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Ecological correlations between neurocranial and limb bone measurements: toward the solution of the brachycephalization problem

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Abstract As a step toward clarifying the causes of brachycephalization, ecological correlations, i.e. inter-group correlations, between neurocranial and limb bone measurements were investigated using Spearman's rank correlation coefficient on the basis of 24 male and 23 female samples from prehistoric, historic and modern Japanese populations. It was found that there were significant ecological correlations common to males and females between cranial length and some thickness measurements of the radius, ulna, femur, and tibia, but no consistent correlations between cranial breadth and any limb bone measurements. These findings are compatible with one of the tendencies seen in previous intra-group analyses, and suggest that brachycephalization or dolichocephalization associated with cranial length may have been partly caused by diachronic change in the degree of development of skeletal muscles. This, in turn, may have occurred in accordance with diachronic changes in quality and quantity of available nutrition, physical activity, etc.

Key words: cranial length, limb bone measurements, secular change, inter-group covariation, rank correlation coefficient

Introduction

In many regions of the world, the phenomena of brachycephalization and dolichocephalization have been reported (Weidenreich, 1945). In both eastern and western Japan, the same phenomena are well known. From 1500 years ago until approximately 1000 years ago, dolichocephalization proceeded, and then, between 1000 and 500 years ago, the contrasting trend towards brachycephalization began and is continuing up to the present day (Suzuki, 1956; Nakahashi, 1987).

The causes of brachycephalization or dolichocephalization, however, still remain to be elucidated, although various hypotheses have been proposed (Mizoguchi, 1992a, 2000b). An overriding problem is the difficulty in obtaining adequate information on the environmental factors that may have promoted changes in growth and development, including climate and diet, from archeological sites. The acquisition of data relating to such paleoenvironmental factors together with cranial data would enable us to examine how the shape of the skull changed through the process of adaptation to these paleoenvironmental factors. But, as already stated, given the lack of paleoenvironmental data, it is difficult at present to examine the parallel tendencies in diachronic changes.

As the next best alternative, therefore, we may estimate ecological correlations (Yasuda, 1969), i.e. inter-group correlations, between cranial measurements and environmental variables in modern human populations because contemporary geographic variations in cranial measurements may be the results of adaptation to some environmental factors. Beals (1972), Guglielmino-Matessi et al. (1979), Beals et al. (1983, 1984), Mizoguchi (1985), Kouchi (1986), and others, have investigated ecological correlations between the head shape and climatic variables, and confirmed that brachycephalic people live in higher latitudes or colder regions.

In addition to climatic factors, we can also consider the possibility that some biomechanical factors, e.g. the degree of development of the masticatory apparatus, body build, posture, may determine, at least partly, the shape of the skull. In this case, we usually need some experiments to test the influence of biomechanical stresses on cranial shape in fossil and modern humans. These experiments may be made by mechanical methods (e.g. Endo, 1966; Molnar and Ward, 1977; Ward and Molnar, 1980) or by computer simulations such as finite element analysis (e.g. Ishida et al., 2002).

Furthermore, evidence of biomechanical factors may also be found by investigating the degree of parallelism in diachronic changes or the degree of geographical covariation between the neurocranium and the splanchnocranium or postcranial skeleton. This can be evaluated by estimating ecological correlations between them. Even so, a considerable effort is needed to collect data from many regions or archeological sites in biomechanically different environments to conduct such analyses. Again, this is not so easy.

Mizoguchi (1992a), therefore, first attempted to examine intra-group, rather than inter-group, correlations to find evidence for any biomechanical factors. This is, of course, an indirect way of searching for the causes and mechanisms of inter-group variations or changes such as brachycephaliza-

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tion because what an ecological or inter-group correlation means is not necessarily the same as that of the corresponding intra-group correlation.

Nevertheless, if we can find a significant intra-group correlation between a substructure of the skull and a substructure of a postcranial bone, and if the functional significance of the postcranial substructure is easy to understand from a biomechanical viewpoint, we may be able to specify the functional or adaptive significance of the relevant cranial substructure. With such an expectation, the present author (Mizoguchi, 1992a) analyzed intra-group correlations between the neurocranium and postcranial bones, and found some strong associations. These findings stimulated the author to further analyze intra-group correlations between the neurocranium and individual postcranial bones in more depth. A series of such analyses (Mizoguchi, 1994, 1995, 1996, 1997, 1998a, b, 1999, 2000a, 2001, 2002, 2003a, b, 2004a, 2005) showed very interesting results. However, as repeatedly stated, these are all based on intra-group correlations of bone measurements. Therefore, we need to confirm whether or not these intra-group associations are consistent with the corresponding inter-group associations among the same measurements. The present study is a preliminary examination to confirm this point.

In order to understand the background of the present study, the results of the above series of multivariate analyses on intra-group correlations are, first, briefly presented below.

Previous analyses on intra-group correlations

The statistical methods used in the previous analyses are basically principal component analysis (Lawley and Maxwell, 1963; Okuno et al., 1971, 1976; Takeuchi and Yanai, 1972) and Kaiser's normal varimax rotation method (Asano, 1971; Okuno et al., 1971). The significance of factor loadings was tested by the bootstrap method (Efron, 1979a, b, 1982; Diaconis and Efron, 1983; Mizoguchi, 1993) in the analyses of 1996 and thereafter. The data used are raw measurements of the same skeletons of 30 male and 20 female modern Japanese who had lived in the Kinai district, previously reported by Miyamoto (1924, 1925, 1927a, b), Hirai and Tabata (1928a, b), Kikitsu (1930a, b), and Okamoto (1930).

The results of the previous research are summarized in Table 1, and the main results on the upper and lower limb bones are illustrated (Figure 1, Figure 2, Figure 3, Figure 4, Figure 5, Figure 6, Figure 7, Figure 8, Figure 9). The horizontal bars in the figures designate factor loadings on principal components or rotated factors. Those variables that have statistically significant loadings are highly associated with one another through the relevant principal component or rotated factor. The analyses were carried out separately for males and females in order to confirm the repeatability of results. If the results for both sexes are found to be significant, they are considered more reliable.

The findings of the previous analyses are as follows. First, basi-bregmatic height is significantly associated with the transverse diameters of the vertebral foramina of almost all the vertebrae and with the size of the talus. Second, cranial breadth is not consistently associated with any measurements of the postcranial bones. Finally, cranial length has strong associations with many postcranial measurements: the sagittal and transverse diameters of the vertebral bodies, sacral breadth, costal chords, many humeral measurements, pelvic breadth and height, femoral length and thickness, and tibial length and thickness.

On the basis of these findings, Mizoguchi (2004b) developed a model to explain how the significant intra-group associations between cranial length and postcranial measurements contribute to the solution of the brachycephalization problem, and tentatively concluded as follows.

1) There are at least three possible causes for brachycephalization or dolichocephalization: diachronic changes in the amount of skeletal muscles, body size (eventually the same as the amount of skeletal muscles because the muscles bearing the weight of the body increase as the body size increases), and pelvic form.
2) Although it is speculative, possible causes for secular changes in body size and/or in the degree of development of skeletal muscles may be diachronic changes in quality and quantity of available nutrition, physical activity, etc.

Materials and Methods

All the data used are those reported by previous authors. They are the mean values of cranial and postcranial measurements in 24 male and 23 female samples from prehistoric, protohistoric, medieval, early modern, and modern populations in various regions of Japan (Appendices 1 and 2).

Since the main purpose of the present study is to find the causes and mechanisms for brachycephalization/dolichocephalization, the best approach would be to analyze a series of samples from different times in a certain region. However, in practice, it is not easy to collect such samples. Therefore, the present author decided to preliminarily analyze those data which came from various ages of various regions, such as shown in Appendices 1 and 2, even if they contained not only diachronic but also geographic variations. Of course, in interpreting the results based on such data, the possibility of influence from both kinds of variations should be taken into account. However, we may at least be able to get information on causative factors of some types of inter-group covariations between cranial and postcranial bone measurements, whether the causative factors diachronically change or geographically vary. In other words, the present study is based on the assumption that human individuals or populations of any kind necessarily respond to certain factors, such as biomechanical ones, in the same manner, whether they are of modern or ancient times or even if they are living in any region.

To examine inter-group correlations, the so-called ecological correlations (Yasuda, 1969), i.e. correlations based on mean values in various populations, were estimated by using Spearman's rank correlation coefficient, ρ (Siegel, 1956). Although the power-efficiency of Spearman's rank correlation is about 91% of Pearson's product–moment correlation (Siegel, 1956), the former can be used even when the distributions of variables are not normal. Since the distribution of a mean value across populations is generally not normal,

Table 1. Summary of previous multivariate analyses on intra-group correlations between neurocranial and postcranial measurements by the present author

Postcranial bones analyzed together with neurocranium	Measurements strongly associated with cranial length	Measurements strongly associated with cranial breadth	Measurements strongly associated with basi-bregmatic height	Reference
Cervical vertebrae	—	—	Transverse diameter of vertebral foramen, and ventral and central heights of vertebral body	Mizoguchi (1995, 1996)
Thoracic vertebrae	Sagittal and/or transverse diameters of vertebral body	—	Sagittal or transverse diameters of vertebral foramen, and sagittal and/or transverse diameters of vertebral body	Mizoguchi (1997)
Lumbar vertebrae	—	—	Sagittal and transverse diameters of vertebral foramen	Mizoguchi (1994)
Sacrum	Anterior superior transverse arc, anterior superior breadth, and maximum breadth	—	—	Mizoguchi (1998b)
All vertebrae	Superior, middle, and inferior sagittal and transverse diameters of vertebral body	—	Transverse diameter of vertebral foramen	Mizoguchi (1998a)
Sternum	—	—	—	Mizoguchi (1999)
Ribs	Costal chords (in females)	—	—	Mizoguchi (1999)
Scapula	—	—	—	Mizoguchi (2000a)
Clavicle	—	—	—	Mizoguchi (2000a)
Humerus	Maximum length, total length, breadth of proximal end, uppermost transverse diameter, epicondylar breadth, maximum epicondylar breadth, minimum circumference of shaft, maximum vertical and transverse diameters of head, circumference of head, maximum and minimum deltoid diameters, etc.	—	—	Mizoguchi (2001)
Ulna	—	—	—	Mizoguchi (2002)
Radius	—	—	—	Mizoguchi (2002)
Pelvis	Height of innominate, maximum pelvic breadth, and anterior upper spinal breadth	—	—	Mizoguchi (2005)
Femur	Maximum length, bicondylar length, maximum trochanteric length, physiological trochanteric length, diaphyseal length, sagittal diameter at midshaft, transverse diameter at midshaft, circumference at midshaft, sagittal subtrochanteric diameter, transverse subtrochanteric diameter, maximum subtrochanteric diameter, and minimum subtrochanteric diameter	—	—	Mizoguchi (2003b)
Patella	—	—	—	Mizoguchi (2003a)
Tibia	Total length, maximum length, medial condyle-malleolus length, distance between superior and inferior articular surfaces, maximum breadth of proximal end, maximum breadth of distal end, sagittal diameter of distal end, maximum diameter at midshaft, transverse diameter at midshaft, sagittal diameter at nutrient foramen, and transverse diameter at nutrient foramen	—	—	Mizoguchi (2003a)
Fibula	—	—	—	Mizoguchi (2003a)
Talus	—	—	Length, breadth, height, medial height, lateral height, length of trochlea, middle breadth of trochlea, anterior breadth of trochlea, and posterior breadth of trochlea	Mizoguchi (2004a)
Foot bones except talus	—	—	—	Mizoguchi (2004a)

The strong associations shown here were observed in both sexes except for the ribs.

