Revista Argentina de Antropología Biológica

BRIEF COMMUNICATION

Effect of intentional cranial modification on cranial shape and size: Revisiting the contribution of radiographic data

Efecto de la modificación intencional del cráneo en la forma y tamaño craneales: revisión de la contribución de la información radiográfica

Efeito da modificação intencional do crânio na forma e tamanho craniano: revisão da contribuição da informação radiográfica

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Abstract

The current availability of CT-generated lateral cephalograms has repositioned the use of information contained in two-dimensional data for assessing intentional cranial modification, with traditional lateral radiography (2D) still in use for this purpose. Considering this, the aim of the present work is twofold: i) to revisit the contribution of radiographic data compared to three-dimensional (3D) models for studying intentional cranial modification, and ii) to assess the effect of this practice on cranial size. The pattern of cranial shape and size variation was analyzed on a set of radiographs and 3D models of intentionally deformed crania belonging to the same individuals (adults from archaeological and contemporary samples), considering a geometric morphometrics semilandmark approach. Our main results show that: i) the

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shape and size components of intentionally modified crania, when comparing teleradiographs and 3D models from the same individuals, were highly concordant, thus supporting the contribution of 2D data as reliable imaging information for studying this biocultural practice, and ii) the intentionally modified crania were smaller than the non-deformed ones, probably due to the common effect of modification that mostly affects the antero-posterior growth axis, which prevents normal sagittal development of the cranial base. Rev Arg Antrop Biol 27(2), 112, 2025. https://doi.org/10.24215/18536387e112

Keywords: centroid size; intentionally modified crania; geometric morphometrics

Resumen
La disponibilidad actual de cefalogramas laterales generados por tomografía computarizada (CT) ha reposicionado el uso de la información contenida en datos bidimensionales para evaluar la modificación craneal intencional (ICM), siendo la radiografía lateral tradicional aún la utilizada para este propósito. A partir de esta información, los principales objetivos del presente trabajo son: i) revisar la contribución de los datos radiográficos en dos dimensiones (2D) para estudiar la modificación craneal intencional en comparación con modelos tridimensionales (3D) y ii) evaluar el efecto de la ICM en el tamaño del cráneo. El patrón de variación de la forma y el tamaño craneal se analizó en una muestra de radiografías y modelos 3D de cráneos intencionalmente deformados pertenecientes a los mismos individuos (adultos provenientes de muestras arqueológicas y actuales) desde un enfoque estándar de morfometría geométrica con uso de semi-hitos. De acuerdo con nuestros principales resultados: i) los componentes de forma y tamaño de los cráneos modificados intencionalmente al comparar teleradiografías y modelos 3D de los mismos individuos fueron altamente concordantes, lo que corrobora la contribución de los datos 2D como información imagenológicamente sólida para estudiar esta práctica biocultural, y ii) los cráneos modificados intencionalmente fueron más pequeños que los no deformados, probablemente debido al efecto común de la modificación que afecta principalmente el eje de crecimiento anteroposterior, lo que evitaría el desarrollo sagital normal de la base del cráneo. Rev Arg Antrop Biol 27(2), 112, 2025. https://doi.org/10.24215/18536387e112

Palabras Clave: tamaño del centroide; cráneos modificados intencionalmente; morfometría geométrica

Resumo
A disponibilidade atual de cefalogramas laterais gerados por tomografia computadorizada (TC) reposicionou o uso da informação contida em dados bidimensionais para avaliar a modificação craniana intencional (MCI), sendo a radiografia lateral tradicional ainda em uso para esse propósito. Com base nessas informações, os principais objetivos do presente trabalho são: i) revisar a contribuição dos dados radiográficos bidimensionais (2D) para o estudo da modificação craniana intencional em comparação com modelos tridimensionais (3D) e ii) avaliar o efeito da MCI no tamanho do crânio. O padrão de variação do formato e tamanho do crânio foi analisado em uma amostra de radiografias e modelos 3D de crânios intencionalmente deformados pertencentes aos mesmos indivíduos (adultos provenientes de amostras arqueológicas e atuais), a partir de uma abordagem padrão de morfometria geométrica com uso de semimarcos. De acordo com nossos principais resultados: i) os componentes de

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forma e tamanho dos crânios intencionalmente modificados, comparando telerradiografias e modelos 3D dos mesmos indivíduos, foram altamente concordantes, o que corrobora coma contribuição dos dados 2D como informações imagenologicamente sólidas para o estudo dessa prática biocultural, e ii) os crânios intencionalmente modificados foram menores do que os não deformados, provavelmente devido ao efeito comum da deformação que afeta principalmente o eixo de crescimento anteroposterior, o que evitariao desenvolvimento sagital normal da base do crânio. Rev Arg Antrop Biol 27(2), 112, 2025. https://doi.org/10.24215/18536387e112

Palavras-chave: tamanho do centróide; crânios modificados intencionalmente; morfometria geométrica

Intentional cranial modification (ICM), a biocultural practice having caught the attention of scholars from the 19th Century to the present (Broca, 1871; Morton, 1839; as cited in O'Brien, 2024), consists of the modification of the magnitude and direction of the vectors of growth and development of the crania, through compressive forces generated by modifying devices during the early years of post-natal life (Püschel *et al.,* 2020). ICM has been described in human populations of different geographical origins, periods and cultures, from late Pleistocene (Brown, 1981) to the 20th century (Dembo & Imbelloni, 1938; Gerszten & Gerszten 1995; Özbek, 2001; Weiss, 1961), being widely represented in Central Eastern Asia, Central Southern Andes, and Mesoamerica (as cited in Dingwall, 1931; Tiesler, 2022). It should be noted that it is unclear whether cranial modifications are intentional or unintentional in all cases, so some authors prefer to refer to them as cultural or artificial cranial modifications, or simply cranial modifications, like when fixing children to a cradle with bandages for transportation (Dembo & Imbelloni, 1938, p. 19). It is also uncertain whether ICM was always intended to serve as an ethnic marker (Serna, 2019).

The practice of intentional cranial modification has been, for a long time, the focus of physical anthropologists (as cited in Dembo & Imbelloni, 1938; O'Brien, 2024), bioarchaeologists (as cited in Tiesler, 2022), and clinicians (Allison *et al.,* 1981; Broca, 1871; Gerszten & Gerszten, 1995). Each of these disciplines has posed specific questions about the purpose of ICM, how, why, and when it was done, what kind of devices were used for modifying the crania of newborns, and whether this practice alters brain functions. Despite the diversity of questions posed -for a century and a half- to understand ICM (Dingwall, 1931; Gosse, 1855; Morton, 1839; O'Brien, 2024), the study of ICM, from a historical perspective, was initially descriptive, then based on the statistical analysis of interlandmark distances, until the present consolidation of geometric morphometric analysis of landmark coordinates (Fig. 1).

