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Fractions of Variation of Neurocranial Form Associated with Facial and Postcranial Bones: Within-group Analysis

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Abstract Taking into account the craniofacial and postcranial measurements supposedly associated with brain size, oxygen intake, thermoregulation, skeletal muscle mass, body size, anteroposterior head balance, and parturition, the interrelationships between such measurements and three main neurocranial measurements were examined through principal component analyses of within-group data to elucidate the determinants of neurocranial form. The data used are of 30 males and 20 females of modern Japanese. As a result, it was found, in both males and females, that there was at least a common factor that was relatively strongly associated with cranial length, nasal height, the sagittal diameter of the femoral midshaft, and the vertical diameter of the femoral head and talar length, but not associated with body height. These findings suggest that heavier individuals who have a longer/thicker gut and a comparatively large amount of skeletal muscle (except the nuchal ones), which consume a relatively large amount of oxygen, tend to have a shorter (and probably wider) neurocranium, regardless of brain size and body height. Furthermore, positive associations were found between cranial breadth, the vertical diameter of the femoral head, nasal height, and maximum pelvic breadth. This is compatible with the cold adaptation hypothesis and Ruff's cylindrical thermoregulatory model. In order to more concretely clarify the determinants of neurocranial form, however, multivariate among-group analyses should also be conducted using both morphological measurements and environmental variables.

Key words: Neurocranial form, Body form, Controlling factors, Principal component analysis, Bootstrap method

Many investigations have been conducted to clarify the causes of variation in neurocranial form (size and shape). The present author also carried out a series of multivariate analyses of within-group correlations between three main neurocranial maesurements (i.e., cranial length and breadth, and basi-bregmatic height) and postcranial measurements to elucidate the causes of brachycephalization (Mizoguchi, 1992, 1994, 1995, 1996, 1997, 1998a, c, 1999, 2000, 2001, 2002, 2003a, b, 2004a, b, 2005, 2007b, 2008, 2009) on the premise that population differences are extensions of individual differences, as stated by Howells (1973). As a result, he found that, while cranial breadth has no consistent associations with any postcranial measurements, cranial length is significantly associated with many postcranial measurements, such as vertebral body size, costal chord, pelvic widths, and limb bone lengths and thicknesses, and considered that the variation in cranial length may, in part, be related to the degree of development of skeletal muscles or body size and, besides, that the form of the maternal pelvic inlet may be another important determinant of neurocranial form.

Alongside the aforementioned series of within-group analyses, Mizoguchi (1998b) performed among-group analyses as well, although they were concerned only with craniofacial measurements. The results showed that, while cranial breadth, bizygomatic breadth, upper facial height, and nasal height always vary in parallel with one another, cranial length and nasal breadth vary independently of each other and of the above four measurements. At that time, the present author could not imagine the reason why cranial length and nasal breadth vary independently of the other cranial measurements. Later, however, he found two interesting descriptions in Houghton (1996): One is of Miyashita and Takahashi's (1971) finding based on Japanese data that there is a strong correlation between body mass and airway height (nasal height), and the other is of some data from Papua New Guinea suggesting that both nasal height and nasal breadth give a better approximation of the size of the nasal passage, with a high correlation being found between body mass and nasal dimensions. These are very suggestive in interpreting the independent variations of nasal breadth and cranial length within the craniofacial structure. According to Mizoguchi (2007b), there is no significant association between these two measurements also in within-group analyses of only craniofacial measurements. Therefore, even if they were correlated with each other through some common factors related to postcranial bones or body size, the contribution of such common factors would not be so high. But they may, independently of each other, be strongly associated with other different factors common to postcranial characters. To confirm these points, the present study attempts to find such common factors by combining some postcranial measurements with a data set of craniofacial measurements including both cranial length and nasal dimensions.

In addition, there are a few other issues to be examined. Mizoguchi (2007a) preliminarily estimated ecological (or among-group or inter-population) correlations between neurocranial and limb bone measurements simply using Spearman's rank correlation coefficient, and found that, in both males and females, there are significant associations between cranial length and the thickness measurements of the radius, ulna, femur, and tibia. It should be noted here that the limb bone measurements significantly associated with cranial length are almost always thicknesses, not lengths. In the case of within-group analyses (Mizoguchi, 2001, 2003a, b), cranial length is significantly correlated with both maximum lengths and thickness measurements of major limb bones. This discrepancy between the among-group and within-group analyses suggests that limb bone length and thickness are associated with cranial dimensions in different ways. Decomposing body form after Ruff (2002), it is divided into body size and body shape. Body size is further subdivided into body height or length (stature), body breadth (e.g., bi-iliac or maximum pelvic breadth), and body mass (weight), while body shape (or relative body mass) is expressed by body mass index (BMI = weight/height^2, a.k.a. Quetelet's Index). Using these concepts, limb bone lengths, especially of the lower extremities, seem to be associated with body height, and limb bone thickness measurements, to be related to body mass (Ruff *et al.*, 1991) or skeletal muscle mass. In the present study, keeping the differential contributions of these factors in mind, it is examined again whether multivariate within-group analyses of limb bone lengths and thicknesses based on different combinations of craniofacial and postcranial measurements from those used in Mizoguchi's work (2001, 2003a, b, 2009) show the same tendencies as those suggested by Mizoguchi's (2007a) bivariate among-group analysis.

Recently, Mizoguchi (2012a) found, through principal component analyses of the three dimensional structural deviations in the neighborhood of cranial landmarks obtained by a finite element scaling method, that the degree of occlusal wear on the maxillary first molar (UM1) is significantly associated with the magnitude of strain at the inion in Japanese. This finding suggests that craniofacial form may vary in response to mechanical stresses from the masticatory and/or nuchal muscles. An exaggerative extrapolation of this tendency further suggests the anteroposterior elongation of both the palate and the occipital bone in those individuals who have heavy UM1 occlusal wear (Mizoguchi, 2012b). If so, this may support Yamaguchi's (1984) hypothesis of anteroposterior head balance for brachy- and dolicho-cephalization. In the present study, this hypothesis is also examined by adding facial and maxillo-alveolar lengths to the data sets of craniofacial and postcranial measurements to be analyzed.

Finally, the head and body forms are well known to vary in response to climatic changes. For example, Beals (1972) showed on a world-wide scale that the mean cephalic index of modern humans is higher in colder regions. This implies that temperature may be one of the determinants of human neurocranial form, and is consistent with a famous ecogeographical rule, Allen's rule. Later, Crognier (1981), using European, North African and Middle Eastern male samples, quantitatively showed that not only head and face dimensions but also body size are significantly correlated with temperature and precipitation. To explain the relationship of human body form with climatic factors, Ruff (1991, 2002) proposed the 'cylindrical thermoregulatory model' that maintaining a constant body breadth results in a constant surface area-to-body mass ratio, despite changes in height, and showed that, while absolute bi-iliac breadth has little variation within the human populations living in similar climatic zones, this breadth changes across different climatic zones, namely, increases from warmer to colder climates, regardless of stature. On the other hand, in Mizoguchi's (2005, 2009) within-group analyses, the pelvic breadth is significantly associated with cranial length. From an obstetrical perspective, children of mothers with a wider pelvis should have longer heads. According to Ruff's cylindrical thermoregulatory model and Allen's rule above, however, people living in colder regions must have wider pelves and shorter heads. This is also an issue to be examined.

As mentioned above, there are many candidates for the determinants of or factors controlling neurocranial form. In the present study, some candidates, particularly biomechanical factors, are first explored by referring to previous studies, and then, the facial and postcranial measurements that are supposedly associated with such plausible factors are selected. Although the plausible factors set up in this way are hypothetical, analysis of the interrelationships between the selected measurements is considered very helpful in understanding the formation of our morphology, especially at an early stage of research. In the present study, multivariate within-group analyses are carried out to clarify the degree of influence of the factors plausibly affecting neurocranial form.

Materials

The data used are the cranial and postcranial measurements reported by Miyamoto (1924, 1925, 1927), Okamoto (1930), Kikitsu (1930), and Hirai and Tabata (1928a, b). They were obtained from the same adult individuals, 30 male and 20 female modern Japanese, who lived in the Kinai region. However, the values of "stature" (Miyamoto, 1924) are those of living stature, except for one individual. The basic statistics for the measurements analyzed are listed in Table 1.

Incidentally, these samples are the same as those used in previous studies (Mizoguchi, 1994, 1995, 1996, 1997, 1998a, b, 1999, 2000, 2001, 2002, 2003a, b, 2004a, b, 2005, 2007b, 2008, 2009).

Methods

First of all, candidates for the determinants of or factors controlling neurocranial form are searched for by referring to previous studies. Some of them may affect ontogenetic processes, and others may act in evolutionary processes or in both. In the present study, however, their relationships with neurocranial form are preliminarily examined through multivariate within-group analyses on the premise that population differences are extensions of individual differences (Howells, 1973).

Candidates of the factors influencing neurocranial form

Among the plausible controlling factors that

Table 1. Means and standard deviations for the cranial and postcranial measurements of Japanese males and females used in the present study.[1)]

Variable[2)]		Males			Females		
		n	Mean	SD	*n*	Mean	SD
SKULL							
1	Cranial length	30	178.4	5.6	20	169.4	4.9
5	Cranial base length	30	102.3	3.5	20	94.8	3.6
8	Cranial breadth	30	141.0	4.7	20	137.8	4.1
17	Basi-bregmatic height	30	139.8	5.8	20	132.1	3.8
31(2)	Inion-opisthion chord	30	40.5	4.6	20	41.0	4.7
37(2)	Cranial base angle	30	29.2	2.6	20	29.0	3.6
38	Endocranial capacity (cubic root)[3)]	30	11.4	0.3	20	11.0	0.3
40	Facial length	29	100.2	4.0	19	94.4	4.7
45	Bizygomatic breadth	30	133.4	5.3	20	125.9	3.8
54	Nasal breadth	30	26.3	1.8	20	25.0	1.7
55	Nasal height	30	52.5	2.9	20	48.9	2.5
60	Maxillo-alveolar length	29	54.1	2.9	19	50.9	2.5
70	Ramus height	30	61.1	5.0	20	55.4	3.4
71	Minimum ramus breadth	30	33.7	2.8	20	31.5	2.3
THORACIC VERTEBRA VIII							
4	Superior sagittal diameter of vertebral body	30	26.4	2.0	19	23.8	1.9
7	Superior transverse diameter of vertebral body	30	31.6	2.5	19	28.3	1.5
RIB IV							
4	Chord	—	—	—	20	142.3	9.0
HUMERUS							
2	Total length	30	289.8	15.7	20	269.5	12.5
6	Minimum diameter of midshaft	30	17.4	1.5	20	14.6	0.9
PELVIS							
2	Maximum pelvic breadth	30	258.8	13.8	20	251.9	14.4
FEMUR							
1	Maximum length	30	413.7	24.0	20	382.3	20.6
6	Sagittal diameter at midshaft	30	27.1	2.3	20	23.3	1.8
18	Vertical diameter of head	30	45.6	2.2	20	41.2	2.8
TIBIA							
1a	Maximum length	30	331.9	20.5	20	305.1	17.2
TALUS							
1	Length	29	50.7	2.1	20	45.6	1.9
BODY SIZE							
	Stature	29	1577.1	72.0	19	1489.2	55.9

[1)] The estimates of basic statistics were recalculated here on the basis of raw data published by previous authors. Skull and stature: Miyamoto (1924); vertebrae: Okamoto (1930); ribs: Kikitsu (1930); humerus: Miyamoto (1925); pelvis: Miyamoto (1927); femur and tibia: Hirai and Tabata (1928a); and talus: Hirai and Tabata (1928b). When measurements were available for both sides, only those from the right side were used.

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

[3)] The cubic root was calculated by the present author.

may influence neurocranial form (size and shape), the ones that first come to mind are brain size and shape. The problem of whether brain form determines neurocranial form or *vice versa* has been discussed for over a hundred years (Macalister, 1898; Sullivan, 1978). Although data for brain shape are not given by Miyamoto (1924), he reported that for endocranial capacity, which can be used as a measure of brain size. Furthermore, according to Kean and Houghton (1990), it is likely that the cranial base, early to develop and stable in form because of its intimate relationship with the brain and cranial nerves, constitutes a major architectural template in the developing head. In the present study, therefore, cranial base length is also considered to reflect the size of the basal region of the brain.