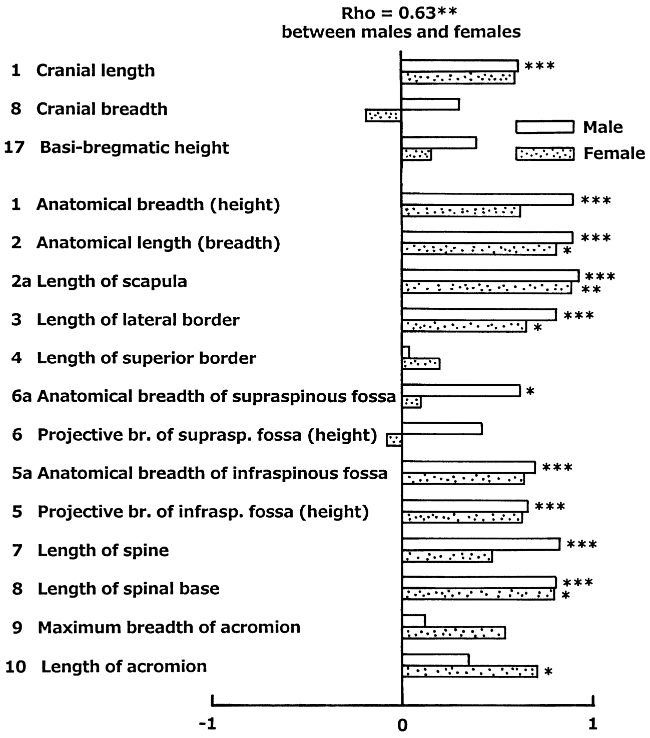

Figure 1. Factor loadings of the first principal components extracted from neurocranial and scapular measurements for males and females. The numbers preceding variables are those according to Martin and Saller (1957). Drawn on the basis of the data shown in Mizoguchi (2000a). * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$ (significance of factor loadings was tested by a two-tailed bootstrap test).

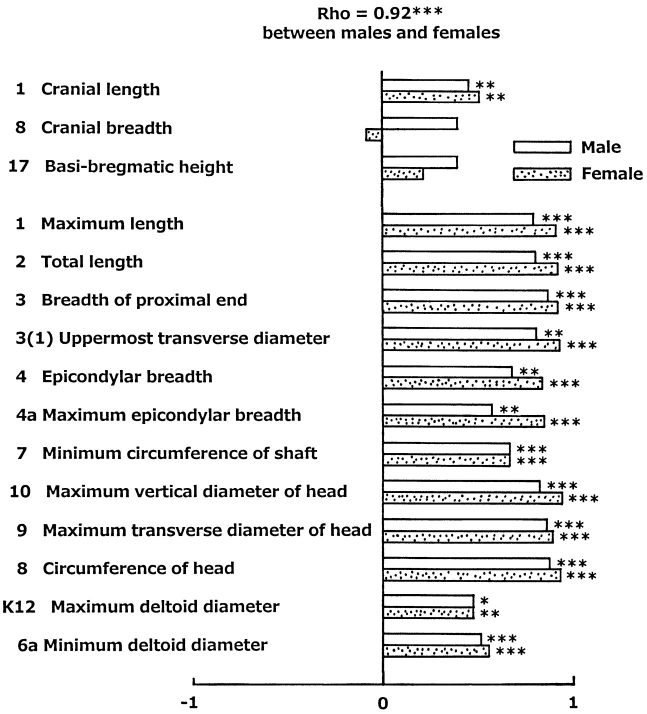

Figure 2. Factor loadings of the first principal components extracted from neurocranial and humeral measurements for males and females. Bare-numbered variables are those according to Martin and Saller (1957), and those prefixed with the letter K are according to Kiyono's (1929) measurement system. Drawn on the basis of the data shown in Mizoguchi (2001). * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$ (significance of factor loadings was tested by a two-tailed bootstrap test).

rank correlation coefficients are useful for detecting some tendency of inter-group covariation between variables.

Calculations of the rank correlation coefficients were executed with the mainframe HITACHI MP5800 System at the Computer Centre, University of Tokyo, using the RKCNCT program written in FORTRAN by the present author.

Results

Spearman's rank correlation coefficients were calculated to estimate ecological or inter-group correlations between cranial and postcranial measurements. The results for males and females are shown in Table 2 and Table 3, respectively.

The present study is a preliminary one based on a small number of samples. In order to find reliable tendencies at the early stage of research, it would be better to compare the results from two or more independent sets of samples. From such a viewpoint, the reproducibility of a tendency was examined using two sets of samples, i.e. male and female. The findings common to males and females are as follows:

1) Postcranial measurements having significant correlations with cranial length: sagittal diameter of the radial shaft, the dorsovolar diameter of the ulna, the sagittal midshaft diameter of the femur, the maximum midshaft diameter of the tibia, the sagittal diameter of the tibia at the nutrient foramen, the circumference of the tibia at the nutrient foramen, and the minimum circumference of the tibial shaft. All of these are positively correlated with cranial length.
2) Postcranial measurements having significant correlations with cranial breadth: none.
3) Postcranial measurements having significant correlations with basi-bregmatic height: minimum circumference of the radial shaft, the maximum length of the femur, the sagittal diameter of the femoral midshaft, and the circumference of the tibial midshaft. All of these are inversely correlated with basi-bregmatic height.

Discussion

The present inter-group analyses (Table 2, Table 3) confirm previous intra-group analyses (Mizoguchi, 1997, 1998a, b, 1999, 2000a, 2001, 2002, 2003a, b, 2005) in demonstrating that while cranial length is systematically associated with postcranial bone measurements, cranial breadth is not. Although basi-bregmatic height is also consistently associated with some postcranial bone measurements, it is not significantly associated with cranial length or breadth in the inter-group analyses (Table 2, Table 3). In the following sections, therefore, the findings on basi-bregamatic height and cranial breadth are briefly discussed first, and then those on cranial length are reported in more depth.

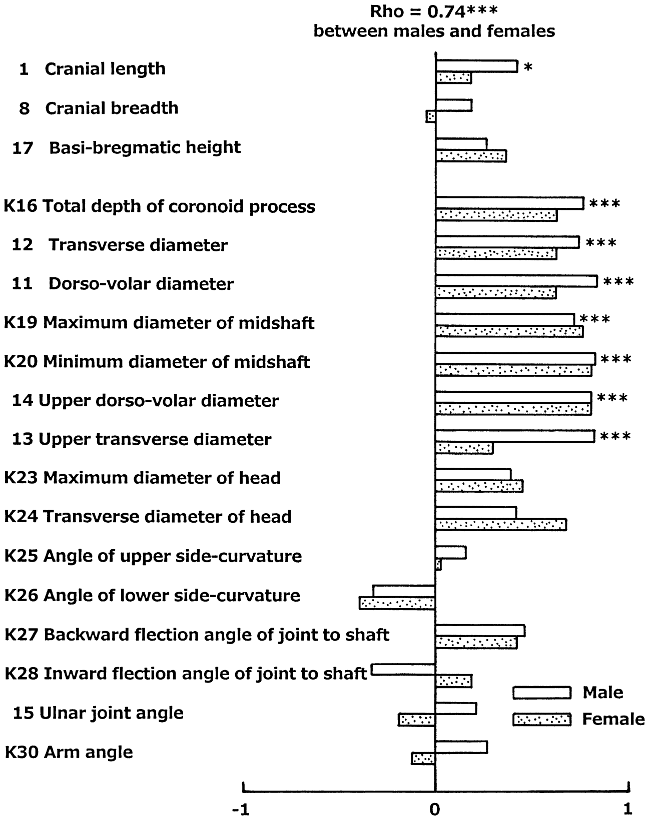

Figure 3. Factor loadings of the first principal components extracted from neurocranial and ulnar measurements for males and females. Bare-numbered variables are those according to Martin and Saller (1957), and those prefixed with the letter K are according to Kiyono's (1929) measurement system. Drawn on the basis of the data shown in Mizoguchi (2002). * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$ (significance of factor loadings was tested by a two-tailed bootstrap test).

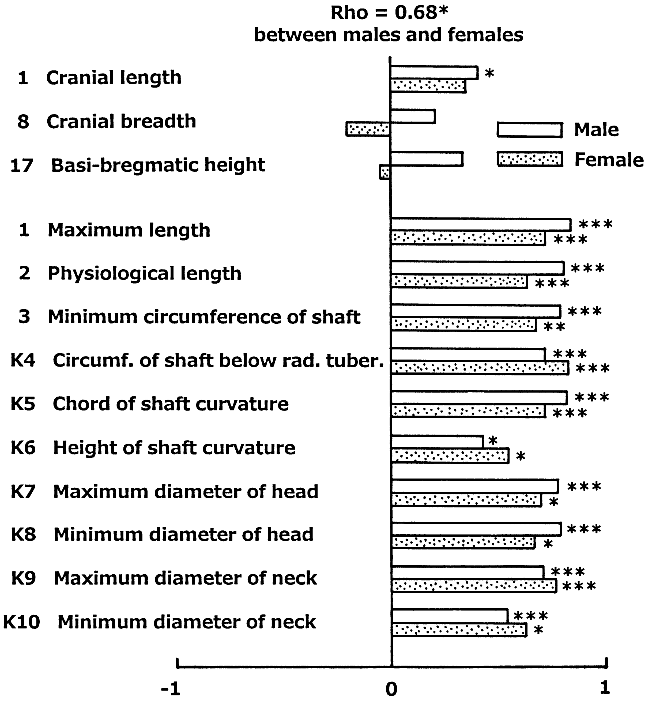

Figure 4. Factor loadings of the first principal components extracted from neurocranial and radial measurements for males and females. Bare-numbered variables are those according to Martin and Saller (1957), and those prefixed with the letter K are according to Kiyono's (1929) measurement system. Drawn on the basis of the data shown in Mizoguchi (2002). * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$ (significance of factor loadings was tested by a two-tailed bootstrap test).

Ecological correlations of basi-bregamatic height with postcranial measurements

Previous intra-group analyses have shown that basi-bregmatic height is significantly associated with the transverse diameters of the vertebral foramina (Mizoguchi, 1998a) and with many talar measurements (Mizoguchi, 2004a). Unfortunately, in the present inter-group analysis there were too few data available to examine the associations between cranial, vertebral, and foot bone dimensions. Therefore, the correspondence between intra-group and inter-group analyses is not investigated here for the measurements of these bones.

However, it is interesting that, in the present inter-group analyses, some other postcranial measurements, which have not been found to be associated with basi-bregmatic height in the intra-group analyses, are inversely correlated with this measure of neurocranial height at the 5% level of significance (Table 2, Table 3). These measurements are the thickness of the radius, femur, and tibia as well as the length of the femur. This implies that those people whose skeletal muscles are well developed tend to have low neurocranial heights. For the present, however, it seems that this tendency is not concerned with brachycephalization or dolichocephalization because the ecological correlations of basi-bregmatic height with cranial length and breadth are not statistically significant (Table 2, Table 3).

Cranial breadth changes in parallel with stature?

As already stated, from the present preliminary inter-group and previous intra-group analyses on bone measurements, it seems clear that cranial breadth is not systematically associated with any of postcranial measurements.

Angel (1944) reported serial cross-sectional data of Greeks from several ancient periods. The present author, using this data, calculated Spearman's rank correlation coefficients between a few cranial measurements and stature. The results showed that neither cranial breadth nor cranial index was significantly correlated with stature (Table 4), though this may be due to the small number of samples. In any case, this is not inconsistent with the inter- and intra-group analyses reported by the present author.

Abbie (1947) suggested, on the basis of 50 male and 38 female samples from various populations across the world, that there was no significant ecological correlation between the cephalic index and stature in either males or females. Although the correlations seem to have been estimated by using Pearson's product–moment correlation coefficient, this finding is again not inconsistent with the inter- and intra-group analyses reported by the present author.

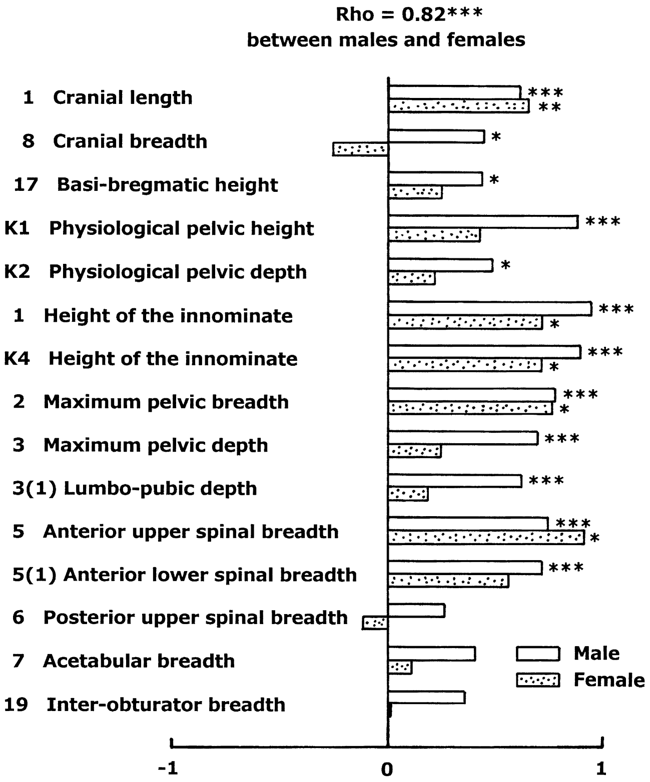

Figure 5. Factor loadings of the first principal component for males and the first rotated factor for females extracted from neurocranial and pelvic measurements. Bare-numbered variables are those according to Martin and Saller (1957), and those prefixed with the letter K are according to Kiyono's (1929) measurement system. Drawn on the basis of the data shown in Mizoguchi (2005). * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$ (significance of factor loadings was tested by a two-tailed bootstrap test).

