Exploring Artificial Cranial Deformation Using Elliptic Fourier Analysis of Procrustes Aligned Outlines

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ABSTRACT The anatomical effects of artificial cranial deformation on the face and the base have been subject to various metric approaches, including standard linear as well as finite element techniques, and have produced controversial results (Antón [1989] Am. J. Phys. Anthropol. *79:*253–267; Kohn et al. [1993] Am. J. Phys. Anthropol. *90:*147–158). It can be argued that diverging observations partly result from methodological constraints. The present study compares samples of intentionally deformed and undeformed human crania, using elliptic Fourier analysis (EFA), a morphometric approach which has been shown to be particularly appropriate for characterizing the shape of two-dimensional outlines and associated shape changes. We improve the standard EFA approach by adding a preliminary orientation of the outlines following the rotation parameters of a Procrustes superimposition, using multiple homologous landmarks called control points. The results confirm that circumferentially deformed skulls exhibit modifications of the basioccipital region, together with increased anterior and inferior facial projection. However, the degree to which basioccipital flattening is modified in circumferentially deformed Peruvians was found to be less marked than changes observed in the face. Some of the modifications observed here can be related to morphological trends existing in the population from which our sample was taken. The observation of other modifications may be subject to methodological constraints of standard morphometric approaches. Am J Phys Anthropol 122:11–22, 2003.

Artificial cranial deformation has been frequently practiced in various regions of the world and in different historical contexts (Brothwell, 1963, 1975). Anthropologists have particularly focused on the Americas (Dembo and Imbelloni, 1938; Falkenburger, 1938), although this widespread cultural phenomenon has been observed on virtually all continents (Dingwall, 1931). Beyond the numerous attempts to classify the different types of intentional deformation, additional attention has been drawn to secondary effects of cranial deformation on the face and the base (Antón, 1989b; Cheverud et al., 1992; Kohn et al., 1993).

The purpose of this study was to contribute to the statistical identification of shape changes in cases of intentional cranial deformation, and to improve the discrimination of deformed and undeformed skulls. This study uses outlines which a priori provide more information than the homologous landmarks or equivalent distances used in previous work (Pereira da Silva and Sakka, 1983; Hanihara, 2000). The need to improve the characterization of artificially modified crania arises from two different anthropological perspectives. On the one hand, artificial cranial deformation can potentially bias results of metric comparisons or studies of anatomical variation, as for example the occurrence of sutural bones, which has been reported to increase in cases of deformation (El-Najjar and Dawson, 1977; Ossenberg, 1970; White, 1996). On the other hand, anthropologists need reliable reports on deformation in ethnographic or historical contexts (Antón and Weinstein, 1999; Brothwell, 1975; Maureille et al., 1995; Pereira da Silva and Cussenot, 1989; Simon, 1978; Trinkaus, 1983).

The effects of artificial deformation on the cranial base and face have been addressed in previous studies (for a major review, see Antón, 1989b). Some of these studies do not agree in important aspects of this issue. For example, several authors (Oetteking, 1930; McNeill and Newton, 1965; Antón, 1989b) concluded that platybasia are a general result of the two major deformation types (described below), namely circumferential (C) and anteroposterior (AP) deformations. As pointed out by Antón (1989b), some

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ambiguities remain, because Moss (1958) had reported that effects depend on the deformation type. Using a different classification system, Moss (1958) reported platybasic skulls only in one deformation type, the so-called oblique type, whereas his "vertical" group was found to exhibit basal kyphosis. Whether his "oblique" group corresponded to the circumferential deformation type used in other studies including our own, while his "vertical" type was equivalent to the anteroposterior deformation type, remains unclear. Nevertheless, in a detailed discussion, Antón (1989b) suggested that none of the groups in Moss (1958) was exclusively circumferential, but a mix of C and AP types.

Changes in the angle of the anterior cranial base potentially affect the posterior cranial architecture. Several, but not all of the preceding studies reported a superior shift of the *foramen magnum*, resulting in a more horizontal orientation relative to the Frankfurt plane (Antón, 1989b; Kohn et al., 1993). In addition, Kohn et al. (1993) specified that the posterior border of the *foramen magnum* (opisthion) shifts more superiorly than the anterior border (basion). Moss (1958) observed that in both "vertical" and "oblique" crania, the clivoforaminal angle was more reduced (i.e., more acute) than in the control series. McNeill and Newton (1965) reported a reduced clivoforaminal angle in C deformed skulls, whereas normal and AP deformed skulls had similar angles. They concluded that the *foramen magnum* was positioned more "superiorly" in cases of circumferential deformation. Antón (1989b) reported significantly reduced angles in both groups.

Reports on an increase in facial height and protrusion associated with circumferential deformation are inconsistent (Antón, 1989b), leaving the question of morphological changes induced by intentional vault modifications largely open. Several studies (Oetteking, 1924; Schendel et al., 1980; Brown, 1981) found increased upper facial and orbital heights in circumferentially deformed crania, whereas others (Cocilovo, 1975; Antón, 1989b) reported no significant differences with regard to these dimensions. Instead, the comparisons by Antón (1989a,b) of C types with either undeformed or AP deformed skulls showed a decrease in facial breadth measurements, while Cocilovo (1975) maintained that deformation has no effect at all on the face. Kohn et al. (1993) equally observed a change in facial breadths depending on the deformation type, as well as an anteroposteriorly elongated face resulting from circumferential deformation in one of their samples, but not in the other. Finally, Rogers (1975) found that while AP deformed skulls exhibited no significant differences with regard to facial measurements, circumferentially deformed skulls had more protruding faces.

Given these inconsistent results, we hope to contribute to an understanding of craniofacial shape variation and shape change associated with circumferential deformation, and thereby to clarify some of the craniofacial modifications that have been reported to occur. Based on results from earlier studies, we will test the effect of intentional vault modification on the basioccipital, the *foramen magnum* orientation, and the face, as seen in lateral view.

TABLE 1. Cranial samples used for two separate analyses[1]

Sample and origin	N vault	N cranium
Peruvian C*+	36	14
Peruvian ND*	37	37
Japanese*	46	46
Inuit+	31	
Total	150	97

[1]Collections housed at Musée de l'Homme, Paris (Peruvian C, Peruvian ND, and Japanese); and University Museum of Pennsylvania, Philadelphia (Peruvian C and Inuit). The Peruvian sample is of geographically mixed origin. Japanese sample comes from Hiogo-Kobe (Set-Tsu province). Inuit are equally of Alaskan and Greenland origin.

