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# Evaluating the efficiency of isolated calvaria bones shape changes in the identification and differentiation of artificial cranial modification techniques among pre-Hispanic west Mesoamerican populations

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**Title:** Evaluating the efficiency of isolated calvaria bones shape changes in the identification and differentiation of artificial cranial modification techniques among pre-Hispanic western and central Mesoamerican populations

**Authors:** Sélim Natahi<sup>1</sup>, Michael Coquerelle<sup>2</sup>, Véronique Darras<sup>3</sup>, Brigitte Faugère<sup>3</sup>, Christopher T. Fisher<sup>4</sup>, Grégory Pereira<sup>3</sup> & Priscilla Bayle<sup>1</sup>

**Author affiliation(s):**

<sup>1</sup> Université de Bordeaux, CNRS, MCC, UMR 5199 PACEA, Bâtiment B8, Allée Geoffroy St Hilaire, CS 50023, 33615 Pessac Cedex, France.

<sup>2</sup> Department of Medicine and Surgery (Stomatology Area), Universidad Rey Juan Carlos, 28922 Alcorcón, Spain

<sup>3</sup> UMR 8096, Archéologie des Amériques, CNRS-Paris 1, Maison René-Ginouès, 21, Allée de l'Université, 92023 Nanterre, France

<sup>4</sup> Department of Anthropology, Colorado State University, C-207 Andrew G. Clark Bldg., Fort Collins, CO 80523-1787, United States of America

**Correspondence**

Sélim Natahi, Université de Bordeaux, CNRS, MCC, UMR 5199 PACEA, Bâtiment B8, Allée Geoffroy St Hilaire, CS 50023, 33615 Pessac Cedex, France.

Email: [selim.natahi@gmail.com](mailto:selim.natahi@gmail.com)

**HIGHLIGHTS**

- In Mesoamerican archaeology, identifying and characterizing artificial cranial modifications is of great value as they can provide valuable information about the social and/or cultural identity of an individual.
- The state of preservation of the bone occasionally limits the possibility of diagnosing and differentiating artificial cranial modifications.
- To test whether artificial cranial modifications could be identified and characterized when a cranium is partially preserved, we used 3D geometric morphometrics to quantify the shape differences of isolated calvaria bones among four groups of individuals with distinct forms of artificial cranial modifications and a control group of unmodified skulls.
- The shape of isolated calvaria bones can be informative for the identification and the characterization of artificial cranial modification in western and central Mesoamerica.

## **Abstract**

### **Introduction**

Artificial cranial modification (ACM) is a widespread cultural phenomenon that has been reported in human populations from Late Pleistocene to present day all over the world. Although ACM techniques have been documented in western and central Mesoamerica, the state of preservation of bone has occasionally limited the possibility of diagnosing and differentiating ACM variants. To explore how informative fragmentary skull remains can be in this matter, here we used 3D geometric morphometrics to quantify shape variation of isolated calvaria bones.

### **Materials and Methods**

49 well preserved individuals from west and central Mesoamerica were selected and divided into five groups: four showing distinct forms of ACM, and a control group of unmodified skulls. Using medical computed tomography and laser surface scanning, we measured the 3D shape changes in three isolated calvaria bones. We calculated the morphological differences within and between groups by computing pairwise Procrustes distances for all possible combinations of individuals. Finally, we used 3D digital meshes to describe the shape changes in an ACM variant compared to the other ones and to the control group.

### **Results**

Irrespective of which bone of the calvaria is considered, the variation between the individuals showing ACM and the unmodified individuals always exceeds the variation measured within the unmodified group. Furthermore, some ACM variants can be characterized by examining certain calvaria bones in isolation.

### **Discussion**

The study of isolated calvaria bones can help to identify individuals with ACM from the background physiological variation. Our study also provides information pertaining to the techniques employed to produce certain ACM variants and we discuss the standardization of these processes.

**KEYWORDS** Artificial cranial modification, isolated calvaria bones, 3D geometric morphometrics, Mesoamerican Archaeology

## 1. INTRODUCTION

Artificial Cranial Modification (ACM) is a pervasive cultural phenomenon, practiced in all continents (except Antarctica; Dingwall, 1931) with the earliest reported evidence of expression dating back to Late Pleistocene in Australia (Brothwell, 1975; Brown, 1981; Antón & Weinstein, 1999; Durband, 2008; Brown, 2010; Durband, 2014) and North-East China (Wu, 1961; Brothwell, 1975; Ni et al., 2019; Zhang et al., 2019). The ACMs were performed via the implementation of a cranial device upon a child's skull from an early age so that cranial growth was prevented in certain directions (Moss, 1958; Antón & Weinstein, 1999; Tiesler, 2014). This results in a specific modification of the skull's shape that depends on the nature of the cranial device employed, its location upon the infant's skull, as well as the magnitude of pressure applied. The initiation time and the duration of the procedure are two other factors that likely account for the variation observed among cranial shapes (e.g., Ambialet, 1893; Ewing, 1950; Blackwood & Danby, 1955; Lieberman et al., 2000; Hutchison et al., 2004; Graham et al., 2005; Rogers, 2011; Tiesler, 2014). The cranial devices employed in ACM are manifold and can consist of rigid tablets (e.g., Dembo & Imbelloni, 1938; Romano, 1965; Tiesler, 2014), systems made of bands or chords (e.g., Dembo & Imbelloni, 1938; O'Brien & Stanley, 2013), headdresses or caps (e.g., Ambialet, 1893; Hatt, 1915), or cradle systems integrating constraining elements (e.g., Romano, 1974; Piper, 2002; Tiesler, 2014). The modification of the cranial shape could also have been reached via the performance of daily head massages, so the skull is molded to fit a particular shape (Hatt, 1915; Dingwall, 1931; Romano, 1974; Motte-Florac, 1997; Tiesler, 1998; Yon et al., 2017).

Modified heads have been associated with various cultural meanings such as indicating social status (e.g., Marcus & Flannery, 2004; Ricci et al., 2008; Geller, 2011; Khudaverdyan, 2011; Sharapova & Razhev, 2011; Okumura, 2014), or an ethnic identity (e.g., Özbek, 2001; Torres-Rouff, 2002; Blom, 2005; Ricci et al., 2008; Hakenbeck, 2009; Lozada, 2011; Tiesler, 2014; Mayall et al., 2017; Veeramah et al., 2018; Fernandes et al., 2019; Mayall & Pilbrow, 2019), denoting religious faith (e.g., Houston, 2006; Fletcher et al., 2008; Tiesler & Cucina, 2010; García & Tiesler, 2011), healthcare beliefs (e.g., Icart, 1784; Delisle, 1880; Ambialet, 1893, p. 19; Hatt, 1915; Motte-Florac, 1997; Logan et al., 2003; Duncan & Hofling, 2011) or simply for esthetic considerations (e.g., Hatt, 1915; Dingwall, 1931; Lorentz, 2003).

