cumulative proportion (%)	23.21	44.76	62.59	75.18	82.56	82.56

[1)] The sample size is 19. For the way of determination of the principal component number, see the first footnote to Table 5. The result of the BARTLETT's approximate significance test is as follows: $\chi^2 = 102.5$, d.f. $= 54$, $P < 0.001$ (for details, also see the first footnote to Table 5).

[2)] See the footnote to Table 3.

* Greater than 0.30 in absolute value.

Table 18. Principal component analysis of the correlation matrix on the measurements of the neurocranium and the seventh cervical vertebra of Japanese females.[1)]

Variable[2)]	Factor loadings PC I	II	III	IV	V	Total variance (%)
1 Cranial length	.65*	.05	.43*	−.16	−.24	69.53
8 Cranial breadth	−.17	.23	−.26	.65*	.58*	91.41
17 Basi-bregmatic height	.24	.71*	.10	−.22	.47*	84.43
1 Vent. height of v. body	−.33*	.83*	−.36*	−.09	−.14	95.97
3 Cent. height of v. body	−.40*	.78*	−.31*	−.16	−.19	93.45
2 Dors. height of v. body	−.60*	.72*	−.21	−.04	−.21	96.42
4 Sup. sag. d. of v. body	.80*	.11	−.54*	−.11	−.08	96.25
6 Mid. sag. d. of v. body	.82*	.04	−.47*	−.12	.17	93.21
5 Inf. sag. d. of v. body	.71*	.01	−.53*	−.30*	.18	91.09
9 Mid. trans. d. of v. b.	.30	.19	−.26	.79*	−.25	87.19
8 Inf. trans. d. of v. b.	.45*	.41*	.24	.50*	−.31*	77.47
10 Sagit. d. of v. foramen	−.18	.64*	.50*	−.17	.34*	83.80
11 Trans. d. of v. foramen	.47*	.25	.51*	.27	.28	70.14
K12 Max. wid. trans. proc.	.47*	.65*	.10	.01	−.12	66.14
K13 Max. wid. s. art. proc.	.50*	.37*	.49*	−.14	−.22	69.39
Total contribution (%)	26.45	24.19	14.82	10.97	7.96	84.39
Cumulative proportion (%)	26.45	50.64	65.46	76.43	84.39	84.39

[1)] The sample size is 17. For the way of determination of the principal component number, see the first footnote to Table 5. The result of the BARTLETT's approximate significance test is as follows: $\chi^2 = 177.2$, d.f. $= 54$, $P < 0.001$ (for details, also see the first footnote to Table 5).

[2)] See the footnote to Table 3.

* Greater than 0.30 in absolute value.

height, five PCs from different PCAs were found to have relatively high correlations not only with this cranial measurement but also with the ventral and central heights of the vertebral body as well as with the transverse diameter of the vertebral foramen (Fig. 3).

Although the results of the PCAs for the atlas, axis and seventh cervical vertebra were not directly compared with those for the third to the sixth cervical vertebrae because of the differences in sort and number of the measurement items analyzed, the PCs which had the highest correlations with each of the cranial measurements were also sought in each of the PCAs for the three vertebrae and were compared between males and females.

In the results on the atlas (Tables 5 and 12), both the first PCs from males and females were found to have relatively high correlations with cranial length and, at the same time, with total transverse diameter and the sagittal and transverse diameters of the vertebral foramen. The PCs having the highest correlations with cranial breadth were the PC III for males and the PC II for females, which, however, had no common measurements correlated with them in the same direction. Regarding basi-bregmatic height, the PC I from males and the PC II from females were found to have the highest correlations with it. They are also relatively highly correlated with total sagittal diameter and the sagittal diameter of the vertebral foramen simultaneously.

In the case of the axis (Tables 6 and 13), the PCs having the highest correlations with cranial length were the PC V for males and the PC II for females. But they had no common measurements correlated with them in the same direction. The PCs with which cranial breadth was most highly correlated were the PC I for males and the PC II for females, and both of them were found to be relatively highly correlated with the total breadth of the axis. The PCs having the highest correlations with basi-bregmatic height in practice were also the PC I for males and the PC II for females. The common measurement correlated with them in the same direction is therefore, again, the total breadth of the axis.