In this study, we use elliptic Fourier analysis (Kuhl and Giardina, 1982; Lestrel, 1997; Rohlf, 1986, 1990) to parameterize the outline coordinates of both the cranium and the vault. A common orientation framework is traditionally achieved by a two-point registration method (Rohlf, 1990). We use a multiple landmark extension to provide a more precise reference system. Elliptic Fourier coefficients were used as shape variables in order to separate circumferentially deformed from undeformed crania, as well as to describe the shape change associated with the deformation. Outline variations along directions of the multidimensional space (e.g., canonical or discriminant axes, allometry) are illustrated using outline reconstructions as introduced by Monti et al. (2000).

MATERIALS AND METHODS

The study is based on samples of unambiguously deformed and undeformed Peruvian crania. Additional comparative samples of undeformed crania include Inuit and Japanese. A total of 150 individuals forms the main sample used for the subsequent analyses (Table 1).

Only adult individuals, based on the eruption of the upper M3 and the fusion of the spheno-occipital synchondrosis, were used. The Peruvian crania were a priori identified by one of us (M.F.) as either undeformed or as circumferentially (C) deformed (Dembo and Imbelloni, 1938; Falkenburger, 1938). Although numerous classifications exist, and despite their partial disagreement in terminology, the basic distinction of the circumferential deformation type from the so-called anteroposterior deformation (AP) has repeatedly been adopted and considered as roughly reflecting differences in the means used to deform the human head (Antón, 1989b; Cheverud et al., 1992; Kohn et al., 1993). An AP deformation is generally obtained by binding pads on the head or by fixing it in a cradleboard, whereas C deformations result from the use of a soft apparatus such as wrapping of tissue around the head. A further distinction into "erect and oblique" variants (Dembo and Imbelloni, 1938) was not used.

Kohn et al. (1993) emphasized the inclusion of deformed and undeformed crania derived from the same population in order to maintain the homogeneity of the sample. However, using a reference sample of undeformed Peruvian crania is somewhat arbitrary and appears debatable from a theoretical point of view, because minor deformations occur with a certain probability among most South American cranial series, and may not be detected visually (see also Frieß, 1999). In order to avoid circular assumptions, it is necessary to include reference series that are reasonably comparable to South American populations in terms of cranial morphology (Howells, 1973), and/or that represent geographic areas in which artificial deformation is not significant or unknown (Dingwall, 1931). We chose Inuit and Japanese populations as external undeformed reference samples. While this approach may have the potential to "confound interpopulation morphological differences with the effects of modification" (Kohn et al., 1993, p. 149), it limits the alternative error of including slightly deformed crania in a supposedly undeformed sample.

We used distortion-free lateral outline drawings (using a Martin-type dioptrograph and a diagraph; Knußmann, 1988) for raw data acquisition. The drawings of the Japanese sample were obtained from a previous study, which combined outline tracings and teleradiography (Pellerin, 1979). By pooling data that were collected from different sources, we assume that the accuracy for both data sets is comparable. In fact, both outline drawings were made under conditions of parallel projection, which provides an exact reproduction of the cranial contour at natural scale. Landmarks are marked on the drawing as the aiming device crosses the corresponding point on the specimen. In the case of the published outlines, the landmark definitions of the author (Pellerin, 1979) were used. In addition, their accuracy was controlled by reproducing, on the tracing, a series of linear measurements provided by the author. The mean deviation between the two sets of distances was less than 1 mm (Frieß, 1999). This discrepancy was estimated to be negligible, and can probably be related to interobserver error, an important issue that cannot be addressed within the scope of this paper.

The sex was reported only in a very restricted number of cases. Consequently, sexual dimorphism was not taken into account in the present study. Whether an unbalanced sex ratio of the sample could have an impact on our results would depend on the extent to which sexual dimorphism affects the facial and basioccipital architecture. While this constitutes an important aspect, sexual dimorphism was not given further consideration in this study.

We analyzed two different outline configurations, which were defined as follows (Fig. 1): the vault extends from nasion to opisthion, bridging the *foramen magnum* with a straight line and closing the contour with a second straight line from the basion to nasion. The outline for the cranium includes parts of the face and the basioccipital. In this configuration, the outline starts at nasion, follows the vault to the opisthion and basion as in the case of the vault, and continues along the clivus to the spheno-occipital synchondrosis, from which a straight line is projected to the maxillary tuberosity. The outline follows along the alveolar process to prosthion, and continues to the *spina nasalis anterior*, from which it connects to the nasion by passing the margin of the *apertura piriformis* and the *sutura nasomaxillaris*. As with most two-dimensional (2D) data, the final outline corresponds to an orthogonal projection in a single plane of elements that originally may be located in different planes. For this second configuration, the cranial contour was closed by two lines from the tuberosity to the projection and from basion to opisthion, covering the external profile of the basioccipital (see Fig. 1).

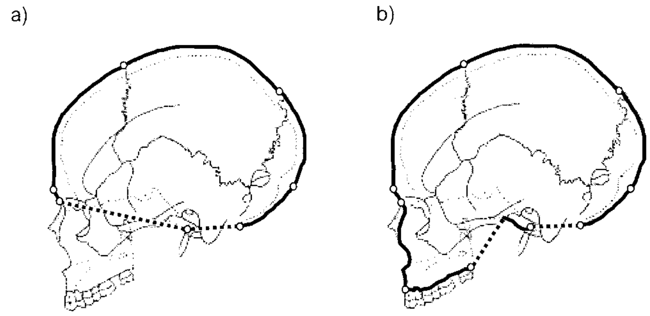

Fig. 1. Schematic representation of two outlines used in this study. **a:** Vault. **b:** Cranium. Landmarks (open circles) are homologous control points used for generalized Procrustes superimposition process. Dashed lines represent straight lines connecting two landmarks.

Basicranial flexion is commonly measured internally. Ross and Henneberg (1995), Ross and Ravosa (1993). May and Sheffer (1999) claimed that internal and external measures are uncorrelated. In this study, we used the orientation of the external basioccipital relative to the axis of the *foramen magnum* as an expression of basioccipital flatness, without inferring any strict relationship to internal or anterior cranial base measurements.

Due to incomplete data sets, approximately 2/3 of the sample was suitable for the comparison of facial outlines and was therefore included in the analysis of the cranium (i.e., the configuration including portions of the face and the basioccipital). Use of the Inuit sample was restricted to the analysis of the vault. Below, we present the results obtained for cranial shape differences and, where significant, briefly compare them to results obtained from analyses of the vault.