A child's head, and the way various anatomical regions grow and develop, is central to the world view of many Mesoamerican populations (Ruiz de Alarcón, 1953; Motte-Florac, 1997; López Austin, 2004, pp. 224-225; Ponce, 2014; Tiesler, 2014, p. 143). For example, among the Nahuas, an individual's spirit was thought to reside in the head. Therefore, the fontanelles of infants were considered as possible exit points through which the spirit may escape (López Austin, 2004). Protecting the spirit from leaving the body of the infant via these openings was a major concern of the Nahua's belief system. For this reason, some authors have proposed that the action of modifying the shape of a skull should be considered as a complex cultural process that originates from different yet complementary intentions. They suggest that to fully understand the cultural complexity of ACM it is essential to distinguish the underlying intentions behind the process, whether these relate to childcare (López Austin, 2004, p. 212; Tiesler, 2014, p. 143) or proclaiming an ethnic identity, hierarchical status or any other cultural statements (Duncan, 2009, 2018). Therefore, assessing and characterizing reliably the various forms of ACM is an important concern because this may inform us of the societal structure and relationships within and between populations in pre-Hispanic Mesoamerica (e.g., Tiesler, 2014; Alvarado Viñas & Manzanilla, 2018; Pereira, 2018).

The identification and classification of marked forms of ACM among pre-Hispanic populations is generally addressed using the typological system developed by Dembo and Imbelloni (1938). The system is specifically designed so that ACM variants among pre-Hispanic populations could be differentiated. The method consists of examining several morphological features among which the most significant are flattening and broadening of specific bones. The authors have defined three major categories of cranial modifications, each corresponding to the cephalic devices used. The annular forms, with symmetric circular constrictions are associated with devices composed of bandages, chords, or headdresses. The tabular erect types, display two parallel constriction planes oriented postero-superiorly, which are usually thought to result from infant cradleboarding practices. Finally, the tabular-oblique form refers to individuals exhibiting non-parallel constriction planes that affect the anterior and posterior parts of the vault. The two tabular forms utilize mostly rigid tablets to achieve the desired ACM. Each one of these forms (annular, tabular erect and tabular oblique) are further subdivided into different variants; indicating various ACM techniques throughout the Americas.

Other studies employ morphometrics such as linear measurements and angles in order to identify and differentiate ACMs (e.g., Dembo & Imbelloni, 1938; Falkenburger, 1938;

Romano, 1965; Comas & Marquer, 1969; Romano, 1974; Clark et al., 2007; Pomeroy et al., 2010; O'Brien & Stanley, 2013). For almost four decades, the rise of geometric morphometrics techniques has provided efficient tools for analyzing variation in biological shape (Bookstein, 1991; Slice, 2005). Geometric morphometrics has also been applied to identify and characterize ACM shapes. It has been demonstrated to be efficient in differentiating variants even in the case of subtle ACM (Cheverud et al., 1992; Kohn et al., 1995; Friess & Baylac, 2003; Manríquez et al., 2006; Gómez-Valdés et al., 2007; Perez, 2007; Perez et al., 2009; Burchi et al., 2016; Kuzminsky et al., 2016; Mayall et al., 2017; Mayall & Pilbrow, 2018; Alejandro et al., 2019; Natahi et al., 2019).

However, multiple cranial alterations, unrelated to any cultural practices, can originate from ante-mortem conditions (e.g., pathological conditions or occupational causes such as the use of tumplines for carrying heavy loads; Gervais, 1989; Tiesler, 1999; Gervais, 2001), and/or postmortem ones (e.g., taphonomic processes or biases related to the restoration process; Shipman, 1981; Lyman, 1994; Ricci et al., 2008; Arbour & Currie, 2012; Tiesler, 2014) and this can substantially complicate the recognition and characterization of ACMs. In some contexts, the overlying sediments may exert compression forces on the skull causing distortions and discontinuities between and within certain cranial elements (Laitman & Heimbuch, 1982; Franciscus & Trinkaus, 1988; Gunz et al., 2009; Weber & Bookstein, 2011; Tiesler, 2014; Jurda et al., 2015) that can be subsequently mistaken for ACMs. In others, the soil characteristics (e.g. acidity or alkalinity) can severely affect the bone leading to its degradation and destruction, making the identification and characterization of ACMs extremely difficult (Emery, 2004). Therefore, under certain conditions a skull may only be represented by a few usable cranial elements, hindering reliable and in-depth investigations of ACM practices (Tiesler, 2014, p. 70; Jácome Hernández et al., 2018; Montiel Mendoza, 2018). Currently, assessing the degree of ACM and differentiating the form variants based on isolated calvaria bone fragments is challenging and may lead to serious biases and misinterpretations.

Some authors have proposed that the combination of certain morphological criteria, found on individual calvaria, can be utilized as reliable indicators for diagnosing ACM (Magitot, 1885; Goldstein, 1940; Stewart, 1976; Weiss, 1981; Holliday, 1993; Antón & Weinstein, 1999; Tiesler, 2012a, 2012b, 2014; Tiesler & Gómez-Valdés, 2018; Natahi et al., 2019). However, to date, the potential of using isolated calvaria bones to identify and differentiate ACMs has never been systematically investigated.

Although various authors have reported the expression of ACM techniques in western and central Mesoamerica (e.g., Hulse, 1945; Stewart, 1948; Dávalos Hurtado, 1951; Dávalos Hurtado & Romano, 1955; Meighan & Foote, 1968; Romano, 1972; Gill, 1985; Bautista, 1986; Lagunas Rodríguez, 1989; Uruñuela y Ladron de Guevara, 1994; Acosta, 2003; Bautista & Ortega, 2005; Pereira, 2018; Serrano Sánchez & Montiel Mendoza, 2018; Natahi et al., 2019), the preservation state of bone limited some studies where fragmented or poorly preserved material reduced substantially the size of the sample considered (e.g., Jácome Hernández, 2012, p. 315; Jácome Hernández et al., 2018, p. 690). In order to improve the possibility of diagnosing ACMs and differentiating variants relying on fragmentary cranial remains, we investigate how informative the bones of the calvaria can be for the identification and the differentiation of ACM variants. Using 3D geometric morphometrics, we aim to quantify shape variation of isolated calvaria bones within and among different groups composed of unmodified individuals (i.e., the control group) as well as groups consisting of individuals with known diverse ACM variants.