In recent decades the emergence of three-dimensional (3D) imaging resources and the concomitant application of geometric morphometrics techniques have improved ICM research (Frieß & Baylac, 2003; Khonsari *et al.,* 2013; Kuzminsky *et al.,* 2016; Püschel *et al.,* 2020). In this context, although during the 20th century, radiographs were used sporadically mostly as a complement to the ICM descriptive approach (Dembo & Imbelloni, 1938; Soto-Heim, 1987; Weiss, 1961), the current availability of CT-generated lateral cephalograms has repositioned the use of the information carried by two-dimensional data to assess ICM (Cottin *et al.,* 2017), with traditional lateral radiography still in use for this purpose (Pérez-Vargas *et al.,* 2021). Synthetic computed tomography-like imaging

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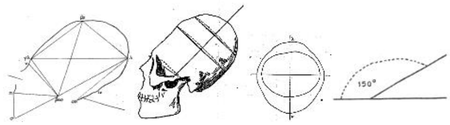
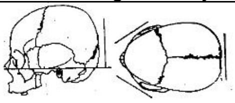
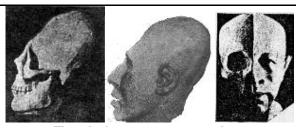
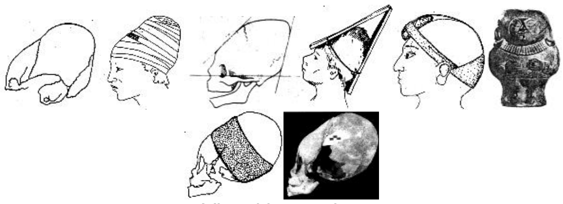
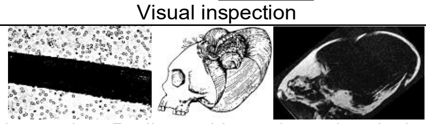
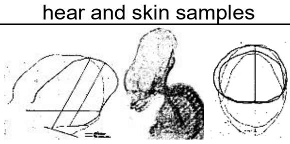
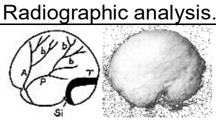
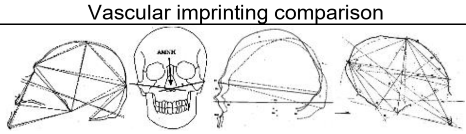
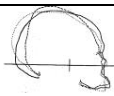
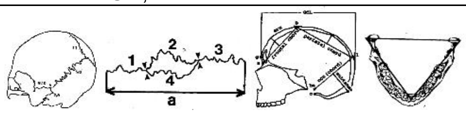
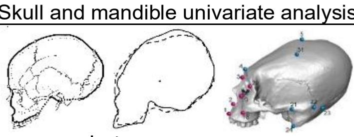
Approach	Problem	Raw data	Type of analysis	References
Descriptive	Classification	Angular measurements	 Cranial trigonometry	Dembo & Imbelloni (1938); Imbelloni (1921, 1925); Hjortsjö (1972)
		Cranial traits	 Visual inspection	Hrdlicka (1912); Latcham (1938); Stewart (1943); Stewtart & Newman (1963)
			 Facial reconstruction	Imbelloni (1963)
		Type of modifying device (mostly inferred after contrasting archaeological and anthropological data)	 Visual inspection	Allison *et al.* (1981); Hoshower *et al.* (1995); Munizaga (1964, 1965, 1974); Ozbek (2001); Reichlein (1982)
			 Visual inspection. Radiographic, and geochemical analysis of facial masks. AB0 blood typing using hear and skin samples	Soto-Heim (1987, 1990)
			 Superimposition of cranial vault profiles. Radiographic analysis.	Weiss (1961)
	Paleopathological condition	Cranial endocasts	 Vascular imprinting comparison	Dean (1995); O'Loughlin (1996)
Traditional morphometrics of metric and non-metric traits	Classification cultural and biological affinities	Interlandmark distances, angular measurements, non metric traits	 Multivariate statistics	Cocilovo *et al.* (1982); O'Brien & Stanley (2013); Rothhamer *et al.* (1984); Sutter & Mertz (2004); Soto-Heim (1986, 1990, 2001a, b); Varela & Cocilovo (2002)
	Paleopathological condition	Interlandmark distances, angular measurements	 Uni, and bivariate statistics	Hershkovitz & Koblyliansky (1992); McNeill & Newton (1965)
		Cranial vault suture pattern and malocclusion class	 Skull and mandible univariate analysis	Anton *et al.* (1992); Cheverud & Midkiff (1992); White (1996)
Geometric morphometrics	Classification cultural and biological affinities	2D and 3D landmark coordinates	 Elliptical Fourier analysis. Generalized Procrustes Analysis. Multivariate statistical analyses applied to landmark cordinates	Friess & Baylac (2003); Kuzminsky *et al.* (2016); Perez (2007); Manríquez *et al.* (2006); Püschel *et al.* (2020); Serna *et al.* (2019)

FIGURE 1. Comprehensive view of the main approaches, problems, types of raw data, and analyses for studying Intentional cranial modification (ICM) in the Southern Central Andes.

from conventional radiographs using AI tools (i.e. deep learning and convolutional neural networks, generative adversarial networks and statistical shape models) is an emergent field in medical imaging analysis that corroborates the benefits and potential of conventional radiography for reducing radiation risk while simultaneously addressing financial and logistical obstacles that impede global access to CT imaging (De Wilde *et al.,* 2025).