Kean and Houghton (1990) argue that there is a clear and direct relationship between increase in airway size, in measures of lung size such as vital capacity, and that in body oxygen demand, as indicated particularly by skeletal muscle mass. In the present study, nasal height and costal chord are used as measures of oxygen intake. According to Crognier (1981), both nasal height and body weight have significant negative associations with temperature. Therefore, nasal height must be considered from the two viewpoints of body oxygen demand and thermoregulation.

Nasal breadth, which was suggested by Mizoguchi (1998b) in among-group analyses to be relatively independent of other craniofacial measurements, may be regarded as a composite measure of thermoregulation and/or humidity regulation. Wolpoff (1968) shows that there is a tendency for nasal breadth to decrease in two populations, namely, Australian Aborigines and so-called Alaskan Eskimos, as the climate becomes cooler and drier. In contrast with these findings, Crognier (1979, 1981) reports on the basis of European, North African and Middle Eastern samples that, while nose breadth certainly has a significant positive correlation with the mean temperature of the hottest month (only in females), it has a significant negative correlation with mean precipitation (of the rainiest month in males and, in females, of the driest month). Incidentally, stature (in both sexes) and body weight (only in males) have significant negative correlations with mean annual temperature and positive correlations with the mean precipitation of the driest month (Crognier, 1979, 1981). Although Houghton (1996) suggests that both nasal height and nasal breadth give a better approximation of the size of the nasal passage and there is a high correlation between body mass and nasal dimensions, the relationships of nasal size (height and breadth) with body size (height, breadth, and mass) and their relationships with temperature and humidity (or precipitation) seem to be very complicated. In the present study, nasal breadth is tentatively assumed to be a composite measure of thermoregulation and humidity regulation.

Mizoguchi's (2001, 2003a, b, 2009) multivariate within-group analyses show that both limb bone lengths and thicknesses are significantly associated with cranial length. However, Mizoguchi's (2007a) bivariate among-group analysis suggests that only limb bone thicknesses, not lengths, are strongly associated with cranial length. Ruff (2002) states that lower limb articular size, especially femoral head size, is an effective predictor of body mass in humans because, while long-bone diaphyses change their diameters in response to mechanical loading, articular dimensions are less sensitive to differences in activity level than diaphyseal breadth dimensions. If this is the case, the diameters of long-bone midshafts may be considered to reflect skeletal muscle mass. In fact, Wescott (2006), using data of prehistoric and historic North American populations, suggested that there is significant variation in femur midshaft shape and robusticity in all populations analyzed, and that, while inferred mobility levels do not correspond consistently with femur midshaft structure in either males or females, sexual dimorphism is generally greater in more mobile populations. Furthermore, Weiss (2010), observing 65 prehistoric Californian Native Americans, reported that aggregate upper limb muscle marker value has significant correlations with the aggregate cross-sectional robusticity of the humerus (Spearman's rho $=$ 0.536; $P < 0.01$), cranial length (rho $=$ 0.377; $P < 0.01$), cranial breadth (rho $=$ 0.293; $P < 0.05$), and body mass calculated from femoral head breadths (rho $=$ 0.385; $P < 0.01$). Ibáñez-Gimeno *et al.* (2013), using 62 upper limb specimens from Catalonia and the Balearic Islands, also maintain that individuals with strongly marked entheseal changes have increased diaphyseal rigidities, and that large muscular scars are related to diaphyseal shape. In the present study, therefore, the minimum diameter of the humeral midshaft and the sagittal diameter of the femoral midshaft are used as measures of skeletal muscle mass. And maximum femoral and tibial lengths as well as total humeral length are used as measures that are associated with body height, in addition to stature itself. As regards body mass, not only the vertical diameter of the femoral head but also the diameters of the vertebral body of the eighth thoracic vertebra and talar length are employed as predictors of body weight.

Weijs and Hillen (1986) reported that head width had a significant correlation with the cross-sectional area of the masseter muscle. On the other hand, the strong association between cranial breadth and bizygomatic breadth has been confirmed in both within-group (Mizoguchi, 1992) and among-group (Mizoguchi, 1998b) analyses. From these findings, it can be inferred that the zygomatic arch plays an important role as an intermediate between cranial breadth and the amount of masticatory (masseter and temporal) muscle. In addition, as the insertion sites of all the masticatory muscles (masseter, temporal, and medial and lateral pterygoid muscles) are located on the mandibular ramus, the ramus form must also be taken into consideration. In the present study, therefore, bizygomatic breadth as well as ramus height and minimum ramus breadth are used as measures of masticatory muscle mass.

In Mizoguchi's (2001, 2003a, b, 2004b) hypothesis, the nuchal planum plays an important role as an intermediate between cranial length and postcranial measurements. He considered that the degree of general development of skeletal muscles, including nuchal muscles, was a cause of the strong association between cranial length and limb bone measurements. Later, however, Mizoguchi (2008), examining direct relationships between cranial length and occipital measurements, did not find any significant associations between them. Furthermore, Mizoguchi (2009) confirmed on the basis of Japanese and Australian Aboriginal data that the inion-opisthion chord was not significantly associated with cranial length or with any postcranial measurements. Therefore, he concluded that the inion-opisthion chord at least is not an appropriate measure for the size of the nuchal planum, presumably because of the difficulty in determining a landmark, the inion (Mizoguchi, 2009). Recently, however, as was stated in the Introduction, Mizoguchi (2012a) found that the degree of occlusal wear on the UM1 was significantly associated with the magnitude of strain at the inion in Japanese, and Mizoguchi (2012b) showed that those individuals who had heavy UM1 occlusal wear tended to have an anteroposteriorly elongated palate and occipital bone. These findings imply that craniofacial form may change in response to mechanical stresses from the masticatory and/or nuchal muscles and, at the same time, may support Yamaguchi's (1984) hypothesis of anteroposterior head balance. In the present study, therefore, facial and maxillo-alveolar lengths and the inion-opisthion chord as well as the cranial base angle are used mainly as measures of anteroposterior head balance. The inion-opisthion chord is also employed to reconfirm the involvement of nuchal muscles in general skeletal muscles by using different sets of craniofacial and postcranial measurements from those used in previous analyses. As regards cranial base angle, Kean and Houghton (1990) state that, in Polynesians, with their large cranial base angle, the upper facial skeleton with the contained airway is positioned in a markedly antero-inferior manner and, hence, nasal height becomes large relative to that of most other groups of *Homo sapiens*. From this viewpoint, cranial base angle is also regarded as a measure of oxygen intake.

According to Ruff's (1991, 2002) cylindrical thermoregulatory model and Allen's rule, people living in colder regions tend to have wider pelves and shorter or wider heads. On the other hand, Mizoguchi's (2005, 2009) within-group analyses show that the pelvic breadth is significantly associated with cranial length, suggesting that the children of mothers with a wider pelvis tend to have longer heads. In the present study, therefore, maximum pelvic breadth is used as a composite measure of thermoregulation and parturition.

In summary, the candidates of controlling factors that are considered to be associated with the formation of neurocranial form and are practically taken into account in the present study are as follows: brain size, oxygen intake, thermoregulation (cold adaptation), humidity regulation, skeletal muscle mass, body size (height, breadth, and mass or weight), anteroposterior head balance, and parturition.

Statistical analysis

Because of the statistical restriction on sample size given the number of variables, three sets of measurements to be analyzed were constructed from the measurements selected in the above section. The first set is concerned with skeletal muscle mass and all the other controlling factors; the second, with body height instead of muscle mass; and the third, with body mass or weight. Typical combinations of measurements are shown in Tables 2, 9, and 16. Furthermore, only in the case of females, the data of costal chord are available. Therefore, the additional data sets including costal chord were also analyzed, as shown in Tables 7, 14, and 21.

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

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

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

Statistical calculations were executed using programs written by the author in FORTRAN: BSFMD for calculating basic statistics, BTPCA for principal component analysis and Kaiser's normal varimax rotation, and RKCNCT for rank correlation coefficients. The FORTRAN 77 com-

Table 2. Principal component analysis of the correlations between three main neurocranial measurements and the craniofacial and postcranial measurements (excluding costal chord) that are supposedly associated with brain size, muscle mass, antero-posterior head balance, oxygen intake, parturition, or thermoregulation (males).[1]

Variable[2]		Factor loadings							Total variance (%)
		PC I	II	III	IV	V	VI	VII	
1	Cranial length	0.72	−0.02	0.06	−0.49***	0.15	0.10	−0.24***	84.81
8	Cranial breadth	0.56	−0.17	−0.53**	0.45*	0.18*	−0.13	−0.16**	89.13
17	Basi-bregmatic height	0.47	0.49	−0.41**	−0.37*	−0.15	0.23**	0.13	86.00
5	Cranial base length	0.71	0.30**	−0.42***	−0.09	−0.05	0.15*	−0.23***	85.13
38	Endocran. cap. (cub. r.)	0.69	−0.12	−0.36**	−0.13	0.09	−0.21***	−0.05	69.34
45	Bizygomatic breadth	0.70	0.29*	−0.06	0.04	0.44***	−0.04	0.07	76.84
70	Ramus height	0.69	0.20	0.14	0.13	−0.26	−0.38**	0.33***	87.75
71	Minimum ramus breadth	0.45	−0.41	−0.05	−0.41*	0.34*	0.00	0.54***	93.70
6	Min. diam. of hum. midshaft	0.56	0.25	0.25	0.15	−0.20	0.53***	−0.03	78.17
6	Sag. diam. of fem. midshaft	0.73	0.16	0.29	0.32*	−0.13	−0.12	0.12	78.96
31(2)	Inion-opisthion chord	0.07	0.05	0.62*	−0.51*	0.16	−0.35***	−0.23**	85.62
37(2)	Cranial base angle	−0.15	0.83	0.10	−0.34*	−0.17	−0.02	0.10	87.95
40	Facial length	0.65	−0.55*	−0.04	−0.03	−0.32***	−0.08	0.00	83.95
60	Maxillo-alveolar length	0.52	−0.36**	0.18	−0.12	−0.66***	−0.03	−0.06	88.95
55	Nasal height	0.40	0.51*	0.35	0.51***	0.16	−0.14	0.01	84.34
2	Maximum pelvic breadth	0.66	−0.13	0.31**	−0.01	0.20*	−0.05	−0.26*	66.16
54	Nasal breadth	0.36	−0.33	0.44**	0.14	0.22	0.55***	0.11	81.70
Total contribution (%)		32.35	13.34	10.41	9.21	7.21	6.15	4.19	82.85
Cumulative proportion (%)		32.35	45.69	56.10	65.31	72.51	78.66	82.85	82.85

[1] Sample size is 29. Number of principal components was determined so that the cumulative proportion of the variances of the principal components exceeded 80%.
[2] Variable number according to Martin and Saller (1957).
* $P<0.05$; ** $P<0.01$; *** $P<0.001$, according to a two-tailed bootstrap test.

Table 3. Rotated solution of the first seven principal components extracted from the correlations between three main neurocranial measurements and the craniofacial and postcranial measurements (excluding costal chord) that are supposedly associated with brain size, muscle mass, antero-posterior head balance, oxygen intake, parturition, or thermoregulation (males).[1)]

Variable[2)]		Factor loadings						
		Fac I	II	III	IV	V	VI	VII
1	Cranial length	0.04	−0.17	−0.58	−0.56	−0.23	0.25	0.24
8	Cranial breadth	0.26	−0.84**	−0.27	0.18	−0.06	−0.04	0.02
17	Basi-bregmatic height	0.10	0.16	−0.89**	0.12	−0.05	−0.04	0.14
5	Cranial base length	0.20	−0.31	−0.83*	−0.03	−0.13	0.06	−0.06
38	Endocranial capacity (cubic root)	0.18	−0.49	−0.47	−0.16	−0.25	−0.12	0.31*
45	Bizygomatic breadth	0.52**	−0.30	−0.47	−0.22	0.21	0.15	0.28
70	Ramus height	0.77**	−0.01	−0.21	−0.03	−0.41	−0.12	0.22
71	Minimum ramus breadth	−0.02	−0.13	−0.12	−0.13	−0.13	0.15	0.92***
6	Min. diam. of hum. midshaft	0.36	0.10	−0.41	0.04	−0.22	0.63**	−0.17
6	Sag. diam. of fem. midshaft	0.77**	−0.13	−0.16	−0.09	−0.31	0.23	0.03
31(2)	Inion-opisthion chord	0.07	0.29	0.13	−0.86***	−0.04	−0.07	0.07
37(2)	Cranial base angle	0.19	0.71	−0.40	−0.07	0.25	−0.26	−0.19
40	Facial length	0.09	−0.40	−0.10	−0.07	−0.76**	0.14	0.25
60	Maxillo-alveolar length	0.09	−0.02	−0.10	−0.10	−0.92***	0.13	−0.00
55	Nasal height	0.85***	−0.05	−0.04	−0.09	0.21	0.16	−0.21
2	Maximum pelvic breadth	0.32	−0.33	−0.14	−0.52	−0.20	0.33	0.08
54	Nasal breadth	0.09	−0.09	0.11	−0.09	−0.09	0.85***	0.22

[1)] Sample size is 29. Cumulative proportion of the variances of the seven principal components is 82.85%.
[2)] Variable number according to Martin and Saller (1957).
* $P<0.05$; ** $P<0.01$; *** $P<0.001$, according to a two-tailed bootstrap test.