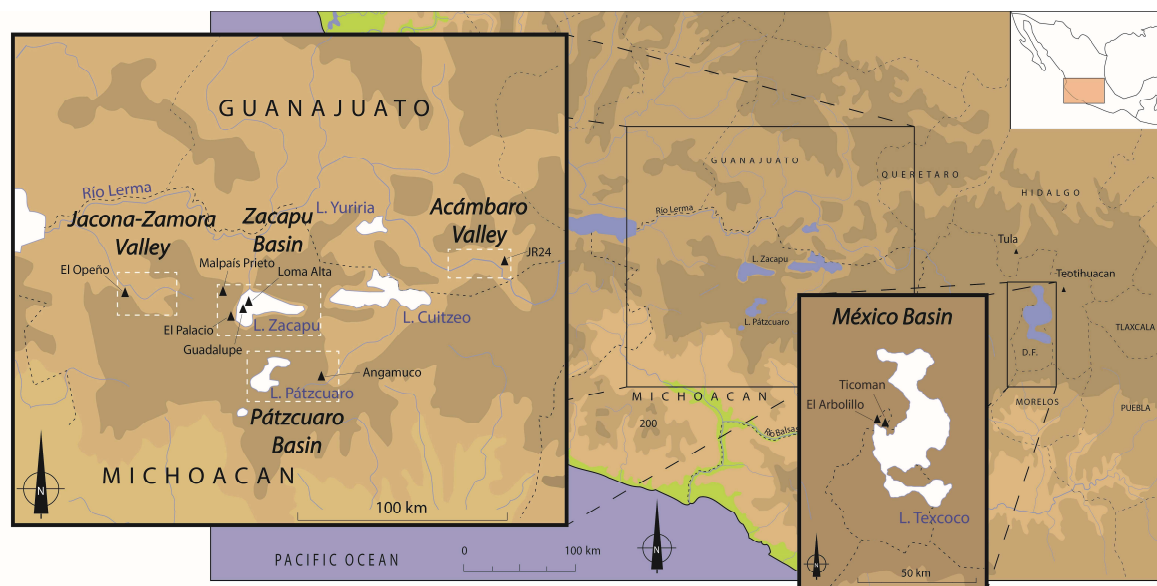
## **2. MATERIALS AND METHODS**

### **2.1 Sample composition**

Our sample includes a group of 49 archeological individuals all in an excellent state of preservation. In order to avoid mixing the shape signal related to the ACMs with shape signals due to interpopulation differences, we have only considered pre-Hispanic individuals coming from archaeological excavations carried out in western and central Mesoamerica, specifically in three nearby Mexican states: the states of Guanajuato, México and Michoacán (Figure 1). The archaeological sites are located in five different regions: the valleys of Acámbaro and Zamora-Jacona and the basins of Zacapu, Pátzcuaro and México (Figure 1; Table 1). The individuals from Early and Middle Formative are respectively coming from the sites of El Opeño (Jacona-Zamora Valley; Oliveros, 2004) and El Arbolillo (México basin; Vaillant, 1935). The individuals from the sites JR24 (in the Acámbaro valley; Darras & Faugère, 2007), Loma Alta (Zacapu basin; Arnauld et al., 1993; Carot, 1993; Pereira, 1999) and Ticomán (México basin; Vaillant, 1931) date back to the Late Formative (400 BC - 300 AD). One individual from the site of Guadalupe dates to the Epiclassic period (600 - 900 AD; Pereira, 1999, 2010). Individuals from El Palacio (Lumholtz & Hrdlička, 1898; Lumholtz,

1902) and Malpaís Prieto (Pereira et al., 2021) for the Middle Postclassic (1200 - 1400 AD; Pereira et al., 2021), two other sites of the Zacapu basin, were also included. For the Pátzcuaro basin, all the individuals come from Angamuco (Fisher et al., 2019) and belong to the Late Postclassic – Early Colonial period (1200 - 1600 AD; Fisher et al., 2015; Cohen, 2016).

Individuals have been classified into five groups: four of them show the distinct forms of ACM mainly expressed in western and central Mesoamerica (Pereira, 2018; Serrano Sánchez & Montiel Mendoza, 2018). They have been differentiated according to the typology of Dembo and Imbelloni (1938; i.e., the Fronto-Obelionic or FO type; the Tabular Erect Fronto-Occipital and Plano-Lambdoid variants, respectively TEFO and TEPL; the Tabular Oblique or TO type; Figure 2). A group of unmodified individuals was used as a control group (Table 1). Individuals were assigned to the control group based on the results of Natahi et al. (2019). All control group individuals were from El Palacio and Malpaís Prieto and their shape fall within the 95% confidence ellipse of a group composed of unmodified Mexican Indians and French medieval individuals from Natahi et al. (2019).



**FIGURE 1** Locations of the archaeological sites.

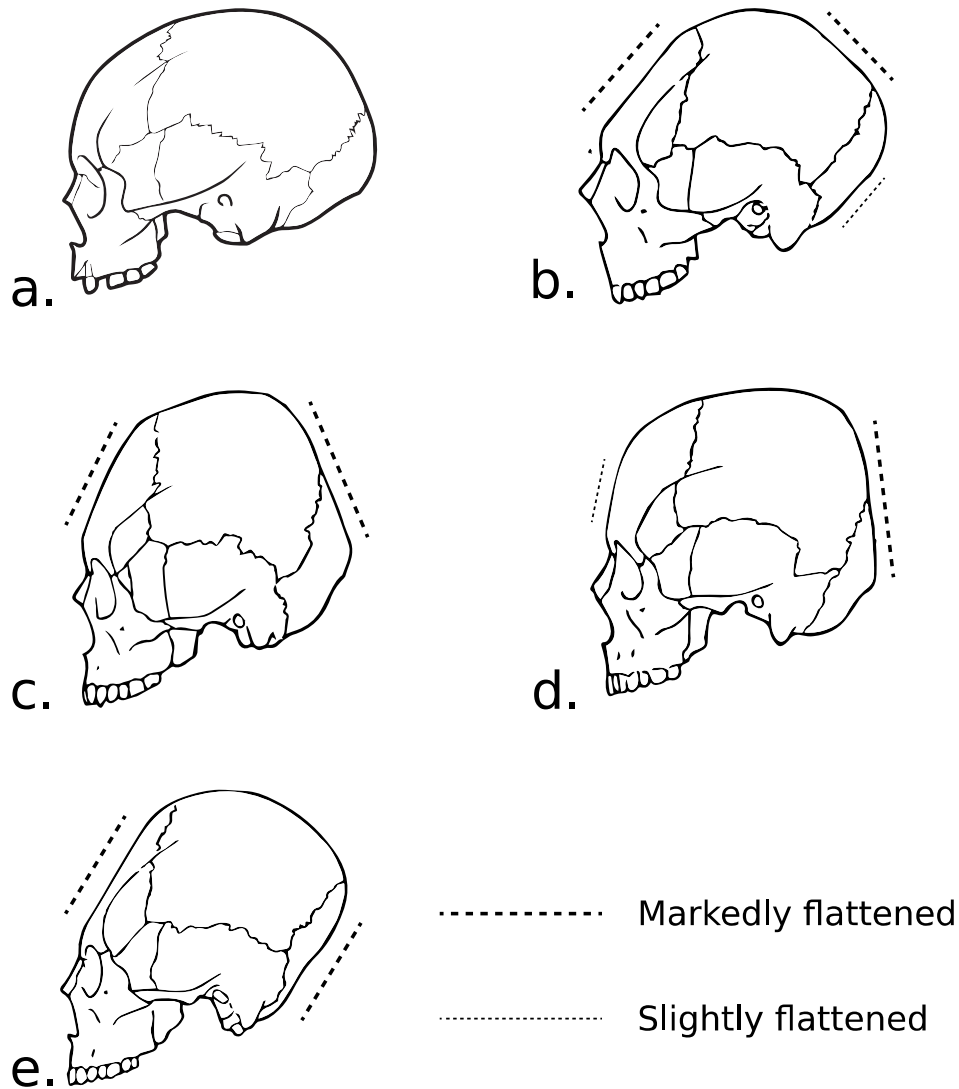
All the individuals considered in the study were adults, except one (the individual Tarascan 153 from El Palacio). The age at death for this immature individual was estimated, from dental mineralization and eruption stages (Moorrees et al., 1963; Demirjian et al., 1973;



Ubelaker, 1978; AlQahtani et al., 2010), as being between 10-20 years. This age-at-death overlaps with lower-bound for neurocranial maturity (as documented by Bastir et al., 2006), and as such we have included this individual in our analyses.