Further, Jantz et al. (1992) found a similar tendency in the inter-population variation of Native American tribes. Jantz et al. (1992) carried out two multivariate analyses of the anthropometric data collected by Franz Boas and others. One was a canonical analysis of the variation–covariation among 64 tribes in northern America, and the other was a principal component analysis of the variance–covariance matrix among 38 tribes in the American Northwest. In both analyses, the sexes were pooled or standardized before the data were analyzed. As a result, the canonical analysis revealed that the first canonical variate, highly correlated with standing and shoulder heights (canonical structure coefficient = 0.74 and 0.73, respectively), had a relatively low negative correlation with head width (–0.42). The principal component analysis showed that the first principal component, highly correlated with standing and shoulder heights (element of eigenvector = 0.86 and 0.74, respectively, in females, and 0.82 and 0.72 in males), had a very low negative correlation with head width (–0.10 in females and –0.01 in males). These results suggest a low inter-group association between head breadth and stature.

Table 5 and Table 6 list Spearman's rank correlation coefficients between some head and body measurements. These were calculated by the present author based on male data from eight native groups in Sarawak, Malaysia (Kurisu, 1970), and male and female data from 16 regions in Russia (Ivanovsky, 1923). In these cases it can again be seen that head breadth or cephalic index is not always significantly correlated with stature or arm/leg length.

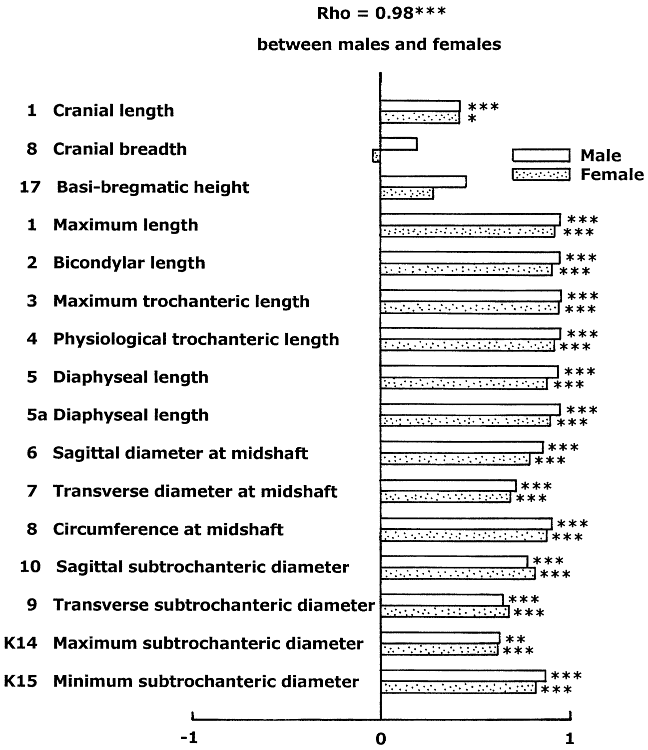

Figure 6. Factor loadings of the first principal components extracted from neurocranial and femoral measurements for males and females. Bare-numbered variables are those according to Martin and Saller (1957), and those prefixed with the letter K are according to Kiyono's (1929) measurement system. Adopted from Mizoguchi (2003b). * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$ (significance of factor loadings was tested by a two-tailed bootstrap test).

In contrast, Suzuki (1969, 1981) presented an illustration of the cranial index changing in parallel with stature in the post-Aeneolithic Yayoi period of Japan, and Cameron et al. (1990) found a similar association between the cranial index and femur length in native South African males from 1880 to 1934.

Kouchi (2000, 2004) argued on the basis of somatometric data that both head breadth and cephalic index of Japanese had a similar pattern of secular change to that of stature over the last 100 years, and suggested that nutritional improvement in prenatal and early postnatal life was a plausible cause for the increased soft-tissue component of head breadth and, in turn, for brachycephalization. In fact, Spearman's rank correlation coefficients calculated by the present author on the basis of Kouchi's data (Kouchi, 2004) show that the head breadth of females and the cephalic indices of both sexes are significantly correlated with stature (Table 7).

Further, Buretic-Tomljanovic's (2004) illustrations suggest that, as body height increased, cephalic index and head breadth tended to decrease from 1939 to 1983 in Croatian males. This means an inverse correlation between cranial

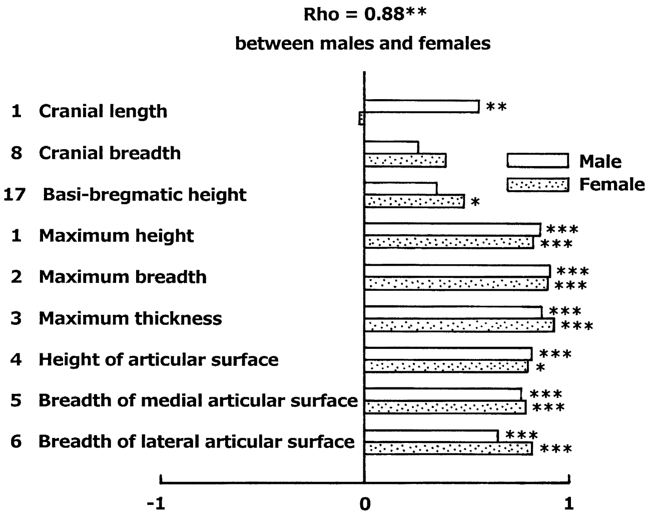

Figure 7. Factor loadings of the first principal components extracted from neurocranial and patellar measurements for males and females. The numbers preceding variables are those according to Martin and Saller (1957). Drawn on the basis of the data shown in Mizoguchi (2003a). * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$ (significance of factor loadings was tested by a two-tailed bootstrap test).

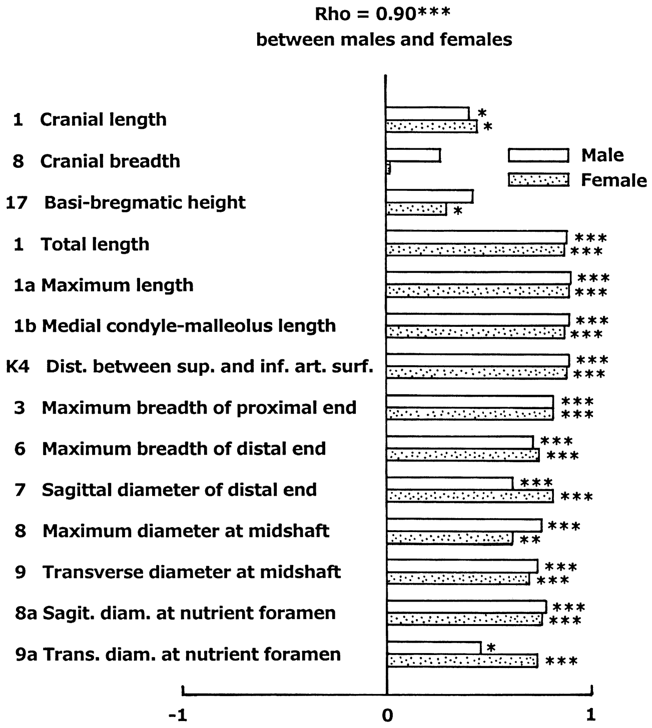

Figure 8. Factor loadings of the first principal components extracted from neurocranial and tibial measurements for males and females. Bare-numbered variables are those according to Martin and Saller (1957), and those prefixed with the letter K are according to Kiyono's (1929) measurement system. Adopted from Mizoguchi (2003a). * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$ (significance of factor loadings was tested by a two-tailed bootstrap test).

breadth and body height, which is inconsistent not only with the above findings by Suzuki (1969, 1981), Cameron et al. (1990), and Kouchi (2000, 2004) but also with the present preliminary inter-group analysis.

Therefore, regarding the inter-group association between cranial breadth and stature, more detailed examinations are needed.

Cranial length changes in parallel with stature?

The series of intra-group analyses conducted by the present author have shown that cranial length is strongly associated with many postcranial measurements, especially the size of the vertebral bodies, the sagittal diameter of the thorax, both the length and thickness of limb bones, and the breadth of the pelvis (Mizoguchi, 2004b). In the present preliminary inter-group analyses (Table 2, Table 3), it was also found that cranial length was significantly associated with many limb bone measurements. In this case, however, all of the measurements were related to limb bone thickness, not to their length. If these results of the inter-group analyses are correct, they imply that, while brachycephalization/dolichocephalization may be associated with the diachronic changes in the thickness of limb bones, these phenomena may not be related with the secular change of limb bone length or stature.

Kouchi (2000), using some serial cross-sectional data of Japanese, reported that head length was not significantly correlated with stature either in males or in females. Although she did not describe what kind of correlation coefficient was used for analyzing such diachronic data, the Spearman's rank correlation coefficients calculated by the present author using Kouchi's data (Kouchi, 2004) certainly show the same tendency (Table 7). This is compatible not only with the inter-group analyses based on the present and Angel's (1944) bone measurement data (Table 2, Table 3, Table 4) but also with those based on Kurisu's (1970) and Ivanovsky's (1923) anthropometric data (Table 5, Table 6).

However, the above-mentioned analyses by Jantz et al. (1992) suggest that there may be a relatively high inter-population association between cranial length and stature. The canonical analysis reveals that the first canonical variate, highly correlated with standing and shoulder heights (canonical structure coefficient = 0.74 and 0.73, respectively), has a higher correlation with head length (0.64) than with head width (–0.42). Furthermore, the principal component analysis reveals that the first principal component, highly correlated with standing and shoulder heights (element of eigenvector = 0.86 and 0.74, respectively, in females, and 0.82 and 0.72 in males), has a somewhat higher correlation with head length (0.33 in females and 0.43 in males) than with head width (–0.10 in females and –0.01 in males). Furthermore, Buretic-Tomljanovic's (2004) illustrations also suggest that head length increased in parallel with body height from 1939 to 1983 in Croatian males.

Cranial length may change in response to the development of muscles

As already stated, both intra-group (Mizoguchi, 2004b) and inter-group (Table 2, Table 3) analyses showed that cranial length was significantly associated with limb bone thickness.

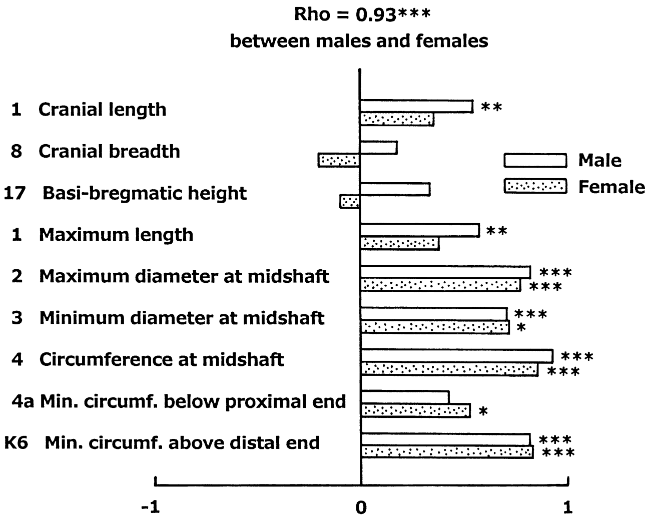

Figure 9. Factor loadings of the first principal components extracted from neurocranial and fibular measurements for males and females. Bare-numbered variables are those according to Martin and Saller (1957), and those prefixed with the letter K are according to Kiyono's (1929) measurement system. Adopted from Mizoguchi (2003a). * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$ (significance of factor loadings was tested by a two-tailed bootstrap test).