Table 4. Principal component analysis of the correlations between three main neurocranial measurements and the craniofacial and postcranial measurements (excluding costal chord) that are supposedly associated with brain size, muscle mass, antero-posterior head balance, oxygen intake, parturition, or thermoregulation (females).[1)]

Variable[2)]		Factor loadings						Total variance (%)
		PC I	II	III	IV	V	VI	
1	Cranial length	0.24	0.01	−0.58***	−0.48***	0.52***	0.01	89.96
8	Cranial breadth	0.03	0.46*	0.69***	0.30***	−0.13	−0.22**	84.66
17	Basi-bregmatic height	0.21	0.62**	0.38**	0.11	0.44***	0.14*	79.39
5	Cranial base length	0.79	0.31	−0.21	−0.04	0.28***	0.08	84.08
38	Endocranial capacity (cubic root)	0.09	0.61**	0.47***	−0.06	0.44***	0.04	80.64
45	Bizygomatic breadth	0.80	0.25	0.09	0.05	−0.12**	−0.15***	74.16
70	Ramus height	0.05	−0.23	−0.31	0.83***	0.17	−0.09	88.02
71	Minimum ramus breadth	0.67	−0.29	−0.05	0.59***	−0.01	−0.26***	94.52
6	Min. diam. of hum. midshaft	0.27	0.44**	−0.67***	−0.18	−0.42***	0.02	91.89
6	Sag. diam. of fem. midshaft	−0.07	0.62***	−0.39*	0.20	−0.35**	−0.20	74.17
31(2)	Inion-opisthion chord	−0.41	0.31	0.07	−0.02	0.09	−0.37***	41.57
37(2)	Cranial base angle	−0.53	0.44	−0.31	0.30*	−0.01	0.23**	71.42
40	Facial length	0.79	−0.36**	0.18*	−0.15*	−0.14*	0.08	83.77
60	Maxillo-alveolar length	0.73	0.03	0.23**	0.02	−0.32***	0.46***	91.17
55	Nasal height	−0.15	0.75***	0.12	−0.05	−0.34***	0.34***	83.34
2	Maximum pelvic breadth	0.40	0.56**	−0.36**	−0.11	0.08	−0.50***	87.32
54	Nasal breadth	0.01	0.15	−0.44*	0.44**	0.28	0.52***	75.30
Total contribution (%)		21.74	18.57	14.41	10.42	8.31	7.46	80.91
Cumulative proportion (%)		21.74	40.31	54.72	65.14	73.45	80.91	80.91

[1)] Sample size is 19. Number of principal components was determined so that the cumulative proportion of the variances of the principal components exceeded 80%.
[2)] Variable number according to Martin and Saller (1957).
* $P<0.05$; ** $P<0.01$; *** $P<0.001$, according to a two-tailed bootstrap test.

piler used was FTN77 for personal computers, provided by Salford Software Ltd. To increase efficiency during programming and calculation, a GUI for programming, CPad, provided by "kito," was used.

Results

The results of principal component analyses (PCAs) and their rotated solutions for the data sets possibly associated with skeletal muscle mass are shown in Tables 2 to 5. Spearman's rank correlation coefficients between males and females for the variation patterns of factor loadings on the principal components (PCs) and/or rotated factors (Facs) are listed in Table 6.

Remarkable findings are as follows. First, male and female PC IIIs (Tables 2 and 4, respectively) indicate that cranial breadth and basi-

Table 5. Rotated solution of the first six principal components extracted from the correlations between three main neurocranial measurements and the craniofacial and postcranial measurements (excluding costal chord) that are supposedly associated with brain size, muscle mass, antero-posterior head balance, oxygen intake, parturition, or thermoregulation (females).[1)]

	Variable[2)]	Factor loadings					
		Fac I	II	III	IV	V	VI
1	Cranial length	0.02	0.02	−0.14	−0.06	0.94***	0.02
8	Cranial breadth	−0.04	0.59*	−0.08	0.05	−0.66***	−0.21*
17	Basi-bregmatic height	0.07	0.88***	−0.03	−0.04	−0.02	0.14
5	Cranial base length	0.54*	0.42*	−0.36	0.20	0.45**	0.04
38	Endocranial capacity (cubic root)	−0.05	0.88***	0.02	−0.17	−0.02	−0.02
45	Bizygomatic breadth	0.59*	0.32	−0.41	0.23	−0.00	−0.26**
70	Ramus height	−0.08	−0.13	0.02	0.83***	−0.08	0.41***
71	Minimum ramus breadth	0.45	−0.02	−0.09	0.85***	−0.07	−0.11
6	Minimum diameter of humeral midshaft	0.19	−0.22	−0.85**	−0.18	0.21	0.18
6	Sagittal diameter of femoral midshaft	−0.22	0.02	−0.78**	0.00	−0.19	0.21
31(2)	Inion-opisthion chord	−0.57	0.19	−0.15	−0.06	−0.11	−0.13
37(2)	Cranial base angle	−0.46	0.03	−0.23	−0.13	−0.15	0.64***
40	Facial length	0.82*	−0.05	0.10	0.15	0.11	−0.35***
60	Maxillo-alveolar length	0.92***	0.12	−0.06	−0.08	−0.17	0.05
55	Nasal height	0.01	0.32	−0.42	−0.55	−0.38*	0.32**
2	Maximum pelvic breadth	−0.04	0.31	−0.77**	0.17	0.32	−0.23
54	Nasal breadth	0.07	0.07	−0.04	0.20	0.20	0.81***

[1)] Sample size is 19. Cumulative proportion of the variances of the six principal components is 80.91%.
[2)] Variable number according to Martin and Saller (1957).
* $P<0.05$; ** $P<0.01$; *** $P<0.001$, according to a two-tailed bootstrap test.

Table 6. Spearman's rank correlation coefficients between males and females in the patterns of variation of factor loadings of the principal components and/or rotated factors obtained from the data set on cranial and postcranial measurements, some of which are supposedly associated with muscle mass.[1)]

Male	PC I	II	III	IV	V	VI	VII	Fac I	II	III	IV	V	VI	VII
Female PC I	—	—	—	—	—	—	—	—	—	—	—	—	—	—
II	—	.52*	—	—	—	—	—	.53*	—	—	—	—	—	—
III	—	—	.51*	—	—	—	—	—	—	—	—	—	.59*	—
IV	—	—	—	—	—	—	.69**	—	—	—	—	—	—	—
V	—	—	—	.58*	—	—	—	—	—	—	—	—	—	—
VI	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Fac I	—	—	—	—	—	.52*	—	—	—	—	—	—	—	—
II	—	—	—	—	—	—	—	—	—	—	—	—	—	—
III	—	—	—	—	—	—	—	—	—	—	—	—	—	.52*
IV	—	—	—	—	—	—	—	—	—	—	—	—	—	.53*
V	—	—	—	—	—	.57*	—	—	—	—	—	—	—	—
VI	—	—	—	—	—	—	—	—	.62**	—	—	—	—	—

[1)] Only rank correlation coefficients significant at the 5% level are listed here. The signs of rank correlation coefficients are removed because the signs of factor loadings are reversible. The original factor loadings are listed in Tables 2, 3, 4, and 5.
* $P<0.05$; ** $P<0.01$; *** $P<0.001$, according to a two-tailed test.

bregmatic height are positively associated with endocranial capacity and, simultaneously, inversely associated with maximum pelvic breadth and nasal breadth in both sexes. The Spearman's rho between these two PCs is 0.51 ($P<0.05$), as shown in Table 6.

Both male PC IV and female PC V (Tables 2 and 4) show that cranial length and basi-bregmatic height are inversely associated with the sagittal diameter of the femoral midshaft and nasal height. The Spearman's rho between them is 0.58 ($P<0.05$).

The highest rank correlation coefficient in Table 6 is 0.69 ($P<0.01$) between male PC VII (Table 2) and female PC IV (Table 4), which shows that cranial length is inversely associated with mandibular ramus height and minimum ramus breadth.

In Tables 7 and 8, the results of the PCA and its rotated solution for the female data set including costal chord are shown. PC II in Table 7 (or Fac V in Table 8) indicates that nasal height is significantly associated not only with the sagittal diameter of the femoral midshaft, as shown by female PC II (Table 4) and male Fac I (Table 3), but also with costal chord.

The results on body height are shown in Tables 9 to 12. Spearman's rank correlation coefficients between males and females are listed in Table 13. One of the major findings common to both sexes is that there is a factor, as represented by male Fac VI and female PC III (rho of 0.71 between them being significant at the 1% level) , which is significantly correlated with cranial length, maximum tibial length, and maximum pelvic breadth, and, at the same time, inversely correlated with cranial breadth and nasal height (Tables 10 and 11).

Another factor common to males and females (male PC VI in Table 9 and female PC V in Table 11; rho = 0.62, $P<0.05$) reveals that cranial length is significantly associated with endocranial capacity, inion-opisthion chord, maximum pelvic breadth, and, simultaneously, inversely

Table 7. Principal component analysis of the correlations between three main neurocranial measurements and the craniofacial and postcranial measurements (including costal chord) that are supposedly associated with brain size, muscle mass, antero-posterior head balance, oxygen intake, parturition, or thermoregulation (females).[1)]

Variable[2)]		Factor loadings						Total variance (%)
		PC I	II	III	IV	V	VI	
1	Cranial length	0.30	0.22	−0.60***	−0.45***	0.33***	0.19*	84.70
8	Cranial breadth	0.04	0.17	0.83***	0.24**	0.01	−0.26***	84.87
17	Basi-bregmatic height	0.29	0.45**	0.53***	0.04	0.44***	0.22***	80.93
5	Cranial base length	0.85	0.26	−0.11	−0.04	0.23***	0.14*	87.69
38	Endocranial capacity (cubic root)	0.15	0.40*	0.65***	−0.11	0.37***	0.17*	77.52
45	Bizygomatic breadth	0.81	0.04	0.21**	0.06	−0.10*	−0.17***	74.04
70	Ramus height	0.03	−0.14	−0.33	0.81***	0.30*	−0.09	88.51
71	Minimum ramus breadth	0.61	−0.40*	−0.10	0.56***	0.14	−0.28***	94.36
6	Min. diam. of hum. midshaft	0.38	0.54**	−0.43**	−0.01	−0.55***	−0.02	92.15
6	Sagittal diameter of femoral midshaft	0.04	0.65***	−0.08	0.32*	−0.39**	−0.22	73.45
31(2)	Inion-opisthion chord	−0.35	0.38	0.12	−0.06	0.18	−0.36***	44.36
37(2)	Cranial base angle	−0.44	0.57*	−0.12	0.35*	−0.05	0.22**	70.65
40	Facial length	0.71	−0.52***	0.05	−0.16*	−0.12	0.03	82.54
60	Maxillo-alveolar length	0.69	−0.24	0.30**	0.06	−0.37***	0.36***	89.32
55	Nasal height	−0.05	0.66***	0.40**	0.02	−0.39***	0.24**	79.81
4	Costal chord	0.21	0.66***	−0.42***	−0.17	0.26*	−0.11	76.21
2	Maximum pelvic breadth	0.52	0.59**	−0.15	−0.07	0.07	−0.43***	83.47
54	Nasal breadth	0.05	0.21	−0.29	0.51***	0.11	0.60***	76.53
Total contribution (%)		20.61	19.21	14.85	10.00	8.24	7.15	80.06
Cumulative proportion (%)		20.61	39.82	54.67	64.67	72.91	80.06	80.06

[1)] Sample size is 19. Number of principal components was determined so that the cumulative proportion of the variances of the principal components exceeded 80%.