<b>Id</b>	<b>Site</b>	<b>Region</b>	<b>Age</b>	<b>ACM type</b>	<b>Period</b>
JR24_sep1	JR24	Acámbaro Valley	Adult	Tabular Oblique	Late Formative (600 BCE - 300 CE)
JR24_sep6	JR24	Acámbaro Valley	Adult	Tabular Erect Fronto-Occipital	Late Formative (600 BCE - 300 CE)
JR24_sep8	JR24	Acámbaro Valley	Adult	Tabular Erect Fronto-Occipital	Late Formative (600 BCE - 300 CE)
El_Openo_sep5_ind18	El Opeño	Jacona-Zamora Valley	Adult	Tabular Erect Plano-Lambdaoid	Early Formative (1500 - 1000 BC)
El_Arbolillo_99_9714	El Arbolillo	México Basin	Adult	Tabular Erect Fronto-Occipital	Middle Formative (1000 - 600 BCE)
El_Arbolillo_99_9715	El Arbolillo	México Basin	Adult	Tabular Erect Plano-Lambdaoid	Middle Formative (1000 - 600 BCE)
El_Arbolillo_99_9716	El Arbolillo	México Basin	Adult	Tabular Erect Plano-Lambdaoid	Middle Formative (1000 - 600 BCE)
Ticomán_99_9620	Ticomán	México Basin	Adult	Tabular Erect Plano-Lambdaoid	Late Formative (600 BCE - 300 CE)
Ticomán_99_9623	Ticomán	México Basin	Adult	Tabular Erect Plano-Lambdaoid	Late Formative (600 BCE - 300 CE)
Ticomán_99_9624	Ticomán	México Basin	Adult	Tabular Erect Plano-Lambdaoid	Late Formative (600 BCE - 300 CE)
Ticomán_99_9625	Ticomán	México Basin	Adult	Tabular Erect Plano-Lambdaoid	Late Formative (600 BCE - 300 CE)
Ticomán_99_9626	Ticomán	México Basin	Adult	Tabular Erect Plano-Lambdaoid	Late Formative (600 BCE - 300 CE)
Ticomán_99_9627	Ticomán	México Basin	Adult	Tabular Erect Fronto-Occipital	Late Formative (600 BCE - 300 CE)
Ticomán_99_9631	Ticomán	México Basin	Adult	Tabular Erect Plano-Lambdaoid	Late Formative (600 BCE - 300 CE)
Ticomán_99_9632	Ticomán	México Basin	Adult	Tabular Erect Plano-Lambdaoid	Late Formative (600 BCE - 300 CE)
Angamuco_sep14_ind2	Angamuco	Pátzcuaro Basin	Adult	Tabular Erect Plano-Lambdaoid	Late Postclassic (1400 - 1600 CE)
Angamuco_sep8	Angamuco	Pátzcuaro Basin	Adult	Tabular Erect Plano-Lambdaoid	Late Postclassic (1400 - 1600 CE)
Angamuco_sep9_ind1	Angamuco	Pátzcuaro Basin	Adult	Tabular Erect Plano-Lambdaoid	Late Postclassic (1400 - 1600 CE)
Tarascan135	El Palacio	Zacapu Basin	Adult	Fronto Obelionic	Middle Postclassic (1200 - 1400 CE)
Tarascan151	El Palacio	Zacapu Basin	Adult	Fronto Obelionic	Middle Postclassic (1200 - 1400 CE)
Tarascan153	El Palacio	Zacapu Basin	Sub-adult	Fronto Obelionic	Middle Postclassic (1200 - 1400 CE)
Tarascan154	El Palacio	Zacapu Basin	Adult	Fronto Obelionic	Middle Postclassic (1200 - 1400 CE)
Tarascan155	El Palacio	Zacapu Basin	Adult	Fronto Obelionic	Middle Postclassic (1200 - 1400 CE)
Tarascan156	El Palacio	Zacapu Basin	Adult	Fronto Obelionic	Middle Postclassic (1200 - 1400 CE)
Tarascan157	El Palacio	Zacapu Basin	Adult	Fronto Obelionic	Middle Postclassic (1200 - 1400 CE)
Tarascan158	El Palacio	Zacapu Basin	Adult	Fronto Obelionic	Middle Postclassic (1200 - 1400 CE)
Tarascan130	El Palacio	Zacapu Basin	Adult	Control Group	Middle Postclassic (1200 - 1400 CE)
Tarascan137	El Palacio	Zacapu Basin	Adult	Control Group	Middle Postclassic (1200 - 1400 CE)
Tarascan141	El Palacio	Zacapu Basin	Adult	Control Group	Middle Postclassic (1200 - 1400 CE)
Tarascan149	El Palacio	Zacapu Basin	Adult	Control Group	Middle Postclassic (1200 - 1400 CE)
Tarascan150	El Palacio	Zacapu Basin	Adult	Control Group	Middle Postclassic (1200 - 1400 CE)
Tarascan160	El Palacio	Zacapu Basin	Adult	Control Group	Middle Postclassic (1200 - 1400 CE)
Tarascan165	El Palacio	Zacapu Basin	Adult	Control Group	Middle Postclassic (1200 - 1400 CE)
Tarascan173	El Palacio	Zacapu Basin	Adult	Control Group	Middle Postclassic (1200 - 1400 CE)
Tarascan174	El Palacio	Zacapu Basin	Adult	Control Group	Middle Postclassic (1200 - 1400 CE)
Tarascan211	El Palacio	Zacapu Basin	Adult	Control Group	Middle Postclassic (1200 - 1400 CE)
Mich215_sep43_ind2	Guadalupe	Zacapu Basin	Adult	Fronto Obelionic	Epiclassic (600 - 900 CE)
Loma_Alta_sep27	Loma Alta	Zacapu Basin	Adult	Tabular Erect Plano-Lambdaoid	Late Formative (600 BCE - 300 CE)
Loma_Alta_sep13-IndA	Loma Alta	Zacapu Basin	Adult	Tabular Erect Fronto-Occipital	Late Formative (600 BCE - 300 CE)
Mich31_sep20	Malpaís Prieto	Zacapu Basin	Adult	Control Group	Middle Postclassic (1200 - 1400 CE)
Mich31_sep24	Malpaís Prieto	Zacapu Basin	Adult	Control Group	Middle Postclassic (1200 - 1400 CE)
Mich31_sep34_ind1	Malpaís Prieto	Zacapu Basin	Adult	Control Group	Middle Postclassic (1200 - 1400 CE)
Mich31_sep34_ind3	Malpaís Prieto	Zacapu Basin	Adult	Control Group	Middle Postclassic (1200 - 1400 CE)
Mich31_sep34_ind4	Malpaís Prieto	Zacapu Basin	Adult	Control Group	Middle Postclassic (1200 - 1400 CE)
Mich31_sep37_ind2	Malpaís Prieto	Zacapu Basin	Adult	Control Group	Middle Postclassic (1200 - 1400 CE)
Mich31_sep37_ind3	Malpaís Prieto	Zacapu Basin	Adult	Control Group	Middle Postclassic (1200 - 1400 CE)
Mich31_sep37_ind6	Malpaís Prieto	Zacapu Basin	Adult	Control Group	Middle Postclassic (1200 - 1400 CE)
Mich31_sep40	Malpaís Prieto	Zacapu Basin	Adult	Control Group	Middle Postclassic (1200 - 1400 CE)
Mich31_sep42	Malpaís Prieto	Zacapu Basin	Adult	Control Group	Middle Postclassic (1200 - 1400 CE)

**TABLE 1** List of individuals.



**FIGURE 2** Unmodified cranium and four different artificial cranial modifications types preferentially expressed in western and central Mesoamerica: (a) Unmodified cranium, (b) the Fronto-Obelionic type (FO), (c) the Tabular-Erect Fronto-Occipital type (TEFO), (d) the Tabular-Erect Plano-Lambdoid type (TEPL) and (e) the Tabular Oblique type (TO). Modified from Pereira (2018).