Unfortunately, there are few studies on ecological correlations between cranial and postcranial measurements or between head and extremity dimensions. However, a principal component analysis, which was carried out by Mizoguchi (1992a) on the basis of the intra-group correlation matrices on anthropometric data from Japanese males reported by Hoshi and Kouchi (1978), shows some interesting results. Namely, the first principal component, which is most highly correlated with head length among three main head measurements (factor loading = 0.38), is also highly correlated with maximum hip breadth (factor loading = 0.78), neck girth (0.77), forearm girth (0.75), thigh girth (0.74), foot length (0.72), calf girth (0.71), upper arm girth (0.69), etc. On the other hand, this principal component has relatively low correlations with the lengths of the extremities, with the factor loadings being 0.49 for upper arm length, 0.59 for forearm length, 0.36 for thigh length, and 0.56 for tibial height. Although these results were not statistically tested, there is nevertheless a tendency for the thickness of the neck and extremities to have relatively high correlations with head length. If so, this is not inconsistent with the present preliminary inter-group analyses on bone measurements (Table 2, Table 3).

A possible factor that immediately comes into mind as a cause for the associations between cranial or head length and the limb bone or extremity thickness dimensions is the general development of skeletal muscles. Mizoguchi (2001) noted the suggestion of Howells (1957, 1972) and Kanda (1968) that cranial length varies in parallel with the anteroposterior length of the occipital bone, and the degree of skeletal muscle development is considered to be associated both with the size of attachment area of the nuchal muscles on the occipital bone, i.e. the anteroposterior length of the occipital bone, and with the limb bone thickness, which resists the pressure and tension from skeletal muscles. If this inference is correct, it is likely that such a brachycephalization/dolichocephalization phenomenon as produced via cranial length, if any, has been affected, at least in part, by the diachronic change in the degree of general development of skeletal muscles, which, in turn, may have occurred in accordance with the diachronic changes in quality and quantity of available nutrition, physical activity, etc.

This hypothesis is supported by a significantly high ecological correlation between head length and body weight obtained on the basis of Kouchi's (2004) serial cross-sectional data, though only in females (Table 7).

It should be noted here, however, that, even if a diachronic change of available nutrition or physical activity is a cause for brachycephalization or dolichocephalization, it is only one of many possible causes. Okazaki (2004) suggested the possibility that the average shape of the neurocranium for a population may be determined during the early stages of growth. If so, physical activity may not be the principal cause but a modifier acting during the adult stage. However, a poor or rich nutrition may influence the shape of the skull during the early stages of growth, as was suggested by Shimada (1974), or the potential for future increases in body size, though the mechanism is unknown.

It can be said for the present, therefore, that a diachronic change in average neurocranial shape may be caused by a change in gene composition generated through adaptation to an environmental factor (e.g. a shift of temperature from high to low) and/or by a coincident influence of a certain environmental factor on most members of a population with no change in gene composition (e.g. a change in the diet preference of young people from hard meat to soft hamburgers). In order to seek concrete causes for the variation in the head form, Mizoguchi (2006) attempted to estimate ecological correlations between the cephalic index and the ways of subsistence, such as hunting-gathering, cattle breeding, agriculture, etc., using data from modern humans. However, he was unable to find any significant associations between them. In the future, therefore, much more detailed analyses are required to determine the concrete causes for brachycephalization or dolichocephalization.

In passing, Goldstein (1939) stated in his growth study of the head that the mean cephalic index in females was usually more or less higher than in males, and ascribed this to the sex difference in the development of the glabella region. In the above discussion, only the attachment area of nuchal muscles has been treated as a major possible cause for the variation in cranial length. However, this is not a confirmed fact. In the future, therefore, it must also be determined whether it is the nuchal planum or the glabella region that plays a more important role in causing the variation of cranial length, especially in the context of the association with the development of skeletal muscles.

Association between cranial length and pelvic breadth

What should be noted finally is a strong association between cranial/head length and pelvic/hip breadth. Although pelvic measurements were not examined in the present preliminary inter-group analyses of Japanese bone data, such a

Table 2. Spearman's rank correlation coefficients between cranial and postcranial measurements based on the mean values of 24 male samples from prehistoric, protohistoric, medieval, early modern, and modern populations in Japan

	1 Cranial length	8 Cranial breadth	17 Basi-bregmatic height
SKULL			
1 Cranial length	—		
8 Cranial breadth	−0.06 (24)	—	
17 Basi-bregmatic height	−0.10 (22)	−0.40 (22)	—
HUMERUS			
1 Maximum length	0.38 (17)	−0.36 (17)	0.05 (15)
2 Total length	0.39 (17)	−0.28 (17)	−0.24 (15)
5 Maximum diameter of midshaft	0.31 (20)	0.54 (20)*	−0.30 (18)
6 Minimum diameter of midshaft	0.18 (20)	0.12 (20)	−0.04 (18)
7 Minimum circumference of shaft	0.17 (20)	0.14 (20)	0.02 (18)
7a Circumference of midshaft	0.16 (17)	0.28 (17)	−0.60 (16)*
RADIUS			
1 Maximum length	0.42 (14)	0.38 (14)	−0.77 (13)**
2 Physiological length	0.51 (13)	0.36 (13)	−0.71 (12)*
3 Minimum circumference of shaft	0.27 (17)	0.44 (17)	−0.53 (16)*
4 Transverse diameter of shaft	0.40 (18)	0.02 (18)	−0.31 (16)
4a Transverse midshaft diameter after Gieseler	0.21 (14)	0.11 (14)	−0.52 (13)
5 Sagittal diameter of shaft	0.67 (18)**	−0.16 (18)	0.01 (16)
5a Sagittal midshaft diameter after Gieseler	0.42 (14)	0.11 (14)	−0.26 (13)
ULNA			
1 Maximum length	0.38 (12)	0.27 (12)	−0.64 (11)*
2 Physiological length	0.64 (14)*	0.20 (14)	−0.71 (13)**
3 Minimum circumference	0.32 (16)	−0.23 (16)	−0.07 (15)
11 Dorso-volar diameter	0.50 (18)*	0.50 (18)*	−0.42 (16)
12 Transverse diameter	0.12 (18)	−0.01 (18)	−0.32 (16)
FEMUR			
1 Maximum length	0.25 (21)	0.21 (21)	−0.47 (20)*
2 Bicondylar length	0.34 (21)	0.22 (21)	−0.39 (19)
6 Sagittal diameter at midshaft	0.44 (23)*	0.46 (23)*	−0.46 (21)*
7 Transverse diameter at midshaft	0.27 (23)	−0.20 (23)	−0.14 (21)
8 Circumference at midshaft	0.40 (21)	0.26 (21)	−0.43 (20)
9 Transverse subtrochanteric diameter	0.42 (20)	−0.03 (20)	−0.18 (20)
10 Sagittal subtrochanteric diameter	0.09 (20)	0.43 (20)	−0.22 (20)
TIBIA			
1 Total length	0.34 (15)	0.10 (15)	−0.49 (14)
1a Maximum length	0.32 (16)	0.19 (16)	−0.50 (15)
8 Maximum diameter at midshaft	0.62 (19)**	0.54 (19)*	−0.41 (17)
8a Sagittal diameter at nutrient foramen	0.51 (18)*	0.26 (18)	−0.37 (17)
9 Transverse diameter at midshaft	0.16 (14)	−0.13 (14)	0.20 (13)
9a Transverse diameter at nutrient foramen	0.02 (14)	−0.49 (14)	0.58 (13)*
10 Circumference at midshaft	0.47 (18)*	0.42 (18)	−0.60 (17)*
10a Circumference at nutrient foramen	0.67 (17)**	0.23 (17)	−0.29 (16)
10b Minimum circumference of shaft	0.64 (20)**	0.22 (20)	−0.25 (18)
FIBULA			
1 Maximum length	0.20 (10)	−0.25 (10)	−0.39 (10)
2 Maximum diameter at midshaft	0.59 (16)*	0.47 (16)	−0.41 (14)
3 Minimum diameter at midshaft	0.54 (16)*	0.33 (16)	−0.30 (14)
4 Circumference at midshaft	0.27 (15)	0.18 (15)	−0.51 (14)
4a Minimum circumference below proximal end	0.39 (13)	−0.15 (13)	−0.49 (13)

Data source: see Appendix 1. Variable numbers are according to Martin and Saller (1957), and numbers in parentheses are the numbers of pairs. * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$.

strong association has been found in previous intra-group analyses of Japanese bone measurements (Mizoguchi, 1998b, 2005), in an intra-group analysis of Japanese anthropometric data (Mizoguchi, 1992a), and in an inter-group analysis of anthropometric data from Sarawak (Table 5). There is a possibility that a secular change in the form of the pelvis has affected the brachycephalization/dolichocephalization phenomenon by way of cranial length.

In the 1930s, Greulich and Thoms (1938), measuring the dimensions of the pelvic inlet of 789 living European females by Thoms' method of Roentgen pelvimetry, showed that, while the patients from an obstetrical clinic in the United States tended to have an anteroposteriorly flattened pelvic inlet, the student nurses with superior physical status from a higher economic group tended to have a round or anteroposteriorly elongated pelvic inlet. They considered that this was due to the difference in nutrition during early life and other factors which made for the attainment of maximum, normal

Table 3. Spearman’s rank correlation coefficients between cranial and postcranial measurements based on the mean values of 23 female samples from prehistoric, protohistoric, medieval, early modern, and modern populations in Japan

	1 Cranial length	8 Cranial breadth	17 Basi-bregmatic height
SKULL			
1 Cranial length	—		
8 Cranial breadth	−0.33 (23)	—	
17 Basi-bregmatic height	−0.35 (20)	−0.36 (20)	—
HUMERUS			
1 Maximum length	−0.01 (12)	0.07 (12)	−0.04 (10)
2 Total length	0.10 (12)	−0.02 (12)	−0.04 (10)
5 Maximum diameter of midshaft	0.82 (16)***	−0.25 (16)	−0.33 (14)
6 Minimum diameter of midshaft	0.21 (16)	−0.18 (16)	−0.08 (14)
7 Minimum circumference of shaft	0.55 (17)*	0.02 (17)	−0.52 (14)
7a Circumference of midshaft	0.44 (14)	−0.20 (14)	−0.22 (13)
RADIUS			
1 Maximum length	0.48 (12)	0.40 (12)	−0.42 (10)
2 Physiological length	0.40 (13)	0.36 (13)	−0.47 (11)
3 Minimum circumference of shaft	0.39 (13)	0.37 (13)	−0.66 (12)*
4 Transverse diameter of shaft	0.47 (16)	−0.10 (16)	−0.27 (14)
4a Transverse midshaft diameter after Gieseler	0.21 (12)	0.48 (12)	−0.51 (11)
5 Sagittal diameter of shaft	0.61 (16)*	−0.12 (16)	−0.23 (14)
5a Sagittal midshaft diameter after Gieseler	0.46 (12)	0.37 (12)	−0.57 (11)
ULNA			
1 Maximum length	0.33 (12)	0.44 (12)	−0.21 (10)
2 Physiological length	0.34 (11)	0.61 (11)*	−0.55 (10)
3 Minimum circumference	0.35 (12)	0.59 (12)*	−0.43 (11)
11 Dorso-volar diameter	0.60 (16)*	0.19 (16)	−0.69 (13)**
12 Transverse diameter	0.53 (16)*	−0.05 (16)	−0.25 (13)
FEMUR			
1 Maximum length	0.42 (14)	0.40 (14)	−0.67 (13)*
2 Bicondylar length	0.34 (13)	0.39 (13)	−0.61 (11)*
6 Sagittal diameter at midshaft	0.47 (23)*	0.22 (23)	−0.57 (20)**
7 Transverse diameter at midshaft	0.33 (23)	0.12 (23)	−0.27 (20)
8 Circumference at midshaft	0.48 (21)*	0.19 (21)	−0.60 (19)**
9 Transverse subtrochanteric diameter	0.50 (20)*	−0.05 (20)	−0.43 (19)
10 Sagittal subtrochanteric diameter	0.12 (20)	0.18 (20)	−0.52 (19)*
TIBIA			
1 Total length	0.49 (9)	0.13 (9)	−0.23 (9)
1a Maximum length	0.44 (12)	0.23 (12)	−0.21 (11)
8 Maximum diameter at midshaft	0.59 (17)*	0.41 (17)	−0.80 (15)***
8a Sagittal diameter at nutrient foramen	0.59 (17)*	0.45 (17)	−0.69 (15)**
9 Transverse diameter at midshaft	0.46 (13)	0.21 (13)	−0.43 (12)
9a Transverse diameter at nutrient foramen	0.35 (14)	0.07 (14)	−0.41 (12)
10 Circumference at midshaft	0.48 (15)	0.58 (15)*	−0.86 (14)***
10a Circumference at nutrient foramen	0.58 (14)*	0.41 (14)	−0.83 (12)***
10b Minimum circumference of shaft	0.57 (18)*	0.43 (18)	−0.86 (15)***
FIBULA			
1 Maximum length	0.50 (7)	−0.13 (7)	0.04 (7)
2 Maximum diameter at midshaft	0.57 (12)	0.35 (12)	−0.72 (11)*
3 Minimum diameter at midshaft	0.32 (12)	0.33 (12)	−0.54 (11)
4 Circumference at midshaft	0.41 (11)	0.49 (11)	−0.68 (11)*
4a Minimum circumference below proximal end	0.28 (9)	0.48 (9)	−0.50 (9)

Data source: see Appendix 2. Variable numbers are according to Martin and Saller (1957), and numbers in parentheses are the numbers of pairs.
* $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$.

body size. Furthermore, Greulich and Thoms (1939) showed that the average pelvic indices of contemporary European males and females were considerably higher than those reported 50 years previously, and stated that, although the shape of the pelvic inlet in both sexes appeared to have changed materially, the difference between the two periods might be due to the difference in nutritional and other factors which were associated with economic level.