The interest generated by the practice of ICM on human crania has been mostly focused on cranial shape changes. The works that explicitly treated the effect of this practice on cranial size have been contradictory in their conclusions. Thus, Morton (1849, p. 226) reported intentionally modified crania of two adults from ancient Peru having cranial capacities of 1.098 and 1.197 cubic centimeters, while Broca (1871) mentioned a crania belonging to an adult female with Toulousian type of modification of just 1.043 cubic centimeters, "(…) *the smallest capacity I've observed so far in non-microcephalic human* (crania)" (p. 108). By contrast, Moss (1958), Gerszten (1993) and, more recently, Khonsari *et al.* (2013) argue that this practice does not alter the size compared to crania that have not been intentionally modified. While Moss (1958) does not provide any direct evidence to support his conclusion, Gerszten (1993) and Khonsari *et al.* (2013) do, using sand and CT scans, respectively. Regarding the use of sand for inferring the cranial volume, Gerszten (1993) reports:

> *Although the shape of the skull is changed, its volume remains the same. This fact was concluded after measuring the cranial capacities of the deformed skulls by filling them with sand and then measuring the quantity of sand. No difference was apparent between the cranial capacities of the deformed and the undeformed skulls, lending support to the view that normal brain function is unaffected by the deforming procedure* (Gerszten, 1993, p. 96).

Gerszten (1993) does not provide any evidence on which to base this conclusion, although he is still quoted to claim that there would be no effect of the practice of ICM on cranial size (O'Brien, 2024).

Based on this background, the main aim of the present work is: i) to compare, through a semilandmark approach, the pattern of shape variation in lateral teleradiographs and 3D models obtained from the same sample of intentionally modified crania, and ii) to use centroid size as an estimator of size in intentionally modified compared to non-modified crania. Our hypotheses state that: i) the direction and magnitude of the force vectors producing the intentional modification of the cranium do not differ significatively when using lateral teleradiographs and 3D models obtained from the same individuals, and that ii) the centroid sizes calculated from intentionally deformed and non-deformed crania do not have statistically significant differences. Both hypotheses will be tested on crania belonging to adults from archaeological and contemporary samples.

MATERIALS AND METHODS

Sample

The total sample consisted of 130 crania from Loa River basin Formative (ca. 600 B.C.-500 A.D.), and Late Intermediate (ca. 950-1400 A.D.) periods, and from the San Pedro de Atacama Middle Horizon (ca. 500-950 A.D.), and Late Intermediate periods (Table 1). To test our hypotheses (i.e. 2D data and 3D data represent a similar pattern of shape and size variation), a contemporary non-modified sample consisting of 43 crania was used as a control. In the present study sex was not included as a variable due to the absence of information about the pelvis and the proximal epiphysis of the femoral bone in the archaeological individuals. Moreover, frontal and zygomatic bones, two particularly relevant structures for detecting sex differences in the human cranium (Escobar-Ramírez & Manríquez, 2024), change in shape and size under the pressure of the devices used to intentionally modify the form of the cranium (Beltrán *et al.,* 2024). The X-Ray material was used following standard radiographic procedures (Frankfurt plane anatomical position, 60 Kv, 2 mA/2 seconds, at a 2m distance from the target film using a Portable Geo Ray II X Ray system as an X-Ray source). The respective 3D models were obtained using a NextEngine 3D laser scanner. Prior to applying the standard geometric morphometric workflow, each model was cleaned, centered, smoothed, holes were closed with MeshLab software (Cignoni *et al.,* 2008) and then converted to a valid R environment format (R Core Team, 2008). In order to establish the age of the individuals, the eruption of the third molar and fusion of the spheno-occipital synchondrosis were considered. Subsequently, following Püschel *et al.* (2020) individuals were classified as non-deformed (ND), antero-posterior (AP) and oblique (OB) (Supplementary Information, Fig. S1) by a unique observer (GM) and then confirmed in both X-rays and 3D models by an independent observer (BER). In order to determine the minimum sample size for each data type we followed Rodríguez (2017), applying a MANOVA Global effects (α err prob = 0.05, statistical power = 0.8) using G*Power software (Faul *et al.,* 2007) for assessing the sample size of the two-dimensional (2D) sample (n = 15, Pillai trace V = 1.3), and 3D data (n = 15, Pillai trace V = 1.4).

TABLE 1. Origin of the sample (n= 173) used in the present study, geographical area, chronological period, and type of artificial cranial modification.

Archaeological site/ Origin*	Geographical area	Period	Antero-posterior	Non-modified	Oblique
Chorrillos	Middle Loa Basin	Formative	0	0	18
Toconao	San Pedro de Atacama	Formative	0	1	0
Toconao Oriente	San Pedro de Atacama	Formative	2	0	1
Topater	Middle Loa Basin	Formative	2	0	2
Coyo Oriente	San Pedro de Atacama	Middle Horizon	10	3	0
Coyo 3	San Pedro de Atacama	Middle Horizon	2	1	0
Quitor 5	San Pedro de Atacama	Middle Horizon	0	0	1
Quitor 6	San Pedro de Atacama	Middle Horizon	4	0	2
Sequitor Alambrado	San Pedro de Atacama	Middle Horizon	0	0	2
Sequitor Alambrado Oriente	San Pedro de Atacama	Middle Horizon	3	3	0
Solcor	San Pedro de Atacama	Middle Horizon	8	0	0
Solcor 3	San Pedro de Atacama	Middle Horizon	2	3	4
Caspana	Upper Loa Basin	Late Intermediate	7	2	11
Catarpe	San Pedro de Atacama	Late Intermediate	0	0	1
Catarpe 2	San Pedro de Atacama	Late Intermediate	2	9	0
Chunchuri	Middle Loa Basin	Late Intermediate	2	0	1
Solor 3	San Pedro de Atacama	Late Intermediate	2	0	0
Tchecar	San Pedro de Atacama	Late Intermediate	6	0	1
Tchilimoya	San Pedro de Atacama	Late Intermediate	3	0	7
Toconce	Upper Loa Basin	Late Intermediate	2	0	1
Santiago	Santiago de Chile	mid 20th Century	0	43	0
Total			57	64	52

*The archaeological skulls are housed at Museo Arqueológico R. P. Gustavo Le Paige, San Pedro de Atacama, Chile, excluding Chorrillos (Corporación Cultural y de Turismo, Calama, Chile), and Chunchuri (Musée de l'Homme, Paris, France). The non-modified skulls from middle 20th Century are housed at Colección Osteológica Subactual de Santiago (COSS), Universidad de Chile.

Data acquisition

Six fixed landmarks were registered on each X-ray by a unique observer (GM) using tpsDig2 v 2.32 software (Rohlf, 2021) (Supplementary Table S1).

In order to obtain the head outline for each individual, 17 semilandmarks were semi-automatically placed on the contour of the cranial vault among pairs of fixed landmarks (6 between 2 and 3, 5 between 3 and 4, 3 between 4 and 5, and 4 between 5 and 6) as 17 resampled points of the curves connecting each pair of landmarks (Fig. 2).