## 2.2 Data acquisition

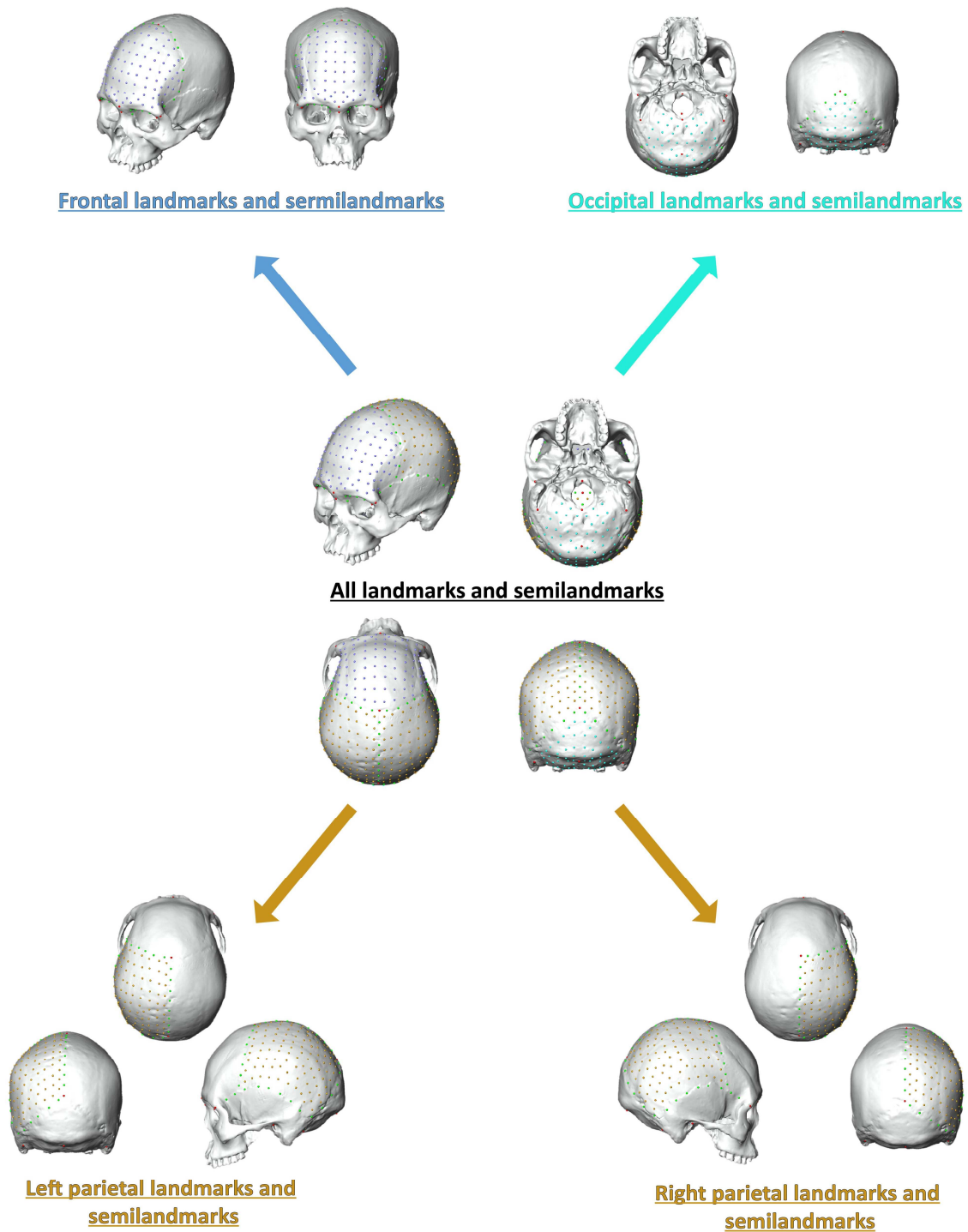
The individuals from the JR24, Angamuco, El Palacio, Guadalupe, Loma Alta and Malpaís Prieto have been all scanned using medical computed tomography (Mount Sinai Radiology, New York, United States of America; CT Scanner del Sur, Ciudad de México, México; with slice intervals varying from 0.5mm to 0.625mm and pixel sizes ranging from 0.38 to 0.56mm

; SI Table 1). Each surface has been generated using the HMH segmentation procedure (Half Maximum Height ; Spoor et al., 1993). Subsequent corrections were applied manually in the Avizo software (Avizo Lite 8.0; Thermo Fisher Scientific). The rest of the sample (i.e., all individuals from El Opeño, El Arbolillo and Ticomán) has been scanned via surface laser scanning (i.e., with a NextEngine laser scanner, 3D Scanner Ultra HD, NextEngine, Inc.) with resolution parameters identical to those described in Natahi et al. (2019).

From each scanned cranium the shape of three calvaria bones have been analyzed in isolation: the frontal squamous part, the parietal and the posterior part of the occipital bone. The complete ectocranial surface of each bone was analyzed except for the occipital (Figure 3). The signal describing the shape of the occipital bone was restricted to the occipital squama and the posterior part of the occipital base (i.e., the anatomical regions where the posterior elements of the cranial devices employed in ACM are usually arranged). The first structure is delimited anteriorly and superiorly by the two parietal bones (i.e., the lambdoid sutures) and laterally and inferiorly by the two petrous parts of the temporal bones. The limits of the second structure are defined by (from the anterior and median to the lateral parts): the posterior margin of the foramen magnum, the posterior margins of the posterior condylar foramina, the paracondylar processes and the occipitomastoid suture laterally.

As mentioned in Gunz and Mitteroecker (2013), the calvaria has relatively few homologous anatomical structures which complicates any shape fine shape quantification relying only on traditional craniometric landmarks. Therefore, we have included semilandmarks in order to capture the three-dimensional shape of each calvaria bone (Bookstein, 1997; Gunz et al., 2005). A 3D-template of 463 landmarks and semilandmarks was specifically digitized on the entire calvaria (Figure 3, center; Table 2). The latter has been warped onto each skull using the software Viewbox (dHAL software, Kifissia, Greece).

The missing data do not account for more than 4.3% of information loss for an individual (i.e., no more than 20 missing landmarks for the entire calvaria). If missing, their coordinates have been estimated in accordance with the standard protocol developed by Gunz (2005) and Gunz et al. (2009).



**FIGURE 3** Landmark template, with the four groups of landmarks and semilandmarks considered. The red, green and blue dots represent respectively the anatomical landmarks, the curve semilandmarks and the surface semilandmarks.