Outline digitization and normalization

Outlines and control points were digitized using the TPSDig program (Rohlf, 1996). Outlines need to be superimposed to a common basis before being analyzed, because Fourier parameters are sensitive to starting point, location, size, and orientation of objects (Rohlf, 1990). Kuhl and Giardina (1982) introduced a normalization using outline information, which is geometrically but rarely biologically justified (Bookstein, 1991; Rohlf, 1990). For instance, normalization for orientation uses the major axes of the outlines, which is sensitive to contour irregularities and for which homology from outline to outline hardly applies. Rohlf (1990) proposed using a common orientation axis defined by two homologous landmarks. This approach was used in recent studies and provided reliable results (Monti et al., 2000). Nevertheless, the introduction into geometric morphometrics of the Procrustes superimposition method clearly showed the superiority of multiple-point superimpositions (Dryden and Mardia, 1998; Rohlf, 1990) over two-point registration methods and, particularly in anthropology, over the traditional orientation planes (Frieß, 1999; Penin and Baylac, 1995, 1999).

In the present study, we used a multiple-point reorientation, which uses homologous landmarks called control points (Fig. 1a,b): control points were superimposed using a generalized Procrustes analysis (GPA, formerly called generalized least-squares Procrustes superimposition; Rohlf, 2000). This procedure comprises preliminary centering and size normalization by centroid size, i.e., the square root of the sum of squared distances between the centroid location and all landmarks of an object. Objects are iteratively rotated to minimize the sum of squared distances between the mean configuration, taken as a reference or consensus. Outlines are first centered and size-normalized by dividing, specimen by specimen, the coordinates by the square root of the outline surface. Rotation parameters calculated for the control points are applied to their corresponding outlines at each iteration. This classic normalization procedure is an isometric one, which does not modify the proportions of the objects. Therefore, allometries are not eliminated by the size normalization, and may be specifically visualized or extracted by multivariate regression of harmonics on size.

We used 9 control points for superimposing the craniofacial outline and 7 points for the vault. Taking nasion as the starting point and following the outline in the left lateral view, the points are (clockwise): glabella, bregma, lambda, inion, opisthion, basion, maxillary tuberosity, and prosthion, the latter two being the points omitted in the analysis of the vault.

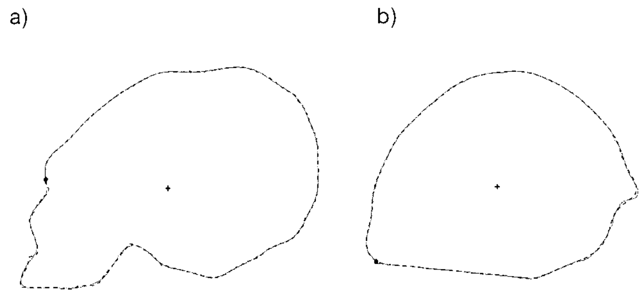

Fig. 2. Comparison of original and reconstructed outlines of (**a**) cranium (30 harmonics) and (**b**) vault (15 harmonics). Solid lines are original outline; dashed lines represent reconstructed outline, and are only visible where deviations between two outlines occur.

Elliptic fourier approximation of outlines

The method of elliptic Fourier approximation described by Kuhl and Giardina (1982) consists of the decomposition of a curve into a sum of harmonically related ellipses. In brief, each closed contour can be described by a vector function of the outline distance

$$\mathrm{V(d)} = \begin{bmatrix} x(d) \\ y(d) \end{bmatrix} \tag{1}$$

The functions x(d) and y(d) are periodic with period D (the outline perimeter) and are equal to

$$\mathrm{x(d)} = \mathrm{A}_0 + \sum_{n=1}^{D} \mathrm{a_n} \cos\frac{2n\pi d}{D} + b_n \quad \sin\frac{2n\pi d}{D} \tag{2}$$

and

$$\mathrm{y(d)} = \mathrm{B}_0 + \sum_{n=1}^{D} C_n \cos\frac{2n\pi d}{D} + t_n \sin\frac{2n\pi d}{D} \tag{3}$$

where n is the harmonic frequency. For a given n, the vectors so-defined generate an ellipse

$$\mathrm{S_n(d)} = \begin{bmatrix} \mathrm{A_n} \\ \mathrm{B_n} \end{bmatrix} \qquad \text{with, } \mathrm{A}_n = a_n \cos\frac{2n\pi d}{D} + b_n \sin\frac{2n\pi d}{D} \tag{4}$$

and

$$\mathrm{B_n} = c_n \cos\frac{2n\pi d}{D} + d_n \sin\frac{2n\pi d}{D} \tag{5}$$

where $\mathrm{A_n}$ and $\mathrm{B_n}$ represent the ellipse axes.

We used 30 harmonics for the cranium, summing up to 122 Fourier coefficients. For the vault, we used only 15 harmonics. In both cases, these harmonic numbers provided good accuracy when outlines were reconstructed (Fig. 2a,b). For statistical and multivariate analyses, we reduced the dimensionality of the Fourier space by a preliminary principal components analysis (PCA) of the covariance matrix of the Fourier coefficients, retaining the first 15 to 20 PCA axes. In all cases, these axes accounted for more than 97% of the outline variance. Components were used for canonical discriminant analyses or for the computation of discriminant functions. We used the procedure explained in Monti et al. (2000) to visualize directly the outline deformations along the directions of interest in the Fourier space, such as canonical or principal components axes, or size in order to depict allometric patterns. In a first step, the predicted Fourier coefficients were calculated by multivariate regression (Krzanowski, 1988) over a variate representing the direction of interest (projections onto the canonical or principal axes, size). These coefficients were then used in an inverse Fourier transformation in order to reconstruct the deformed outlines. Graphic representations, calculated using 15 or 30 harmonics, were visually undistinguishable. All included reconstructions were calculated using 30 harmonics. GPA, elliptic Fourier coefficients, statistical analyses, and graphic outputs were calculated using MATLAB programs devised by one of us (M.B.).

RESULTS

Between-group differences

In order to gain insight into the overall variation of the cranial outlines across the whole sample, we computed an exploratory analysis with three groups (circumferentially deformed, undeformed Peruvians, and undeformed Japanese; see Table 1). Based on the first 15 principal components (97.3% of the explained variance), the statistical discrimination of all three groups was globally satisfying, since separation between deformed and undeformed, as well as between both undeformed populations, is complete (100% correct reassignment).

