Bull. Natn. Sci. Mus., Tokyo, Ser. D, **27**, pp. 19–36, December 22, 2001

# Strong Associations between Cranial Length and Humeral Measurements: Toward the Solution of the Brachycephalization Problem

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**Abstract** As a step toward clarifying the causes of brachycephalization, it was examined whether there was any association between the neurocranium and the humerus. Principal component analyses based on 30 male and 20 female skeletons show that cranial length is highly significantly associated with many measurements of the humerus, *e.g.*, the circumference of the head, maximum length, minimum circumference of the shaft, minimum deltoid diameter, *etc*. On the other hand, cranial breadth is found to have no consistent association with any of the humeral measurements dealt with. These results support the previous suggestion by the present author that cranial length and cranial breadth tend to have some different kinds of connections with postcranial bones. As a cause for such different tendencies, it is inferred that the general development of skeletal muscles including nuchal ones and those of the upper limbs has more influence on the variation of cranial length than on that of cranial breadth.

**Key words:** Brachycephalization, Neurocranium, Humerus, Principal component analysis, Bootstrap method

Using two kinds of multivariate analysis methods, Mizoguchi (1992) attempted to estimate the degrees of relation between some arbitrarily selected cranial and postcranial measurements in order to clarify the causes of brachycephalization. His preliminary analyses consistently showed that cranial length was highly correlated not only with the size of jaws but also with some postcranial measurements like the body diameters of a lumbar vertebra and the size of the pelvis, and that cranial breadth had a high correlation at least with bizygomatic breadth. These findings made the present author decide to more thoroughly analyze the correlations between three main neurocranial measurements and those of postcranial bones. As a result, it has been shown up to the present that, while cranial breadth has no consistent associations with any measurements of the vertebrae, ribs, or shoulder girdle, cranial length is strongly or considerably associated with the sagittal and transverse diameters of the vertebral bodies, sacral breadths, costal chords, and the size of the scapula (Mizoguchi, 1994, 1995, 1996, 1997, 1998a, b, 1999, 2000a).

In the present study, the correlations between neurocranial and humeral mesurements are further examined toward solving the brachycephalization problem.

## Materials and Methods

The original measurement data reported by Miyamoto (1924, 1925) were used in the present study. They are those of the neurocrania (Miyamoto, 1924) and of the right humeri (Miyamoto, 1925) from the same 30 male and 20 female modern Japanese who lived in the Kinai district. The basic statistics for three main neurocranial measurements, *i.e.,* cranial length, cranial breadth and basi-bregmatic height, are presented in Mizoguchi (1994), and those for humeral measurements are listed in Table 1.

For examining the overall relations between the neurocranial and the humeral

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

| Variable[2] | | Males | | | Females | | |
|---|---|---|---|---|---|---|---|
| | | *n* | Mean | SD | *n* | Mean | SD |
| 1 | Maximum length | 30 | 294.1 | 15.6 | 20 | 273.9 | 12.7 |
| 2 | Total length | 30 | 289.8 | 15.7 | 20 | 269.5 | 12.5 |
| 3 | Breadth of proximal end | 30 | 46.4 | 2.3 | 20 | 41.8 | 2.5 |
| 3(1) | Uppermost transverse diameter | 30 | 49.4 | 3.1 | 20 | 43.9 | 2.7 |
| 4 | Epicondylar breadth | 30 | 57.8 | 2.9 | 20 | 50.5 | 2.6 |
| 4a | Maximum epicondylar breadth | 30 | 58.9 | 3.0 | 20 | 51.5 | 2.7 |
| 7 | Minimum circumference of the shaft | 30 | 64.5 | 4.0 | 20 | 54.6 | 2.4 |
| 10 | Maximum vertical diameter of the head | 30 | 43.1 | 2.5 | 20 | 37.9 | 2.8 |
| 9 | Maximum transverse diameter of the head | 30 | 40.5 | 2.2 | 20 | 35.9 | 2.3 |
| 8 | Circumference of the head | 30 | 132.8 | 9.0 | 20 | 118.3 | 7.6 |
| K12 | Maximum deltoid diameter | 30 | 22.7 | 1.8 | 20 | 19.8 | 1.0 |
| 6a | Minimum deltoid diameter | 30 | 18.0 | 1.9 | 20 | 14.9 | 1.1 |
| 5 | Maximum diameter of the midshaft | 30 | 22.3 | 1.4 | 20 | 19.5 | 0.9 |
| 6 | Minimum diameter of the midshaft | 30 | 17.4 | 1.5 | 20 | 14.6 | 0.9 |
| 7a | Circumference of the midshaft | 30 | 66.3 | 4.3 | 20 | 57.2 | 2.6 |
| 11 | Breadth of the trochlea | 30 | 26.4 | 1.5 | 20 | 22.0 | 1.1 |
| 12 | Breadth of the capitulum | 30 | 17.1 | 0.9 | 20 | 14.6 | 0.8 |
| 13 | Depth of the trochlea | 30 | 25.1 | 1.7 | 20 | 21.6 | 1.3 |
| 14 | Breadth of the olecranon fossa | 30 | 26.4 | 1.6 | 20 | 22.9 | 1.4 |
| 15 | Depth of the olecranon fossa | 30 | 11.4 | 1.0 | 20 | 11.1 | 1.1 |
| 17 | Capito-diaphyseal angle | 30 | 47.0 | 3.8 | 20 | 49.2 | 2.1 |
| 16 | Cubital angle | 30 | 82.4 | 1.9 | 20 | 81.0 | 2.6 |
| 18 | Angle of torsion | 30 | 152.0 | 10.6 | 20 | 162.6 | 7.7 |

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

[2] Variable number according to Martin and Saller (1957) except that with the letter 'K' preceding the number, which is a measurement item no. in Kiyono's (1929) measurement system.