No	Anatomical landmarks	Unilateral/Bilateral	Comments
1	Nasion	Unilateral	
2	Glabella	Unilateral	
3	Bregma	Unilateral	
4	Lambda	Unilateral	
5	Inion	Unilateral	
6	Opisthion	Unilateral	
7	Basion	Unilateral	
8, 9	Frontomalare temporal	Bilateral	
10, 11	Frontomalare orbital	Bilateral	
12, 13	Porion	Bilateral	
14, 15	Mastoid notch	Bilateral	
12,18	Asterion	Bilateral	
13,19	Pterion	Bilateral	
	<b>Curve semilandmarks</b>		
20:25, 26:31	Inferior orbital margin (n= 6 x 2)	Bilateral	Rim of the orbital opening to frontomalare orbital
32:36, 37:41	Sphenofrontal suture (n= 5 x 2)	Bilateral	Cranial suture between sphenoid and frontal bone
42:49, 50:57	Coronal suture (n= 8 x 2)	Bilateral	Cranial suture separating the frontal from the two parietal bones
42:49, 50:57	Squamosal suture (n= 13 x 2)	Bilateral	Cranial suture separating the temporal squama from the two parietal bones
84:89, 90:95	Lambdoid suture (n= 6 x 2)	Bilateral	Cranial suture separating the occipital from the two parietal bones
96:103	Sagittal suture (n= 8)	Bilateral	Cranial suture expanding from bregma to lambda
	<b>Surface semilandmarks</b>		
104:154, 284:334	Frontal patch (n= 51 x 2)	Bilateral	
155:253, 335:433	Parietal vault patch (n= 99 x 2)	Bilateral	
254:283, 434:463	occipital vault patch (n= 30 x 2)	Bilateral	

**TABLE 2** List of landmarks, curve and surface semilandmarks.

In order to analyze the shapes of each four calvaria bones separately, seven semilandmark curves have been digitized: along the left and right sphenofrontal sutures, squamous sutures, lambdoid sutures and along the sagittal suture (Figure 3, green dots). When using the minimization of the bending energy as criterion to perform the sliding of the semilandmarks (see below), the anatomical landmarks and curve semilandmarks constrain the displacements of the surface semilandmarks, guaranteeing that no surface semilandmarks slide beyond the limits of the surface of interest (Gunz & Mitteroecker, 2013). Therefore, in the subsequent analyses we have defined five sliding groups (i.e., subset of landmarks and semilandmarks; Table 2) as follows: one for the frontal, one for the left parietal, one for the right parietal and one for the occipital. After digitization and warping, using the R “Morpho” package (Schlager, 2017), the 3D semilandmarks of the five subsets were independently allowed to slide along curves and surfaces in order to minimize the bending energy of the Thin-Plate Spline (TPS) interpolation function that is computed between each specimen calvaria bone configuration and the respective sample Procrustes average (Bookstein, 1997; Gunz et al., 2005).

High degrees of neurocranium asymmetry have been observed in individuals expressing different ACM types (Neumann, 1942; Romano, 1974; Kohn et al., 1995; Tiesler, 1998; Clark et al., 2007; Pomeroy et al., 2010; Natahi et al., 2019). The quantification of asymmetry being not relevant to our study, the symmetric component of shape variation was used in the subsequent analyses (Klingenberg et al., 2002). The entire calvaria, the frontal bone, the occipital bone all display an internal symmetry plane so their symmetric configuration has been computed as the average of their respective original and reflected relabeled configurations (Mardia et al., 2000; Klingenberg et al., 2002; Savriama & Klingenberg, 2011; Klingenberg, 2015). In order to evaluate the shape changes related to the parietal bone only, we have proceeded differently and chosen to consider it with a matching symmetry (i.e., right and left parietal bones are mirror images of each other). Right configurations were reflected by changing the sign of the x coordinates (Klingenberg et al., 2002; Zelditch et al., 2012). Subsequently, the two configurations of each individual were superimposed in pairs via a Procrustes fit in order to compute their respective mean shape. After the sliding, the semilandmarks were treated as homologous points and combined with traditional landmarks so they can be transformed into Procrustes shape coordinates via a Generalized Procrustes Analysis (GPA; Rohlf & Slice, 1990; Bookstein, 1996; Mitteroecker & Gunz, 2009). Each configuration is scaled to have a unit Centroid Size (CS: square root of the summed squared

Euclidean distances from all semilandmarks to their centroid; Dryden & Mardia, 1998). Then all configurations are translated and rotated to minimize the overall sum of the squared distances between the corresponding landmarks and semilandmarks.

### **2.3 Analyses of shape variation**

In order to explore the informative potential of calvaria bones shapes in the identification and differentiation of ACM, we have evaluated their morphological differences within and between the five aforementioned groups (i.e., an Unmodified group used as control, a group composed of individuals with FO ACM, one with TEFO ACM, one with TEPL ACM and one with TO ACM). The morphological differences within and between group were measured following Stelzer et al. (2018). This consisted of computing Procrustes distances pairwise for all possible combinations within a group (except for the TO group which is represented by one individual) and between groups. The within variation of the TO group could not be explored since the sample size limited to one individual.

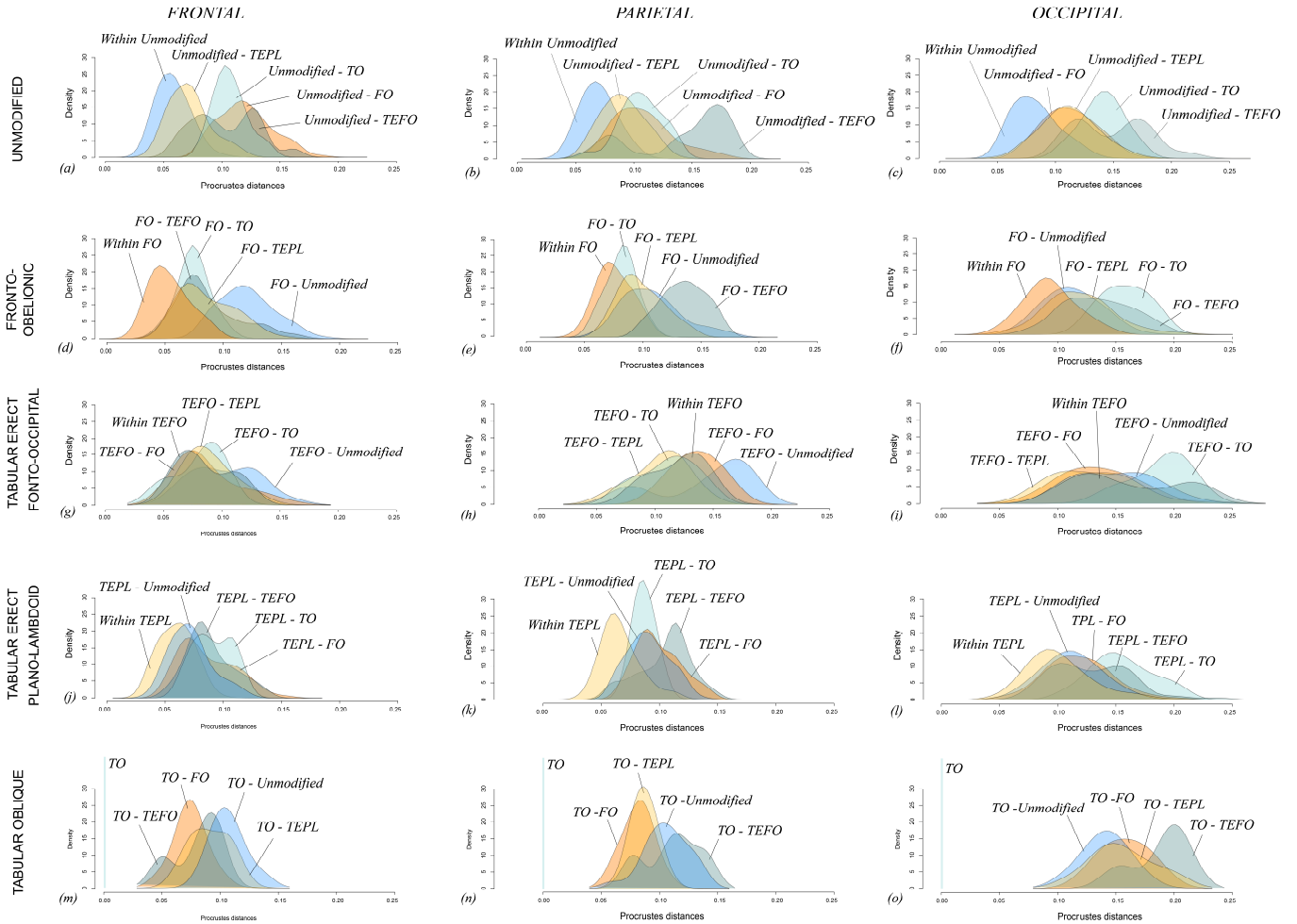
### **2.4 Visualization patterns of shape variation**

In order to provide morphological elements that can help identifying a form based on isolated bones, we have observed the morphological variations between each group mean shape through the displacements of their corresponding landmarks. We have also generated 3D digital meshes of the three calvaria bones. They have been respectively warped towards the mean shapes of our five groups for each calvaria bone. We have used the landmarks displacements and the generated meshes to visualize and describe the shape changes that characterize an ACM in comparison to another on one isolated bone.