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

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

Table 8. Rotated solution of the first six principal components extracted from the correlations between three main neurocranial measurements and the craniofacial and postcranial measurements (including costal chord) that are supposedly associated with brain size, muscle mass, antero-posterior head balance, oxygen intake, parturition, or thermoregulation (females).[1)]

Variable[2)]		Factor loadings					
		Fac I	II	III	IV	V	VI
1	Cranial length	0.06	0.90***	−0.12	−0.11	0.08	0.08
8	Cranial breadth	−0.02	−0.53	0.67*	0.09	−0.17	−0.27*
17	Basi-bregmatic height	0.04	0.14	0.88***	−0.01	−0.02	0.12
5	Cranial base length	0.54*	0.60***	0.36	0.21	−0.20	0.05
38	Endocranial capacity (cubic root)	−0.01	0.03	0.86***	−0.18	0.04	−0.00
45	Bizygomatic breadth	0.63*	0.13	0.31	0.25	−0.31	−0.26**
70	Ramus height	−0.12	−0.05	−0.12	0.84***	0.01	0.38***
71	Minimum ramus breadth	0.47	−0.04	−0.03	0.84***	−0.01	−0.08
6	Min. diam. of hum. midshaft	0.21	0.35	−0.24	−0.14	−0.82***	0.11
6	Sag. diam. of fem. midshaft	−0.19	−0.03	0.05	0.06	−0.83***	0.10
31(2)	Inion-opisthion chord	−0.57	0.01	0.21	−0.03	−0.15	−0.22**
37(2)	Cranial base angle	−0.52	−0.06	0.08	−0.08	−0.36*	0.54***
40	Facial length	0.83*	0.08	−0.07	0.12	0.18	−0.26**
60	Maxillo-alveolar length	0.91**	−0.16	0.15	−0.06	−0.10	0.10
55	Nasal height	−0.05	−0.19	0.41	−0.47	−0.57**	0.22
4	Costal chord	−0.25	0.74**	0.13	0.03	−0.37*	0.02
2	Maximum pelvic breadth	0.02	0.53	0.26	0.21	−0.59***	−0.31*
54	Nasal breadth	0.04	0.13	0.04	0.19	−0.08	0.84***

1) Sample size is 19. Cumulative proportion of the variances of the six principal components is 80.06%.
2) Variable number according to Martin and Saller (1957).
* $P<0.05$; ** $P<0.01$; *** $P<0.001$, according to a two-tailed bootstrap test.

Table 9. Principal component analysis of the correlations between three main neurocranial measurements and the craniofacial and postcranial measurements (excluding costal chord) that are supposedly associated with brain size, body height, antero-posterior head balance, oxygen intake, parturition, or thermoregulation (males).[1)]

Variable[2)]		Factor loadings						Total variance (%)
		PC I	II	III	IV	V	VI	
1	Cranial length	0.67	0.09***	0.13***	0.53***	0.23***	−0.28***	87.94
8	Cranial breadth	0.46	0.50***	0.35***	−0.45***	0.16**	−0.09	82.68
17	Basi-bregmatic height	0.46	−0.26***	0.69***	0.28***	0.06	0.10*	83.79
5	Cranial base length	0.67*	0.00	0.61***	0.04	0.06	−0.01	83.12
38	Endocranial capacity (cubic root)	0.68*	0.27***	0.29***	0.07	0.09*	−0.14***	65.18
2	Total humeral length	0.84**	−0.27***	−0.07	−0.11	−0.05	0.05	79.14
1	Maximum femoral length	0.88**	−0.35***	−0.18**	−0.14	−0.15**	0.06	96.67
1a	Maximum tibial length	0.80*	−0.30***	−0.33***	−0.24*	−0.05	0.04	90.25
	Stature	0.50	−0.17***	−0.04	−0.20***	−0.61***	−0.18*	73.58
31(2)	Inion-opisthion chord	0.13	−0.33	−0.51**	0.54***	0.05	−0.27***	74.69
37(2)	Cranial base angle	−0.09	−0.80***	0.28	0.30**	0.07	0.30***	91.41
40	Facial length	0.57	0.63***	−0.10	0.19**	−0.18**	0.26***	87.38
60	Maxillo-alveolar length	0.56	0.34***	−0.24***	0.33***	−0.29**	0.49***	92.49
55	Nasal height	0.43	−0.43***	−0.14	−0.46***	0.44***	0.21**	84.86
2	Maximum pelvic breadth	0.73*	0.03	−0.30***	0.00	0.13*	−0.35***	76.54
54	Nasal breadth	0.26	0.32**	−0.42**	0.09	0.57***	0.21**	72.65
Total contribution (%)		34.95	14.20	11.94	8.99	7.30	5.27	82.65
Cumulative proportion (%)		34.95	49.15	61.09	70.08	77.38	82.65	82.65

1) Sample size is 28. Number of principal components was determined so that the cumulative proportion of the variances of the principal components exceeded 80%.
2) Variable number according to Martin and Saller (1957).
* $P<0.05$; ** $P<0.01$; *** $P<0.001$, according to a two-tailed bootstrap test.

Table 10. Rotated solution of the first six principal components extracted from the correlations between three main neurocranial measurements and the craniofacial and postcranial measurements (excluding costal chord) that are supposedly associated with brain size, body height, antero-posterior head balance, oxygen intake, parturition, or thermoregulation (males).[1)]

Variable[2)]		Factor loadings					
		Fac I	II	III	IV	V	VI
1	Cranial length	0.16	0.12	0.75*	0.20	0.15	−0.47***
8	Cranial breadth	0.18	0.53***	0.47	0.05	0.10	0.53***
17	Basi-bregmatic height	0.10	−0.42**	0.79*	0.03	−0.12	0.09
5	Cranial base length	0.26	−0.05	0.83*	0.10	−0.10	0.22***
38	Endocranial capacity (cubic root)	0.24	0.29**	0.68	0.22	0.02	0.04
2	Total humeral length	0.79***	−0.02	0.35	0.19	−0.06	−0.07
1	Maximum femoral length	0.90***	−0.04	0.25	0.23	−0.14	−0.11
1a	Maximum tibial length	0.92***	0.06	0.11	0.17	−0.02	−0.12*
	Stature	0.52**	0.15	0.09	0.17	−0.64***	−0.03
31(2)	Inion-opisthion chord	0.16	−0.10	−0.07	0.02	0.07	−0.84***
37(2)	Cranial base angle	0.09	−0.91***	0.11	−0.21	−0.05	−0.12**
40	Facial length	0.10	0.35***	0.28	0.81***	0.09	0.05
60	Maxillo-alveolar length	0.22	0.01	0.11	0.93***	0.05	−0.08
55	Nasal height	0.76***	−0.17	0.02	−0.24	0.39*	0.20**
2	Maximum pelvic breadth	0.59***	0.41**	0.32	0.09	0.10	−0.36***
54	Nasal breadth	0.16	0.22	−0.00	0.25	0.76***	−0.13*

1) Sample size is 28. Cumulative proportion of the variances of the six principal components is 82.65%.
2) Variable number according to Martin and Saller (1957).
* $P<0.05$; ** $P<0.01$; *** $P<0.001$, according to a two-tailed bootstrap test.

Table 11. Principal component analysis of the correlations between three main neurocranial measurements and the craniofacial and postcranial measurements (excluding costal chord) that are supposedly associated with brain size, body height, antero-posterior head balance, oxygen intake, parturition, or thermoregulation (females).[1)]

Variable[2)]		Factor loadings						Total variance (%)
		PC I	II	III	IV	V	VI	
1	Cranial length	0.17	0.46***	−0.60***	0.16***	0.50***	0.15**	88.54
8	Cranial breadth	0.25	−0.06	0.83***	−0.29***	−0.04	−0.19***	88.08
17	Basi-bregmatic height	0.45	0.28***	0.54***	0.25***	0.30***	−0.29***	80.70
5	Cranial base length	0.29	0.82***	0.05	0.09**	0.09*	0.25***	83.75
38	Endocranial capacity (cubic root)	0.36	0.14***	0.68***	0.06	0.52***	0.04	88.20
2	Total humeral length	0.74*	0.46***	−0.33***	−0.10	−0.09	−0.18***	92.11
1	Maximum femoral length	0.86***	0.09*	−0.22***	−0.03	−0.26***	−0.32***	96.06
1a	Maximum tibial length	0.86**	−0.02	−0.11**	−0.01	−0.34***	0.03	87.26
	Stature	0.63	−0.24***	−0.02	−0.48***	−0.12***	0.39***	85.54
31(2)	Inion-opisthion chord	0.42	−0.43*	−0.02	−0.39***	0.20***	0.32***	65.83
37(2)	Cranial base angle	0.43	−0.51*	−0.13	0.62***	−0.10*	−0.26***	91.96
40	Facial length	−0.39	0.79***	0.04	−0.23***	−0.25***	−0.05	89.36
60	Maxillo-alveolar length	−0.30	0.73***	0.35***	0.15**	−0.42***	0.16***	96.39
55	Nasal height	0.47	−0.17***	0.51***	0.26***	−0.26***	0.34***	75.78
2	Maximum pelvic breadth	0.63	0.42***	−0.17***	−0.21**	0.18**	−0.06	67.59
54	Nasal breadth	0.22	0.06	−0.05	0.74***	−0.05	0.38***	74.09
Total contribution (%)		26.19	19.14	15.02	10.57	7.60	5.93	84.45
Cumulative proportion (%)		26.19	45.34	60.35	70.93	78.52	84.45	84.45

1) Sample size is 18. Number of principal components was determined so that the cumulative proportion of the variances of the principal components exceeded 80%.
2) Variable number according to Martin and Saller (1957).
* $P<0.05$; ** $P<0.01$; *** $P<0.001$, according to a two-tailed bootstrap test.

Table 12. Rotated solution of the first six principal components extracted from the correlations between three main neurocranial measurements and the craniofacial and postcranial measurements (excluding costal chord) that are supposedly associated with brain size, body height, antero-posterior head balance, oxygen intake, parturition, or thermoregulation (females).1)

Variable2)		Factor loadings					
		Fac I	II	III	IV	V	VI
1	Cranial length	0.20	0.04	−0.02	0.04	0.92***	0.06
8	Cranial breadth	0.06	−0.17	0.66*	−0.17	−0.61***	0.10
17	Basi-bregmatic height	0.27	0.20**	0.82**	0.12	−0.02	−0.00
5	Cranial base length	0.33*	0.01	0.31	0.23	0.42***	0.64***
38	Endocranial capacity (cubic root)	−0.04	−0.17*	0.92***	0.10	0.03	0.01
2	Total humeral length	0.90***	−0.06	0.07	−0.02	0.29***	0.13*
1	Maximum femoral length	0.96***	−0.07	0.05	0.06	−0.04	−0.18**
1a	Maximum tibial length	0.81***	−0.32***	0.02	0.30	−0.13	−0.11
	Stature	0.39***	−0.83***	−0.01	0.03	−0.12	−0.06
31(2)	Inion-opisthion chord	0.08	−0.74**	0.07	−0.07	0.00	−0.31***
37(2)	Cranial base angle	0.30**	0.22	−0.01	0.48***	−0.13***	−0.73***
40	Facial length	0.02	0.31**	−0.09	−0.27*	0.04	0.85***
60	Maxillo-alveolar length	−0.06	0.34***	0.05	0.23	−0.17**	0.87***
55	Nasal height	0.14	−0.30**	0.32	0.61***	−0.41***	−0.01
2	Maximum pelvic breadth	0.64***	−0.20*	0.26	−0.11	0.36***	0.14
54	Nasal breadth	0.03	0.11	0.03	0.82***	0.22*	−0.05

1) Sample size is 18. Cumulative proportion of the variances of the six principal components is 84.45%.
2) Variable number according to Martin and Saller (1957).
* $P<0.05$; ** $P<0.01$; *** $P<0.001$, according to a two-tailed bootstrap test.

Table 13. Spearman's rank correlation coefficients between males and females in the patterns of variation of factor loadings of the principal components and/or rotated factors obtained from the data set on cranial and postcranial measurements, some of which are supposedly associated with body height.1)

	Male	PC I	II	III	IV	V	VI	Fac I	II	III	IV	V	VI
Female PC I		—	.73**	—	.56*	—	—	.71**	—	—	—	.50*	—
II		.55*	.54*	—	—	—	—	—	—	.61*	.58*	—	—
III		—	—	—	—	—	—	—	—	—	—	—	.71**
IV		—	—	—	—	.52*	.52*	—	—	—	—	—	—
V		—	—	—	—	.52*	.62*	—	—	.52*	—	—	—
VI		—	—	—	—	—	—	—	—	—	—	—	—
Fac I		.50*	.62*	—	—	—	—	.58*	—	—	—	.53*	—
II		—	—	—	.56*	—	.65**	.58*	—	—	—	—	—
III		—	—	—	—	—	—	—	—	—	—	—	—
IV		—	—	—	—	—	.51*	—	.51*	—	—	—	—
V		—	—	—	—	—	—	—	—	—	—	—	—
VI		—	.72**	—	—	—	—	—	—	.52*	—	—	—

1) Only rank correlation coefficients significant at the 5% level are listed here. The signs of rank correlation coefficients are removed because the signs of factor loadings are reversible. The original factor loadings are listed in Tables 9, 10, 11, and 12.
* $P<0.05$; ** $P<0.01$; *** $P<0.001$, according to a two-tailed test.

associated with cranial base angle, facial length, maxillo-alveolar length, and nasal height.