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

In practice, the measurements of the humerus were arbitrarily divided into two groups in carrying out the above multivariate analyses because of a statistical restriction on sample size and the number of variables. Namely, the number of individuals was too small, particularly in females, compared with the total number of variables to obtain the solutions.

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

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

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

## Results

The direct results of principal component analyses and the rotated solutions for the neurocranium and the humerus are shown in Tables 2 to 9. In Tables 10 and 11, Spearman's rank correlation coefficients are listed to show similarities between males and females in the variation patterns of factor loadings on principal components (PCs) or rotated factors.

In these results, it is clear that the first PCs from the first set of measurements (Tables 2 and 4) have highly significant correlations with cranial length and, at the same time, with many humeral measurements in both sexes, and that the first PCs from the second set of measurements (Tables 6 and 8) have relatively high correlations with cranial length and highly significant correlations with some humeral mea-

Table 2. Principal component analysis of the correlation matrix on the first set of measurements of the neurocranium and the humerus from Japanese males.[1]

| Variable[2] | | Factor loadings | | | | | Total variance (%) |
|---|---|---|---|---|---|---|---|
| | | PC I | II | III | IV | V | |
| 1 | Cranial length | .46** | .04 | .60 | –.31 | .10 | 67.66 |
| 8 | Cranial breadth | .40 | –.15 | .32 | .48 | .49 | 75.76 |
| 17 | Basi-bregmatic height | .40 | –.37 | .40 | –.50 | .14 | 72.97 |
| 1 | Maximum length | .80*** | –.33 | –.24 | –.35 | .12 | 93.75 |
| 2 | Total length | .81*** | –.31 | –.23 | –.32 | .11 | 92.38 |
| 3 | Breadth of proximal end | .88*** | –.22 | .06 | .32 | –.10 | 93.84 |
| 3(1) | Uppermost trans. diam. | .82** | –.04 | .16 | .23 | .16 | 78.29 |
| 4 | Epicondylar breadth | .69** | .44 | –.33 | –.05 | .17 | 80.96 |
| 4a | Max. epicondylar breadth | .58** | .44 | –.23 | .15 | .43 | 79.78 |
| 7 | Min. circum. of shaft | .68*** | .56*** | .08 | –.19 | –.02 | 80.95 |
| 10 | Max. vert. diam. of head | .83*** | –.31* | –.01 | .18 | –.24 | 88.70 |
| 9 | Max. trans. diam. of head | .87*** | –.23 | –.10 | .13 | –.22 | 88.95 |
| 8 | Circumference of head | .88*** | –.16 | –.22 | .05 | –.27 | 92.98 |
| K12 | Max. deltoid diameter | .48* | .74** | –.04 | –.20 | –.09 | 82.58 |
| 6a | Min. deltoid diameter | .52*** | .46 | .47 | .15 | –.37 | 86.60 |
| Total contribution (%) | | 48.54 | 13.74 | 8.10 | 7.54 | 5.82 | 83.74 |
| Cumulative proportion (%) | | 48.54 | 62.28 | 70.38 | 77.92 | 83.74 | 83.74 |

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

[2] See the second footnote to Table 1.

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

surements. The reality of these PCs can be confirmed by the Spearman's rank correlation coefficients between males and females (Table 10). No other PCs nor rotated factors correlated with cranial length show any consistent tendencies common to males and females in the variation patterns of factor loadings.

Regarding cranial breadth and basi-bregmatic height, there is no evidence for insisting that they have consistent associations with certain humeral measurements in any of the direct results of the principal component analyses and of the rotated solutions.

## Discussion

In the present study, principal component analyses suggested that cranial length was strongly associated with many humeral measurements: the circumference of the head, maximum transverse and vertical diameters of the head, breadth of the proximal end, uppermost transverse diameter, maximum and total lengths, minimum circum-