Finally, the PCAs for the seventh cervical vertebrae of males and females (Tables 11 and 18) showed that the PCs having the highest correlations with cranial length in practice were the PC III both for males and for females. These PCs were found to be relatively highly correlated with the sagittal diameter of the vertebral foramen. As for cranial breadth, such PCs were the PC V for males and the PC IV for females, which were found to have relatively high correlations with the middle and inferior transverse diameters of the vertebral body. The PCs which had the highest correlations with basi-bregmatic height were the PC III for males and the PC II for females. They both have relatively high correlations with the ventral height of the vertebral body and the sagittal diameter of the vertebral foramen.

Table 19. Two principal components from the principal component analysis for each cervical vertebra showing the variation patterns of the factor loadings similar to that of a principal component which is obtained from the principal component analysis for another cervical vertebra and most highly correlated with cranial length.[1)]

Two PCs most highly correlated with cranial length	Principal component (SPEARMAN's rank correlation)							
	Male							
	Cerv. vert. 3		Cerv. vert. 4		Cerv. vert. 5		Cerv. vert. 6	
Male cervical vertebra 3								
PC V	—	—	VI (.53*)	III (.40)	III (.46)	V (.35)	III (.49)	IV (.40)
PC IV	—	—	III (.78***)	IV (.43)	III (.75**)	I (.30)	III (.80***)	II (.26)
Male cervical vertebra 4								
PC I	II (.73**)	I (.46)	—	—	I (.84***)	II (.80***)	II (.69**)	I (.60*)
PC V	I (.41)	III (.33)	—	—	IV (.51)	V (.35)	V (.41)	IV (.32)
Male cervical vertebra 5								
PC VI	V (.28)	III (.19)	II (.23)	VI (.13)	—	—	IV (.49)	I (.49)
PC V	V (.35)	III (.29)	VI (.54*)	IV (.43)	—	—	IV (.33)	I (.16)
Male cervical vertebra 6								
PC IV	I (.71**)	III (.60*)	II (.48)	IV (.38)	IV (.50)	VI (.49)	—	—
PC VI	VI (.63*)	I (.43)	VI (.32)	IV (.16)	VI (.39)	I (.19)	—	—
Female cervical vertebra 3								
PC III	IV (.46)	V (.36)	IV (.54*)	VI (.36)	V (.72**)	III (.36)	III (.41)	II (.31)
PC V	III (.46)	II (.34)	V (.66**)	VI (.48)	IV (.53*)	III (.39)	V (.59*)	III (.37)
Female cervical vertebra 4								
PC IV	II (.46)	IV (.40)	V (.43)	IV (.34)	IV (.54*)	III (.27)	V (.57*)	II (.29)
PC III	IV (.67**)	V (.57*)	IV (.57*)	III (.44)	III (.53*)	V (.51)	III (.58*)	IV (.29)
Female cervical vertebra 5								
PC VI	I (.57*)	III (.43)	IV (.45)	VI (.41)	IV (.59*)	V (.54*)	IV (.72**)	I (.35)
PC IV	IV (.66**)	II (.42)	IV (.56*)	III (.43)	IV (.46)	III (.35)	V (.49)	III (.45)
Female cervical vertebra 6								
PC III	IV (.59*)	II (.57*)	IV (.56*)	V (.50)	IV (.73**)	III (.51)	V (.64*)	III (.46)
PC I	III (.86***)	V (.44)	I (.53*)	IV (.50)	I (.64*)	II (.58*)	II (.70**)	IV (.44)

Table 19. (Continued)