In Tables 14 and 15, the results of the female data set on body height including costal chord are shown. Fac VI in Table 15 indicates that nasal height and costal chord are significantly associated with the maximum tibial length and stature. These associations except for costal chord are already indicated by female Fac II in Table 12 and male PC IV in Table 9.

The results of the analyses on body mass or weight are shown in Tables 16 to 19. Spearman's rank correlation coefficients between males and females are listed in Table 20. One of the notable findings common to males and females (male PC IV in Table 16 and female PC II in Table 18; rho = 0.50, $P<0.05$) is that cranial breadth, the vertical diameter of the femoral head, talar

Table 14. Principal component analysis of the correlations between three main neurocranial measurements and the craniofacial and postcranial measurements (including costal chord) that are supposedly associated with brain size, body height, antero-posterior head balance, oxygen intake, parturition, or thermoregulation (females).[1)]

Variable[2)]		Factor loadings						Total variance (%)
		PC I	II	III	IV	V	VI	
1	Cranial length	0.28	0.49***	−0.56***	0.16***	0.43***	−0.15**	86.22
8	Cranial breadth	0.13	−0.14**	0.86***	−0.29***	−0.07	−0.19***	91.00
17	Basi-bregmatic height	0.42	0.22***	0.59***	0.25***	0.27***	−0.25***	76.68
5	Cranial base length	0.37	0.80***	0.11**	0.09**	0.17***	0.28***	90.85
38	Endocranial capacity (cubic root)	0.30	0.06	0.71***	0.06	0.48***	−0.20***	87.29
2	Total humeral length	0.77**	0.41***	−0.18***	−0.10	−0.24***	−0.26***	92.62
1	Maximum femoral length	0.84**	0.03	−0.08	−0.03	−0.41***	−0.30***	97.27
1a	Maximum tibial length	0.84**	−0.08*	0.01	−0.01	−0.40***	−0.05	88.36
	Stature	0.64	−0.28***	0.00	−0.48***	−0.01	0.42***	89.32
31(2)	Inion-opisthion chord	0.39	−0.46*	−0.01	−0.39***	0.16***	−0.14***	56.63
37(2)	Cranial base angle	0.40	−0.53*	−0.12	0.62***	−0.12**	−0.06	85.99
40	Facial length	−0.34	0.81***	0.08	−0.23***	−0.26***	−0.06	90.19
60	Maxillo-alveolar length	−0.30	0.72***	0.39***	0.15**	−0.36***	0.20***	94.90
55	Nasal height	0.42	−0.24***	0.52***	0.26***	−0.10	0.55***	88.27
4	Costal chord	0.74*	0.14*	−0.31***	−0.00	0.28***	0.31***	82.81
2	Maximum pelvic breadth	0.67*	0.38***	−0.08	−0.21**	0.14**	0.03	66.11
54	Nasal breadth	0.21	0.04	−0.01	0.74***	−0.08	−0.03	59.68
Total contribution (%)		27.36	18.14	14.72	9.95	7.44	6.17	83.78
Cumulative proportion (%)		27.36	45.50	60.21	70.17	77.61	83.78	83.78

[1)] Sample size is 18. Number of principal components was determined so that the cumulative proportion of the variances of the principal components exceeded 80%.
[2)] Variable number according to Martin and Saller (1957).
* $P<0.05$; ** $P<0.01$; *** $P<0.001$, according to a two-tailed bootstrap test.

Table 15. Rotated solution of the first six principal components extracted from the correlations between three main neurocranial measurements and the craniofacial and postcranial measurements (including costal chord) that are supposedly associated with brain size, body height, antero-posterior head balance, oxygen intake, parturition, or thermoregulation (females).[1)]

Variable[2)]		Factor loadings					
		Fac I	II	III	IV	V	VI
1	Cranial length	0.10	0.01	−0.07	0.11	0.82***	−0.40***
8	Cranial breadth	0.16	0.00	0.72	−0.28	−0.49***	0.23***
17	Basi-bregmatic height	0.18	0.09	0.81*	0.21	0.14*	0.03
5	Cranial base length	0.17	0.56***	0.26	−0.04	0.67***	0.19***
38	Endocranial capacity (cubic root)	−0.04	−0.07	0.92***	−0.00	0.09	0.10
2	Total humeral length	0.86***	0.09	0.08	0.00	0.39***	−0.09
1	Maximum femoral length	0.96***	−0.14	0.08	0.16	0.08	0.04
1a	Maximum tibial length	0.85***	−0.16	0.06	0.18	0.06	0.31***
	Stature	0.40***	−0.41***	−0.04	−0.33	0.19*	0.65***
31(2)	Inion-opisthion chord	0.26**	−0.64*	0.12	−0.24	−0.03	0.10***
37(2)	Cranial base angle	0.21*	−0.42	−0.04	0.78***	−0.08	0.16***
40	Facial length	0.06	0.81***	−0.05	−0.40*	0.04	−0.28***
60	Maxillo-alveolar length	−0.05	0.96***	0.10	−0.03	−0.09	0.08
55	Nasal height	0.07	0.00	0.29	0.30	−0.07	0.83***
4	Costal chord	0.34*	−0.22**	−0.02	0.07	0.75***	0.32***
2	Maximum pelvic breadth	0.50***	0.01	0.19	−0.17	0.57***	0.12
54	Nasal breadth	0.08	0.13	0.08	0.75***	0.11	0.01

[1)] Sample size is 18. Cumulative proportion of the variances of the six principal components is 83.78%.
[2)] Variable number according to Martin and Saller (1957).
* $P<0.05$; ** $P<0.01$; *** $P<0.001$, according to a two-tailed bootstrap test.

Table 16. Principal component analysis of the correlations between three main neurocranial measurements and the craniofacial and postcranial measurements (excluding costal chord) that are supposedly associated with brain size, body mass (weight), antero-posterior head balance, oxygen intake, parturition, or thermoregulation (males).[1)]

Variable[2)]		Factor loadings PC I	II	III	IV	V	VI	VII	Total variance (%)
1	Cranial length	0.76	0.11	0.21*	0.25**	0.41***	−0.02	0.03	86.01
8	Cranial breadth	0.51	−0.36	−0.58**	−0.23*	0.16*	−0.11	−0.20**	85.60
17	Basi-bregmatic height	0.53	0.54*	−0.39	0.31**	−0.10	0.08	0.23***	88.79
5	Cranial base length	0.69	0.21	−0.45**	0.16	0.23**	0.15*	−0.17*	84.90
38	Endocranial capacity (cubic root)	0.73	−0.08	−0.25**	0.10	0.16*	−0.24***	−0.04	69.61
4	Sup. sag. diam. of vert. b. (Th.VIII)	0.66	0.40*	0.22	−0.07	0.27	−0.30*	0.08	82.11
7	Sup. tr. diam. of vert. b. (Th.VIII)	0.68	0.04	0.25	0.27	−0.08	0.31*	0.11	71.43
18	Vertical diameter of femoral head	0.72	0.01	0.08	−0.24**	−0.50***	−0.17	0.02	86.18
1	Talar length	0.63	0.26**	−0.16	−0.37***	−0.38***	−0.14	0.21*	83.86
31(2)	Inion-opisthion chord	0.13	0.26	0.77*	0.01	0.07	−0.35***	−0.34***	91.86
37(2)	Cranial base angle	−0.11	0.85*	0.07	0.23	−0.12	0.29**	−0.18**	92.25
40	Facial length	0.59	−0.62**	0.03	0.28*	−0.05	0.05	−0.27***	88.46
60	Maxillo-alveolar length	0.54	−0.40**	0.22	0.37**	−0.43***	0.18	−0.17	89.34
55	Nasal height	0.29	0.27	−0.01	−0.65**	0.04	0.44*	−0.44***	96.16
2	Maximum pelvic breadth	0.71	−0.09	0.29	−0.32**	0.02	−0.04	0.16	72.63
54	Nasal breadth	0.31	−0.34	0.39	−0.24	0.27	0.48***	0.36**	85.03
Total contribution (%)		33.11	13.99	11.38	8.54	6.48	6.21	4.93	84.64
Cumulative proportion (%)		33.11	47.10	58.49	67.02	73.50	79.70	84.64	84.64

1) Sample size is 29. Number of principal components was determined so that the cumulative proportion of the variances of the principal components exceeded 80%.
2) Variable number according to Martin and Saller (1957).
* $P<0.05$; ** $P<0.01$; *** $P<0.001$, according to a two-tailed bootstrap test.

Table 17. Rotated solution of the first seven principal components extracted from the correlations between three main neurocranial measurements and the craniofacial and postcranial measurements (excluding costal chord) that are supposedly associated with brain size, body mass (weight), antero-posterior head balance, oxygen intake, parturition, or thermoregulation (males).[1)]

Variable[2)]		Factor loadings Fac I	II	III	IV	V	VI	VII
1	Cranial length	0.73***	0.01	0.37	−0.08	−0.23	0.36**	0.05
8	Cranial breadth	0.48	−0.63	−0.29	−0.18	−0.12	−0.11	−0.29**
17	Basi-bregmatic height	0.68**	0.46	−0.25	−0.37	−0.03	−0.08	0.11
5	Cranial base length	0.84***	0.03	−0.17	−0.12	−0.17	−0.04	−0.26*
38	Endocranial capacity (cubic root)	0.68*	−0.31	0.05	−0.28	−0.22	−0.01	0.02
4	Sup. sag. diam. of vert. b. (Th.VIII)	0.59**	0.05	0.51	−0.40	0.12	0.19	−0.00
7	Sup. tr. diam. of vert. b. (Th.VIII)	0.39	0.26	0.09	−0.24	−0.51*	0.41**	0.01
18	Vertical diameter of femoral head	0.14	−0.09	0.13	−0.82***	−0.36	0.03	−0.12
1	Talar length	0.26	0.02	−0.06	−0.87***	0.01	0.02	−0.13
31(2)	Inion-opisthion chord	−0.06	0.14	0.94***	−0.04	−0.08	−0.01	−0.04
37(2)	Cranial base angle	0.13	0.89**	0.11	0.05	0.12	−0.22*	−0.21*
40	Facial length	0.28	−0.42	0.02	0.00	−0.79***	0.10	−0.01
60	Maxillo-alveolar length	0.06	−0.02	0.04	−0.19	−0.91***	0.10	0.06
55	Nasal height	0.07	0.08	0.05	−0.20	0.06	0.14	−0.94***
2	Maximum pelvic breadth	0.24	−0.21	0.27	−0.53	−0.17	0.47**	−0.13
54	Nasal breadth	−0.01	−0.13	−0.02	−0.01	−0.13	0.89***	−0.11

1) Sample size is 29. Cumulative proportion of the variances of the seven principal components is 84.64%.
2) Variable number according to Martin and Saller (1957).
* $P<0.05$; ** $P<0.01$; *** $P<0.001$, according to a two-tailed bootstrap test.