Table 3. Solution obtained through the normal varimax rotation of the first five principal components for the correlation matrix on the first set of measurements of the neurocranium and the humerus from Japanese males.[1)]

| Variable[2)] | | Factor loadings | | | | |
|---|---|---|---|---|---|---|
| | | Fac I | II | III | IV | V |
| 1 | Cranial length | .09 | .16 | .70 | .34 | .18 |
| 8 | Cranial breadth | .18 | .03 | .12 | .04 | .84 |
| 17 | Basi-bregmatic height | .24 | –.07 | .81 | –.04 | .05 |
| 1 | Maximum length | .74 | .31 | .45 | –.31 | .01 |
| 2 | Total length | .75 | .31 | .44 | –.28 | .02 |
| 3 | Breadth of proximal end | .83*** | .14 | .10 | .23 | .40 |
| 3(1) | Uppermost trans. diam. | .58 | .32* | .22 | .19 | .51 |
| 4 | Epicondylar breadth | .36 | .82* | –.01 | –.01 | .09 |
| 4a | Max. epicondylar breadth | .20 | .77 | –.07 | –.07 | .39 |
| 7 | Min. circum. of shaft | .24 | .75 | .24 | .37 | .01 |
| 10 | Max. vert. diam. of head | .89*** | .06 | .13 | .19 | .19 |
| 9 | Max. trans. diam. of head | .89*** | .19 | .11 | .15 | .14 |
| 8 | Circumference of head | .91*** | .28 | .07 | .12 | .01 |
| K12 | Max. deltoid diameter | .06 | .81 | .07 | .37* | –.16 |
| 6a | Min. deltoid diameter | .21 | .32 | .12 | .83** | .10 |

[1)] The sample size is 30. The cumulative proportion of the variances of the five principal components is 83.74%.

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

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

ference of the shaft, minimum and maximum deltoid diameters, epicondylar breadth, maximum epicondylar breadth, circumference of the midshaft, minimum and maximum diameters of the midshaft, *etc*. On the other hand, cranial breadth was not found to have consistent associations with any humeral measurements. These results support the previous suggestion by Mizoguchi (2000a) that cranial length and cranial breadth tend to have some different kinds of associations with postcranial bones. If so, what makes such tendencies? In the following, some previous reports are reviewed to seek the causes for them.

### *Cranial length and breadth* vs. *postcranial measurements*

More than 100 years ago, Boas (1899), examining somatometric data for 243 adult males of the Sioux tribe, pointed out that head length was more influenced by stature than head breadth (the correlation coefficient of stature with head length being 0.26 and that with head breadth, 0.09), and that, while head breadth was very closely correlated with facial breadth (cor. coef.=0.52), head length was more closely correlated with facial height (cor. coef.=0.36) than with facial breadth (cor. coef.=0.27).

Table 4. Principal component analysis of the correlation matrix on the first set of measurements of the neurocranium and the humerus from Japanese females.[1]

| Variable[2] | | Factor loadings | | | Total variance (%) |
|---|---|---|---|---|---|
| | | PC I | II | III | |
| 1 | Cranial length | .52** | –.13 | –.66 | 71.51 |
| 8 | Cranial breadth | –.08 | –.09 | .92* | 85.85 |
| 17 | Basi-bregmatic height | .22 | –.66 | .48 | 71.99 |
| 1 | Maximum length | .92*** | .00 | .02 | 85.21 |
| 2 | Total length | .93*** | –.04 | .03 | 85.94 |
| 3 | Breadth of proximal end | .93*** | –.10 | –.02 | 87.89 |
| 3(1) | Uppermost trans. diam. | .94*** | –.08 | .03 | 88.15 |
| 4 | Epicondylar breadth | .85*** | –.31 | –.04 | 81.72 |
| 4a | Max. epicondylar breadth | .86*** | –.31 | .05 | 83.71 |
| 7 | Min. circum. of shaft | .68*** | .54 | .33 | 86.07 |
| 10 | Max. vert. diam. of head | .95*** | –.03 | .01 | 91.24 |
| 9 | Max. trans. diam. of head | .90*** | –.05 | –.08 | 82.38 |
| 8 | Circumference of head | .94*** | –.11 | .01 | 89.81 |
| K12 | Max. deltoid diameter | .48** | .78 | .16 | 86.65 |
| 6a | Min. deltoid diameter | .56*** | .66 | .02 | 75.20 |
| Total contribution (%) | | 58.99 | 13.55 | 11.02 | 83.55 |
| Cumulative proportion (%) | | 58.99 | 72.54 | 83.55 | 83.55 |

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

[2] See the second footnote to Table 1.

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

Further, in seven series, living or cranial, of adult males mainly from native Americans, he found that the correlation between head length and breadth was very low, with the correlation coefficient varying from 0.04 to 0.47 (average=0.18). Here, Boas noted that the "apparent" correlation between head length and breadth might be influenced by various causes. Then, he attempted to eliminate the influences of such causes from the "apparent" correlation by the method developed by Karl Pearson. On the basis of 57 skulls of adult males from the Sioux tribe, he calculated the statistics called "double, triple, and quadruple correlations" between the length, breadth and height of the skull, the bizygomatic diameter of the face, and the cubic root of cranial capacity. From the results, Boas inferred that the diameters of the skull were primarily determined by its capacity; and that cranial height appeared to be most closely associated with cranial capacity, and cranial length, to be least closely related. He presumed that such a weak association between cranial length and capacity was feasible if the development of the frontal sinuses and of the occipital protuberances did not depend upon the form of the inner cavity of the skull but upon the general develop-