The use of Procrustes superimposition allows for a description of shape differences independently from any reference plane (e.g., Frankfurt horizontal). Instead of expressing shape differences relative to a fixed anatomical plane, Procrustes superimposition has the effect of spatially "distributing" such shape differences over the complete cranial outline, so that they can be described relative to the overall geometry of the object.

As can be seen from the projections as well as from the visualization of the outline deformations along the canonical axes (Fig. 3), the circumferential deformation produces the most "deviant" cranial outline, with a marked conical vault protruding posteriorly and superiorly, and flattened frontally as well as occipitally. Facial projection both anteriorly and inferiorly is very marked in this group, but relative upper facial length (nasion to prosthion) appears not to be significantly modified compared to the undeformed populations. The deformed skulls also show a reduced protrusion of glabella, which leaves nasion roughly in the same coronal plane as glabella. This pattern, so far only observed in a single case (Duday, 1983), is consistently associated with circumferentially deformed skulls among our samples, but is not seen in undeformed skulls.

The basioccipital portion also shows significant modifications associated with circumferential deformations. The angle formed by the *foramen magnum* axis and the nuchal plane is clearly more acute, whereas the outline from the foramen magnum to the basioccipital is virtually angled in the same manner. However, the Procrustes registration of the outlines illustrates that the overall orientation of the *foramen magnum* is much more horizontal in circumferentially deformed skulls than it is in the two undeformed populations.

The projection onto the second canonical axis (Fig. 3) basically reflects differences between the two undeformed populations. Undeformed Peruvians have positive scores on this second axis which are associated with a more acute angle of the *foramen magnum* axis relative to the nuchal plane, whereas its angle with the basioccipital is much flatter compared to the Japanese sample. Consequently, the axis of the foramen is much more vertically oriented in undeformed Peruvians. The facial profiles of the two undeformed samples are relatively similar, although the undeformed Peruvians tend to exhibit a face that is overall protruding anteriorly.

Mahalanobis D^2 distances (Table 2) confirm that the most important shape differences occur between circumferentially deformed individuals on the one hand, and both undeformed groups (Peruvians and Japanese) on the other. The highest distance value is observed between circumferentially deformed and Japanese crania.

A discriminant function was computed in order to further examine the shape differences between Japanese and undeformed Peruvians. The visualization (Fig. 4a) confirms the observations made in the first analysis: it illustrates that undeformed Peruvians show a marked flattening in the lambdoid region compared to the Japanese; their faces are more anteriorly projected, and they exhibit a relatively flat basioccipital/foramen angle. Again, the axis of the *foramen magnum* is more vertically oriented in the sample of undeformed Peruvians. Therefore, the discriminant function allows for a 100% separation between both groups, based on the differences in basioccipital orientation, lambdoid curvature, and relative facial projection (reduced in the Japanese; see Fig. 4a). Clearly, Peruvian crania, whether exposed to effects of circumferential deformation or not, show a distinguishable configuration of their facial and basioccipital portions. They are relatively flatter and more horizontally oriented in the anterior portion (clivoforaminal angle) and more angled in the posterior part (foramen/occipital plane angle). This observation was also confirmed by a simple PCA of the superimposed control points (not shown here). Although, in this analysis, separation less than 100%, the population difference was again mainly