If the differences in the pelvic shape between two samples found by Greulich and Thoms (1938, 1939) are really explained by some differences in nutritional condition between groups, dolichocephalization and brachycephalization in Japan may also be explained in part by diachronic changes in pelvic shape, which were originally caused by some changes in nutritional condition. However, Greulich et al. (1939) stated that, while the sample of student nurses was mainly of English, German, Scottish, and other descent, the clinic sample was mainly of Italian, Polish, and other parentage. If so,

Table 4. Spearman's rank correlation coefficients between cranial measurements and stature based on the means of eight male samples from ancient Greece

	Cranial length	Cranial breadth	Cranial index
Cranial breadth	0.05 (8)	—	—
Cranial index	−0.71 (8)*	0.62 (8)	—
Stature	−0.09 (6)	−0.54 (6)	−0.26 (6)

Data source: Angel (1944). Numbers in parentheses are the pair numbers of samples. The sample size for the mean values used here ranges from 5 to 57.

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

Table 5. Spearman's rank correlation coefficients between head and body measurements based on the means of male samples from eight native groups in Sarawak, Malaysia

	Head length	Head breadth	Length-breadth index
Head breadth	−0.62	—	—
Length-breadth index	−0.74*	0.95***	—
Arm length	−0.31	0.67	0.67
Leg length	0.69	−0.57	−0.57
Biacromial breadth	0.57	−0.02	−0.17
Biiliac breadth	0.86**	−0.81*	−0.90**
Trunk length	−0.21	0.55	0.55
Stature	0.12	0.36	0.38

Data source: Kurisu (1970). The sample size for the mean values used here ranges from 26 to 91.

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

the above findings by Greulich and Thoms (1938, 1939) may be explained by the biological diversity among local populations in Europe rather than by the differences in nutritional condition between the samples.

Angel (1978) reported that less severe dietary deficiency allowed an inlet index drop of about 10% down to 3% (World War I vs. 1920s). This supports the above thought by Greulich and Thoms (1938) that the differences in the pelvic shape may be caused by different nutritional conditions. However, Angel further pointed out that inlet index did not necessarily change in parallel with other health measures such as stature, longevity, and dental status.

Overall, it is not completely clear whether there is a definite association between pelvic shape and nutritional condition. Therefore, this point should be examined in more depth in the future.

Summary and Conclusions

Ecological correlations, i.e. inter-group correlations, between three main neurocranial dimensions and several measurements of major limb bones were estimated using Spearman's rank correlation coefficient. These correlations

Table 6. Spearman's rank correlation coefficients between head and body measurements based on the means of male and female samples obtained from various regions in Russia before the Three Years' Famine

	Antero-posterior diameter of head		Transverse diameter of head		Cephalic index	
	Male	Female	Male	Female	Male	Female
Transverse diameter of head	0.15	0.40	—	—	—	—
Cephalic index	−0.39	−0.22	0.78***	0.69**	—	—
Arm length[1]	−0.06	−0.03	0.16	0.51	0.28	0.52*
Leg length[2]	0.24	0.35	−0.05	0.60*	−0.14	0.41
Thoracic circumference[3]	−0.65**	—	0.35	—	0.71**	—
Trunk length	−0.28	—	0.03	—	0.13	—
Stature	−0.20	−0.10	0.06	0.43	0.13	0.44

Data source: Ivanovsky (1923). The male samples were extracted from 16 regions, and the female ones from 15 regions in Russia. The sample size for the mean values used here ranges from 55 to 105 in males, and from 36 to 100 in females.

[1] From the acromion to the point of the medius (recalculated from the percentage of stature by the present author).

[2] From the great trochanter to the ground (recalculated from the percentage of stature by the present author).

[3] Recalculated from the percentage of stature by the present author.

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

Table 7. Spearman's rank correlation coefficients between head and body measurements based on the serial cross-sectional samples of Japanese males and females

	Head length		Head breadth		Cephalic index	
	Male	Female	Male	Female	Male	Female
Head breadth	0.01 (12)	−0.21 (10)	—	—	—	—
Cephalic index	−0.45 (12)	−0.71 (10)*	0.82 (12)**	0.80 (10)**	—	—
Height	−0.35 (11)	−0.18 (10)	0.54 (11)	0.88 (10)***	0.75 (11)**	0.67 (10)*
Weight	−0.12 (12)	0.76 (10)*	0.54 (12)	−0.21 (10)	0.40 (12)	−0.62 (10)

Data source: Kouchi (2004). Numbers in parentheses are the pair numbers of samples. The sample size for the mean values used here ranges from 32 to 3067 in males, and from 58 to 1011 in females.

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

showed that, while cranial breadth was not consistently correlated with any of the limb bone measurements examined, cranial length and basi-bregmatic height were significantly correlated with a considerable number of limb bone measurements, especially thicknesses. These results are not necessarily compatible with those of previous intra-group analyses. However, at least some of the results on cranial length support a previous suggestion from the intra-group analyses that brachycephalization or dolichocephalization may have proceeded in parallel with diachronic changes in the development of skeletal muscles. In order to completely determine the causes for brachycephalization or dolichocephalization, however, diachronic changes and geographical variations in bone measurements as well as in possible paleoenvironmental factors, including sociocultural ones, should be investigated in more depth in the future.

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Appendix 1. Mean values of cranial and postcranial measurements of 24 male samples from prehistoric, protohistoric, medieval, early modern, and modern populations in Japan[1]

SITE	Ebishima[2]	Sanganji[3]	Tsukumo[4]	Doigahama[5]	Kanenokuma[5]	Ohtomo[6]	Hirota[7]	W Japan[5]	Zaimokuza[8]	Yuigahama-minami[9]	Yoshimo-hama[10]	Fukagawa
PREFECTURE	Iwate	Fukushima	Okayama	Yamaguchi	Fukuoka	Saga	Kagoshima		Kanagawa	Kanagawa	Yamaguchi	Tokyo
PERIOD	Jomon	Jomon	Jomon	Yayoi	Yayoi	Yayoi	Yayoi	Kofun	Medieval	Medieval	Medieval	Early modern
SKULL												
1 Cranial length	184.5 (13)[18]	180.8 (15)[19]	185.0 (32)[20]	182.8 (52)	182.3 (24)	183.7 (24)[21]	164.4 (23)	181.7 (24)	184.2 (170)[22]	184.4 (79)	181.8 (16)	182.1 (153)[23]
8 Cranial breadth	141.7 (12)[18]	145.8 (16)[19]	145.3 (40)[20]	142.6 (54)	142.0 (23)	143.3 (24)[21]	146.8 (23)	140.8 (24)	136.5 (164)[22]	138.3 (85)	136.2 (17)	140.0 (158)[23]
17 Basi-bregmatic height	—	—	133.1 (29)[20]	134.7 (43)	136.0 (24)	135.6 (20)[21]	129.9 (15)	133.1 (23)	137.2 (96)[22]	138.1 (61)	139.4 (17)	137.0 (134)[23]
HUMERUS												
1 Maximum length	299.5 (11)	291.2 (18)	284.3 (36)	299.4 (15)	—	291.4 (11)	—	—	—	303.1 (17)	295.8 (14)	—
2 Total length	298.2 (12)	289.1 (19)	280.6 (35)	295.4 (14)	—	—	—	—	—	298.1 (17)	291.6 (14)	—
5 Maximum diameter of midshaft	23.2 (12)	23.4 (19)	24.1 (50)	22.6 (53)	23.6 (12)	23.4 (34)	—	22.4 (13)	—	21.7 (40)	22.6 (20)	—
6 Minimum diameter of midshaft	16.9 (12)	17.2 (19)	17.8 (50)	17.2 (54)	17.1 (12)	17.6 (33)	—	17.4 (13)	—	16.8 (40)	17.6 (20)	—
7 Minimum circumference of shaft	62.3 (12)	62.6 (19)	64.0 (50)	64.5 (53)	63.6 (14)	63.5 (33)	62.0 (20)	60.2 (14)	—	61.6 (38)	62.5 (20)	—
7a Circumference of midshaft	—	67.5 (19)	69.3 (50)	—	68.3 (12)	68.2 (33)	—	—	—	64.6 (39)	66.1 (20)	—
RADIUS												
1 Maximum length	—	231.3 (17)	230.6 (27)	232.8 (17)	238.8 (12)	—	—	—	—	—	228.0 (17)	—
2 Physiological length	—	216.2 (17)	217.4 (28)	219.6 (20)	—	—	—	—	—	—	213.6 (16)	—
3 Minimum circumference of shaft	—	42.8 (16)	44.0 (38)	42.7 (36)	42.6 (17)	44.7 (15)	42.6 (11)	—	—	41.3 (26)	41.9 (20)	—
4 Transverse diameter of shaft	17.3 (11)	16.5 (17)	17.1 (42)	17.0 (39)	17.1 (17)	17.1 (25)	16.5 (13)	—	—	16.3 (27)	16.9 (20)	—
4a Transverse midshaft diameter after Gieseler	—	15.2 (17)	—	15.8 (30)	16.3 (16)	16.4 (25)	—	—	—	15.0 (26)	15.5 (20)	—
5 Sagittal diameter of shaft	12.3 (11)	11.9 (17)	12.0 (42)	12.0 (39)	12.3 (17)	12.4 (25)	11.4 (13)	—	—	12.3 (27)	12.1 (20)	—
5a Sagittal midshaft diameter after Gieseler	—	12.0 (17)	—	13.3 (29)	12.4 (16)	12.4 (26)	—	—	—	12.2 (26)	11.9 (20)	—
ULNA												
1 Maximum length	—	250.5 (11)	249.1 (19)	258.5 (11)	—	—	—	—	—	—	247.4 (14)	—
2 Physiological length	—	220.9 (11)	219.7 (25)	227.6 (13)	—	222.9 (13)	—	—	—	—	217.5 (12)	—
3 Minimum circumference	—	37.0 (12)	37.7 (34)	37.4 (29)	36.9 (19)	37.2 (22)	36.5 (11)	—	—	36.9 (16)	37.5 (17)	—
11 Dorso-volar diameter	14.7 (12)	14.1 (12)	14.3 (50)	13.3 (40)	13.1 (23)	15.0 (26)	12.8 (16)	—	—	12.6 (28)	12.8 (19)	—
12 Transverse diameter	15.3 (12)	15.5 (12)	16.3 (50)	16.9 (40)	16.8 (23)	17.2 (26)	17.9 (16)	—	—	16.4 (28)	17.6 (19)	—
FEMUR												
1 Maximum length	—	423.7 (28)	414.1 (19)	438.3 (15)	438.6 (11)	420.1 (15)	—	—	419.9 (11)	418.8 (21)	419.1 (16)	412.2 (44)[24]
2 Bicondylar length	421.9 (11)	418.4 (30)	411.0 (19)	428.7 (15)	—	413.9 (17)	—	—	408.8 (10)	415.0 (21)	418.1 (15)	408.2 (44)[24]
6 Sagittal diameter at midshaft	29.5 (13)	29.6 (30)	29.0 (47)	28.6 (53)	29.4 (30)	28.6 (41)	—	27.2 (22)	27.2 (69)	27.4 (89)	28.1 (19)	27.2 (44)[24]
7 Transverse diameter at midshaft	25.9 (13)	25.4 (30)	26.0 (47)	26.6 (53)	27.7 (30)	26.4 (42)	—	26.8 (22)	26.8 (69)	26.4 (89)	27.7 (19)	27.4 (44)[24]
8 Circumference at midshaft	—	88.4 (30)	87.4 (47)	87.4 (54)	90.0 (30)	87.0 (41)	—	85.9 (21)	86.0 (69)	85.0 (89)	87.8 (19)	85.0 (44)[24]
9 Transverse subtrochanteric diameter	—	—	30.7 (43)	32.9 (51)	32.9 (24)	31.6 (38)	—	29.0 (20)	31.6 (90)	31.1 (88)	32.1 (19)	—
10 Sagittal subtrochanteric diameter	—	—	25.5 (43)	25.8 (51)	25.8 (24)	25.2 (38)	—	28.4 (17)	23.9 (90)	23.7 (88)	24.4 (19)	—
TIBIA												
1 Total length	—	339.3 (22)	340.0 (20)	—	—	345.3 (10)	—	—	—	338.1 (23)	341.9 (12)	—
1a Maximum length	—	343.0 (22)	343.6 (22)	—	345.3 (11)	354.8 (11)	—	—	—	343.4 (24)	348.0 (11)	—
8 Maximum diameter at midshaft	32.3 (13)	31.1 (22)	32.3 (46)	29.6 (50)	31.6 (17)	31.0 (43)	—	28.9 (17)	—	29.3 (67)	29.6 (20)	—
8a Sagittal diameter at nutrient foramen	—	34.6 (22)	35.2 (38)	34.4 (45)	36.0 (29)	34.5 (35)	31.9 (14)	33.3 (17)	—	33.5 (69)	33.8 (20)	—
9 Transverse diameter at midshaft	—	21.2 (22)	20.4 (46)	21.2 (50)	22.9 (17)	21.4 (43)	—	21.4 (16)	—	—	21.6 (20)	—
9a Transverse diameter at nutrient foramen	—	24.0 (22)	22.2 (38)	24.0 (52)	25.5 (29)	23.3 (36)	21.5 (14)	23.4 (17)	—	—	24.0 (20)	—
10 Circumference at midshaft	—	82.8 (22)	84.5 (45)	81.4 (50)	85.4 (17)	83.4 (41)	—	80.9 (16)	—	80.3 (67)	80.8 (20)	—
10a Circumference at nutrient foramen	—	92.8 (22)	92.8 (38)	93.2 (45)	97.2 (29)	92.6 (34)	85.3 (14)	90.7 (17)	—	91.4 (69)	90.8 (20)	—
10b Minimum circumference of shaft	76.4 (14)	75.5 (22)	76.7 (41)	74.8 (44)	77.5 (26)	75.6 (38)	69.3 (15)	72.6 (15)	—	73.2 (61)	74.5 (20)	—
FIBULA												
1 Maximum length	—	—	329.5 (13)	—	—	—	—	—	—	333.1 (13)	335.0 (10)	—
2 Maximum diameter at midshaft	17.3 (11)	18.9 (13)	17.8 (44)	16.5 (29)	—	—	—	—	—	15.2 (48)	16.1 (17)	—
3 Minimum diameter at midshaft	11.1 (11)	12.5 (13)	12.2 (44)	10.7 (29)	—	—	—	—	—	10.9 (48)	10.8 (18)	—
4 Circumference at midshaft	—	53.7 (13)	51.3 (44)	44.5 (29)	—	—	—	—	—	43.9 (48)	44.8 (17)	—
4a Minimum circumference below proximal end	—	—	39.2 (29)	39.4 (20)	—	—	—	—	—	36.4 (39)	37.3 (19)	—