Table 5. Solution obtained through the normal varimax rotation of the first three principal components for the correlation matrix on the first set of measurements of the neurocranium and the humerus from Japanese females.[1]

| Variable[2] | | Factor loadings | | |
|---|---|---|---|---|
| | | Fac I | II | III |
| 1 | Cranial length | .53* | –.05 | –.66 |
| 8 | Cranial breadth | –.04 | .05 | .92 |
| 17 | Basi-bregmatic height | .44* | –.45 | .57 |
| 1 | Maximum length | .86*** | .33 | –.05 |
| 2 | Total length | .88*** | .30 | –.03 |
| 3 | Breadth of proximal end | .91*** | .23 | –.07 |
| 3(1) | Uppermost trans. diam. | .90*** | .27 | –.02 |
| 4 | Epicondylar breadth | .90*** | .01 | –.04 |
| 4a | Max. epicondylar breadth | .91*** | .03 | .04 |
| 7 | Min. circum. of shaft | .44* | .80 | .19 |
| 10 | Max. vert. diam. of head | .90*** | .32 | –.05 |
| 9 | Max. trans. diam. of head | .86*** | .26 | –.14 |
| 8 | Circumference of head | .92*** | .23 | –.04 |
| K12 | Max. deltoid diameter | .17 | .92 | –.00 |
| 6a | Min. deltoid diameter | .28 | .81 | –.12 |

[1] The sample size is 20. The cumulative proportion of the variances of the three principal components is 83.55%.

[2] See the second footnote to Table 1.

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

ment of the skeleton which was partly expressed by stature. And, finally, he stressed that the law of compensation, which Virchow had originally formulated for the skulls with premature synostosis of sutures, held good also for the normal skulls analyzed in his investigation, namely, that cranial breadth was compensated by cranial height and length.

Among the above findings and suggestions by Boas (1899), it is particularly interesting that cranial breadth seems to be relatively strongly associated with facial breadth, while cranial length seems to be relatively intimately connected with the external factors from the outside of the skull which may be associated with the formation of the occipital protuberances or stature. The former strong association between cranial and facial breadths has been supported by the principal component analyses of both within-group and between-group covariance matrices on craniofacial measurements (Mizoguchi, 1992, 1998c), and the latter possibility may be buttressed by the present study and the series of principal component analyses for correlations between neurocranial and postcranial measurements by Mizoguchi (1997, 1998a, b, 1999, 2000a). The different ways of connection of cranial length and breadth with

Table 6. Principal component analysis of the correlation matrix on the second set of measurements of the neurocranium and the humerus from Japanese males.1)

| Variable2) | | Factor loadings | | | | | | | Total variance (%) |
|---|---|---|---|---|---|---|---|---|---|
| | | PC I | II | III | IV | V | VI | VII | |
| 1 | Cranial length | .43* | –.08 | .33 | .31 | –.46 | –.20 | –.18 | 67.51 |
| 8 | Cranial breadth | .32 | .01 | .40 | –.44 | –.06 | .52 | –.43 | 91.77 |
| 17 | Basi-bregm. height | .32 | –.19 | .63 | .38 | –.31 | .12 | .18 | 82.99 |
| 5 | Max. d. of midshaft | .78*** | –.28 | –.35 | –.05 | –.02 | –.22 | –.10 | 87.29 |
| 6 | Min. d. of midshaft | .82*** | –.23 | .07 | .21 | .25 | –.14 | –.01 | 85.54 |
| 7a | Circ. of midshaft | .89*** | –.18 | –.11 | .04 | .12 | –.21 | –.12 | 90.90 |
| 11 | Br. of trochlea | .71*** | –.07 | .16 | –.39 | –.03 | .03 | .00 | 69.39 |
| 12 | Br. of capitulum | .63** | .31 | –.20 | –.05 | –.16 | .45 | .22 | 81.82 |
| 13 | Dep. of trochlea | .71*** | –.01 | –.13 | –.10 | .14 | .14 | .52* | 83.25 |
| 14 | Br. of olecr. fossa | .33 | .72 | –.03 | –.26 | .15 | –.32 | –.23 | 87.38 |
| 15 | Dep. of olecr. fossa | .18 | .67 | –.42 | .28 | –.30 | .13 | .08 | 85.29 |
| 17 | Capito–diaph. angle | .24 | .71 | .43 | .21 | .04 | –.14 | –.06 | 81.43 |
| 16 | Cubital angle | .16 | –.11 | –.44 | .52 | .20 | .37 | –.44 | 88.14 |
| 18 | Angle of torsion | –.01 | .16 | .41 | .25 | .73* | .14 | .11 | 81.60 |
| Total contribution (%) | | 29.26 | 12.93 | 11.63 | 8.42 | 7.99 | 6.79 | 6.15 | 83.17 |
| Cumulative prop. (%) | | 29.26 | 42.19 | 53.82 | 62.24 | 70.23 | 77.01 | 83.17 | 83.17 |

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

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

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

postcranial measurements may really be one of the reasons for the low correlation between cranial length and breadth, as noted by Boas (1899).