Two PCs most highly correlated with cranial length	Principal component (SPEARMAN's rank correlation)							
	Female							
	Cerv. vert. 3		Cerv. vert. 4		Cerv. vert. 5		Cerv. vert. 6	
Male cervical vertebra 3								
PC V	III (.36)	II (.32)	III (.57*)	I (.36)	II (.44)	VI (.39)	I (.44)	V (.34)
PC IV	III (.46)	IV (.34)	III (.67**)	IV (.40)	IV (.66**)	I (.50)	III (.59*)	IV (.44)
Male cervical vertebra 4								
PC I	I (.67**)	III (.06)	II (.70**)	I (.45)	II (.57*)	III (.44)	II (.55*)	I (.53*)
PC V	V (.66**)	III (.36)	IV (.43)	III (.31)	III (.69**)	V (.40)	IV (.65**)	III (.50)
Male cervical vertebra 5								
PC VI	II (.55*)	I (.06)	I (.39)	III (.16)	VI (.25)	III (.16)	V (.55*)	I (.18)
PC V	III (.72**)	II (.22)	III (.51)	V (.30)	VI (.54*)	II (.31)	IV (.27)	I (.25)
Male cervical vertebra 6								
PC IV	II (.23)	III (.21)	III (.29)	V (.23)	VI (.72**)	I (.43)	I (.44)	V (.33)
PC VI	IV (.26)	II (.23)	V (.60*)	I (.42)	IV (.23)	II (.16)	V (.35)	IV (.23)
Female cervical vertebra 3								
PC III	—	—	III (.79***)	II (.23)	VI (.49)	II (.46)	IV (.57*)	I (.50)
PC V	—	—	IV (.48)	II (.29)	III (.49)	V (.37)	III (.61*)	IV (.40)
Female cervical vertebra 4								
PC IV	IV (.76***)	V (.48)	—	—	IV (.79***)	I (.29)	III (.79***)	IV (.36)
PC III	III (.79***)	IV (.38)	—	—	I (.60*)	IV (.51*)	I (.59*)	IV (.57*)
Female cervical vertebra 5								
PC VI	III (.49)	I (.26)	III (.49)	IV (.19)	—	—	I (.37)	IV (.24)
PC IV	IV (.52*)	V (.31)	IV (.79***)	III (.51*)	—	—	III (.76**)	I (.19)
Female cervical vertebra 6								
PC III	V (.61*)	IV (.53*)	IV (.79***)	III (.45)	IV (.76**)	I (.67**)	—	—
PC I	III (.50)	I (.50)	II (.81***)	III (.59*)	II (.69**)	VI (.37)	—	—

$^{*}P<0.05$; $^{**}P<0.01$; $^{***}P<0.001$.

1) The similarity in the variation patterns of factor loadings between two principal components 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 principal components compared are only those from the analyses for the third to the sixth cervical vertebrae of both sexes (Tables 7 to 10 and Tables 14 to 17).

Table 20. Two principal components from the principal component analysis for each cervical vertebra showing the variation patterns of the factor loadings similar to that of a principal component which is obtained from the principal component analysis for another cervical vertebra and most highly correlated with cranial breadth.[1)]

Two PCs most highly correlated with cranial breadth	Principal component (SPEARMAN's rank correlation)							
	Male							
	Cerv. vert. 3		Cerv. vert. 4		Cerv. vert. 5		Cerv. vert. 6	
Male cervical vertebra 3								
PC I	—	—	II (.74**)	I (.46)	IV (.49)	II (.46)	IV (.71**)	I (.60*)
PC V	—	—	VI (.53*)	III (.40)	III (.46)	V (.35)	III (.49)	IV (.40)
Male cervical vertebra 4								
PC V	I (.41)	III (.33)	—	—	IV (.51)	V (.35)	V (.41)	IV (.32)
PC II	I (.74**)	II (.65**)	—	—	II (.84***)	I (.48)	I (.72**)	II (.64*)
Male cervical vertebra 5								
PC V	V (.35)	III (.29)	VI (.54*)	IV (.43)	—	—	IV (.33)	I (.16)
PC III	IV (.75**)	V (.46)	III (.93***)	IV (.31)	—	—	III (.95***)	V (.11)
Male cervical vertebra 6								
PC III	IV (.80***)	V (.49)	III (.92***)	IV (.34)	III (.95***)	V (.14)	—	—
PC V	II (.59*)	III (.31)	IV (.62*)	V (.41)	IV (.70**)	VI (.14)	—	—
Female cervical vertebra 3								
PC III	IV (.46)	V (.36)	IV (.54*)	VI (.36)	V (.72**)	III (.36)	III (.41)	II (.31)
PC II	V (.32)	IV (.23)	III (.36)	IV (.26)	VI (.55*)	I (.35)	I (.42)	V (.30)
Female cervical vertebra 4								
PC III	IV (.67**)	V (.57*)	IV (.57*)	III (.44)	III (.53*)	V (.51)	III (.58*)	IV (.29)
PC IV	II (.46)	IV (.40)	V (.43)	IV (.34)	IV (.54*)	III (.27)	V (.57*)	II (.29)
Female cervical vertebra 5								
PC III	III (.58*)	IV (.27)	V (.69**)	I (.44)	I (.49)	IV (.46)	II (.44)	V (.39)
PC II	II (.49)	I (.47)	I (.57*)	II (.48)	I (.65**)	II (.63*)	II (.73**)	I (.61*)
Female cervical vertebra 6								
PC IV	IV (.44)	V (.28)	V (.65**)	III (.43)	III (.44)	II (.29)	III (.49)	V (.38)
PC II	III (.59*)	II (.48)	I (.55*)	II (.50)	I (.69**)	II (.65**)	II (.80***)	I (.48)