Table 18. Principal component analysis of the correlations between three main neurocranial measurements and the craniofacial and postcranial measurements (excluding costal chord) that are supposedly associated with brain size, body mass (weight), antero-posterior head balance, oxygen intake, parturition, or thermoregulation (females).[1)]

Variable[2)]		Factor loadings						Total variance (%)
		PC I	II	III	IV	V	VI	
1	Cranial length	0.30	0.37***	0.63***	0.16***	−0.44***	0.21***	88.16
8	Cranial breadth	0.32	−0.35***	−0.78***	−0.17**	−0.08	0.19***	89.91
17	Basi-bregmatic height	0.65	−0.16***	−0.35***	0.27***	−0.31***	−0.09**	74.85
5	Cranial base length	0.64*	0.63***	0.04	0.26***	−0.06*	−0.01	87.10
38	Endocranial capacity (cubic root)	0.52	−0.21***	−0.44***	0.24***	−0.47***	0.24***	84.97
4	Sup. sag. diam. of vert. b. (Th.VIII)	0.56	0.47***	0.30***	0.18	0.42***	0.19**	86.86
7	Sup. tr. diam. of vert. b. (Th.VIII)	0.59	0.05	0.08	−0.26***	0.06	−0.27***	49.86
18	Vertical diameter of femoral head	0.73*	−0.21***	0.23***	−0.39***	0.16**	−0.08	82.08
1	Talar length	0.54	−0.44***	0.10*	−0.38***	−0.25***	−0.25***	76.65
31(2)	Inion-opisthion chord	0.10	−0.40*	0.18	0.11	0.24***	0.74***	82.46
37(2)	Cranial base angle	0.16	−0.64***	0.34*	0.36***	0.25***	−0.40***	91.15
40	Facial length	0.08	0.84***	−0.32***	−0.25***	0.04	−0.01	87.74
60	Maxillo-alveolar length	0.23	0.63***	−0.54***	0.16**	0.33***	−0.18***	90.32
55	Nasal height	0.46	−0.44***	−0.29***	0.37***	0.50***	0.03	87.80
2	Maximum pelvic breadth	0.76**	0.08	0.36***	−0.15*	0.00	0.08	74.30
54	Nasal breadth	−0.07	0.07	0.11	0.79***	−0.22*	−0.22***	73.61
Total contribution (%)		22.93	19.05	13.98	10.44	8.31	7.03	81.74
Cumulative proportion (%)		22.93	41.98	55.96	66.40	74.70	81.74	81.74

1) Sample size is 18. Number of principal components was determined so that the cumulative proportion of the variances of the principal components exceeded 80%.
2) Variable number according to Martin and Saller (1957).
* $P<0.05$; ** $P<0.01$; *** $P<0.001$, according to a two-tailed bootstrap test.

Table 19. Rotated solution of the first six principal components extracted from the correlations between three main neurocranial measurements and the craniofacial and postcranial measurements (excluding costal chord) that are supposedly associated with brain size, body mass (weight), antero-posterior head balance, oxygen intake, parturition, or thermoregulation (females).[1)]

Variable[2)]		Factor loadings					
		Fac I	II	III	IV	V	VI
1	Cranial length	0.15	0.06	−0.01	−0.10	−0.92***	0.07
8	Cranial breadth	0.13	−0.03	−0.71*	−0.19	0.57***	0.13*
17	Basi-bregmatic height	0.24	0.16	−0.78**	0.20	−0.05	−0.10*
5	Cranial base length	0.22	0.72***	−0.26	−0.07	−0.48***	−0.10
38	Endocranial capacity (cubic root)	0.07	−0.01	−0.91***	−0.02	−0.08	0.10
4	Sup. sag. diam. of vert. b. (Th.VIII)	0.31	0.73***	0.13	0.06	−0.34**	0.32***
7	Sup. tr. diam. of vert. b. (Th.VIII)	0.65***	0.20	−0.09	0.03	−0.02	−0.16*
18	Vertical diameter of femoral head	0.88***	0.06	−0.07	0.10	0.01	0.15*
1	Talar length	0.73***	−0.34**	−0.29	0.11	0.01	−0.12*
31(2)	Inion-opisthion chord	−0.01	−0.13	−0.06	0.10	−0.02	0.89***
37(2)	Cranial base angle	0.21*	−0.19	0.06	0.91***	0.06	0.03
40	Facial length	−0.01	0.60***	0.05	−0.65***	0.00	−0.30***
60	Maxillo-alveolar length	−0.10	0.85***	−0.13	−0.16	0.25**	−0.26***
55	Nasal height	0.16	0.32**	−0.34	0.57**	0.42***	0.37***
2	Maximum pelvic breadth	0.71***	0.23*	−0.12	0.02	−0.37***	0.20*
54	Nasal breadth	−0.46**	0.14	−0.19	0.51*	−0.40***	−0.22***

1) Sample size is 18. Cumulative proportion of the variances of the six principal components is 81.74%.
2) Variable number according to Martin and Saller (1957).
* $P<0.05$; ** $P<0.01$; *** $P<0.001$, according to a two-tailed bootstrap test.

length, and nasal height are positively associated with one another, and, at the same time, inversely associated with cranial length, facial length, and maxillo-alveolar length.

The pattern of variation in factor loadings of the above male PC IV in Table 16 is also similar to that of female Fac VI in Table 19 (rho = 0.55, $P < 0.05$), as shown in Table 20. These factors indicate that cranial breadth, the vertical diameter of the femoral head, nasal height, and maximum pelvic breadth are positively associated with one another, and, at the same time, inversely

Table 20. Spearman's rank correlation coefficients between males and females in the patterns of variation of factor loadings of the principal components and/or rotated factors obtained from the data set on cranial and postcranial measurements, some of which are supposedly associated with body mass (weight).[1)]

Male	PC I	II	III	IV	V	VI	VII	Fac I	II	III	IV	V	VI	VII
Female PC I	.56*	—	—	—	—	—	—	—	—	—	.81***	—	—	—
II	—	.50*	—	.50*	—	—	—	—	—	—	—	.62*	—	—
III	—	—	.55*	—	—	—	—	—	—	.73**	—	—	—	—
IV	—	—	—	—	—	—	—	—	—	—	—	—	—	—
V	—	—	—	—	—	—	.50*	.55*	—	—	—	—	—	—
VI	—	—	—	—	.58*	.65**	—	—	—	—	—	—	—	—
Fac I	—	—	—	—	—	—	—	—	—	—	.74**	—	—	—
II	—	—	—	—	—	—	—	—	—	—	—	—	—	—
III	—	—	.56*	—	—	—	—	—	—	.69**	—	—	—	—
IV	—	.71**	—	—	—	—	—	—	.65**	—	—	.71**	—	—
V	.55*	—	—	—	.60*	—	.54*	—	—	—	—	—	—	—
VI	—	—	—	.55*	—	.52*	—	—	—	.54*	—	—	—	—

[1)] Only rank correlation coefficients significant at the 5% level are listed here. The signs of rank correlation coefficients are removed because the signs of factor loadings are reversible. The original factor loadings are listed in Tables 16, 17, 18, and 19.

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

Table 21. Principal component analysis of the correlations between three main neurocranial measurements and the craniofacial and postcranial measurements (including costal chord) that are supposedly associated with brain size, body mass (weight), antero-posterior head balance, oxygen intake, parturition, or thermoregulation (females).[1)]

	Variable[2)]	Factor loadings						Total variance (%)
		PC I	II	III	IV	V	VI	
1	Cranial length	0.40	0.37***	−0.57***	0.08*	−0.44***	0.14***	83.47
8	Cranial breadth	0.18	−0.32***	0.83***	−0.08	−0.08	0.23***	88.71
17	Basi-bregmatic height	0.60	−0.14***	0.43***	0.30***	−0.31***	−0.08**	75.11
5	Cranial base length	0.65*	0.64***	0.02	0.25***	−0.06*	−0.02	89.33
38	Endocranial capacity (cubic root)	0.43	−0.19***	0.52***	0.27***	−0.47***	0.21***	83.97
4	Sup. sag. diam. of vert. b. (Th.VIII)	0.61	0.48***	−0.21*	0.13	0.42***	0.16**	86.10
7	Sup. tr. diam. of vert. b. (Th.VIII)	0.58	0.06	0.06	−0.29***	0.06	−0.25***	49.84
18	Vertical diameter of femoral head	0.71*	−0.19***	0.01	−0.46***	0.16**	−0.13*	79.69
1	Talar length	0.54	−0.42***	0.07	−0.41***	−0.25***	−0.25***	76.52
31(2)	Inion-opisthion chord	0.18	−0.40*	−0.19	0.11	0.24***	0.73***	82.89
37(2)	Cranial base angle	0.24	−0.65***	−0.28	0.30***	0.26***	−0.44***	90.63
40	Facial length	−0.01	0.85***	0.33***	−0.21***	0.04	0.03	87.35
60	Maxillo-alveolar length	0.09	0.65***	0.57***	0.20**	0.33***	−0.17**	92.53
55	Nasal height	0.42	−0.42***	0.35***	0.38***	0.51***	0.02	87.80
4	Costal chord	0.70*	−0.03	−0.47***	0.13	−0.01	0.14*	75.05
2	Maximum pelvic breadth	0.80**	0.10*	−0.17**	−0.22**	0.00	0.03	72.18
54	Nasal breadth	−0.03	0.06	−0.18	0.76***	−0.21*	−0.27***	73.02
Total contribution (%)		23.85	17.94	14.55	9.95	7.82	6.73	80.83
Cumulative proportion (%)		23.85	41.79	56.34	66.28	74.10	80.83	80.83

[1)] Sample size is 18. Number of principal components was determined so that the cumulative proportion of the variances of the principal components exceeded 80%.

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

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

Table 22. Rotated solution of the first six principal components extracted from the correlations between three main neurocranial measurements and the craniofacial and postcranial measurements (including costal chord) that are supposedly associated with brain size, body mass (weight), antero-posterior head balance, oxygen intake, parturition, or thermoregulation (females).[1)]

Variable[2)]		Factor loadings					
		Fac I	II	III	IV	V	VI
1	Cranial length	0.07	−0.06	−0.02	0.89***	−0.18	−0.03
8	Cranial breadth	0.17	0.04	0.73*	−0.52*	−0.13	0.19**
17	Basi-bregmatic height	0.22	0.14	0.78**	0.15*	0.21*	−0.08
5	Cranial base length	0.19	0.65***	0.24	0.60**	−0.07	−0.10
38	Endocranial capacity (cubic root)	0.05	−0.02	0.91***	0.09	−0.02	0.07
4	Sup. sagit. diam. of vertebral body (Th.VIII)	0.28	0.65***	−0.14	0.48*	0.07	0.32***
7	Sup. trans. diam. of vertebral body (Th.VIII)	0.65***	0.19	0.09	0.13	0.05	−0.12
18	Vertical diameter of femoral head	0.87***	0.03	0.08	0.05	0.11	0.12
1	Talar length	0.73***	−0.35**	0.30	0.02	0.11	−0.12
31(2)	Inion-opisthion chord	−0.03	−0.19	0.07	0.08	0.09	0.88***
37(2)	Cranial base angle	0.19	−0.23	−0.06	−0.00	0.90***	0.01
40	Facial length	0.01	0.65***	−0.05	0.01	−0.62***	−0.25***
60	Maxillo-alveolar length	−0.07	0.90***	0.14	−0.19	−0.11	−0.22***
55	Nasal height	0.17	0.32**	0.35	−0.27	0.62***	0.40***
4	Costal chord	0.36*	0.02	0.05	0.67**	0.26*	0.31***
2	Maximum pelvic breadth	0.67***	0.16	0.12	0.46	0.01	0.16
54	Nasal breadth	−0.50**	0.08	0.17	0.39	0.47***	−0.28***

[1)] Sample size is 18. Cumulative proportion of the variances of the six principal components is 80.83%.
[2)] Variable number according to Martin and Saller (1957).
* $P<0.05$; ** $P<0.01$; *** $P<0.001$, according to a two-tailed bootstrap test.

associated with basi-bregmatic height, facial length, and maxillo-alveolar length.

In Tables 21 and 22, the results of the female data set on body mass (weight) including costal chord are shown. Fac VI in Table 22 indicates that nasal height and costal chord are significantly associated with cranial breadth, the superior sagittal diameter of the vertebral body (Th. VIII), and inion-opisthion chord, and, at the same time, inversely associated facial length, maxillo-alveolar length, and nasal breadth. These associations except for costal chord are already indicated by female Fac VI in Table 19, although, in males, there is no corresponding PC or rotated factor that has a similar pattern of variation of factor loadings.

Discussion

The purpose of a series of within-group analyses by Mizoguchi (1994, 1995, 1996, 1997, 1998a, b, 1999, 2000, 2001, 2002, 2003a, b, 2004a, b, 2005, 2007b, 2008) was to clarify the interrelationships of three main neurocranial measurements, that is, cranial length and breadth, and basi-bregmatic height, with postcranial measurements, facial measurements, and neurocranial measurements other than the three main neurocranial ones. In these analyses, however, mutual relationships across all the measurements from various bones could not be examined because of the statistical restriction on sample size given the number of variables. Therefore, Mizoguchi (2009) attempted to confirm the overall relationships between the limited number of measurements that have been found to be strongly associated with one or more of the three main neurocranial measurements in each of the previous analyses. As a result, he found that all representative measurements of the vertebral body, humerus, pelvis, femur, and tibia were significantly associated with one another and with cranial length. These findings seem to support the present author's previous hypothesis that variation in cranial length is related to the degree of development of skeletal muscles or body size (Mizoguchi, 2001, 2003a, b, 2004b). In Mizoguchi's (2009) analyses, however, the important measurements of another kind, such as nasal height and the size of the femoral head which have been considered in general to be associated with oxygen intake, body weight, and so on, were not taken into consideration. Therefore, in the present study, some additional measurements that were supposedly associated with factors possibly controlling neurocranial form were newly examined to elucidate their relationships with neurocranial form.