The independence of head and body measurements as well as of head length and breadth was also discussed in one of early studies based on factor analysis. Thurstone (1947) analyzed a set of seventeen body measurements including two head measurements ("skull length" and "skull breadth") and two arm measurements (arm length to radial styloid and arm length to tip of medius) by the use of an approximate factor analysis method called "centroid method." In result, Thurstone found that the communalities for "skull length" and "skull breadth" were exceptionally low compared with those for other body measurements, and confirmed that the original correlation between the two head measurements was as low as 0.15. Therefore, Thurstone concluded that at least two factors must primarily be concerned with skull dimensions and are relatively independent of the other body measurements analyzed. These conclusions by Thurstone (1947) are compatible with the above suggestions by Boas (1899) and the present results except for the relations between head length and other body measurements.

Table 7. Solution obtained through the normal varimax rotation of the first seven principal components for the correlation matrix on the second set of measurements of the neurocranium and the humerus from Japanese males.[1]

| Variable[2] | | Factor loadings | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Fac I | II | III | IV | V | VI | VII |
| 1 | Cranial length | .27 | .17 | .72** | .05 | –.22 | .05 | –.07 |
| 8 | Cranial breadth | .06 | .06 | .10 | .02 | .03 | .95* | .06 |
| 17 | Basi-bregm. height | .08 | –.14 | .86* | –.11 | .18 | .11 | .10 |
| 5 | Max. d. of midshaft | .88*** | –.02 | .00 | .13 | –.27 | .01 | .11 |
| 6 | Min. d. of midshaft | .84** | .04 | .27 | .12 | .24 | .02 | .08 |
| 7a | Circ. of midshaft | .92*** | .13 | .14 | .12 | –.02 | .08 | .10 |
| 11 | Br. of trochlea | .60 | .09 | .10 | –.26 | –.04 | .45 | .21 |
| 12 | Br. of capitulum | .28 | .13 | .05 | .09 | –.06 | .23 | .81*** |
| 13 | Dep. of trochlea | .60 | –.09 | –.01 | –.21 | .19 | –.00 | .63** |
| 14 | Br. of olecr. fossa | .21 | .87 | –.23 | –.10 | –.02 | .10 | .07 |
| 15 | Dep. of olecr. fossa | –.13 | .48 | .01 | .30 | –.26 | –.25 | .62** |
| 17 | Capito-diaphyseal angle | –.06 | .77 | .34 | –.06 | .30 | .03 | .13 |
| 16 | Cubital angle | .16 | –.10 | –.05 | .91*** | .06 | –.01 | .08 |
| 18 | Angle of torsion | –.02 | .12 | –.00 | .06 | .89*** | .02 | –.06 |

[1] The sample size is 30. The cumulative proportion of the variances of the seven principal components is 83.17%.

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

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

Howells (1951) also noted the fact that head length had always been found to have a relatively low correlation with head breadth. In addition to this, he, obtaining centroid factors from somatological data on 20 measurements of 152 Wisconsin students, found that the first centroid (orthogonal) factor had relatively high loadings for almost all measurements analyzed there. This can be interpreted as a general size factor. But, examining the results closely, it is clear that the loadings of 0.5 or higher are seen only for stature, sitting height, upper arm length, lower arm length, lower leg length, biacromial breadth, head circumference, head length, bizygomatic breadth, and face height. As it is noteworthy here that, among three main head measurements, *i.e.*, head length, breadth and height, the latter two have lower loadings (0.444 and 0.464, respectively) than that for head length (0.576). In other words, of the three main head measurements, head length is most strongly correlated with the factor which is highly correlated with the general body size. This supports Boas' (1899) findings, and is supported by the present results.

Further, there are interesting studies performed from another point of view. They are those on physical differentiation due to migration. Lasker (1946) found that stature and the measurements highly correlated with stature (such as upper and lower

Table 8. Principal component analysis of the correlation matrix on the second set of measurements of the neurocranium and the humerus from Japanese females.[1]

| | Variable[2] | Factor loadings | | | | | | Total variance (%) |
|---|---|---|---|---|---|---|---|---|
| | | PC I | II | III | IV | V | VI | |
| 1 | Cranial length | .42 | –.00 | –.84 | –.06 | .06 | .17 | 91.31 |
| 8 | Cranial breadth | –.13 | .24 | .68 | –.45 | .38 | –.02 | 88.92 |
| 17 | Basi-bregm. height | .04 | .71 | .07 | –.37 | .19 | –.13 | 70.74 |
| 5 | Max. d. of midshaft | .74*** | –.22 | .41 | .08 | –.18 | –.12 | 81.38 |
| 6 | Min. d. of midshaft | .80*** | –.33 | –.01 | .22 | .20 | –.04 | 83.01 |
| 7a | Circ. of midshaft | .89*** | –.24 | .25 | –.02 | –.07 | –.10 | 92.24 |
| 11 | Br. of trochlea | .54* | .05 | .49 | .46 | –.06 | .08 | 76.32 |
| 12 | Br. of capitulum | .65* | .35 | .02 | –.31 | –.17 | .53* | 94.77 |
| 13 | Dep. of trochlea | .67* | .28 | –.30 | –.35 | –.17 | .01 | 77.32 |
| 14 | Br. of olecr. fossa | .42 | .70 | .01 | .00 | –.02 | –.10 | 67.43 |
| 15 | Dep. of olecr. fossa | –.11 | .40 | .10 | .55 | .40 | .54 | 94.02 |
| 17 | Capito-diaph. angle | .49* | –.17 | –.35 | .09 | .68* | –.24 | 91.19 |
| 16 | Cubital angle | –.13 | .57 | –.18 | .52 | –.30 | –.20 | 77.45 |
| 18 | Angle of torsion | –.16 | –.67 | .04 | –.21 | –.05 | .35 | 64.44 |
| Total contribution (%) | | 27.16 | 17.36 | 13.51 | 10.44 | 7.40 | 6.32 | 82.18 |
| Cumulative proportion (%) | | 27.16 | 44.52 | 58.03 | 68.47 | 75.87 | 82.18 | 82.18 |