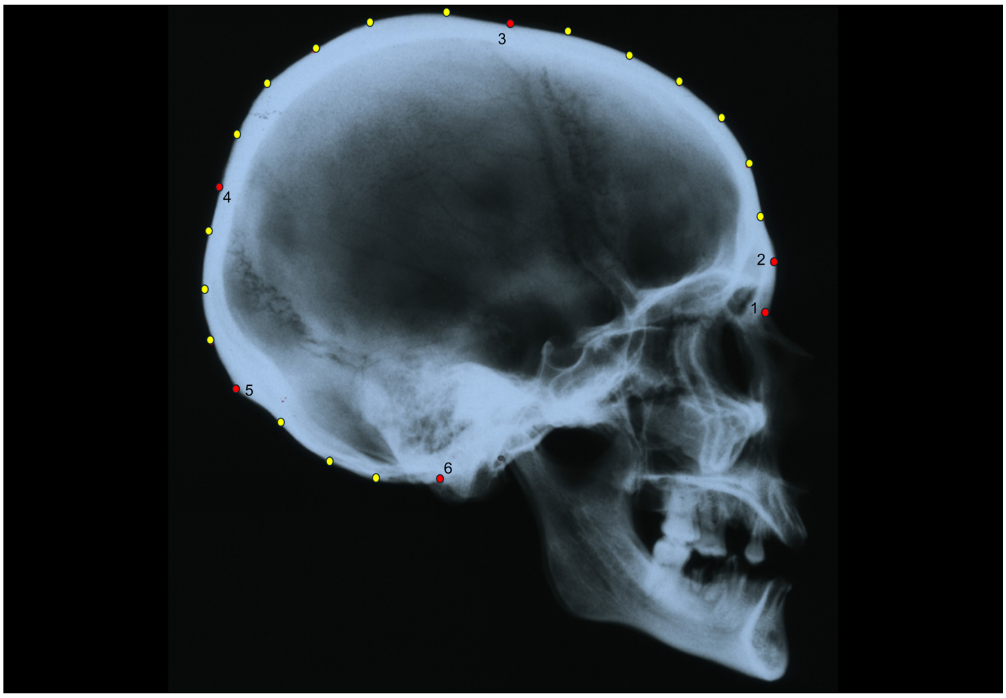


FIGURE 2. 2D landmark and semilandmarks configuration used in the present study. In red, anatomical landmarks; in yellow, semilandmarks.

Each radiograph was manually scaled using tpsDig2 v 2.32 software (Rohlf, 2021) measurement function and a 1 cm. mark as reference. Regarding 3D models, 10 fixed landmarks (Supplementary Table S2) defined by Martin (1957) were recorded on each individual by a single observer (BER) using Stratovan Checkpoint software (Stratovan Corporation, 2018). In addition, 30 semilandmarks were placed on the contour of the supra-orbital ridge (bilateral, 2X5 = 10) and squamous portion of parietotemporal suture (bilateral, 10X2 = 20) (Fig. 3). The patching and sliding procedures (Bardua *et al.,* 2019; Schlager & Rüdell, 2017) were carried out based on previous studies in human crania (Natahi *et al.,* 2021; Pugacheva *et al.,* 2022) in R environment using the *geomorph* (Adams & Otárola-Castillo, 2013) and *Morpho* (Schlager *et al.,* 2018) R packages (Supplementary Information, Section 1). Finally, the intra-observer reliability analysis was carried out following a standard ANOVA for repeated measurements (Supplementary Information, Section 2).

Geometric morphometric analyses

To eliminate differences due to rotation, scale, and translation, a Generalized Procrustes Analysis (GPA) was performed on the combined configuration of landmarks, curves, and surface semilandmarks considered in the present study. GPA aligns the raw coordinates by removing the differences due to translation, and rotation, and scaling each cranial coordinate landmark configuration to a unit centroid size, the square root of the

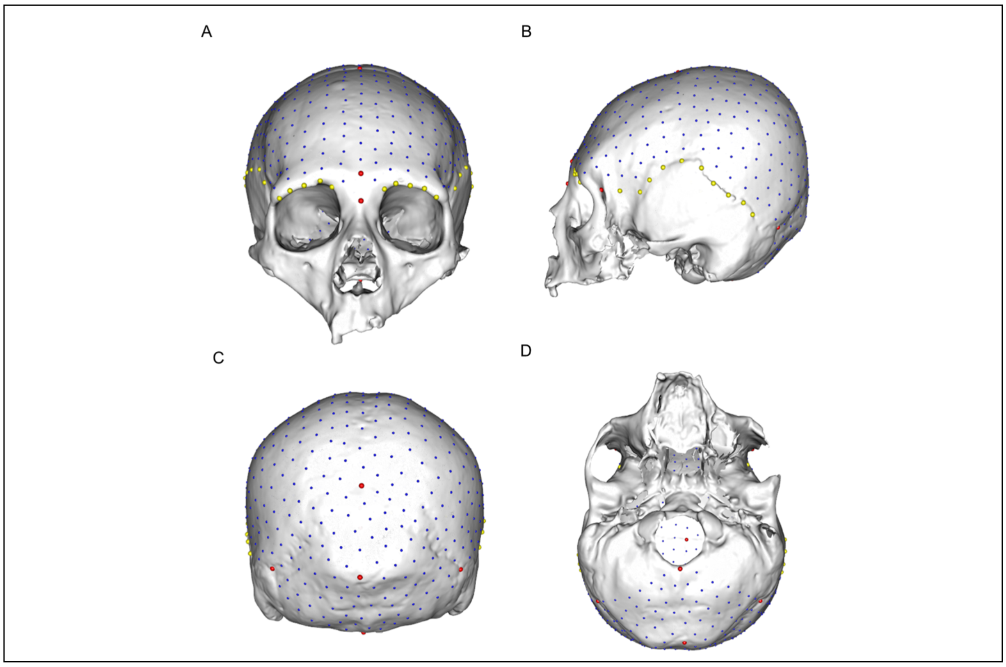


FIGURE 3. 3D landmark and semilandmarks configuration used in the present study in frontal (A), lateral (B), posterior (C), and inferior (D), views. In red, anatomical landmarks; in yellow, curve semilandmarks; in blue, surface semilandmarks.