Table 20. (Continued)

Two PCs most highly correlated with cranial breadth	Principal component (SPEARMAN's rank correlation)							
	Female							
	Cerv. vert. 3		Cerv. vert. 4		Cerv. vert. 5		Cerv. vert. 6	
Male cervical vertebra 3								
PC I	I (.42)	IV (.16)	I (.41)	II (.34)	VI (.57*)	I (.51*)	II (.42)	III (.31)
PC V	III (.36)	II (.32)	III (.57*)	I (.36)	II (.44)	VI (.39)	I (.44)	V (.34)
Male cervical vertebra 4								
PC V	V (.66**)	III (.36)	IV (.43)	III (.31)	III (.69**)	V (.40)	IV (.65**)	III (.50)
PC II	I (.61*)	IV (.25)	II (.63*)	I (.32)	II (.48)	I (.44)	II (.50)	V (.48)
Male cervical vertebra 5								
PC V	III (.72**)	II (.22)	III (.51)	V (.30)	VI (.54*)	II (.31)	IV (.27)	I (.25)
PC III	V (.39)	III (.36)	III (.53*)	IV (.27)	I (.60*)	IV (.35)	III (.51)	IV (.44)
Male cervical vertebra 6								
PC III	III (.41)	V (.37)	III (.58*)	V (.28)	I (.56*)	IV (.45)	IV (.49)	III (.46)
PC V	V (.59*)	I (.30)	IV (.57*)	I (.26)	IV (.49)	I (.43)	III (.64*)	IV (.38)
Female cervical vertebra 3								
PC III	—	—	III (.79***)	II (.23)	VI (.49)	II (.46)	IV (.57*)	I (.50)
PC II	—	—	I (.47)	III (.33)	V (.46)	II (.18)	V (.41)	IV (.34)
Female cervical vertebra 4								
PC III	III (.79***)	IV (.38)	—	—	I (.60*)	IV (.51*)	I (.59*)	IV (.57*)
PC IV	IV (.76***)	V (.48)	—	—	IV (.79***)	I (.29)	III (.79***)	IV (.36)
Female cervical vertebra 5								
PC III	V (.49)	III (.34)	II (.59*)	I (.41)	—	—	IV (.61*)	I (.31)
PC II	I (.62*)	III (.46)	II (.63*)	III (.47)	—	—	II (.71**)	I (.69**)
Female cervical vertebra 6								
PC IV	III (.57*)	V (.40)	III (.57*)	IV (.36)	III (.61*)	V (.25)	—	—
PC II	I (.80***)	IV (.34)	I (.76***)	II (.73**)	II (.71**)	I (.28)	—	—

$^{*}P<0.05$; $^{**}P<0.01$; $^{***}P<0.001$.

[1] See the footnote to Table 19.

Table 21. Two principal components from the principal component analysis for each cervical vertebra showing the variation patterns of the factor loadings similar to that of a principal component which is obtained from the principal component analysis for another cervical vertebra and most highly correlated with basi-bregmatic height.[1)]