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[1] Only those samples whose size was 10 or more were used in the present study; the sample size for each measurement is in parentheses. Variable numbers are according to Martin and Saller (1957).

[2] Yamaguchi (1983). Right limb bones were measured; when the right bone was not available, the left was measured instead.

[3] Baba (1988). Right and left limb bones are combined. [4] Ikeda in Nakahashi (2003). Left limb bones. [5] Nakahashi et al. (1985). Left limb bones.

[6] Matsushita in Nakahashi (2003). Left limb bones. [7] Nakahashi (2003). Left limb bones. [8] Kohara (1956). Left limb bones. [9] Matsushita (2002a). Left limb bones.

[10] Nakahashi and Nagai (1985). Left limb bones. [11] Morimoto et al. (1985). Right limb bones. [12] Kato (1991). Right limb bones.

Appendix 1. (continued)

SITE	Hitotsubashi-Koko[11]	Tentokuji (warrior class)[12]	Shiba-koen (warrior class)[12]	Mushiroda-Aoki[13]	Tenpukuji[13]	Kyomachi (common-alty)[14]	Sogenji (warrior class)[15]	Kyomachi 3 (warrior class)[16]	Kuwa-shima[17]	Shirahama[14]	Kinai	Kyushu[7]
PREFECTURE	Tokyo	Tokyo	Tokyo	Fukuoka	Fukuoka	Fukuoka	Fukuoka	Fukuoka	Kumamoto	Nagasaki		
PERIOD	Early modern	Early modern	Early modern	Early modern	Early modern	Early modern	Early modern	Early modern	Early modern	Early modern	Modern	Modern
SKULL												
1 Cranial length	182.8 (70)	181.8 (53)	182.7 (25)	184.4 (32)	182.6 (38)	180.3 (37)	180.9 (37)	180.6 (19)	180.1 (13)[26]	185.9 (16)	178.4 (30)[27]	182.6 (175)[32]
8 Cranial breadth	139.3 (67)	141.3 (54)	140.8 (26)	139.4 (32)	138.6 (38)	135.2 (30)	140.5 (45)	139.5 (19)	131.0 (13)[26]	134.7 (16)	141.0 (30)[27]	139.9 (175)[32]
17 Basi-bregmatic height	137.5 (60)	137.3 (47)	136.8 (15)	138.1 (29)	139.2 (33)	136.9 (14)	141.0 (32)	139.0 (17)	135.9 (11)[26]	136.6 (14)	139.8 (30)[27]	141.1 (135)[32]
HUMERUS												
1 Maximum length	295.7 (40)	293.6 (36)	298.4 (18)	296.6 (18)	296.9 (21)	—	290.6 (23)	291.8 (12)	293.6 (10)	—	294.1 (30)[28]	295.3 (106)
2 Total length	291.2 (40)	288.2 (34)	293.6 (18)	292.6 (16)	293.3 (19)	—	284.9 (20)	284.7 (10)	293.0 (10)	291.8 (10)	289.8 (30)[28]	290.6 (106)
5 Maximum diameter of midshaft	—	22.5 (73)	22.6 (45)	24.1 (30)	22.9 (22)	22.6 (112)	22.1 (57)	23.1 (18)	20.8 (14)	22.3 (18)	22.3 (30)[28]	21.9 (106)
6 Minimum diameter of midshaft	—	17.0 (73)	17.4 (45)	18.6 (30)	17.7 (22)	17.0 (112)	17.2 (57)	17.8 (18)	15.9 (14)	17.4 (18)	17.4 (30)[28]	16.9 (106)
7 Minimum circumference of shaft	—	—	62.5 (45)	67.1 (28)	63.8 (22)	62.1 (89)	61.8 (49)	65.4 (17)	62.4 (14)	63.0 (18)	64.5 (30)[28]	61.8 (106)
7a Circumference of midshaft	—	65.4 (73)	66.1 (44)	70.0 (30)	66.5 (22)	66.3 (112)	65.7 (57)	67.2 (18)	67.0 (14)	66.9 (18)	66.3 (30)[28]	63.7 (106)
RADIUS												
1 Maximum length	223.5 (53)	223.7 (53)	229.1 (34)	231.4 (19)	228.5 (23)	—	218.6 (26)	224.2 (11)	—	—	223.1 (30)[29]	219.9 (64)
2 Physiological length	207.9 (53)	209.6 (53)	215.3 (36)	215.9 (14)	212.2 (23)	—	204.7 (30)	210.1 (11)	—	—	207.2 (30)[29]	208.2 (64)
3 Minimum circumference of shaft	—	40.6 (70)	40.9 (56)	44.9 (26)	42.2 (23)	41.5 (17)	41.1 (46)	41.7 (17)	—	—	42.1 (30)[29]	40.1 (63)
4 Transverse diameter of shaft	—	16.6 (71)	16.2 (58)	18.3 (27)	17.5 (23)	16.9 (24)	16.4 (50)	16.8 (18)	—	—	16.6 (30)[29]	16.0 (63)
4a Transverse midshaft diameter after Gieseler	—	15.4 (71)	15.2 (56)	16.9 (22)	15.7 (23)	15.7 (23)	15.1 (49)	15.6 (18)	—	—	—	15.2 (63)
5 Sagittal diameter of shaft	—	11.8 (71)	11.7 (58)	13.2 (27)	12.6 (23)	11.7 (23)	12.0 (50)	11.8 (18)	—	—	11.6 (30)[29]	11.7 (63)
5a Sagittal midshaft diameter after Gieseler	—	11.8 (71)	11.7 (56)	13.3 (22)	12.6 (22)	12.0 (22)	12.3 (49)	12.0 (18)	—	—	—	11.9 (63)
ULNA												
1 Maximum length	240.7 (56)	238.1 (44)	243.9 (34)	249.8 (15)	244.6 (18)	—	236.5 (18)	—	—	—	239.2 (30)[29]	236.2 (62)
2 Physiological length	221.0 (58)	209.3 (49)	217.1 (37)	222.6 (13)	214.6 (18)	—	208.3 (24)	211.3 (10)	—	—	210.0 (30)[29]	209.2 (64)
3 Minimum circumference	—	35.3 (65)	36.3 (52)	40.4 (18)	37.5 (20)	—	36.9 (33)	38.8 (16)	—	—	36.8 (30)[29]	35.8 (65)
11 Dorso-volar diameter	—	12.9 (67)	13.0 (57)	13.6 (30)	13.1 (24)	12.8 (31)	12.9 (54)	13.2 (17)	—	—	12.8 (30)[29]	12.8 (63)
12 Transverse diameter	—	16.6 (67)	16.3 (58)	17.6 (30)	17.0 (24)	15.9 (31)	16.0 (54)	16.1 (17)	—	—	15.6 (30)[29]	16.5 (64)
FEMUR												
1 Maximum length	405.7 (51)	407.3 (36)	415.8 (18)	419.6 (31)	415.2 (20)	401.3 (15)	407.8 (23)	412.6 (11)[25]	419.8 (11)	418.3 (12)	413.7 (30)[30]	406.5 (59)
2 Bicondylar length	402.8 (51)	404.1 (36)	418.6 (17)	418.0 (13)	410.0 (18)	398.5 (14)	401.8 (24)	408.7 (11)[25]	416.7 (11)	415.3 (12)	409.9 (30)[30]	403.2 (59)
6 Sagittal diameter at midshaft	26.4 (85)	26.5 (71)	27.2 (51)	28.1 (40)	27.7 (17)	26.6 (162)	26.8 (45)	26.5 (23)	27.1 (16)	27.5 (16)	27.1 (30)[30]	26.5 (59)
7 Transverse diameter at midshaft	26.3 (85)	25.7 (71)	26.7 (51)	29.0 (40)	26.9 (17)	27.0 (162)	25.9 (45)	25.8 (23)	25.2 (16)	26.2 (16)	25.3 (30)[30]	25.6 (59)
8 Circumference at midshaft	—	82.3 (71)	84.8 (51)	89.4 (39)	85.4 (17)	84.9 (161)	83.4 (44)	82.3 (23)	84.0 (14)	84.9 (16)	83.2 (30)[30]	82.4 (59)
9 Transverse subtrochanteric diameter	30.2 (86)	30.7 (70)	31.2 (51)	33.8 (38)	30.4 (14)	31.9 (137)	31.3 (47)	30.5 (20)	30.2 (14)	32.3 (16)	29.3 (30)[30]	29.4 (59)
10 Sagittal subtrochanteric diameter	23.6 (86)	23.5 (70)	23.9 (52)	25.7 (38)	26.3 (14)	24.4 (136)	24.5 (47)	23.9 (20)	23.3 (14)	24.4 (16)	25.2 (30)[30]	24.3 (59)
TIBIA												
1 Total length	325.9 (42)	326.4 (34)	339.4 (15)	330.3 (21)	339.5 (13)	—	326.2 (21)	324.8 (12)	333.4 (12)	—	326.7 (30)[31]	320.3 (61)
1a Maximum length	329.3 (43)	330.5 (35)	343.0 (17)	337.0 (24)	340.1 (16)	—	332.6 (22)	330.3 (12)	339.5 (12)	—	331.9 (30)[31]	326.9 (60)
8 Maximum diameter at midshaft	—	27.4 (72)	28.7 (48)	30.2 (26)	29.4 (14)	28.2 (81)	28.0 (43)	27.8 (19)	27.5 (16)	—	28.5 (30)[31]	27.8 (61)
8a Sagittal diameter at nutrient foramen	—	31.7 (70)	33.0 (48)	34.4 (34)	33.7 (15)	32.4 (55)	32.0 (41)	32.8 (17)	—	—	32.8 (30)[31]	30.6 (60)
9 Transverse diameter at midshaft	—	20.7 (72)	20.8 (48)	22.7 (26)	21.9 (14)	—	—	—	20.4 (17)	—	21.0 (30)[31]	21.1 (61)
9a Transverse diameter at nutrient foramen	—	23.3 (70)	23.5 (49)	24.9 (34)	24.1 (15)	—	—	—	—	—	24.1 (30)[31]	23.7 (61)
10 Circumference at midshaft	—	76.3 (72)	78.8 (48)	83.0 (25)	80.4 (14)	77.1 (81)	77.0 (43)	77.1 (19)	80.5 (17)	—	78.8 (30)[31]	78.4 (62)
10a Circumference at nutrient foramen	—	—	—	93.0 (32)	91.3 (15)	87.9 (54)	87.1 (41)	89.1 (17)	89.7 (17)	—	89.4 (30)[31]	88.9 (61)
10b Minimum circumference of shaft	—	69.7 (71)	71.9 (46)	76.0 (29)	73.7 (15)	70.2 (58)	70.0 (43)	70.2 (17)	73.3 (17)	—	71.8 (30)[31]	71.3 (60)
FIBULA												
1 Maximum length	323.0 (33)	327.5 (27)	336.7 (13)	—	335.3 (12)	—	327.7 (17)	—	—	—	326.9 (30)[31]	322.9 (58)
2 Maximum diameter at midshaft	—	14.4 (64)	14.9 (43)	15.2 (24)	14.3 (13)	14.4 (20)	14.6 (48)	14.5 (16)	14.5 (15)	—	14.1 (30)[31]	14.5 (59)
3 Minimum diameter at midshaft	—	10.8 (65)	10.6 (43)	11.2 (24)	10.8 (13)	10.4 (20)	10.8 (48)	10.4 (16)	10.7 (15)	—	10.3 (30)[31]	10.0 (59)
4 Circumference at midshaft	—	41.4 (64)	42.9 (43)	43.7 (24)	40.5 (13)	41.7 (20)	42.7 (48)	42.1 (16)	44.4 (15)	—	41.5 (30)[31]	41.5 (59)
4a Minimum circumference below proximal end	—	34.6 (61)	34.0 (34)	38.0 (14)	35.9 (10)	—	35.3 (36)	36.3 (15)	38.4 (13)	—	35.0 (30)[31]	35.6 (59)