sum of squared distances of a set of landmarks (and semilandmarks, if applicable) from their centroid (Bookstein, 1989, 1991). Following Gunz *et al.* (2005), the semilandmark approach involves the iterative adjustment of points along curves or surfaces by minimizing or "relaxing" the bending energy to a reference configuration. A principal component analysis (PCA) was then performed in which the aligned coordinates were projected as points to a two-dimensional shape space formed by pairs of the PCs. The influence of artificial modification type on the shape and size variation was evaluated after a Procrustes ANOVA available in the *geomorph* R package using as size estimator its centroid size. To assess the reliability of the ICM classification with and without semilandmarks in both data types, a linear discriminant analysis with leave-one-out cross-validation (LDA) was carried out. The PC scores (defined as 90% of the shape information) were used as dependent variables, considering artificial modification type as the independent variable. Afterwards, the accuracy (80% or more correct classifications of each group) and precision (80% or more of true positives for each group) of the model were calculated using a bootstrap procedure design (1,000 iterations). In each iteration, 120 individuals were randomly sampled. At the end of this iterative procedure, the mean and confidence interval (alpha = 0.05) of the model's accuracy and precision were calculated. To test the level of concordance between both types of data, a Mantel test was performed on the "Multivariate" menu, and the "Test" function of the statistical freeware software PAST (Hammer *et al.,* 2001). The respective distance matrices were calculated using the "Similarity and distance indices" function available in the "Multivariate" menu. Finally, the differences in centroid size were analysed using Procrustes ANOVA, and a *post hoc* Tukey's test.

RESULTS

Pattern of shape and size variation

The pattern of shape and size variation of ICM crania showed a statistically significant association with the 2D (Procrustes ANOVA Shape components: SS = 0.19, MS = 0.097, df = 2, F = 21.52, p = .001; Centroid size: SS = 0.098, MS = 0.098, df =1, F =21.8, p = < .001) as well as with the 3D (Procrustes ANOVA Shape components: SS = 0.23, MS = 0.11, df = 2, F = 36.97, p = < .001; Size: SS = 0.053, MS = 0.053, df = 1, F = 16.98, p = < .001) landmark coordinate data. Regarding LDA, the accuracy and precision of ICM classification were higher in 3D data than in 2D data considering only the true landmarks as well as when semilandmarks were included in the analysis (Table 2). Furthermore, the successful classification tended to be more accurate in OB individuals when semilandmarks were taken into account, compared to AP individuals (Table 2).

TABLE 2. Precision and Accuracy (expressed as a ratio) calculated on 2D and 3D configurations with and without semilandmarks when classifying intentional modification by "shape" variable.

	Accuracy mean (95% CI)	Precision AP mean (95% CI)	Precision ND mean (95% CI)	Precision OB mean (95% CI)
2D (without semilandmarks)	0.838 (0.835-0.841)	0.869 (0.866-0.872)	0.799 (0.794-0.805)	0.836 (0.832-0.841)
2D (with semilandmarks)	0.898 (0.896-0.899)	0.902 (0.900-0.905)	0.880 (0.877-0.884)	0.911 (0.908-0.914)
3D (without semilandmarks)	0.917 (0.915-0.919)	0.917 (0.915-0.920)	0.942 (0.939-0.945)	0.901 (0.898-0.904)
3D (with semilandmarks)	0.940 (0.939-0.942)	0.922 (0.919-0.924)	0.960 (0.958-0.962)	0.947 (0.945-0.950)

CI= Confidence interval

Shape variation

After carrying out a PCA, the first three shape components in 2D data (PC1: 36.71%; PC2: 21.03%; PC3: 15.54%) as well as in 3D data (PC1: 41.22%; PC2: 22.25%; PC3: 9.28%) accounted for more than 70% of the overall variance. The 2D and 3D dataset showed a similar distribution: overall AP individuals were separated from OB and ND by shape components (PCs) (Fig. 4). Furthermore, the number of AP and OB individuals within the 95%