Two PCs most highly correlated with basi-bregmatic height	Principal component (SPEARMAN's rank correlation)							
	Male							
	Cerv. vert. 3		Cerv. vert. 4		Cerv. vert. 5		Cerv. vert. 6	
Male cervical vertebra 3								
PC IV	—	—	III (.78***)	IV (.43)	III (.75**)	I (.30)	III (.80***)	II (.26)
PC II	—	—	I (.73**)	II (.65**)	II (.60*)	IV (.56*)	V (.59*)	I (.57*)
Male cervical vertebra 4								
PC I	II (.73**)	I (.46)	—	—	I (.84***)	II (.80***)	II (.69**)	I (.60*)
PC VI	V (.53*)	III (.50)	—	—	V (.54*)	II (.21)	II (.41)	IV (.38)
Male cervical vertebra 5								
PC I	III (.54*)	II (.52*)	I (.84***)	II (.48)	—	—	II (.79***)	I (.29)
PC VI	V (.28)	III (.19)	II (.23)	VI (.13)	—	—	IV (.49)	I (.49)
Male cervical vertebra 6								
PC II	III (.69**)	II (.38)	I (.69**)	II (.64*)	II (.86***)	I (.79***)	—	—
PC IV	I (.71**)	III (.60*)	II (.48)	IV (.38)	IV (.50)	VI (.49)	—	—
Female cervical vertebra 3								
PC II	V (.32)	IV (.23)	III (.36)	IV (.26)	VI (.55*)	I (.35)	I (.42)	V (.30)
PC V	III (.46)	II (.34)	V (.66**)	VI (.48)	IV (.53*)	III (.39)	V (.59*)	III (.37)
Female cervical vertebra 4								
PC I	II (.59*)	III (.41)	I (.45)	VI (.37)	I (.56*)	VI (.39)	II (.48)	VI (.42)
PC III	IV (.67**)	V (.57*)	IV (.57*)	III (.44)	III (.53*)	V (.51)	III (.58*)	IV (.29)
Female cervical vertebra 5								
PC II	II (.49)	I (.47)	I (.57*)	II (.48)	I (.65**)	II (.63*)	II (.73**)	I (.61*)
PC I	II (.59*)	I (.51*)	IV (.68**)	III (.45)	IV (.66**)	III (.60*)	III (.56*)	IV (.43)
Female cervical vertebra 6								
PC V	V (.34)	I (.18)	II (.48)	VI (.41)	VI (.55*)	II (.43)	I (.41)	V (.37)
PC II	III (.59*)	II (.48)	I (.55*)	II (.50)	I (.69**)	II (.65**)	II (.80***)	I (.48)

Table 21. (Continued)

Two PCs most highly correlated with basi-bregmatic height	Principal component (SPEARMAN's rank correlation)							
	Female							
	Cerv. vert. 3		Cerv. vert. 4		Cerv. vert. 5		Cerv. vert. 6	
Male cervical vertebra 3								
PC IV	III (.46)	IV (.34)	III (.67**)	IV (.40)	IV (.66**)	I (.50)	III (.59*)	IV (.44)
PC II	I (.76**)	IV (.42)	I (.59*)	II (.54*)	I (.59*)	II (.49)	III (.57*)	II (.48)
Male cervical vertebra 4								
PC I	I (.67**)	III (.06)	II (.70**)	I (.45)	II (.57*)	III (.44)	II (.55*)	I (.53*)
PC VI	V (.48)	III (.36)	II (.39)	I (.37)	VI (.41)	II (.32)	V (.41)	I (.39)
Male cervical vertebra 5								
PC I	I (.62*)	II (.35)	II (.73**)	I (.56*)	II (.65**)	III (.49)	II (.69**)	I (.64*)
PC VI	II (.55*)	I (.06)	I (.39)	III (.16)	VI (.25)	III (.16)	V (.55*)	I (.18)
Male cervical vertebra 6								
PC II	I (.65**)	V (.36)	II (.79***)	I (.48)	II (.73**)	III (.44)	II (.80***)	I (.70**)
PC IV	II (.23)	III (.21)	III (.29)	V (.23)	VI (.72**)	I (.43)	I (.44)	V (.33)
Female cervical vertebra 3								
PC II	—	—	I (.47)	III (.33)	V (.46)	II (.18)	V (.41)	IV (.34)
PC V	—	—	IV (.48)	II (.29)	III (.49)	V (.37)	III (.61*)	IV (.40)
Female cervical vertebra 4								
PC I	I (.58*)	II (.47)	—	—	II (.42)	III (.41)	II (.76***)	I (.56*)
PC III	III (.79***)	IV (.38)	—	—	I (.60*)	IV (.51*)	I (.59*)	IV (.57*)
Female cervical vertebra 5								
PC II	I (.62*)	III (.46)	II (.63*)	III (.47)	—	—	II (.71**)	I (.69**)
PC I	I (.56*)	III (.43)	III (.60*)	IV (.29)	—	—	III (.67**)	I (.36)
Female cervical vertebra 6								
PC V	II (.41)	IV (.28)	V (.40)	I (.35)	VI (.23)	V (.18)	—	—
PC II	I (.80***)	IV (.34)	I (.76***)	II (.73**)	II (.71**)	I (.28)	—	—

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

[1] See the footnote to Table 19.