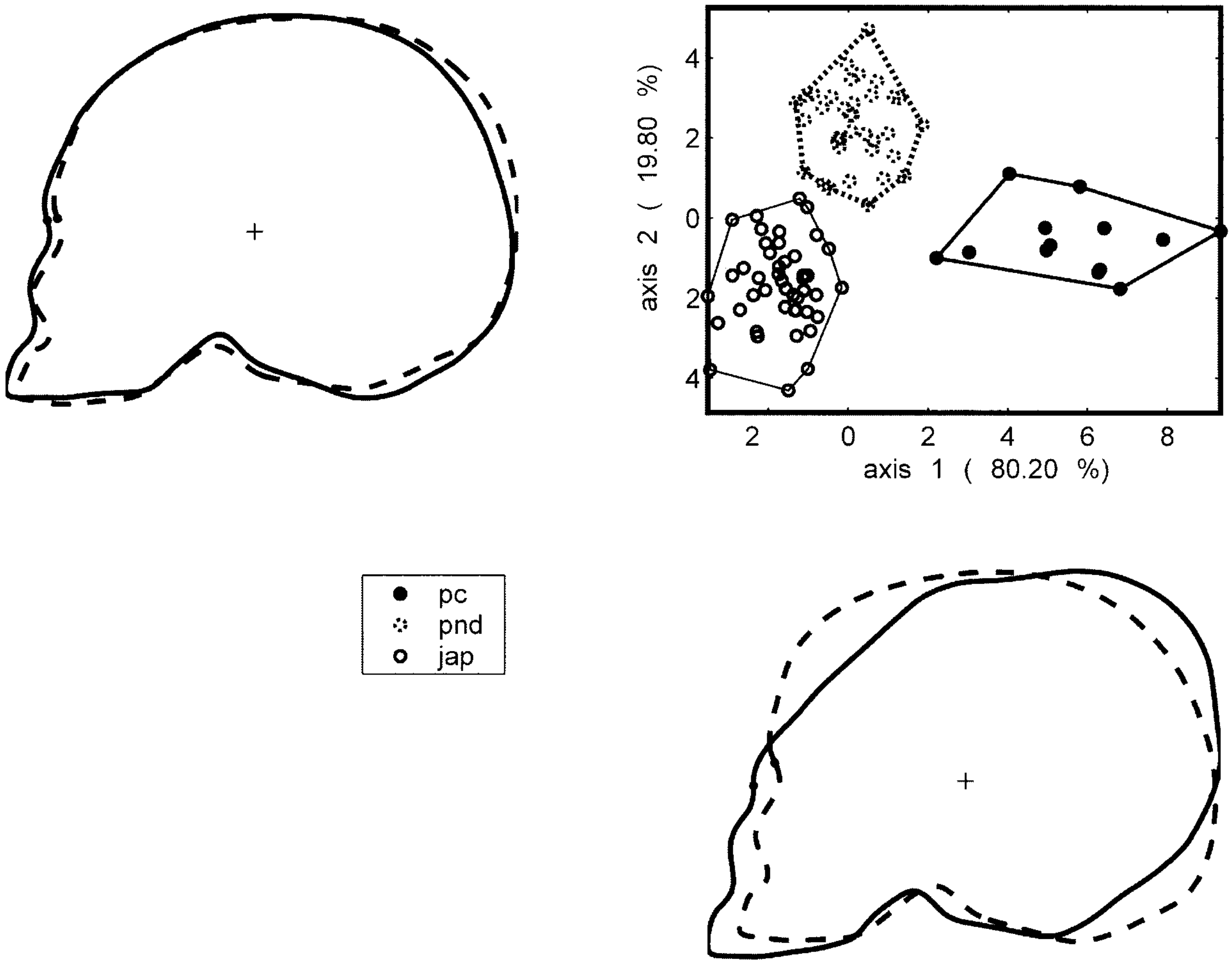

Fig. 3. Discriminant analysis of cranial outlines of three groups. Plot of canonical axes 1 and 2 and associated shape change. Dashed outlines correspond to shapes associated with negative scores along axes; solid outlines correspond to positive scores along axes.

TABLE 2. Mahalanobis d^2 distances for discriminant analyses[1]

	PC	PND	Japanese	Inuit
C-deformed		28.79	45.09	39.82
Undeformed P	38.49		12.48	4.47
Japanese	54.63	19.24		14.36
Inuit	Not included	Not included	Not included	

[1]Below diagonal: D^2 for cranium (3 groups, 30 harmonics, 15 principal components). Above diagonal: D^2 for vault (4 groups, 15 harmonics, 15 principal components).

located around the *foramen magnum*, as opisthion was the only point that clearly showed a more inferior and posterior position in undeformed Peruvians than in the Japanese. In addition, the upper face in undeformed Peruvians is more protruding in an anterior direction when compared to the Japanese.

The question of whether the basioccipitally flattened and facially protruding condition in C-deformed skulls is essentially the same as in undeformed skulls drawn from the same population, or whether it is further modified, was tested by a discriminant function contrasting both Peruvian samples (PC against PND). Based on previous studies (McNeill and Newton, 1965; Antón, 1989a, b), it may be expected that this condition would be reinforced under the effect of circumferential deformation. Figure 4b illustrates the shape differences between the two groups. The angle between the basioccipital and *foramen magnum* axis is very similar for both circumferentially deformed and undeformed Peruvian skulls, and a virtually identical observation was made when the Japanese sample was used instead of the undeformed Peruvians (not shown). However, this analysis confirms clearly that the circumferential deformation leads to major rearrangements of the craniofacial architecture: in addition to the generally anteriorly protruding face among Peruvians, the C-deformed individuals also exhibit an inferior protrusion, as well as an increased anterior protrusion. The nasion is clearly projected anteriorly and inferiorly compared to undeformed crania. The *foramen magnum* is horizontally oriented, leading to a modified nuchal inclination, but the angle between the basioccipital and the *foramen* axis appears unmodi-

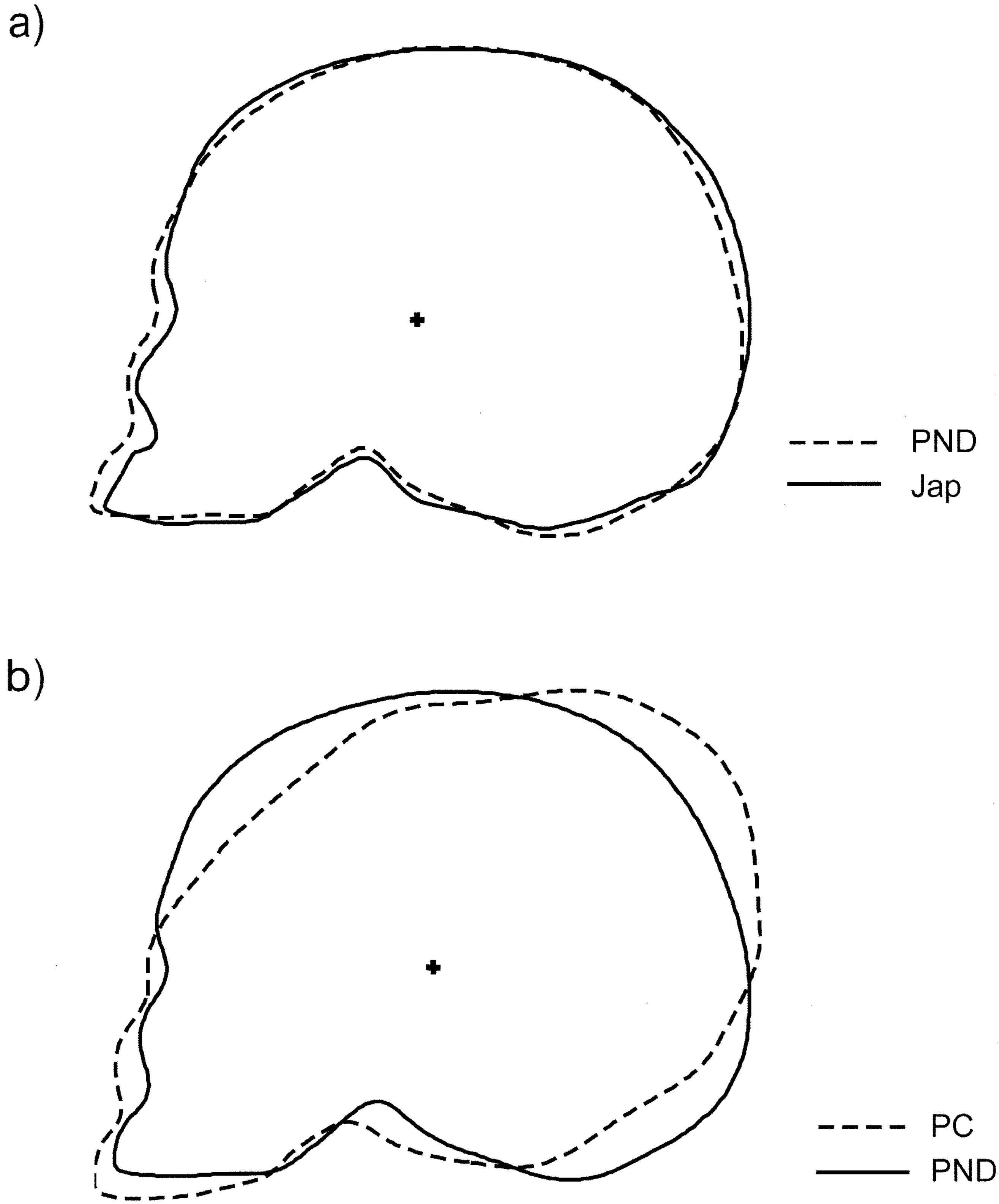

Fig. 4. Fisher's discriminant function of cranial outlines contrasting two groups. **a:** Undeformed Peruvians compared to Japanese. **b:** Undeformed and circumferentially deformed Peruvians.

fied. With the exception of one individual, all of the circumferentially deformed crania could be statistically distinguished from undeformed skulls, but in none of these analyses did the inclination of the basioccipital relative to the *foramen magnum* seem to play a significant role.