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[13] Nakahashi (1993). [14] Matsushita (1993). Right limb bones. [15] Matsushita (1995). Right limb bones. [16] Matsushita (2002b). Right limb bones.
[17] Risshi in Nakahashi (1993). [18] Mizoguchi and Dodo (2001). [19] Hanihara and Uchida (1988). [20] Mizoguchi (1988). [21] Matsushita (2000). [22] Suzuki et al. (1956).
[23] Mizoguchi (1992b). Unkoin Temple in Fukagawa, Tokyo. [24] Hiramoto (1979). Unkoin and Joshinji Temples in Fukagawa, Tokyo. Right femurs. [25] Left bones.
[26] Waki in Nakahashi (1993). [27] Mizoguchi (1994). [28] Mizoguchi (2001). Right bones. [29] Mizoguchi (2002). Right bones. [30] Mizoguchi (2003a). Right bones.
[31] Mizoguchi (2003b). Right bones. [32] Hara in Kanaseki et al. (1955) and Yuan (1960).

Appendix 2. Mean values of cranial and postcranial measurements of 23 female samples from prehistoric, protohistoric, medieval, early modern, and modern populations in Japan[1]

SITE	Ebishima[2]	Sanganji[3]	Tsukumo[4]	Doigahama[5]	Kaneno-kuma[5]	Ohtomo[6]	Hirota[7]	W Japan[5]	Zaimokuza[8]	Yuigahama-minami[9]	Yoshimo-hama[10]	Fukagawa
PREFECTURE	Iwate	Fukushima	Okayama	Yamaguchi	Fukuoka	Saga	Kagoshima		Kanagawa	Kanagawa	Yamaguchi	Tokyo
PERIOD	Jomon	Jomon	Jomon	Yayoi	Yayoi	Yayoi	Yayoi	Kofun	Medieval	Medieval	Medieval	Early modern
SKULL												
1 Cranial length	177.3 (11)[17]	173.4 (16)[18]	176.2 (33)[19]	176.0 (32)	176.8 (26)	178.1 (18)[20]	157.7 (18)	173.1 (14)	177.9 (62)[21]	179.0 (47)	176.4 (26)	173.8 (26)[22]
8 Cranial breadth	136.5 (13)[17]	138.4 (14)[18]	142.0 (34)[19]	138.1 (32)	138.3 (26)	141.2 (17)[20]	143.7 (17)	136.6 (16)	131.8 (60)[21]	134.8 (48)	132.0 (26)	135.4 (27)[22]
17 Basi-bregmatic height	—	—	127.3 (22)[19]	128.1 (29)	131.0 (24)	128.3 (13)[20]	—	128.2 (13)	128.8 (42)[21]	133.7 (36)	133.0 (25)	133.0 (25)[22]
HUMERUS												
1 Maximum length	278.2 (14)	275.2 (13)	264.4 (21)	281.8 (16)	—	—	—	—	—	—	270.0 (19)	—
2 Total length	276.0 (14)	272.4 (13)	259.6 (19)	280.3 (15)	—	—	—	—	—	—	267.4 (18)	—
5 Maximum diameter of midshaft	21.1 (20)	19.6 (14)	19.7 (40)	19.8 (28)	—	21.0 (20)	—	—	—	—	19.9 (28)	—
6 Minimum diameter of midshaft	14.6 (20)	14.4 (14)	14.0 (41)	15.1 (28)	—	15.8 (20)	—	—	—	—	14.8 (28)	—
7 Minimum circumference of shaft	55.9 (21)	54.1 (14)	53.9 (42)	57.1 (28)	56.9 (11)	57.6 (19)	54.2 (14)	—	—	—	54.1 (28)	—
7a Circumference of midshaft	—	57.0 (14)	56.5 (40)	—	—	61.8 (19)	—	—	—	—	57.3 (28)	—
RADIUS												
1 Maximum length	217.6 (13)	215.1 (12)	208.2 (24)	214.1 (14)	—	—	—	—	—	—	206.0 (18)	—
2 Physiological length	203.8 (13)	202.8 (12)	196.4 (26)	201.7 (18)	—	—	—	—	—	—	193.1 (18)	—
3 Minimum circumference of shaft	—	35.9 (13)	36.4 (30)	37.8 (29)	36.5 (22)	—	—	—	—	—	34.6 (27)	—
4 Transverse diameter of shaft	15.1 (19)	14.3 (13)	14.6 (34)	15.5 (30)	15.3 (22)	16.4 (11)	—	—	—	—	15.1 (27)	—
4a Transverse midshaft diameter after Gieseler	—	13.6 (13)	—	14.7 (28)	14.0 (12)	15.9 (11)	—	—	—	—	13.4 (27)	—
5 Sagittal diameter of shaft	10.3 (19)	9.8 (13)	9.8 (34)	10.6 (30)	10.8 (22)	11.2 (11)	—	—	—	—	10.1 (27)	—
5a Sagittal midshaft diameter after Gieseler	—	10.0 (13)	—	10.6 (27)	10.7 (12)	10.9 (12)	—	—	—	—	10.1 (27)	—
ULNA												
1 Maximum length	237.6 (12)	233.3 (11)	227.2 (12)	238.3 (13)	—	—	—	—	—	—	222.4 (20)	—
2 Physiological length	—	205.4 (11)	198.6 (12)	210.4 (15)	—	—	—	—	—	—	196.7 (22)	—
3 Minimum circumference	—	33.5 (11)	32.8 (24)	33.9 (23)	33.9 (13)	—	—	—	—	—	32.5 (25)	—
11 Dorso-volar diameter	13.0 (21)	12.4 (10)	11.3 (37)	11.5 (28)	11.1 (19)	12.8 (12)	10.7 (10)	—	—	—	10.8 (28)	—
12 Transverse diameter	14.6 (21)	14.0 (10)	13.6 (37)	15.4 (28)	15.6 (19)	15.9 (11)	15.2 (10)	—	—	—	14.9 (28)	—
FEMUR												
1 Maximum length	—	393.9 (17)	388.2 (22)	397.0 (13)	405.5 (13)	—	—	—	—	—	378.0 (25)	371.9 (19)[23]
2 Bicondylar length	400.1 (10)	389.3 (19)	381.7 (22)	394.9 (12)	—	—	—	—	—	—	375.4 (24)	368.6 (19)[23]
6 Sagittal diameter at midshaft	26.4 (19)	24.9 (19)	25.2 (45)	24.8 (31)	25.9 (27)	25.5 (30)	22.5 (20)	24.5 (23)	22.9 (27)	24.3 (23)	23.3 (28)	23.3 (19)[23]
7 Transverse diameter at midshaft	24.1 (19)	23.4 (19)	24.2 (45)	25.6 (31)	26.1 (27)	25.2 (30)	23.0 (20)	24.7 (24)	23.5 (27)	24.0 (23)	24.8 (28)	23.1 (19)[23]
8 Circumference at midshaft	—	78.0 (19)	78.0 (45)	79.3 (31)	81.6 (27)	80.4 (29)	72.2 (18)	78.1 (23)	73.8 (26)	76.5 (23)	76.1 (28)	72.6 (19)[23]
9 Transverse subtrochanteric diameter	—	—	28.4 (42)	31.5 (31)	30.1 (22)	29.7 (30)	27.3 (18)	28.2 (19)	28.0 (37)	27.9 (21)	29.1 (28)	—
10 Sagittal subtrochanteric diameter	—	—	22.2 (42)	23.1 (29)	23.6 (22)	22.7 (30)	20.2 (18)	26.6 (17)	20.4 (37)	20.8 (21)	20.9 (28)	—
TIBIA												
1 Total length	—	—	319.8 (17)	326.2 (13)	—	—	—	—	—	—	309.2 (16)	—
1a Maximum length	—	323.9 (10)	324.4 (17)	331.5 (14)	—	—	—	—	—	—	313.8 (17)	—
8 Maximum diameter at midshaft	27.5 (17)	26.6 (16)	27.3 (42)	26.3 (34)	26.2 (13)	27.6 (24)	—	26.9 (12)	—	—	26.1 (26)	—
8a Sagittal diameter at nutrient foramen	—	29.8 (16)	30.5 (37)	30.1 (30)	30.6 (28)	30.4 (19)	28.5 (13)	29.5 (11)	—	—	29.7 (25)	—
9 Transverse diameter at midshaft	—	19.6 (16)	17.9 (42)	19.2 (34)	20.5 (13)	19.7 (26)	—	19.0 (12)	—	—	18.3 (26)	—
9a Transverse diameter at nutrient foramen	—	21.5 (16)	19.4 (36)	21.4 (29)	22.4 (28)	21.1 (20)	20.2 (13)	21.1 (11)	—	—	20.0 (25)	—
10 Circumference at midshaft	—	74.6 (16)	73.4 (42)	73.5 (34)	73.0 (13)	75.3 (23)	—	73.1 (12)	—	—	70.3 (26)	—
10a Circumference at nutrient foramen	—	82.2 (16)	81.3 (35)	83.1 (28)	82.8 (28)	81.6 (18)	76.9 (13)	—	—	—	78.8 (25)	—
10b Minimum circumference of shaft	67.4 (17)	67.0 (16)	67.6 (35)	68.7 (29)	67.7 (24)	68.3 (24)	63.7 (11)	67.0 (12)	—	—	64.9 (25)	—
FIBULA												
1 Maximum length	—	—	—	338.0 (12)	—	—	—	—	—	—	304.7 (13)	—
2 Maximum diameter at midshaft	15.2 (13)	—	14.7 (32)	14.2 (26)	—	—	—	—	—	—	13.7 (23)	—
3 Minimum diameter at midshaft	9.8 (13)	—	10.0 (32)	9.7 (26)	—	—	—	—	—	—	9.7 (23)	—
4 Circumference at midshaft	—	—	42.8 (32)	40.2 (26)	—	—	—	—	—	—	39.2 (22)	—
4a Minimum circumference below proximal end	—	—	34.0 (20)	35.8 (19)	—	—	—	—	—	—	33.0 (22)	—

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[1] Only those samples whose size was 10 or more were used in the present study; the sample size for each measurement is in parentheses. Variable numbers are according to Martin and Saller (1957).