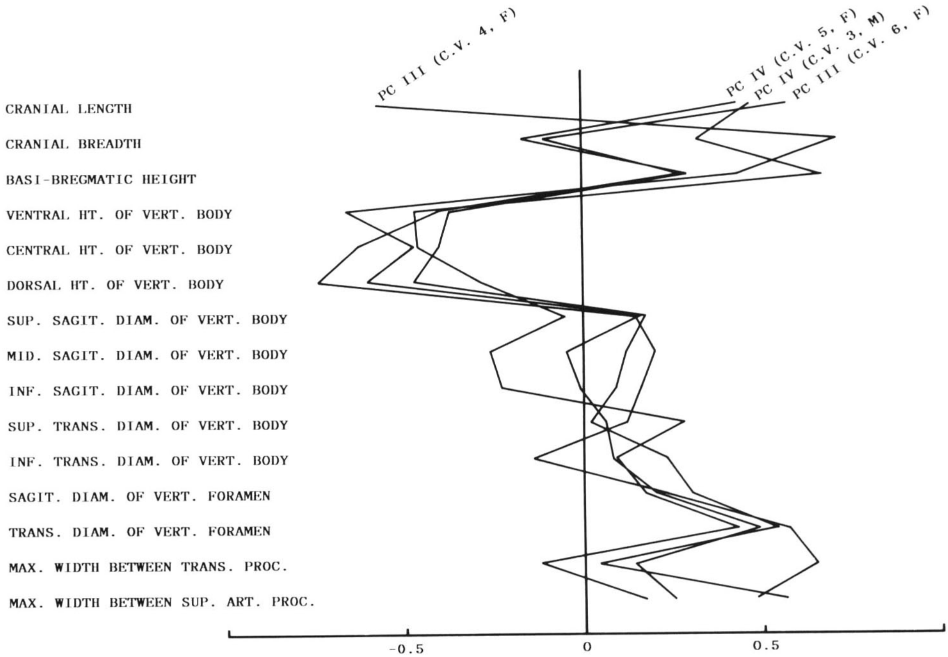

Fig. 1. Factor loadings on the principal components most highly correlated with cranial length. These PCs are extracted through several PCAs from the measurements of the neurocranium and the cervical vertebrae of Japanese males and females. The variation patterns in factor loadings of all the PCs illustrated here are significantly correlated with that of the fourth PC from the PCA for the third cervical vertebrae of males.

Discussion

As regards the interrelations between cranial and lumbar measurements, MIZOGUCHI (1994), using the principal component analysis, suggested that, although cranial length or breadth had no consistent morphological association with any measurements of the lumbar vertebrae, basi-bregmatic height was tightly connected with the sagittal and transverse diameters of the vertebral foramen. Also in the present analyses of the correlations between the neurocranium and the cervical vertebrae, similar results were obtained.

Relations with Cranial Length and Breadth

Of the eight PCAs for the third to the sixth cervical vertebrae of males and females, three showed that cranial length and breadth were relatively highly correlated with the transverse diameter of the vertebral foramen (Figs. 1 and 2).

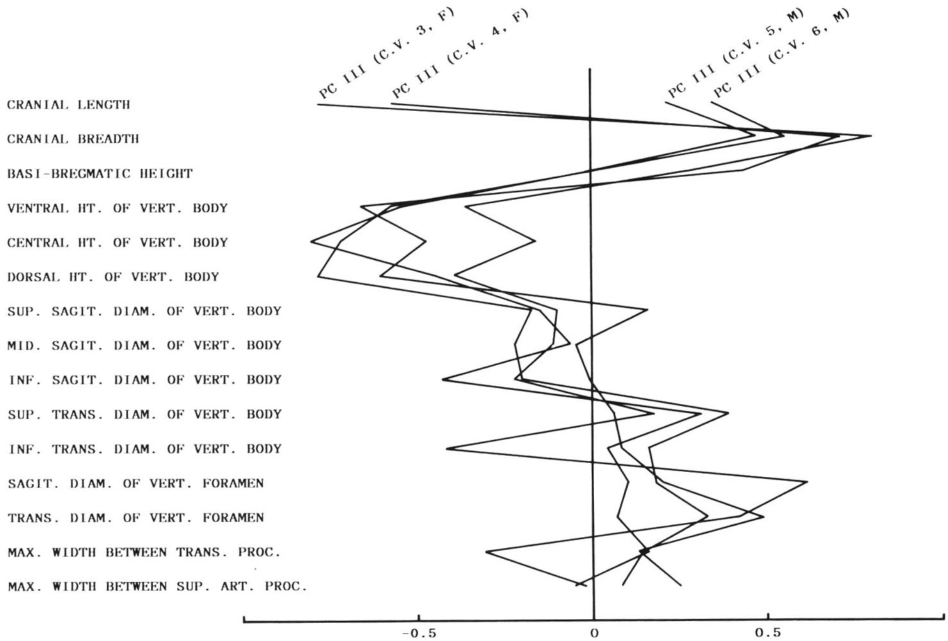

Fig. 2. Factor loadings on the principal components most highly correlated with cranial breadth. The variation patterns in factor loadings of all the PCs illustrated here are significantly correlated with that of the third PC from the PCA for the fourth cervical vertebrae of females. For details, see the legend of Fig. 1.