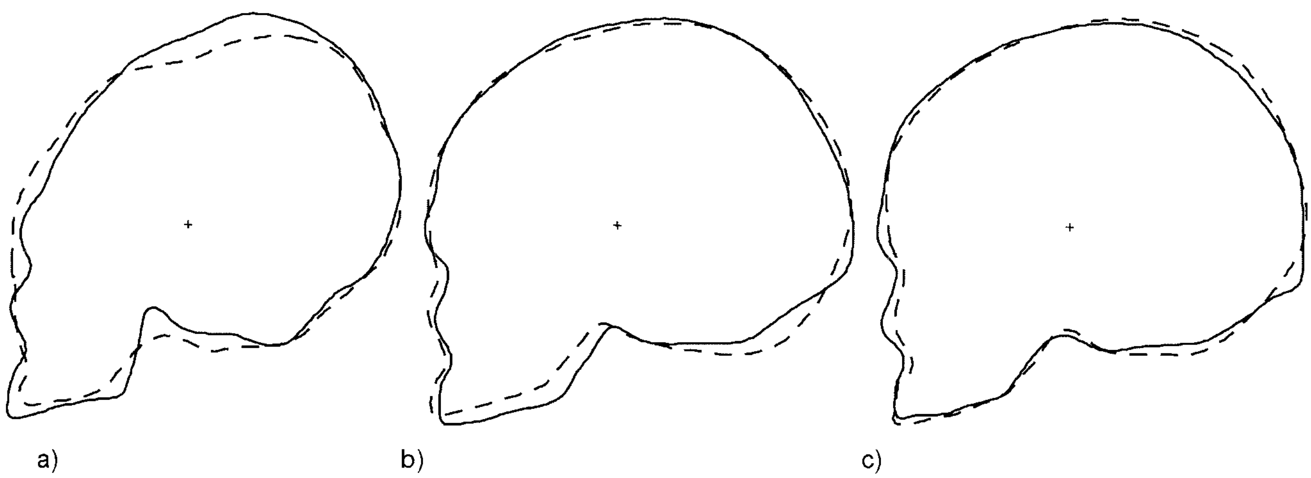

Fig. 5. Allometric shape change computed by multivariate regressions of harmonics onto size (square root of area of bounded outline). **a:** Circumferential deformation. **b:** Undeformed Peruvians. **c:** Japanese. Solid lines, large-sized individuals; dashed lines, small-sized individuals.

Within-group variation and allometry

The analysis of within-group variation serves mainly to establish the homogeneity of the a priori assignments, as well as to ascertain that no deformed individuals remain in the undeformed subsamples. It was argued in earlier studies (Antón, 1989b; Kohn et al., 1993) that misidentification of certain types of deformation might be responsible for contradictory results regarding the effects of deformation on the cranial base, and one might consider this also to be true for unidentified cases of deformation in reference samples that supposedly represent "normal" cranial architecture. The shape variation within each group was first assessed by principal components analysis (PCA), which can be visualized using the same procedure described for canonical axes.

In general, all groups showed variation that was not specifically related to any type of deformation. The within-group shape variability of the Japanese sample was mainly located on the postero-inferior cranial outline, which exhibits a relatively flexed *foramen magnum* axis relative to the nuchal plane. The facial projection also varied slightly along both anterior-posterior and superior-inferior axes. Undeformed Peruvians varied with respect to the midsagittal profile along the parietal portion (lambdoid flattening), as well as in the rotation of the face relative to the vault. None of these shape changes resembles any of the various deformation types and are therefore not further discussed. However, among the Peruvians, there was also an important pattern of variation in the angle formed by the *foramen magnum* and the basioccipital. As shown below, this change correlates with size and hence reflects allometry, rather than artificial deformation. In circumferentially deformed crania, most of the variation was located in the face (overall projection, protrusion of the superciliary arch) and the midsagittal contour, showing varying degrees of the characteristic cone-shaped outline.

Artificial cranial deformation, as known from previous studies, does not seem to alter cranial capacity. Therefore, size effects were not expected to play a significant role in the differences between deformed and undeformed skull outlines. However, despite the unknown sex distribution within our samples, a certain amount of size variation, reflecting sexual dimorphism, can be expected to occur in all groups. It must also be kept in mind that the size measure used here does not directly reflect cranial capacity, and that a deformed skull may appear smaller in lateral view even if its cranial capacity is not altered. Given the nature of circumferential deformation and especially the induced compensation of the skull, through expansion toward the rear rather than toward the sides, the projected area covered by the lateral outline should not be significantly reduced.

The relative square root of the surface areas was compared by an ANOVA and revealed significant differences ($F = 39.172$, $df = 3/126$, $P = 2.2 * 10^{-16}$). The size was found to be larger in the Japanese sample, whereas the deformed and undeformed Peruvians were not distinguished. This result confirms that artificial cranial deformation only alters the shape of the midsagittal outline, but not the size that it encloses.

Multiple regression tests for allometry were significant at the 0.05 level for both Peruvian groups, but not for the Japanese sample. Due to the relatively small sample sizes, only the first 2–5 within-group principal components were tested against size. Among the undeformed Peruvians, 23% ($P = 0.04$) of the overall variance in shape could be explained by size, while 69% ($P = 0.04$) of the shape variance in circumferentially deformed Peruvians were related to size.

In general, allometric shape change appears to relate to pronounced supraorbital and occipital profiles (a marked external occipital protuberance can be observed in large Japanese skulls). Although the lack of data related to sex does not allow for a definitive conclusion, the observed variation is consistent with what can be expected in terms of sexual dimorphism.