Nasal height and costal chord

Before discussing the associations of neurocranial form with facial and postcranial bones, it would be worth noting the intimate connection between nasal height and costal chord. In all analyses of the female data sets including costal chord (PC II in Table 7, Fac VI in Table 15, and Fac VI in Table 22), nasal height and costal chord were found to be significantly associated with each other and, furthermore, with one or more measurements that were assumed to be correlated with skeletal muscle mass (the sagittal diameter of the femoral midshaft and inion-opisthion chord), body height (maximum tibial length and stature), or body mass (the superior sagittal diameter of the vertebral body of the eighth thoracic vertebra). These findings are compatible with Kean and Houghton's (1990) assertion that there is a clear and direct relationship between increase in airway size, in measures of lung size such as vital capacity, and that in body oxygen demand, as indicated particularly by skeletal muscle mass. In fact, Hall (2005) shows, using anthropometric and physiological data, that a factor representing linear and bulk measures of body size and a factor representing lean body mass explain subjects' variation in nose volume, resting volume of oxygen consumed, and resting ventilation volume better than subjects' sex does, while, during exercise, sex explains the volume of oxygen consumed and ventilation volume better than body size factors do. (She considers that this difference between the conditions of rest and exercise is because hormone-mediated muscularity in males produces greater work output).

Thus, the strong associations found here are considered robust evidence that nasal height and costal chord are appropriate indices of oxygen intake.

Cranial length/breadth, nasal height/breadth, and limb bone lenghts/thicknesses

In the present study, three sets of measurements were constructed because of the statistical restriction on sample size given the number of variables. Each of the three sets includes the measurements possibly relating to skeletal muscle mass, body height, or body weight, and all the other controlling factors mentioned above. Namely, the measurements that are supposedly associated with brain size, oxygen intake, thermoregulation (cold adaptation), humidity regulation, anteroposterior head balance, and parturition are common to all the three sets of measurements.

Across these three sets of measurements, a remarkable tendency was found. Specifically, there was a tendency for cranial length to decrease (and, in most cases, for cranial breadth to increase) whenever nasal height increases. This is clearly shown by male PC IV and female PC V in Tables 2 and 4, respectively, and Fig. 1; male Fac VI and female PC III in Tables 10 and 11 and Fig. 2; and male PC IV and female PC II in Tables 16 and 18 and Fig. 3. The common factor correlated with these measurements is also significantly correlated with the sagittal diameter of the femoral midshaft (Fig. 1) and the vertical diameter of the femoral head and talar length (Fig. 3), but not strongly correlated with limb bone lengths or stature (Fig. 2). Furthermore, this common factor is not consistently correlated in the same direction with endocranial capacity (brain size) or with inion-opisthion chord (skeletal muscle mass/anteroposterior head balance), as shown in Figs. 1, 2, and 3. From these findings, it is inferred that there is a common factor that is relatively strongly associated with cranial length (neurocranial form), nasal height (oxygen intake), the sagittal diameter of the femoral mid-

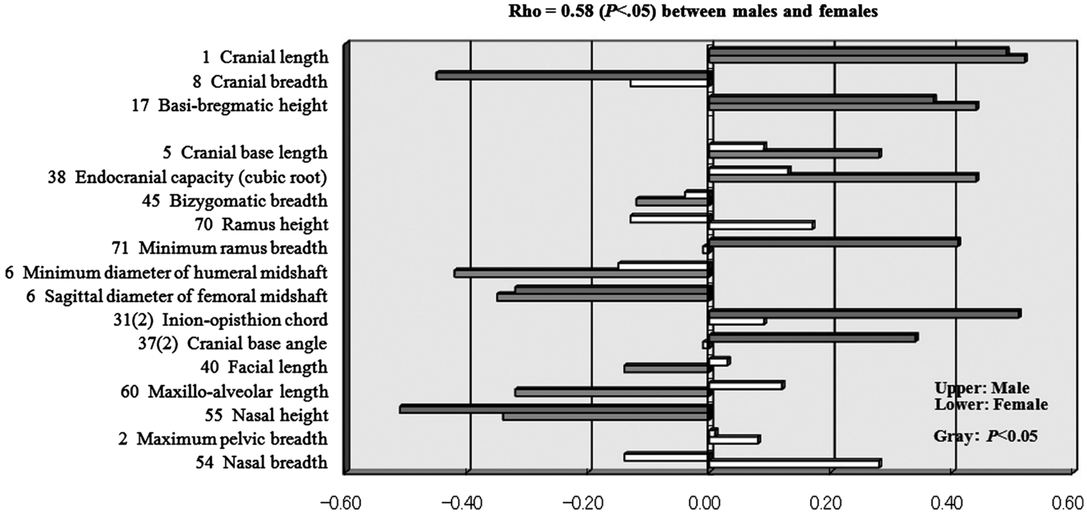

Fig. 1. Factor loadings on male PC IV (Table 2) and female PC V (Table 4) extracted from the data set including the measurements supposedly associated with skeletal muscle mass.

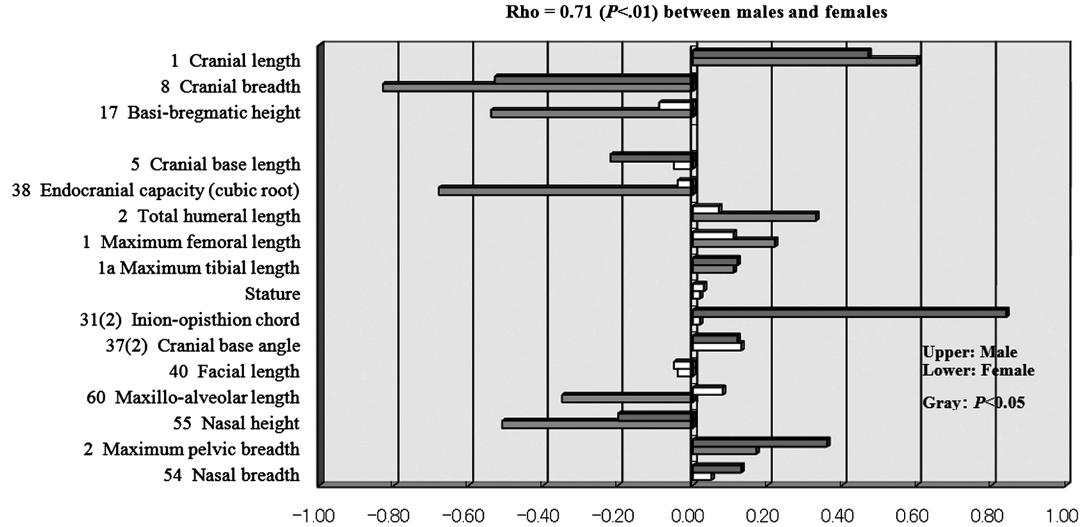

Fig. 2. Factor loadings on male Fac VI (Table 10) and female PC III (Table 11) extracted from the data set including the measurements supposedly associated with body height.

shaft (skeletal muscle mass), and the vertical diameter of the femoral head and talar length (body weight), but not associated with body height. According to Striedter (2005), the gut consumes the most energy, about 70% of the total energy supply, and an average human brain draws about 16% of the entire body's energy consumption. If so, the present findings suggest that heavier individuals who have a longer/thicker gut and a comparatively large amount of skeletal muscle (except the nuchal ones), which consume a relatively large amount of oxygen, tend to have a shorter (and probably wider) neurocranium regardless of brain size and body height.

This suggestion from the within-group analyses does not seem to be inconsistent with the cold

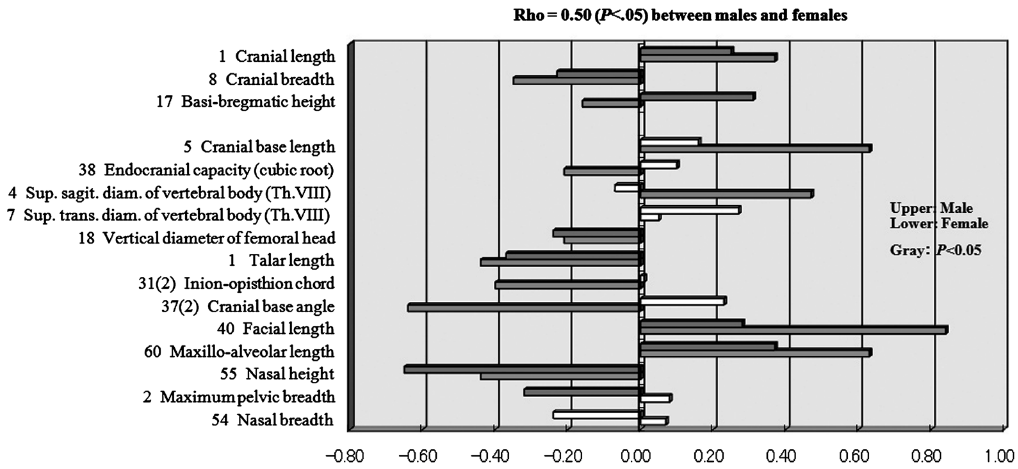

Fig. 3. Factor loadings on male PC IV (Table 16) and female PC II (Table 18) extracted from the data set including the measurements supposedly associated with body mass (weight).

adaptation hypothesis (Coon, 1962). In fact, Crognier (1979, 1981) has reported that, at least in males, mean annual temperature has high inverse correlations with body weight, maximum head breadth, and nose height; and low inverse correlations with standing height and maximum head length. Wells (2012), using data from the literature for nonindustrialized populations excluding Polynesians, also shows that mean annual temperature is significantly negatively correlated with body weight and BMI (body mass index) at the 0.01% level, while, with height, temperature is not correlated in males and weakly negatively correlated in females at the 5% level.

Another remarkable factor relating to femoral head size, frequently used as an indicator of body mass (Ruff, 2002; Weiss, 2010), is suggested by male PC IV in Table 16 and female Fac VI in Table 19. This local common factor indicates that cranial breadth, the vertical diameter of the femoral head, nasal height, and maximum pelvic breadth are positively associated with one another, and they are inversely associated with basi-bregmatic height, facial length, and maxillo-alveolar length.

Male PC IV in Table 16, however, has a pattern of variation of factor loadings similar to those of female Fac VI in Table 19 and of female PC II in Table 18, with Spearman's rho being 0.55 for the former and 0.50 for the latter (Table 20). In general, there is a possibility that a real common factor may be expressed by a PC in a PCA (a factor in a factor analysis) or a rotated factor in another analysis (PCA or factor analysis and a succeeding rotation of the solution). If we have no external criterion for determining the reality of a factor extracted, we are obliged to depend on the reproducibility of a possible factor in two or more samples. In the case of the present study, an indicator of the reproducibility is Spearman's rank correlation coefficient between the patterns of variation of factor loadings of two PCs or rotated factors. As shown above, the Spearman's rank correlation coefficients of male PC IV in Table 16 with female Fac VI in Table 19 and with female PC II in Table 18 are nearly equal. Therefore, both the associations suggested by the two sets of factors, one of which is common, must be interpreted. As the correspondence with female PC II in Table 18 was already discussed above, the correspondence with female Fac VI in Table 19 is discussed here.

First, the positive associations of cranial breadth (neurocranial form) with the vertical diameter of the femoral head (body weight), nasal height (oxygen intake), and maximum pelvic breadth (body breadth) are all acceptable from the viewpoints of the cold adaptation hypothesis (Coon, 1962) and Ruff's (1991, 1993, 1994, 2002) cylindrical thermoregulatory model. In fact, these are, again, well compatible with Crognier's (1979, 1981) report based on male data that mean annual temperature has high inverse correlations with maximum head breadth, body weight, nose height, bi-iliocristal diameter, and bizygomatic breadth (incidentally, mean annual temperature has low inverse correlations with standing height and maximum head length, and a low positive correlation with nose breadth).

The positive association between facial length and maxillo-alveolar length is understandable from their disposition. However, it is difficult to explain the negative associations between these two measurements and the above set of measurements likely relating to cold adaptation. Holton and Franciscus (2008) argue that more variation in nasal breadth can be explained through basion-prosthion length (facial length) rather than anterior palatal breadth dimensions. Male PC IV in Table 16 and female Fac VI in Table 19, however, show no consistent association between facial length and nasal breadth.