But this does not seem sufficient to support the hypothesis that cranial length or breadth is closely associated with the transverse diameter of the vertebral foramen. Although the first PCs from the PCAs for the atlas of both sexes were also found to have relatively high correlations both with cranial length and with the transverse diameters of the vertebral foramen (Tables 5 and 12), further examination should be performed to draw a definite conclusion.

Relations with Basi-bregmatic Height

From the present analyses for the third to the sixth cervical vertebrae and the neurocranium, it may be said in general that basi-bregmatic height is associated with the ventral and central heights of the vertebral body as well as with the transverse diameter of the vertebral foramen. In this case, five of the eight PCAs showed the same tendency (Fig. 3). Further, the PCAs for the seventh cervical vertebrae of males and females also suggested the strong associations of basi-bregmatic height with the ventral height of the vertebral body and the sagittal

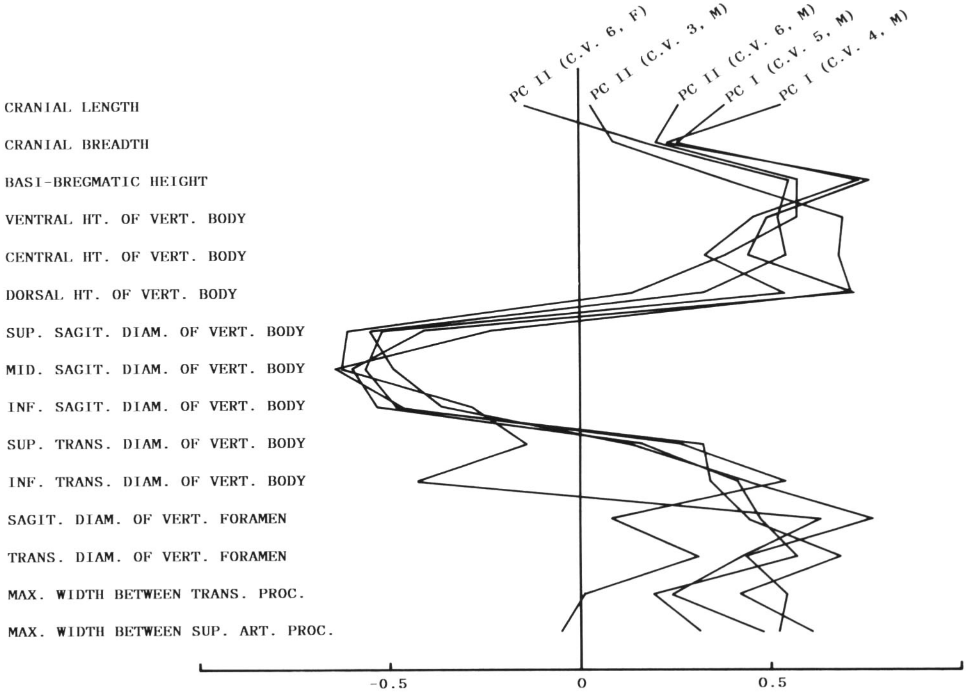

Fig. 3. Factor loadings on the principal components most highly correlated with basi-bregmatic height. The variation patterns in factor loadings of all the PCs illustrated here are significantly correlated with that of the first PC from the PCA for the fourth cervical vertebrae of males. For details, see the legend of Fig. 1.

diameter of the vertebral foramen (Tables 11 and 18).

Of the above results, the high correlation between basi-bregmatic height and the vertebral foramen size (Fig. 3) strengthens the hypothesis offered by MIZOGUCHI (1994) that the vertebral foramen is an extension of the cranial cavity. Regarding the concrete causes for the correlation, SAKURA (1995) is of the opinion that the correlations between the braincase and the vertebral foramina may be caused by the pressure of the cerebrospinal fluid. His opinion, however, seems applicable not only to basi-bregmatic height but also to cranial length and breadth. The latter two measurements, in fact, do not necessarily have consistent correlations with the vertebral foramen size (Tables 5 to 18). This problem remains to be solved.