## **3. RESULTS**

Figure 4 displays the within and between group variation for the Unmodified group used as control and the different types of ACM that we identified via visual examinations. SI Table 2 describes the summary statistics of the within and between group comparisons.





**FIGURE 4** Distribution of the Procrustes distances for all pairwise combinations of calvarial bones within and between the five groups: the Unmodified group, the Fronto-Obelionic group (FO), the Tabular Erect Fronto-Occipital group (TEFO), the Tabular Erect Plano-Lambdoid group (TEPL) and the Tabular Oblique group (TO) composed of one individual.

### 3.1 Within and between group variations

#### *The within and between group variation of the Unmodified group*

Figure 4.a shows that the within group variation for the frontal bone of the Unmodified group overlaps that of the Unmodified – TEPL (i.e. Tabular Erect Plano-Lambdoid) and part of Unmodified – TEFO (i.e., Tabular Erect Fronto-Occipital) comparison. The other part of the variation observed for the Unmodified – TEFO group ranges outside the variation of the Unmodified individuals. The Unmodified – TO (i.e., Tabular Oblique) and Unmodified – FO (Fronto-Obelionic) groups differ clearly from the variation within the Unmodified cluster. When considering the parietal bone (Figure 4.b), the highest values of the within variation for the Unmodified group intersects that of all groups except that of Unmodified – TEFO group.

This group displays a bimodal distribution when compared to the Unmodified one since part of its variation lies in the within-group range of variation of the Unmodified individuals. The other part displays the highest Procrustes distances values (SI Table 2a). The variation of the occipital bone within the Unmodified group is close to that calculated for the Unmodified – FO and Unmodified – TEPL comparisons (Figure 4.c). The Unmodified - TO is distinct from the within-group variation of the Unmodified individuals. The variation observed for the Unmodified – TEFO comparison is bimodal with one section overlapping the Unmodified within-group variation while the other shows the highest values.

#### *The within and between group variation of the Fronto-Obelionic group*

The frontal bone morphological differences we observe among the individuals with a FO ACM differ slightly from the variation measured for FO – TEFO, FO – TEPL and FO – TO comparisons (Figure 4.d; SI Table 2a). The highest differences are those calculated for the FO – Unmodified comparison. The FO within-group variation for the parietal bone, expresses values close to all comparison groups except part of the FO – TEFO variation for which the highest Procrustes distances are observed (Figure 4.e; SI Table 2b). The comparisons of the occipital morphological differences for the FO group reveals that the FO within-group variation is close to the variation computed for the FO – Unmodified comparison (Figure 4.f). The FO – TEFO group shows a flattened distribution with some values located in the FO within-group distribution whereas some exceed it and are much higher (with a 3<sup>rd</sup> quartile of the Procrustes distances of 0.153; SI Table 2c). The FO – TEPL comparison yields a widespread distribution with most of the variation located in the same variation range as the FO – Unmodified distribution. The FO – TO group displays important morphological differences that clearly separate its distribution from that of the FO within-group.

#### *The within and between group variation of the Tabular Erect Fronto-Occipital group*

The TEFO within-group variation for the frontal bone is comparable to all groups except that of the TEFO – Unmodified one (Figure 4.g; SI Table 2a). This latter group exhibits a bimodal distribution with some values laying in the TEFO within-group variation and others exceeding the variation range of the other groups. The variation measured for the parietal bone in the TEFO within group is very important (i.e., a Procrustes distances mean of 0.120) and expresses a bimodal pattern where some values are low and others high (Figure 4.h; SI Table 2b). The variation of this group exceeds the variation displayed by the other groups except the TEFO – FO and the TEFO – Unmodified groups (the latter expressing a bimodal distribution and a Procrustes distances mean of 0.143). For the occipital bone (Figure 4.i), the TEFO

within-group variation also shows a bimodal pattern of variation. Variation in this group is more important (i.e., a Procrustes distances mean of 0.160) than the ones computed for all other groups. Only the variation of the TEFO – TO group is higher than the TEFO within-group variation (with a Procrustes distances means of 0.189).

#### *The between group variation of the Tabular Erect Plano-Lambdoid group*

The variation for the TEPL within-group overlaps in major part that of the TEPL - Unmodified group (Figure 4.j). It also overlays the other groups variation (i.e., TEPL – FO, TEPL – TEFO and TEPL – TO) but to lesser extents. Regarding the parietal bone (Figure 4.k), the within-group TEPL variation differs from the other groups, which present rather similar distributions except for the TEPL-TEFO group. When examining the occipital bone variation (Figure 4.l), the TEPL within-group expresses a large range of variation with some Procrustes distances showing low values whereas others are displaying high ones (SI Table 2c). The lowest values are similar to the ones observed in TEPL – FO, TEPL – TEFO and TEPL – Unmodified groups.