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

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

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

arm lengths, lower leg length, foot length, *etc.*) of Chinese males born and raised in the United States were significantly greater than those of Chinese immigrants born in China. But, in many of head and face measurements (such as head length, breadth and height, bizygomatic and bigonial diameters, upper facial height, nose breadth, *etc.*) and in a few trunk measurements (such as chest depth, bi-iliac diameter, *etc.*), the differences between American-born and immigrant Chinese were found to be less significant. Froehlich (1970) also reported similar results for the immigrant and subsequent two generations of Japanese-Americans in Hawaii. When the immigrant generation (Issei) is compared with the first American-born generation (Nisei), stature, sitting height, lower leg length, biacromial breadth, and head breadth are shown to have significantly increased both in males and in females, and, on the contrary, nasal breadth is found to have significantly decreased in both sexes. Regarding head length and upper arm length, however, there was no significant change common to males and females.

The above two reports indicate at least that upper arm length does not change parallel to head length, suggesting no common environmental factor concerned with

Table 9. Solution obtained through the normal varimax rotation of the first six principal components for the correlation matrix on the second set of measurements of the neurocranium and the humerus from Japanese females.[1]

| Variable[2] | | Factor loadings | | | | | |
|---|---|---|---|---|---|---|---|
| | | Fac I | II | III | IV | V | VI |
| 1 | Cranial length | −.16 | .56* | −.55 | .01 | .52* | −.05 |
| 8 | Cranial breadth | .00 | −.02 | .94* | −.02 | −.09 | .05 |
| 17 | Basi-bregm. height | −.24 | .34 | .52 | .52 | .04 | −.03 |
| 5 | Max. d. of midshaft | .87 | .13 | .03 | −.02 | .02 | −.17 |
| 6 | Min. d. of midshaft | .71 | .15 | −.18 | −.10 | .51* | .02 |
| 7a | Circ. of midshaft | .86 | .29 | .01 | −.06 | .23 | −.21 |
| 11 | Br. of trochlea | .79 | −.00 | .02 | .17 | −.09 | .32 |
| 12 | Br. of capitulum | .30 | .90*** | .09 | .02 | −.09 | .16 |
| 13 | Dep. of trochlea | .19 | .75 | −.08 | .24 | .19 | −.28 |
| 14 | Br. of olecr. fossa | .17 | .42 | .14 | .66** | .05 | .07 |
| 15 | Dep. of olecr. fossa | −.06 | −.02 | .04 | .17 | .02 | .95*** |
| 17 | Capito-diaphyseal angle | .17 | .02 | −.04 | .03 | .94*** | .01 |
| 16 | Cubital angle | −.10 | −.12 | −.35 | .73** | −.25 | .18 |
| 18 | Angle of torsion | −.03 | −.04 | −.07 | −.79*** | −.09 | −.06 |

[1] The sample size is 20. The cumulative proportion of the variances of the six principal components is 82.18%.

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

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

Table 10. Principal components from the measurements of the neurocranium and humerus which show significantly similar loading variation patterns at the 5% level.[1]

| First variable set | | | | Second variable set | | | |
|---|---|---|---|---|---|---|---|
| Principal components compared | | | Spearman's rank corr. | Principal components compared | | | Spearman's rank corr. |
| Male | | Female | | Male | | Female | |
| I | — | I | 0.92*** | I | — | I | 0.93*** |
| I | — | III | 0.55* | III | — | V | 0.58* |

[1] The similarity in the variation patterns of factor loadings between two PCs, one of which was from males and the other from females, was assessed by Spearman's rank correlation coefficient. The signs of rank correlation coefficients are removed because the signs of factor loadings are reversible. The original factor loadings are listed in Tables 2, 4, 6 and 8.