Although it is stated in the above section that nasal height and costal chord are significantly associated with each other and with the sagittal diameter of the femoral midshaft and inion-opisthion chord (skeletal muscle mass), maximum tibial length and stature (body height), or the superior sagittal diameter of the vertebral body (body mass), it should be noted that this is indicated by a different common factor (suggested by PC II in Table 7 or Fac V in Table 8, PC II in Table 4 and Fac I in Table 3; Fac VI in Table 15, Fac II in Table 12 and PC IV in Table 9; and Fac VI in Table 22 and Fac VI in Table 19) from the factor suggested by the PCs or Facs discussed in this section (PC IV in Table 2 and PC V in Table 4; Fac VI in Table 10 and PC III in Table 11; and PC IV in Table 16 and PC II in Table 18). Namely, it may be said that there are at least two different common factors that explain two different fractions of the variation of nasal height.

Similarly, the significant associations between cranial length and limb bone lengths and thicknesses indicated by the first PCs extracted in Mizoguchi's (2001, 2003a, b, 2009) multivariate within-group analyses may also be due to another common factor that differs from the above-mentioned two factors that are associated with nasal height, the sagittal diameter of the femoral midshaft, and so on because a so-called general size factor (usually extracted as the first PC) can also be seen in some cases of the present analyses, for example, in Tables 2 and 9, although their factor loadings are hardly statistically significant.

In Mizoguchi's (2007a) bivariate among-group analyses for males and females, Spearman's rank correlation coefficients show that cranial length is significantly associated with some thickness measurements of the humerus (only in females), radius, ulna, femur, tibia, and fibula (only in males), but not associated with any lengths of all these limb bones except the male ulna. In addition, regarding cranial breadth, a similar tendency can be found: it is significantly associated with some thickness measurements of the humerus (only in males), ulna, femur (only in males), and tibia, but not associated with any lengths of all these limb bones but the female ulna. Although it cannot be judged only from these results of bivariate analyses whether or not the factor causing the former associations and the factor causing the latter ones are the same, at least the factor causing the latter associations can be the same factor that is suggested by the PCs or Facs discussed above (PC IV in Table 2 and PC V in Table 4; Fac VI in Table 10 and PC III in Table 11; and PC IV in Table 16 and PC II in Table 18). This interpretation is, of course, possible only when variations among groups are extensions of within-group variations. Recently, Weiss (2010), observing 65 prehistoric Californian Native Americans, reported that the aggregate cross-sectional robusticity of the humerus is significantly positively correlated with cranial length (Spearman's rho $= 0.438$; $P < 0.01$) and body mass calculated from femoral head breadths (rho $= 0.732$; $P < 0.01$), but not correlated with cranial breadth (rho $= 0.225$; $P > 0.05$);

that aggregate upper limb muscle marker value has significant correlations with cranial length (rho = 0.377; $P < 0.01$), cranial breadth (rho = 0.293; $P < 0.05$), and body mass (rho = 0.385; $P < 0.01$); and that aggregate cranial muscle marker value has a significant correlation with cranial length (rho = 0.248; $P < 0.05$), but is not correlated with cranial breadth (rho = 0.074; $P > 0.05$) or with body mass (rho = 0.190; $P > 0.05$). The stronger associations of muscle markers with cranial length than with cranial breadth are very suggestive, especially in interpreting the strong associations between cranial length and limb bone lengths and thicknesses suggested by the first PCs extracted in Mizoguchi's (2001, 2003a, b, 2009) analyses. To confirm the identity of within-group and among-group controlling factors, however, multivariate among-group analyses should further be conducted for a similar set of craniofacial and postcranial measurements.

Inion-opisthion chord and facial/maxillo-alveolar length

Regarding the association between cranial length and inion-opisthion chord, Mizoguchi (2001, 2003a, b, 2004b) hypothesized that the nuchal planum plays an important role as an intermediate between cranial length and postcranial measurements. However, Mizoguchi (2009) confirmed that the inion-opisthion chord was not significantly associated with cranial length or with any postcranial measurements. At that time, therefore, he concluded that inion-opisthion chord at least is not an appropriate measure for the size of the nuchal planum, presumably because of the difficulty in determining a landmark, the inion (Mizoguchi, 2009). However, Mizoguchi (2012a), using the finite element scaling method, found that the degree of occlusal wear on the UM1 was significantly associated with the magnitude of strain at the inion, and Mizoguchi (2012b) showed that those individuals who had heavy UM1 occlusal wear tended to have an anteroposteriorly elongated palate and occipital bone. Here, if craniofacial form changes in response to mechanical stresses from the masticatory and/or nuchal muscles, it is expected that the inion-opisthion chord is correlated not only with cranial length but also with some measurements supposedly associated with skeletal muscle mass or body size (height, breadth, or weight). The above-mentioned male PC VI and female PC V (Tables 9 and 11) show that, while the inion-opisthion chord is significantly associated with cranial length and maximum pelvic breadth (body breadth), it has no consistent association with any of the limb bone lengths and stature in the same direction. In addition, in the other PCAs of the present study, there is no factor that is simultaneously correlated with cranial length, inion-opisthion chord, and the measurements supposedly associated with skeletal muscle mass or body size. For the present, therefore, we may be obliged to accept the above-mentioned conclusion of Mizoguchi (2009).

Also from the viewpoint of anteroposterior head balance (Yamaguchi, 1984), the inion-opisthion chord is expected to have some positive correlation with facial length or maxillo-alveolar length. However, male PC VI and female PC V (Tables 9 and 11) show that the inion-opisthion chord and cranial length have negative associations with facial length and maxillo-alveolar length. Therefore, the present result does not support Yamaguchi's (1984) hypothesis of anteroposterior head balance. However, this problem should be examined further, particularly through mechanical experiments.

Cranial, nasal, and pelvic breadths

Male and female PC IIIs (in Tables 2 and 4, respectively) are significantly correlated with cranial breadth, basi-bregmatic height and endocranial capacity and, simultaneously, inversely correlated with maximum pelvic breadth and nasal breadth. These two PCs from males and females suggest the existence of a local common factor that is, at least, associated with the tendencies for the breadth and height of the brain case to increase and, at the same time, for pelvic and nasal breadths to be narrow with the increase of brain size. It is very difficult, however, to interpret this local common factor. In Mizoguchi's (2005) analyses on the three main neurocranial and many pelvic measurements, the male first PC and a female rotated factor, which have similar patterns of variation of factor loadings, suggested that cranial length has strong associations with maximum pelvic and anterior upper spinal breadths as well as with innominate height. These associations can be confirmed by the male and female first PCs or a general size factor extracted from the three main neurocranial and various representative postcranial measurements (Mizoguchi, 2009), which are partly different from the measurements used in the present study. In addition to this general size factor, there is another local common factor in the results of Mizoguchi's (2009) PCAs, which has high factor loadings of more than 0.60 for cranial breadth and endocranial capacity, but not for pelvic height or breadth, in both males and females, although the factor loadings are not statistically significant. This local common factor, together with the factor suggested by male and female PC IIIs (Tables 2 and 4) in the present study, points to a stronger connection of brain size with cranial breadth than with cranial length.

Another aspect shown by these male and female PC IIIs (Tables 2 and 4) is a significant positive association between maximum pelvic breadth and nasal breadth. Previously, Mizoguchi (1998c, 2005) had considered the interrelationship between cranial length and pelvic breadth as follows: the shapes of the neurocranium and maternal pelvis have been formed, mutually affecting each other, through the human evolutionary process and, in modern human populations, the close correspondence between neurocranial and pelvic forms is fixed as a population characteristic. Later, Mizoguchi (2009) further analyzed the correlations between the three main neurocranial and various representative postcranial measurements, and found that pelvic breadth and height had significant associations not only with cranial length but also with the size of the vertebral body as well as with the lengths and thicknesses of the humerus, femur, and tibia, although they have no association with stature. From these findings, he concluded that bearing body weight might be a more important function of the pelvis than obstetric function, that is, compatibility with the neurocranium in terms of shape.

On the other hand, according to Crognier (1979, 1981), nose breadth has a significant positive correlation with the mean temperature of the hottest month (only in females) and a significant negative correlation with the mean precipitation of the rainiest month in males and, in females, of the driest month. In addition, bi-iliocristal diameter (in males) and maximum head breadth (in males and females) have significant negative correlations with mean annual temperature and the mean temperatures of the coldest and hottest months, and positive correlations with mean annual precipitation (except for female head breadth) and the mean precipitations of the rainiest and driest months. (Incidentally, maximum head length of males and females has a significant negative correlation only with the mean temperature of the hottest month and a significant positive correlation only with the mean precipitation of the driest month.) As the variables regarding temperature are negatively correlated with the variables regarding precipitation in Crognier's samples, the above Crognier's findings imply that populations inhabiting colder and rainier/snowier regions tend to have a narrower nose and a wider head and wider pelvis. The combination of wider pelvis and colder regions is well compatible with Ruff's (1991, 1993, 1994, 2002) cylindrical thermoregulatory model of the human body.

The negative association between nasal breadth and cranial breadth indicated by male and female PC IIIs in Tables 2 and 4 is compatible with Crognier's findings above from among-group comparisons. However, the results indicated by the same PCs that maximum pelvic breadth is positively associated with nasal breadth and negatively associated with cranial breadth do not seem to be consistent with Crognier's findings.

Another factor suggested by male PC VI and female PC V (Tables 9 and 11) shows a positive association between maximum pelvic breadth and cranial length as well as negative associations of maximum pelvic breadth with nasal height and cranial base angle. The former association has already been pointed out by Mizoguchi (2005, 2009). Recently, Takamuku (2011), using Japanese female samples from the Jomon period to the present, directly confirmed that the temporal changes of the pelvic inlet shape were correlated with the temporal changes of the cranial shape. His finding supports the present author's previous hypothesis (Mizoguchi, 2005, 2009) that children of mothers with a wider pelvis tend to have longer heads. The latter associations may be related to thermoregulation or cold adaptation. According to Kean and Houghton (1990), cranial base angle must be correlated with nasal height, and may, therefore, be regarded as another measure of oxygen intake. It should be noted here, however, that Kean and Houghton's (1990) 'cranial base angle' is the angle of nasion-sella-basion, not equivalent to Martin's 'No. 37 (2) cranial base angle' (Martin and Saller, 1957). Nevertheless, Martin's cranial base angle was also found to be significantly positively associated with nasal height. The inverse association between maximum pelvic breadth and nasal height is, however, not compatible with the negative correlation between nasal height and temperature estimated by Crognier (1981) if Ruff's (1991, 1993, 1994, 2002) cylindrical thermoregulatory model, in which the pelvis tends to be wider in colder regions, is correct.

All of the above findings demand more detailed investigation of the functions of nasal height and breadth and of the interrelationships between cranial, nasal, and pelvic breadths.

Summary and Conclusions

Assuming in advance that some craniofacial and postcranial measurements are supposedly associated with some factors controlling neurocranial form, the interrelationships between such measurements and three main neurocranial mesurements, namely, cranial length and breadth and basi-bregmatic height, were newly examined through principal component analyses of within-group data and varimax rotation of the solutions to elucidate the determinants of neurocranial form.

The results show that there is at least a common factor that is relatively strongly associated with cranial length (neurocranial form), nasal height (oxygen intake), the sagittal diameter of the femoral midshaft (skeletal muscle mass), and the vertical diameter of the femoral head and talar length (body weight), but not associated with body height. This suggests that the heavier individuals who have a longer/thicker gut and a comparatively large amount of skeletal muscle (except the nuchal ones), which consume a relatively large amount of oxygen, tend to have a shorter (and probably wider) neurocranium regardless of brain size and body height.

In addition, positive associations were found between cranial breadth (neurocranial form), the vertical diameter of the femoral head (body weight), nasal height (oxygen intake), and maximum pelvic breadth (body breadth). This is acceptable from the viewpoints of the cold adaptation hypothesis and Ruff's cylindrical thermoregulatory model.

In the present multivariate within-group analyses, many other interrelationships between the three main neurocranial and craniofacial/postcranial measurements were found. However, most of them could not simplistically be interpreted from the viewpoints of biomechanics, metabolism, thermoregulation, humidity regulation, parturition, anteroposterior head balance, and so on. In order to clarify the determinants of neurocranial form, multivariate among-group analyses should also be conducted using both morphological measurements and environmental variables.

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