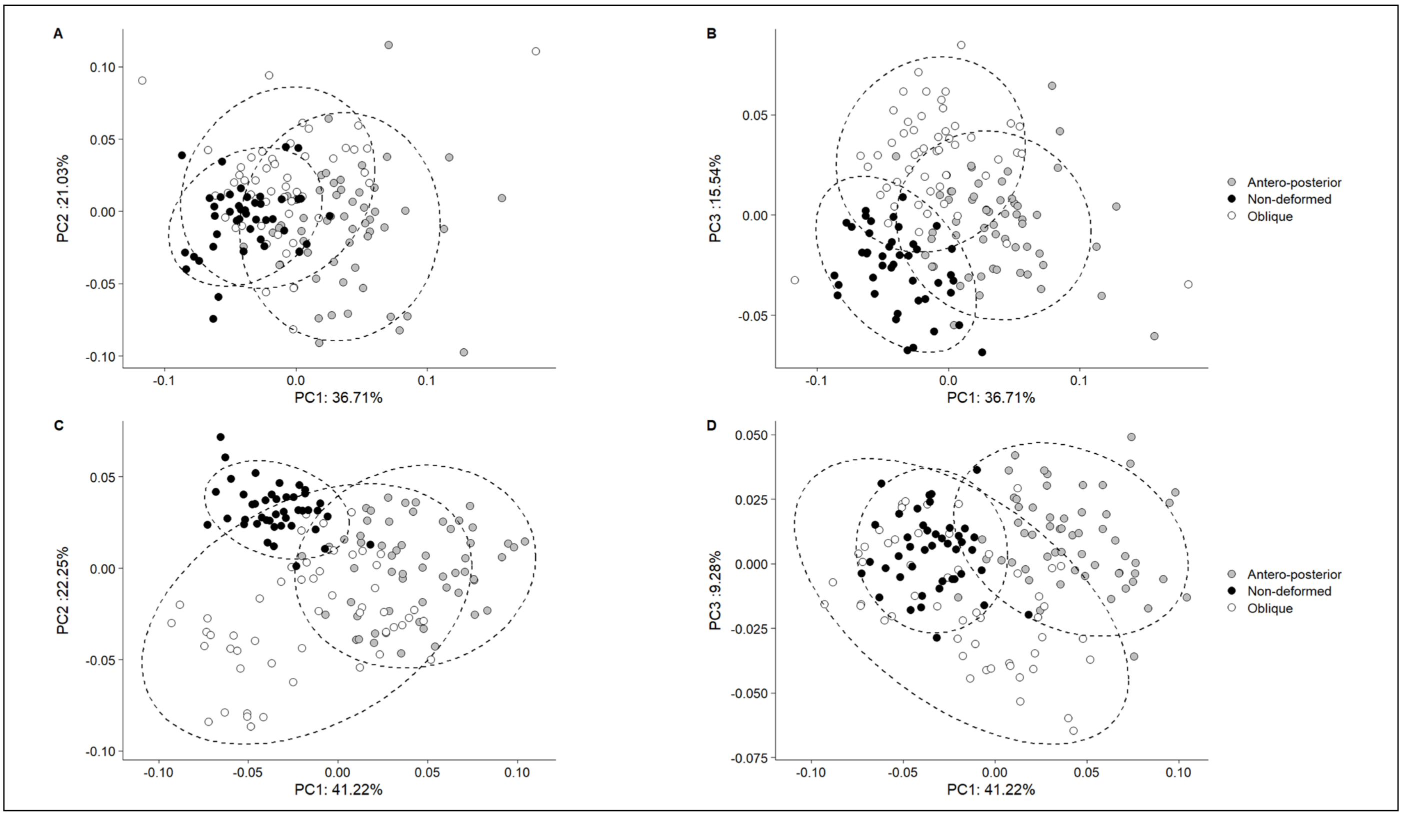


FIGURE 4. Principal component analysis (PCA) obtained from the aligned coordinates of the 2D (A, B) and 3D (C, D) configurations. The percentage of explained variance of each shape component is also shown.

confidence interval were higher in 3D than 2D data (Fig. 4). Regarding the level of the concordance between 2D and 3D shape variation pattern, a positive, statistically significant correlation was observed (Mantel test: $r = 0.37$, $p < .001$, one tailed, 9,999 permutations).

The most representative pattern of shape variation was expressed morphologically as a compression in the cranium at the *lambdo-supraoccipital* regions in AP individuals, while in OB individuals a compression in the cranium at the *fronto-bregmal* region and occipital bone was observed (Fig. 5, 2D). As a result, OB individuals showed a conical and elongated cranium, while AP individuals showed an antero-posterior flattened cranium (Fig. 5, 2D). In relation to surface information, the pattern of shape variation was associated with an asymmetrical expansion/compression of the surface of the cranium. Regarding AP individuals, the most compressed surface in the cranium was located on the occipital bone and the region that goes from the frontal bone to bregma. On the contrary, the lambdo-supraoccipital region and parietal bone were the most expanded (Fig. 5, 3D). Concerning OB individuals, the occipital bone and the region that goes from the frontal bone to bregma were the most expanded surfaces of the cranium followed by the most antero-superior region of the parietal bone; while the *lambdo-supraoccipital* region and the most posterior portion of the parietal bone, followed by a partial region of the frontal bone, were the most compressed surfaces (Fig. 5, 3D).

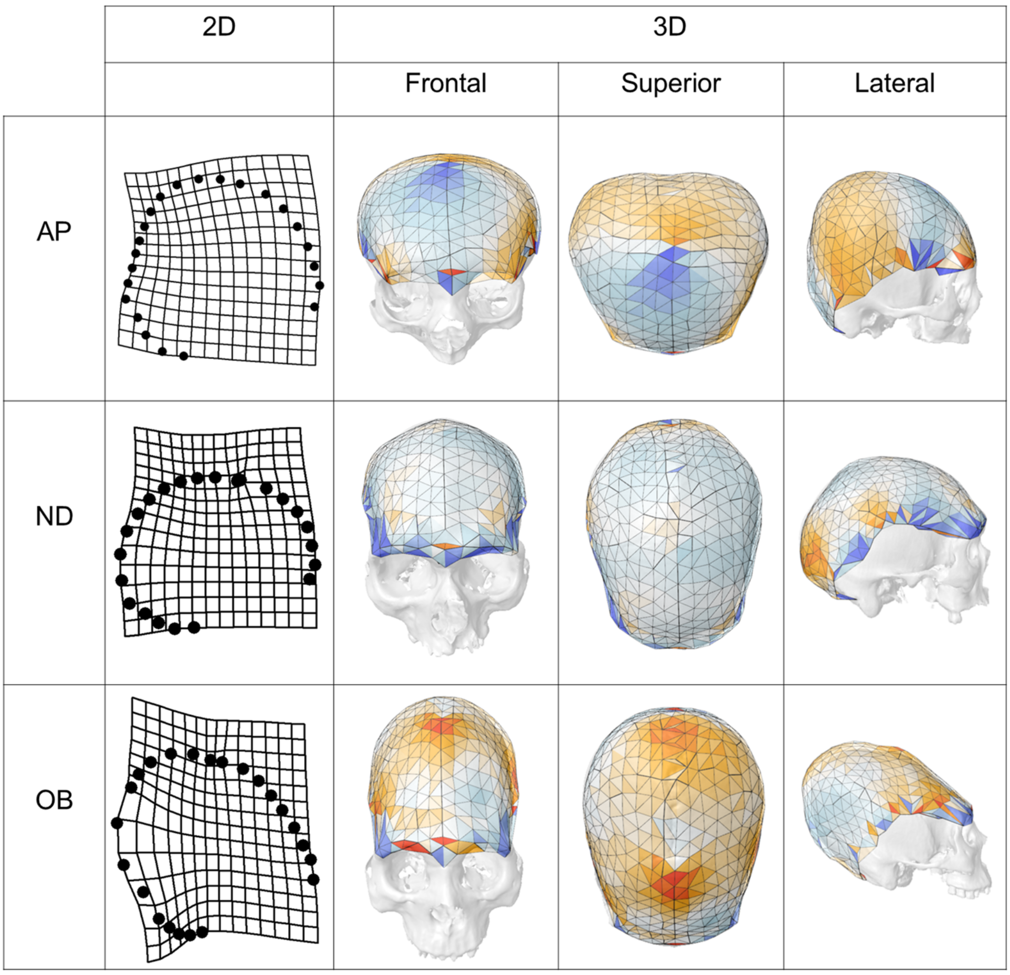


FIGURE 5. Shape variation of the extreme individual configurations of each intentional and non modified type in 2D and 3D. The "warm" (mainly red) colours represent surface expansion, while "cold" (mainly blue) colours represent surface compression. **AP:** Antero-posterior, **OB:** Oblique, **ND:** Non-deformed: archaeological types of cranial modification.

Size variation

Regarding size variation, a high and significant correlation was found between the centroid sizes of 2D and 3D datasets (Pearson's r = 0.79, $p < .001$), with the non-modified individuals in both cases having a higher centroid size value compared to intentionally modified individuals (Tables 3 and 4) (Fig. 6). A post-hoc Tukey's test corroborated these results in all the pairwise comparisons, for both 2D and 3D data (Table 5).