In all three subsamples, a significant increase in size was associated with a very distinct change in external basioccipital morphology (Fig. 5a–c). While the *foramen magnum* axis in the C-deformed skulls tends to change from a more horizontal to a more sloping orientation with increasing size, the opposite allometry seems to exist in the two undeformed samples. In addition, among the undeformed Peruvians, the angle formed by the *foramen magnum* axis and the basioccipital becomes more acute with increasing size, whereas in the deformed sample the angle appears to become flatter.

Analysis of the vault

In order to further assess the effects of artificial deformation on the craniofacial architecture, we performed a shape analysis that was restricted to the vault. The resulting discriminant analyses yielded contrasts that were globally consistent with those based on the cranium, but the statistical separation of groups was weaker, as indicated by the Mahalanobis D^2 distances (Table 2).

Although the first canonical axis (Fig. 6a) clearly reflects differences between the deformed group (C) and the three undeformed populations, the Japanese are more or less completely separated from undeformed Peruvians and Inuit on the second axis. The visualization of the shape differences indicates that the Japanese show a less protruding occipital as well as a lesser flexion of the *foramen magnum* axis relative to the nuchal plane of the occipital, but a more acute angle between the foramen axis and the nasion-basion line. Undeformed Peruvians show much overlap with the Inuit on the second axis, but only marginal overlap with the Japanese. The D^2 values of this analysis are smaller than those obtained from the cranium, but these values may not be comparable because the sample sizes are increased and one additional group (Inuit) is used in the analysis (see Table 2). Inuit and Peruvians also exhibit overlap when canonical axes 2 and 3 are plotted against each other (Fig. 6b), so that their cranial vault shapes can be described as overall very similar. The shape change associated with canonical axis 3 suggests that undeformed Peruvians tend to have a shorter and higher vault, combined with a clearly less flexed *foramen magnum* axis relative to the nasion-basion line.

This result emphasizes that Peruvian skulls have a very specific architecture that exhibits a much less flexed orientation of the *foramen magnum* axis as opposed to the highly flexed pattern observed in the Japanese, relative to the nasion-basion line and therefore to the face. These observations are confirmed by discriminant functions performed on Japanese against undeformed Peruvians as well as on circumferentially deformed Peruvians against undeformed ones. In these analyses (not shown here), the latter exhibited a flattened angle between the foramen magnum axis and the nasion-basion line, even when compared to their deformed counterparts.

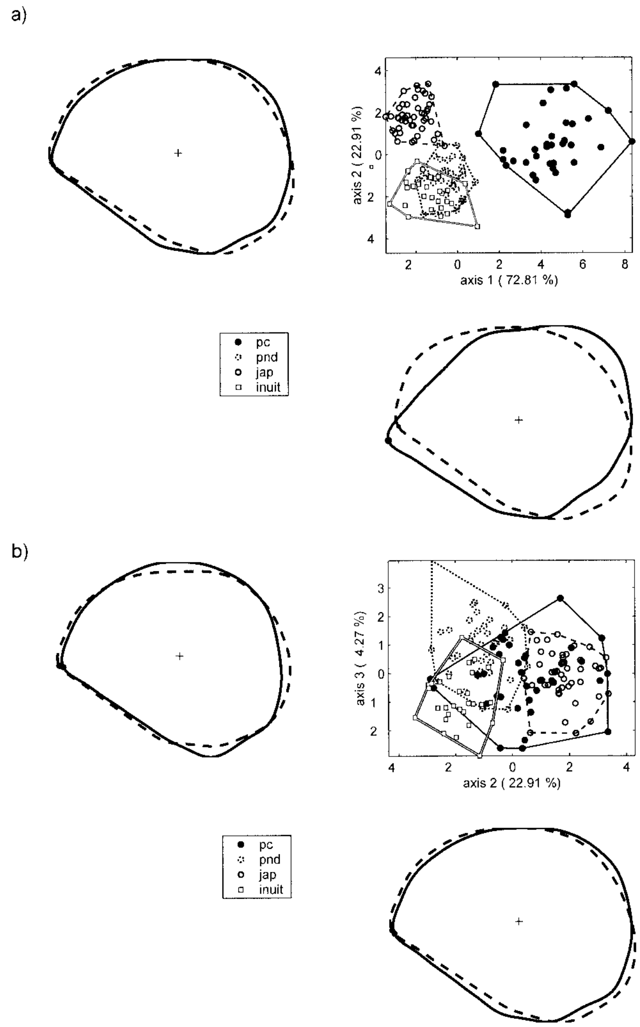

Fig. 6. Discriminant analysis of cranial vault. **a:** Plot of canonical axes 1 and 2. **b:** Plot of canonical axes 2 and 3. Dashed outlines correspond to shapes associated with negative scores along axes; solid outlines correspond to positive scores along axes.

DISCUSSION

Discriminating cranial outlines using Fourier harmonics

As seen in the results of the various discriminant analyses, as well as from the visualizations (Figs. 3, 4, and 6), the two major entities within the sample (deformed and undeformed skulls) are in almost all cases clearly separated from each other. In general, as was a priori expected, the circumferentially deformed individuals show the most deviating lateral outlines when seen in lateral view, resulting in a very distant position within the discriminant space. All undeformed skulls, on the other hand, were expected to group together in marked opposition to the deformed crania, which is what was generally found. Judging from our results, the supposed morphological hiatus between what can be considered as deformation and what cannot be (Antón, 1989b; Antón and Weinstein, 1999) with respect to circumferential deformation appears to be real, and the 2D lateral outline carries most of the relevant information that characterizes this deformation type. Comparisons to other types of deformation, such as the anteroposterior type (AP), are currently under investigation.

Furthermore, it must be emphasized that the statistical separation of deformed and undeformed skulls partly reflects the authors' sampling strategy, which was focused on clearly deformed individuals. From a biological point of view, variation between deformed and undeformed skulls should be thought of as being much more continuous and gradual, which implies that a certain degree of minimal deformation may not be detected visually.

Despite potential differences in their cranial outlines, undeformed Peruvians and Japanese strongly overlap along the discriminant axes and, where separated, mainly show localized shape differences in foramen magnum orientation and occipital curvature. When opposed by a discriminant function, both groups can be separated at 100% on the basis of these shape differences as well as by the degree of facial projection. This result emphasizes that outlines carry important morphological information and that our analytical framework appears well-adapted to this type of data.