Another high correlation found between the ventral height of the vertebral body and the vertebral foramen size (Fig. 3) may be explained with craniocervical posture and the difference in the thickness of the spinal cord between high and low levels. If the ventral height of the vertebral body increases in the development process, the face may be orientated upwards and the spinal cord may sink down.

This may result in the increase of the vertebral foramen size, particularly of inferior cervical vertebrae, because the part of cervical enlargement may shift downward.

Regarding the relations between craniocervical posture and cranial measurements, SOLOW and TALLGREN (1976), using the data of Danish males, showed that basi-bregmatic height had significant, though low, inverse correlations with the inclinations of the foramen magnum line (ba-o) to the posterior tangent to the cervical column (−0.19 and −0.25 for two head positions), and simultaneously had significant positive correlations with the total dorsal height of the cervical column from the apex of the odontoid process of the axis to the most postero-inferior point on the body of the fourth cervical vertebra (0.19 and 0.21 for the same two head positions as the above). This implies that there are weak tendencies for the head to be located in a forward bent position and for the total dorsal height of the vertebral bodies to increase when basi-bregmatic height is large. These tendencies seem incongruous with the present finding that the PC having a high positive correlation with basi-bregmatic height also has a high positive correlation with the ventral height of the vertebral body.

On the other hand, SOLOW *et al.* (1982), examining the interrelations between craniofacial morphology and the posture of the head and cervical column in the two samples of Danish and Australian aboriginal males, found that Australian aboriginals had the shorter cervical column with a less pronounced lordosis, the upper cervical column 8.5 degrees more forward inclined, the head held about 3 degrees lower, a shorter upper facial height, a larger anterior lower facial height, a shorter posterior cranial base length (s-ba), *etc.* These are inter-population differences, but not incompatible with the present results based on within-population variations. Taking into account the fact that basi-bregmatic height is generally shorter in Australian aboriginals than in Europeans (HOWELLS, 1973), it may be said that a skull with shorter basi-bregmatic height is generally borne by the cervical column with a less pronounced lordosis. If the condition of the less pronounced lordosis is associated with the shorter ventral heights of vertebral bodies, this hypothesis is perfectly compatible with the present results, though, as mentioned above, it does not conform to the results obtained by SOLOW and TALLGREN (1976).

In respect to the association between the lordosis of the cervical column and the ventral height of the vertebral body, there is another report, which may indirectly support the above hypothesis. HUGGARE (1992), using the data of females from the northern and the southern areas of Finland, showed that the inhabitants of the northern area had the raised head posture and the antero-posteriorly longer atlas with a larger ventral arch height and a smaller dorsal arch height. HUGGARE interpreted these findings as evidence of morphogenetic reactions to the changes in function related to climatic conditions. Apart from the rationality of this interpretation, it may be suggested by these observations and the results of SOLOW *et al.* (1982) that people with larger ventral heights of the cervical vertebrae have more pronounced conditions of the cervical lordosis because SOLOW *et al.* showed that people with more raised head positions tended to have more pronounced lordoses of the cervical column.

After all, if similarities and differences in morphological characters between populations are on the extension of those between individuals within a population, it may be said from the findings of the present and previous investigations that people with larger basi-bregmatic heights have larger ventral body heights of the cervical vertebrae, more pronounced lordoses of the cervical column, more raised head positions in relation to the cervical column, and larger vertebral foramen size. And, if so, these suggest that, in the developmental process of the cranio-cervical region, there are some common morphogenetic and/or biomechanical factors associated not only with the size and shape of the brain and spinal cord but also with the posture of the head and neck.

Conclusions

The principal component analyses for the neurocranium and the cervical vertebrae suggested that, while cranial length or breadth had no or little consistent associations with any of the measurements of the cervical vertebrae, basi-bregmatic height was relatively highly correlated with the ventral and central heights of the vertebral body and with the transverse diameter of the vertebral foramen. These results, at least, seem to support the conclusion deduced by MIZOGUCHI (1994) from the analyses for the neurocranium and the lumbar vertebrae that the vertebral foramen is an extension of the cranial cavity.

Although the direct evidence of the causes for brachycephalization was not detected in the present study, there is no doubt that such a result itself contributes toward narrowing the range of the still-to-be-solved problem.

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