TABLE 3. Normalized centroid size mean ± standard deviation (cm.) of the 2D and 3D cranial configurations used in the present study.

Group	2D	3D
Antero-posterior	7.78 ± 0.38	267.28 ± 9.30
Oblique	7.92 ± 0.44	264.47 ± 9.46
Non-modified	8.61 ± 0.43	277.06 ± 9.47
Non-modified archaeological	8.20 ± 0.29	273.00 ± 6.63

TABLE 4. One-way ANOVA for the 2D, and 3D data sets." dejando los subtítulos 4a y 4b.

Table 4a. One-way ANOVA for the 2D data set*

	Sum of squares	df	Mean square	F	p (same)	Critical F (p=.05)
Between groups:	18.786	3	6.262	39.14	2.94E-19	2.658
Within groups:	27.040	169	0.160			
Total:	45.827	172				

*Levene´s test for homogeneity of variance from means p (same): .2405

Table 4b. One-way ANOVA for the 3D data set*

	Sum of squares	df	Mean square	F	p (same)	Critical F (p=.05)
Between groups:	4383.8	3	1461.270	17.570	5.62E-10	2.658
Within groups:	14052.5	169	83.151			
Total:	18436.3	172				

*Levene´s test for homogeneity of variance, from means p (same): .1922

TABLE 5. Tukey's pairwise post-hoc test for the statistical significance (Raw p values, sequential Bonferroni significance, alpha = 5%) of centroid size differences among the intentionally modified and non modified skulls (upper diagonal: 2D data; lower diagonal: 3D data). Statistically significant p-values (α= 5%) are highlighted.

	Antero-posterior	Oblique	Non-modified	Non-modified archeological
Antero-posterior		2.63E-01	**0.00E+00**	**3.83E-04**
Oblique	3.77E-01		**0.00E+00**	**3.98E-02**
Non-modified	**2.05E-06**	**1.80E-09**		**9.10E-04**
Non-modified archeological	**4.19E-02**	**1.06E-03**	4.60E-01	

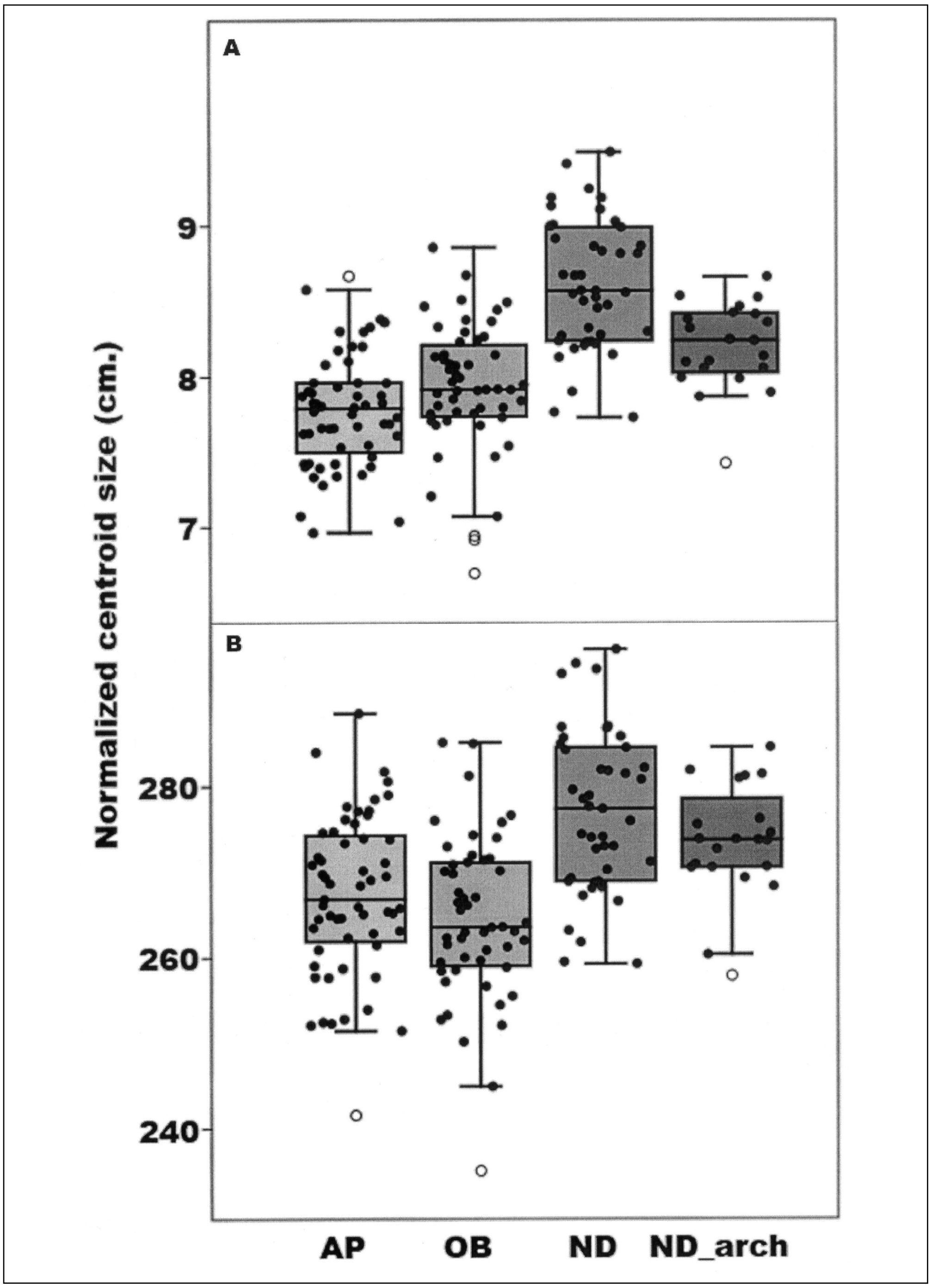


FIGURE 6. Centroid size values for intentional and non-modified type considered in the present study in 2D (A), and 3D (B). **AP:** Antero-posterior, **OB:** Oblique, **ND:** Non-deformed, **ND_arch:** Non-deformed archaeological types of cranial modification.