Effects on the face and the basioccipital

The effects of artificial cranial deformation on the craniofacial architecture have repeatedly been subject to morphometric analyses. In terms of what these effects really are, observations have not consistently led to identical conclusions, particularly with respect to facial features (see Antón, 1989b). Possible explanations for the observed differences may be sought in ambiguities of the various classifications of deformation types, as discussed by Antón (1989b), as well as in the lack of evidence when it comes to ascertaining nondeformation in a specimen. It seems clear now that the classification by Moss (1958) of deformed skulls into "erect and oblique" types cannot be paralleled with the "anteroposterior and circumferential" system (Antón, 1989b, and personal observations): The latter system should be regarded as the basic dichotomy of deformed crania, for each of which one can observe an "oblique" and an "erect" variant.

In addition, we also want to stress the methodological problems of assessing shape change with conventional linear measurements. For instance, while interpreting her observations, Antón (1989b, p. 262) stated, "Either these changes result from direct movements of vault bones . . . or they are due to indirect antero-inferior displacement of the basion-sella plane . . ., or some combination of the above possibly resulting in the spatial transformation of the entire frame of reference." We feel that this underlines the need for methods that allow for a description of shape change without referring to external frames such as anatomical planes. As emphasized by others (Rohlf and Marcus, 1993), shape differences that are assessed relative to a reference plane tend to change as soon as the reference plane itself changes. The methodological improvements that were made in the field of geometric morphometrics after the above-quoted study was published have already been stressed. We therefore suggest that in the context of cranial deformations, the methods that are being applied are one possible source for diverging results. More recently, Cheverud et al. (1992) and Kohn et al. (1993) applied finite-elements methods to examine effects of cranial deformation. While their main approach differed from ours, the authors also used Procrustes superimposition, a technique that is on the verge of becoming standard in morphometrics. However, they did not address the same changes in the basioccipital, and their illustrations do not allow for an unambiguous interpretation of their results with respect to this issue.

Our results show that among Peruvian crania, the effects of artificial deformation on the craniofacial architecture vary, depending on which anatomical portion is considered and with which reference sample one compares. While undeformed Peruvians are globally distinguishable from the other samples by a flat basioccipital architecture, especially the clivoforaminal angle, circumferential deformation does not change this pattern significantly in our samples. This result is not entirely consistent with those reported by others (Antón, 1989b; Cheverud et al., 1992; Moss, 1958). One reason, however, is that our results are not directly comparable to preceding studies, because we measured the relative flatness of the basioccipital, the *foramen magnum*, and the nuchal plane, whereas previous reports focused on the basicranial flexion. One has to keep in mind that the orientation of the clivus (relevant for measures of basicranial flexion) may only loosely affect the angle formed by the basioccipital and the *foramen magnum* (May and Sheffer, 1999), although some degree of relatedness seems inherent. However, even the studies that measured the clivoforaminal angle reported differences compared to undeformed and/or AP deformed crania. It may be that the effects of circumferential deformation on the base have been overestimated simply because of the contrast to AP deformed skulls, which, according to Moss (1958), exhibit basicranial kyphosis. This remains to be further investigated, but if this were the case, it would explain why in our comparisons of C-deformed skulls and undeformed skulls the change in the degree of flatness is much reduced. On the other hand, our results do show that the area around the foramen magnum is clearly modified under the effect of circumferential deformation. The foramen axis is more horizontally reoriented and therefore forms a much smaller angle with the nuchal plane. Furthermore, our results not only confirm this horizontal reorientation of the axis of the *foramen magnum*: in addition, they allow us to specify that this change in orientation results mainly from a shift in the position of the nuchal plane (i.e., the opisthion), whereas the anterior portion, notably the clivoforaminal angle, remains relatively stable.

Finally, the position of the face relative to the braincase is also altered, although not exactly in the way it was previously described. While the face of undeformed Peruvians can be characterized as relatively protruding anteriorly when compared to the Japanese sample, the circumferentially deformed skulls show an increase of this anterior protrusion and, in addition, an inferior protrusion. Relative dimensions of the face seem to remain unaffected by the deformation, which confirms some previous studies (Antón, 1989b). Again, additional comparisons are necessary, particularly with respect to facial modifications that have been reported in anteroposteriorly deformed skulls (for an overview, see Antón, 1989b) and that appear to be in sharp contrast with the modifications observed here in the C-type.

CONCLUSIONS

The present study demonstrates that elliptic Fourier analysis is a useful tool for the characterization of cranial shape differences among various human groups. The statistical power, combined with the visual feedback, allows for a very reliable and more detailed description of the effects of artificial cranial deformation than standard linear or angular measurements that express differences relative to anatomical reference planes. However, the obtained results can almost certainly be improved by extending the analyses to a three-dimensional approach. We believe that, as far as circumferential deformations are concerned, this is a minor improvement, but we expect that this may prove a valuable step for the inclusion of other deformation types, such as those resulting from anteroposterior compression. Therefore, we consider our conclusions to be preliminary.

When seen in lateral view, artificially deformed crania can be accurately distinguished from their undeformed counterparts. For the circumferential deformation type, 2D cranial outlines carry sufficient information. Differences between deformed and undeformed crania are generally not related to differences in overall cranial size; therefore, they involve mostly isometric shape change.

When addressing possible effects of artificial cranial deformation on the craniofacial architecture, the underlying variation of the undeformed population, compared to other populations, should be known. While preceding studies focused on the comparison of deformed and undeformed individuals taken from the same population, we come to the conclusion that the use of a different population as a reference in addition to the deforming population is necessary and improves our understanding of morphological variation associated with deformation. Undeformed Peruvian crania appear to have a craniofacial architecture that is distinct from the corresponding shapes seen in the Japanese and Inuit. They are characterized by anteriorly protruding faces and a relatively flat angle between the *foramen magnum* and the basioccipital, which leads to a more vertically oriented *foramen magnum* axis. In this sense, they are somewhat “flatter.” When exposed to circumferential deformation, this pattern becomes globally reinforced with respect to at least the face. In addition, the face then also protrudes inferiorly, nasion protrudes anteriorly, whereas the *foramen magnum* axis continues to become more horizontal in its orientation. Therefore, our results are generally consistent with previously published data (Antón, 1989b; Kohn et al., 1993), but do not agree in some important aspects. Notably, we find the effects of artificial deformation on the basioccipital to be less than previously observed, whereas the effects on the face observed here are similar to other studies or even more important. Given that statistical discrimination is not as good when facial features are not taken into account, we conclude that the effects of artificial deformation on the face outweigh those observed on the basioccipital portion. Generally, these effects seem to emphasize morphological trends that already exist in populations that practiced intentional deformation.

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