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

Table 11. Rotated factors for the measurements of the neurocranium and humerus which show significantly similar loading variation patterns at the 5% level.[1]

| First variable set | | | | Second variable set | | | |
|---|---|---|---|---|---|---|---|
| Rotated factors compared | | | | Rotated factors compared | | | |
| Male | | Female | Spearman's rank corr. | Male | | Female | Spearman's rank corr. |
| I | — | I | 0.61* | I | — | I | 0.74** |
| | | | | III | — | V | 0.53* |
| | | | | VI | — | III | 0.55* |

[1] The similarity in the variation patterns of factor loadings between two rotated factors, one of which was from males and the other from females, was assessed by Spearman's rank correlation coefficient. The signs of rank correlation coefficients are removed because the signs of factor loadings are reversible. The original factor loadings are listed in Tables 3, 5, 7 and 9.

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

migration between these two measurements. If so, the strong associations found between cranial length and humeral measurements in the present study should be considered to be caused by another kind of factors common to them. For example, it is possible that such factors are genes controlling all skeletal muscles of the body in general.

Mizoguchi (1998a) stated that the causes for the variation of cranial length should be examined from at least three points of view in the future: the ontogenetic relation of the occipital region with vertebrae, the biomechanical role of vertebrae in bearing elongated or shortened skulls, and the adjustment of the neurocranial form to the maternal pelvic inlet. In addition, Mizoguchi (1999) suggested two more possible causes for the variation of cranial length: the posture of the body associated with the anteroposterior diameter of the thorax and the pleiotropic genes relating to both the cranial vault and the thorax which were rigidly fixed in our ancestral population in considerably ancient times. Furthermore, taking account of the present results on the humerus and Mizoguchi's (2000a) findings on the scapula, we may have to add the general strength of muscles as another possible cause for the cranial length variation to the above. If there is a tendency for the volumes of the nuchal muscles and the group of muscles attached to the humerus and scapula to be strongly correlated because of some common genes which control the basic volume of muscles on the whole, the morphology of both occipital bone and humerus/scapula may vary in parallel. If so, this must generate strong correlations between humeral/scapular measurements and the area of the nuchal region of the occipital bone or cranial length. In fact, this hypothesis may be supported by one of Mizoguchi's (1992) previous analyses. Namely, the principal component analysis by Mizoguchi (1992) based on Hoshi and Kouchi's (1978) anthropometric data of the head, face and body from 104 or more Japanese males shows that the first PC, which is considered a general size factor and especially highly correlated with maximum hip breadth (factor loading=0.78), neck girth (0.77), forearm girth (0.75), thigh girth (0.74), *etc.*, has the factor loadings of 0.49 and 0.69 for upper arm length and girth, respectively, and, at the same time, of 0.38 for head length, of 0.18 for head breadth, and of 0.17 for auricular height. This means that, of the three main head measurements, head length is most strongly associated with the thickness of the neck and limbs. In other words, this suggests that the general development of skeletal muscles is one of the causes for the variation of cranial length. An inference like this is an extension of one of the above suggestions by Baos (1899) and is not incompatible with the Howells' (1951) findings mentioned above.

*Peculiarity of cranial length among craniofacial measurements*

In the preceding section, head or cranial length was confirmed to be most strongly associated with body or postcranial measurements among head or neurocranial measurements. The cranial length with such peculiarity seems also peculiar even among craniofacial measurements. Namely, cranial length has been pointed out by a few authors to be relatively independent of other craniofacial measurements. For instance, Howells (1972), applying factor analysis and discriminant analysis to the same data on 70 measurements and angles for 834 male skulls from 17 different populations, stated that interpopulation differences in recent humans involved the same morphological patterns as did individual variation within populations, and that variations in total cranial length and the breadth of the nasal aperture were notable for their lack of importance in such cranial patterns. This is well compatible with the results of the principal component analyses by Mizoguchi (1998c) for among-group correlations on seven craniofacial measurements. Mizoguchi, testing the statistical significance of the results by the bootstrap method, suggested that cranial breadth, bizygomatic breadth, upper facial height, and nasal height had always changed together in the same directions, whereas cranial length and nasal breadth had changed independently of each other and of the above four measurements for the past 10,000 years in Asia.

From the above two reports, it seems clear that the ways of variation or change of cranial length and nasal breadth are peculiar, or rather different from those of most other craniofacial measurements. As a possible cause for such phenomena, Mizoguchi (2000b) supposed a state where some measurements like cranial length and nasal breadth may in part be controlled by external factors outside the skull, whereas others not. For example, while most of craniofacial characters may be determined mainly by internal factors acting only within the skull, cranial length may partly be controlled by the genetic and/or biomechanical factors associated with the sagittal diameters of the vertebrae and the thorax, *etc.*, as mentioned above, and nasal breadth may be related to respiration, *i.e.*, the size of the body, as suggested by Houghton (1996). And it must be stressed here that the general development of skeletal muscles may also be one of such external causes for the peculiar variation of cranial length because strong associations have been found between cranial length and humeral/scapular measurements, as discussed in the preceding section.

*Cranial length and the occipital bone*

Now, if the above inference is correct, the finding that the variation of cranial length is relatively independent of those of other craniofacial measurements is, at least in part, explained by strong relations with some postcranial characters, such as the size of vertebral bodies (Mizoguchi, 1998a), costal chord (Mizoguchi, 1999), many humeral measurements (the present study), *etc*. But why is cranial length related to such measurements? When cranial length is subdivided into several parts, which part is associated with such postcranial measurements? Some previous studies on this problem are reviewed below.