DISCUSSION

The pattern of shape and size variation of intentionally modified crania comparing 2D teleradiographs with 3D models from the same individuals showed a statistically significant concordance, morphologically expressed as a compression in the cranium at the *lambdo-supraoccipital* regions in AP individuals, while OB individuals showed a compression in the cranium at the *fronto-bregmal* region and occipital bone. Additionally, the centroid sizes calculated from intentionally deformed and non-deformed crania showed statistically significant differences. These results reject our two null hypotheses, reifying at the same time the contribution of 2D data (lateral radiographs) as imaging sound information for analyzing ICM, where the force vectors produced by the deforming device affect mostly the occipital region of the cranium between lambda and inion as previous work has pointed out, while the modification observed in the splanchnocranium covaries in direction and magnitude with the changes observed at the base of the cranium. The soundness of the morphological signal provided by 2D imaging data compared with the respective information obtained from 3D data has been recently corroborated in the clinical field. Thus, excluding subtle metatarsal injuries (Tang *et al.,* 2024), and anatomical planes that are missed on radiographs (i.e. superior/superomedial plane) (Mercer *et al.*, 2024), 2D vs. 3D comparative studies have shown that radiographs are a reliable modality for preoperative planning (Oishi *et al.,* 2022), the linear and angular measurement of mandibular structures (Baydar *et al.,* 2024), the diagnosis of airway stenosis in patients with pulmonary tuberculosis (Venkatakrishna *et al.,* 2024), the treatment of sinusitis (Hopfgartner *et al.,* 2024), and the evaluation of tracheal diameter (Seo *et al.,* 2024), among others. Since 3D imaging is a reconstruction of 2D layers obtained using gamma radiation (i.e. "X-rays"), it is not surprising that the generation of synthetic computed tomography-like imaging from radiographs, is becoming a promising field of research in the area of imaging developed using AI tools (De Wilde *et al.,* 2025).

A relevant finding of this study was the shorter centroid size of the modified crania compared to the non-modified crania for both 2D and 3D data. Although Gerszten (1993) and Khonsari *et al.* (2013) did not find size differences between modified and non-modified crania, the classic descriptions made by Morton (1839) and Broca (1871) report a shorter cranial capacity of intentionally modified crania. Regardless of the publication dates, Morton (1839) measured intentionally modified crania from the Southern Central Andes, the same geographical region where the archaeological material used in the present study was obtained. In the case of the Broca's (1871) data, they were obtained from individuals living during Broca's time in the city of Toulouse, a place where ICM was practiced by a large part of the population, as evidenced by a vast photographic and medical record (Khonsari, 2023).

Thus, the effect of ICM resulting in shorter crania in adults would not depend on the geographical origin or ancestry of the individual. A plausible explanation of our finding is that the pressure caused by the deforming devices affects the general growth of the brain, because the deforming device's force vectors do not only act onto the bones of the skull, but also on the brain through the fontanels, which during the perinatal period are very immature. This pressure is a condition that can affect the neuronal proliferation and migration in the early stages of development, potentially generating different degrees of microcephaly (Becerra-Solano *et al.,* 2021; von der Hagen *et al.,* 2014).

Therefore, considering that the cranium base provides a floor for the growth of the vault, a direct effect of the deforming device should be expected not only on the shape but also on the cranium size (i.e. volume of the cranial vault). Specifically, a decrease in the length of the cranium base may be associated with a decrease in the total volume of the cranium. The vector forces acting onto the cranial vault during the process of modification in the infant cranium can alter the natural trajectories of the bones of the cranial vault, altering growth both at the level of the sutures and of the cranial base. According to our results, the main anatomical structures affected by the compressive forces of the modifying device are the occipital and frontal bones, independently from the type of artificial modification. This means that the common effect of the modification is mostly affecting the antero-posterior growth axis avoiding the sagittal normal development of the cranial base.

Among the morphological consequences of ICM, the study of 19th century intentionally modified crania from Toulouse, France, has shown the presence of soft-tissue anomalies due to intentional craniofacial remodeling like the deformation and tissue loss of the external ear, platybasia and mastoid abrasion at the cranial base, collateral venous circulation at the cranial vault (as cited in Galiay *et al.,* 2022). It has also revealed an anterior shift of the glenoid fossa resulting in a prognathic position of the mandible, with the concomitant alteration of malocclusion (Cottin *et al.,* 2017). In relation to the effect that ICM would have had on cognitive aspects, after analyzing the Toulouse photographic archives and the collection of ICM crania with geometric morphometric techniques, Khonsari (2024) arrived at the conclusion that we will never know with certainty the above-mentioned effect due to the absence of standard psychometric or imaging records of those individuals. Despite this shortcoming, according to Khonsari (2024) one cannot exclude the social consequences that ICM would have had for the people of Toulouse who were subjected to this practice, especially due to the obvious differences it left in the soft tissues.

One of the limitations of our study, which are shared by other similar investigations (Kazarnitsky *et al.*, 2024; Natahi *et al.,* 2021; Pugacheva *et al.,* 2022), is that there is no single criterion to determine the number of semilandmarks to capture the surface of the cranial bones. In this regard, we suggest that this number will depend on other variables such as population, region studied, and purpose of the study. While it is currently not possible to determine *a priori* how many surface points are necessary to fully capture the shape variation, we chose a number of points that allowed us to capture the complexity and size of ICM individuals' crania without over-representing any particular region. In this regard, over-representing the regions could result in some surface points falling outside the area of interest, and therefore, increasing the dimensionality of the dataset, which would potentially reduce the power of subsequent analyses as has been pointed out by previous studies (Bardua *et al.,* 2019; Watanabe, 2018).

CONCLUSION

In conclusion, i) the pattern of shape and size variation of intentionally modified crania comparing teleradiographs and 3D models from the same individuals is highly concordant, reifying the contribution of 2D data as imaging sound information for studying ICM, and ii) the statement about the absence of size differences between deformed and non-deformed crania is not supported by the empirical evidence of our results. In fact, the intentionally modified crania were smaller than the non-modified ones, probably due to the common effect of the modification that mostly affects the antero-posterior growth axis avoiding the sagittal normal development of the cranial base. Finally, considering that our results should be interpreted as a starting point in the comparison between 2D and 3D data for studying the ICM, we suggest that further studies be carried out in greater depth reifying 2D data either as unique data or as a complement to 3D models in the study of the morphological variation.

AUTHOR CONTRIBUTIONS

Bastián Escobar-Ramírez: Conceptualization; Formal analysis; Research (data curation); Methodology; Validation; Visualization; Writing (original draft). Alejandro Díaz Muñoz: Conceptualization; Writing (original draft, review & editing). Germán Manríquez: Conceptualization-Lead; Formal analysis; Funding acquisition; Methodology; Validation; Visualization; Writing (original draft, review & editing).

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

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