[2] Yamaguchi (1983). Right limb bones were measured; when the right bone was not available, the left was measured instead. [3] Baba (1988). Right and left limb bones are combined.

[4] Ikeda in Nakahashi (2003). Left limb bones. [5] Nakahashi et al. (1985). Left limb bones. [6] Matsushita in Nakahashi (2003). Left limb bones.

[7] Nakahashi (2003). Left limb bones. [8] Kohara (1956). Left limb bones. [9] Matsushita (2002a). Left limb bones. [10] Nakahashi and Nagai (1985). Left limb bones.

[11] Morimoto et al. (1985). Right limb bones. [12] Kato (1991). Right limb bones. [13] Nakahashi (1993). [14] Matsushita (1993). Right limb bones.

Appendix 2. (continued)

SITE	Hitotsubashi-Koko[11]	Tentokuji (warrior class)[12]	Shiba-koen (warrior class)[12]	Mushiroda-Aoki[13]	Tenpukuji[13]	Kyomachi (common -alty)[14]	Sogenji (warrior class)[15]	Kyomachi 3 (warrior class)[16]	Shirahama[14]	Kinai	Kyushu[7]
PREFECTURE	Tokyo	Tokyo	Tokyo	Fukuoka	Fukuoka	Fukuoka	Fukuoka	Fukuoka	Nagasaki		
PERIOD	Early modern	Early modern	Early modern	Early modern	Early modern	Early modern	Early modern	Early modern	Early modern	Modern	Modern
SKULL											
1 Cranial length	175.8 (24)	171.3 (40)	175.5 (34)	176.9 (26)	174.7 (38)	172.1 (24)	172.7 (35)	174.0 (14)	178.8 (12)	169.4 (20)[25]	176.4 (32)[30]
8 Cranial breadth	137.0 (22)	136.9 (39)	136.0 (34)	133.0 (28)	133.5 (38)	132.3 (24)	136.5 (36)	137.2 (14)	128.7 (11)	137.8 (20)[25]	136.0 (32)[30]
17 Basi-bregmatic height	132.0 (20)	133.0 (35)	133.3 (27)	132.4 (24)	132.7 (35)	134.7 (10)	136.3 (27)	134.6 (10)	130.9 (11)	132.1 (20)[25]	132.9 (32)[30]
HUMERUS											
1 Maximum length	266.1 (16)	270.3 (19)	272.7 (15)	—	273.7 (19)	—	269.8 (12)	—	—	273.9 (20)[26]	271.7 (36)
2 Total length	263.1 (16)	266.5 (19)	268.6 (14)	—	271.4 (15)	—	265.2 (10)	—	—	269.5 (20)[26]	268.6 (36)
5 Maximum diameter of midshaft	—	19.6 (38)	19.6 (32)	21.6 (17)	20.3 (20)	19.4 (46)	19.8 (44)	19.8 (17)	20.6 (11)	19.5 (20)[26]	19.8 (36)
6 Minimum diameter of midshaft	—	14.9 (38)	14.4 (32)	16.2 (17)	15.5 (20)	14.7 (46)	14.7 (44)	15.2 (17)	14.7 (11)	14.6 (20)[26]	14.8 (36)
7 Minimum circumference of shaft	—	—	53.3 (31)	59.1 (17)	56.0 (21)	53.6 (37)	54.5 (36)	54.5 (16)	55.3 (11)	54.6 (20)[26]	54.8 (36)
7a Circumference of midshaft	—	56.9 (38)	56.8 (32)	62.1 (17)	59.3 (20)	56.7 (46)	57.6 (44)	58.1 (17)	58.8 (12)	57.2 (20)[26]	56.9 (36)
RADIUS											
1 Maximum length	198.5 (17)	198.5 (22)	202.5 (21)	—	197.9 (12)	—	198.1 (10)	—	—	201.3 (20)[27]	199.2 (12)
2 Physiological length	185.3 (17)	187.1 (22)	190.3 (21)	—	183.5 (11)	—	184.6 (13)	184.4 (11)	—	187.7 (20)[27]	187.0 (12)
3 Minimum circumference of shaft	—	34.5 (41)	34.3 (45)	40.2 (11)	35.7 (16)	—	35.5 (40)	34.9 (13)	—	35.4 (20)[27]	34.7 (12)
4 Transverse diameter of shaft	—	14.6 (42)	14.5 (48)	16.2 (15)	15.3 (16)	15.3 (12)	14.8 (40)	15.2 (13)	—	14.5 (20)[27]	14.5 (12)
4a Transverse midshaft diameter after Gieseler	—	13.5 (42)	13.5 (47)	—	14.0 (14)	14.4 (12)	13.5 (41)	13.9 (13)	—	—	13.5 (12)
5 Sagittal diameter of shaft	—	10.0 (42)	10.0 (48)	11.5 (15)	10.3 (16)	10.0 (12)	10.1 (40)	9.9 (13)	—	9.6 (20)[27]	9.7 (12)
5a Sagittal midshaft diameter after Gieseler	—	9.9 (42)	9.9 (47)	—	10.2 (14)	10.1 (12)	10.1 (41)	10.1 (13)	—	—	9.7 (12)
ULNA											
1 Maximum length	213.5 (12)	215.8 (23)	219.2 (17)	—	211.1 (11)	—	216.7 (10)	—	—	217.9 (20)[27]	215.0 (12)
2 Physiological length	196.2 (14)	190.8 (25)	192.9 (18)	—	184.3 (11)	—	188.7 (15)	—	—	191.0 (20)[27]	189.2 (12)
3 Minimum circumference	—	31.5 (40)	30.9 (34)	—	32.4 (12)	—	32.4 (29)	33.3 (11)	—	32.3 (20)[27]	32.1 (12)
11 Dorso-volar diameter	—	11.0 (40)	10.4 (37)	11.9 (17)	11.2 (17)	—	10.6 (42)	10.9 (13)	—	10.5 (20)[27]	10.9 (12)
12 Transverse diameter	—	14.2 (40)	14.2 (37)	16.2 (17)	14.3 (17)	—	13.9 (42)	13.9 (13)	—	13.4 (20)[27]	13.9 (12)
FEMUR											
1 Maximum length	366.0 (17)	371.5 (17)	377.7 (15)	389.1 (15)	380.6 (18)	—	370.9 (15)	—	—	382.3 (20)[28]	380.1 (13)
2 Bicondylar length	362.7 (17)	369.6 (16)	374.5 (15)	—	376.7 (16)	—	367.6 (14)	—	—	377.6 (20)[28]	375.9 (13)
6 Sagittal diameter at midshaft	22.1 (38)	23.6 (41)	22.8 (38)	24.8 (25)	23.6 (21)	23.1 (87)	23.2 (49)	23.1 (16)	24.8 (13)	23.3 (20)[28]	23.6 (13)
7 Transverse diameter at midshaft	22.9 (38)	23.6 (41)	23.2 (38)	26.6 (25)	24.0 (21)	23.5 (87)	23.9 (49)	23.7 (17)	22.8 (13)	23.2 (20)[28]	23.2 (13)
8 Circumference at midshaft	—	74.2 (41)	73.0 (38)	80.5 (23)	75.2 (21)	73.5 (87)	74.2 (49)	73.4 (16)	75.0 (13)	74.2 (20)[28]	74.2 (13)
9 Transverse subtrochanteric diameter	27.2 (38)	28.4 (41)	27.6 (38)	30.2 (25)	27.7 (17)	27.9 (73)	27.9 (51)	27.9 (17)	28.5 (12)	27.3 (20)[28]	27.5 (13)
10 Sagittal subtrochanteric diameter	19.8 (38)	21.1 (41)	20.1 (38)	23.0 (25)	22.7 (17)	21.0 (73)	21.4 (50)	20.5 (17)	21.8 (12)	22.3 (20)[28]	21.3 (13)
TIBIA											
1 Total length	295.4 (14)	300.0 (14)	306.3 (12)	—	301.8 (15)	—	—	—	—	300.7 (20)[29]	301.0 (14)
1a Maximum length	300.1 (15)	304.0 (15)	310.3 (12)	314.0 (10)	305.6 (15)	—	312.6 (11)	—	—	305.1 (20)[29]	306.6 (14)
8 Maximum diameter at midshaft	—	23.9 (39)	23.5 (38)	26.1 (10)	24.4 (17)	24.4 (37)	24.0 (34)	23.6 (13)	—	24.0 (20)[29]	24.7 (14)
8a Sagittal diameter at nutrient foramen	—	27.6 (38)	26.6 (36)	29.5 (19)	27.8 (19)	27.5 (23)	27.8 (32)	27.3 (11)	—	27.2 (20)[29]	28.1 (14)
9 Transverse diameter at midshaft	—	18.1 (39)	17.5 (38)	20.1 (10)	18.6 (17)	—	—	—	—	18.7 (20)[29]	18.8 (14)
9a Transverse diameter at nutrient foramen	—	20.1 (38)	19.2 (36)	21.6 (19)	20.7 (19)	—	—	—	—	20.7 (20)[29]	21.1 (14)
10 Circumference at midshaft	—	66.7 (39)	65.7 (38)	—	67.5 (17)	67.4 (37)	66.7 (34)	64.7 (13)	—	67.9 (20)[29]	70.1 (14)
10a Circumference at nutrient foramen	—	—	—	80.6 (19)	76.5 (19)	75.7 (23)	75.4 (32)	74.3 (11)	—	75.9 (20)[29]	78.2 (14)
10b Minimum circumference of shaft	—	61.3 (38)	61.0 (36)	66.1 (15)	62.7 (17)	61.5 (32)	61.1 (34)	58.9 (12)	—	61.9 (20)[29]	63.6 (14)
FIBULA											
1 Maximum length	290.3 (10)	296.3 (18)	302.0 (12)	—	—	—	—	—	—	299.4 (20)[29]	300.6 (14)
2 Maximum diameter at midshaft	—	12.8 (38)	12.7 (33)	—	12.8 (11)	12.4 (10)	12.9 (34)	12.3 (12)	—	13.1 (20)[29]	12.9 (14)
3 Minimum diameter at midshaft	—	9.4 (38)	8.7 (33)	—	9.2 (11)	8.9 (10)	9.0 (35)	8.8 (12)	—	9.0 (20)[29]	8.6 (14)
4 Circumference at midshaft	—	36.7 (38)	36.2 (33)	—	36.6 (11)	34.6 (10)	37.1 (34)	35.3 (12)	—	38.6 (20)[29]	36.8 (14)
4a Minimum circumference below proximal end	—	31.1 (34)	30.1 (31)	—	—	—	33.6 (26)	31.6 (11)[24]	—	32.9 (20)[29]	32.3 (14)

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