On the basis of just 100 male or probably male skulls of European derivation, Howells (1957) obtained a correlation coefficient of 0.579 for cranial length and the greatest depth of the curve of the occipital bone on the sagittal contour (Sag Op-lambda/Max subtense). This was higher than that of 0.311 between cranial length and the greatest depth of the curve of the frontal bone (Sag Nas-bregma/Max subtense). This finding suggests that the protrusion of the occipital bone more greatly contributes to cranial length than that of the frontal bone.

Kanda (1968), using the centroid method of Thurstone and Kaiser's varimax rotation method, carried out factor analyses of craniofacial measurements. He analyzed two Japanese male samples consisting of 67 skulls from the Kinai district (30 reported by Miyamoto, 1924, and 37 by Kanda, 1959) and of 57 skulls from the Tohoku district. In the varimax rotated solution for the Kinai sample, he found a factor which was highly correlated with both cranial length and lower occipital arc (inion-opisthion). But, in the case of the Tohoku sample, such a factor was not found in the direct solution of factor analysis nor in the rotated solution.

Howells (1972) conducted an image-covariance common factor analysis of the pooled within-group variance/covariance matrix on 70 measurements and angles for 834 male skulls from 17 different populations, and, then, orthogonally rotated the first 18 factors extracted. As a result, he found that there was no general size factor associated with cranial length, and that total cranial length was of little or no importance in itself and was distributed over several different factors. Of such different factors, however, the one called "a simple factor of occipital angulation" by Howells is very interesting. This factor not only has high loadings of $-0.93$ for occipital angle and of 0.91 for occipital subtense but also has a relatively high loading of 0.47 for glabello-occipital length.

Moreover, Kanda (1973), using some factor analysis method (not described), analyzed the correlations between cranial length and many almost horizontal linear segments defined in the midsagittal plane of the skull, and showed the varimax rotated solution. Although the derivations and sexes of the 119 adult skulls used are also unknown, his results suggest that cranial length co-varies not only with the linear segments in the anterior and middle sections of the skull but also with those in the occipital section to nearly the same extent.

If the above findings by Howells (1957, 1972) and the varimax rotated solution for the Kinai sample by Kanda (1968) are acceptable, it is likely that the strong associations found by the present author between cranial length and humeral/scapular measurements is represented by those between the anteroposterior length of the occipital bone and humeral/scapular measurements. Of course, this should be confirmed in the future by directly analyzing the correlations between occipital and humeral/scapular measurements. But, if so, it is indirect evidence for the above hypothesis that the general strength of skeletal muscles is one of the causes of the cranial length variation.

In addition, Mizoguchi (1984), calculating the cubic roots of the approximate volumes for eight regions of the neurocranium, *i.e.*, right and left frontal, parietal, temporal and occipital regions, had found that the coefficients of variation for the occipital regions were greater than those for the others, and, applying principal component analysis to the same data, had confirmed that the occipital regions varied relatively independent of the other regions. From these findings, he inferred that the occipital region of the neurocranium was of less adaptive significance in modern humans. And, later, regarding the way of variation of the occipital region, Mizoguchi (2000b) further considered that it might be associated not only with the variation of the nuchal muscles but also with the variation in the optical function which might be correlated with the morphological variation of the visual cortex located in the occipital lobe of the brain. But these, especially the latter speculation, should of course be confirmed in the future.

In 2001, another interesting evidence was reported by Kajikawa (2001). He, using elliptical Fourier functions analysis, examined morphological changes in the base of the skull of Japanese males from the prehistoric Jomon period through the medieval Kamakura and Muromachi to the early modern Edo period. In result, Kajikawa stated that the relative position of the foramen magnum moved forward from the Jomon to the Muromachi period, and backward after that. Although he analyzed the total variation composed of the variation due to chronological change and the variations within groups, his result may indicate that the longer heads of medieval people (Kamakura and Muromachi), which is the well-known fact (Suzuki, 1956; Nakahashi, 1987), have the anteroposteriorly longer area of muscular attachment on the occipital bone. If so, Kajikawa's finding is also well compatible with the above hypothesis that the general development of skeletal muscles is one of the causes of the cranial length variation.

## Summary and Conclusions

Multivariate analyses on the neurocranium and the humerus showed that cranial length was highly significantly associated with many measurements of the humerus. But cranial breadth was not consistently associated with any humeral measurements. These findings support the previous suggestion by the present author that cranial length and cranial breadth tend to have some different kinds of connections with postcranial bones. As a cause for such different tendencies, it was inferred that the general development of skeletal muscles including nuchal ones and those of the upper limbs has intensive influence on the variation of cranial length, but not on that of cranial breadth.

## Acknowledgments

I wish to express my deepest appreciation to Dr. Bin Yamaguchi and Dr. Yousuke Kaifu of the National Science Museum, Tokyo, for their invaluable comments on this manuscript.

This work was partly supported by a Grant-in-Aid for Scientific Research (C) from the Japan Society for the Promotion of Science (No. 13640716).

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