#### *The within and between group variation of the Tabular Oblique group*

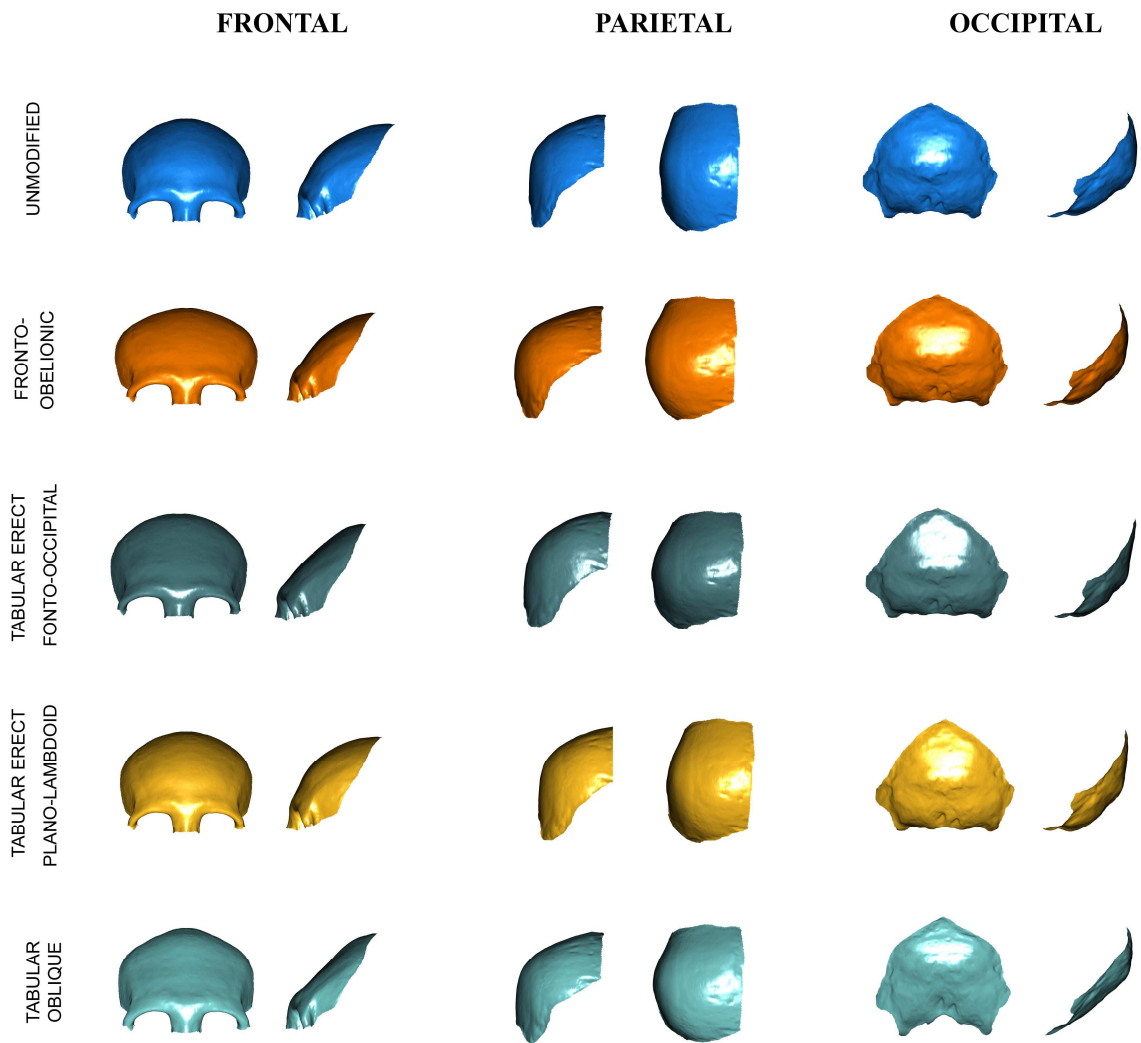
The lowest variation registered for the frontal concerns the two groups TO – FO and TO – TEFO (Figure 4.m; SI Table 2a). TO – Unmodified and TO – TEPL express slightly higher amount of shape variation with respective Procrustes distances means of 0.107 and 0.091. Considering the parietal bone (Figure 4.n), the between-group variations of the TO group are quite similar with the TO – FO and TO – TEPL comparisons displaying the lowest variations. The TO – Unmodified and TO – TEFO show the highest variation with respectively unimodal and bimodal distributions. Regarding the occipital bone, all of the comparisons show a high amount of variation compared to any of the other comparisons measured (Figure 4.o; SI Table 2b). The TO – Unmodified, TO – FO and TO – TEPL groups overlap each other. The TO – TEFO group is the one showing the highest amount of variation and the highest values (Figure 4.o; SI Tables 2a and 2c).

The shape variation computed within and between each group has revealed that some calvaria bones can be informative in the identification and characterization process of ACM.

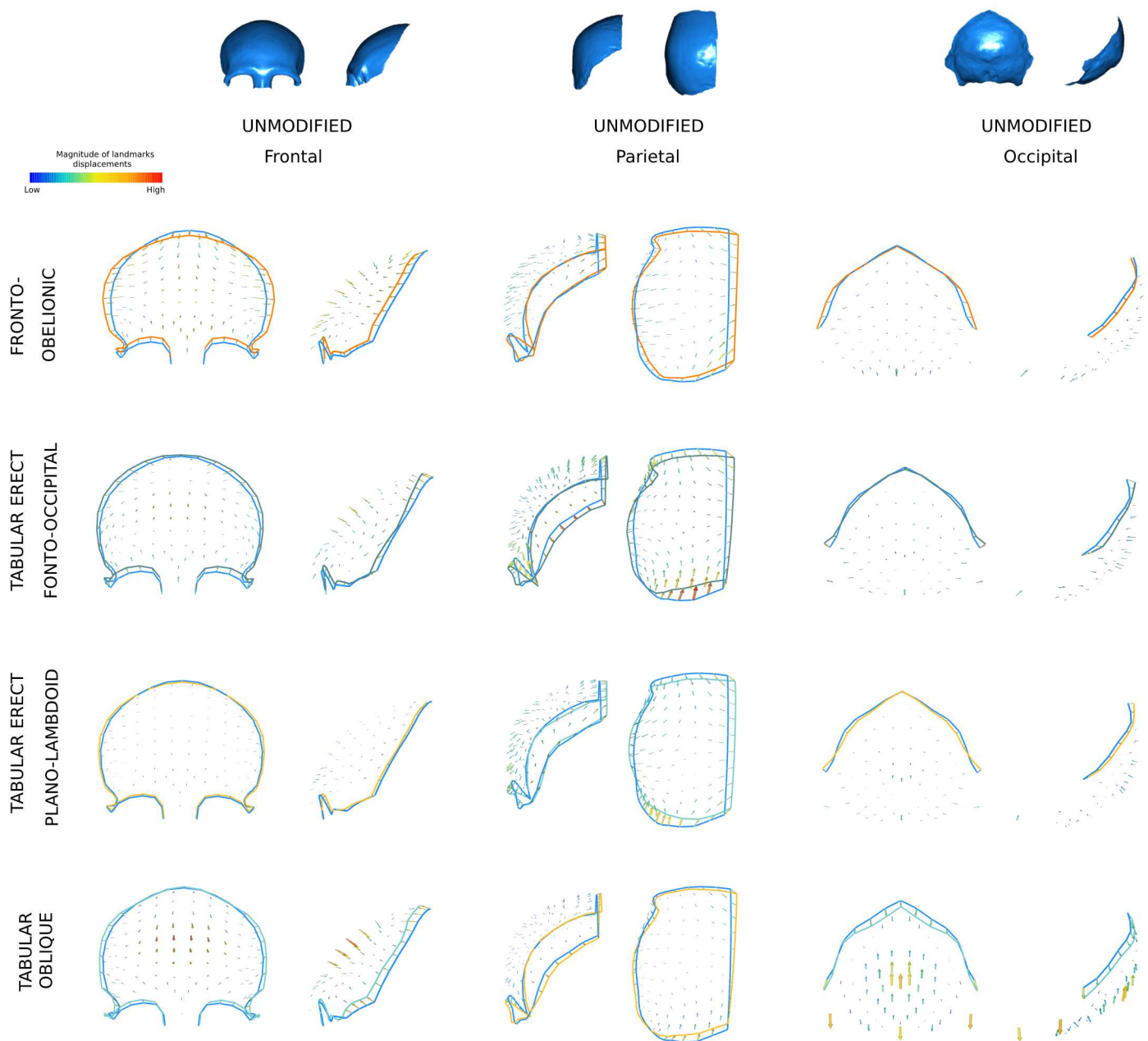
### **3.2 The challenge of identifying and differentiating ACM using isolated calvaria bones**

Firstly, we have shown that the variation observed between the Unmodified individuals and the individuals belonging to other groups always exceeded that of the within-group composed of the Unmodified individuals (SI Table 2). It suggests that regardless of the type of ACM to which it belongs, an isolated calvaria bone of an individual with ACM expresses in most instances morphological differences greater than the physiological variation (i.e., the variation within the Unmodified group) and can be dissociated from it.

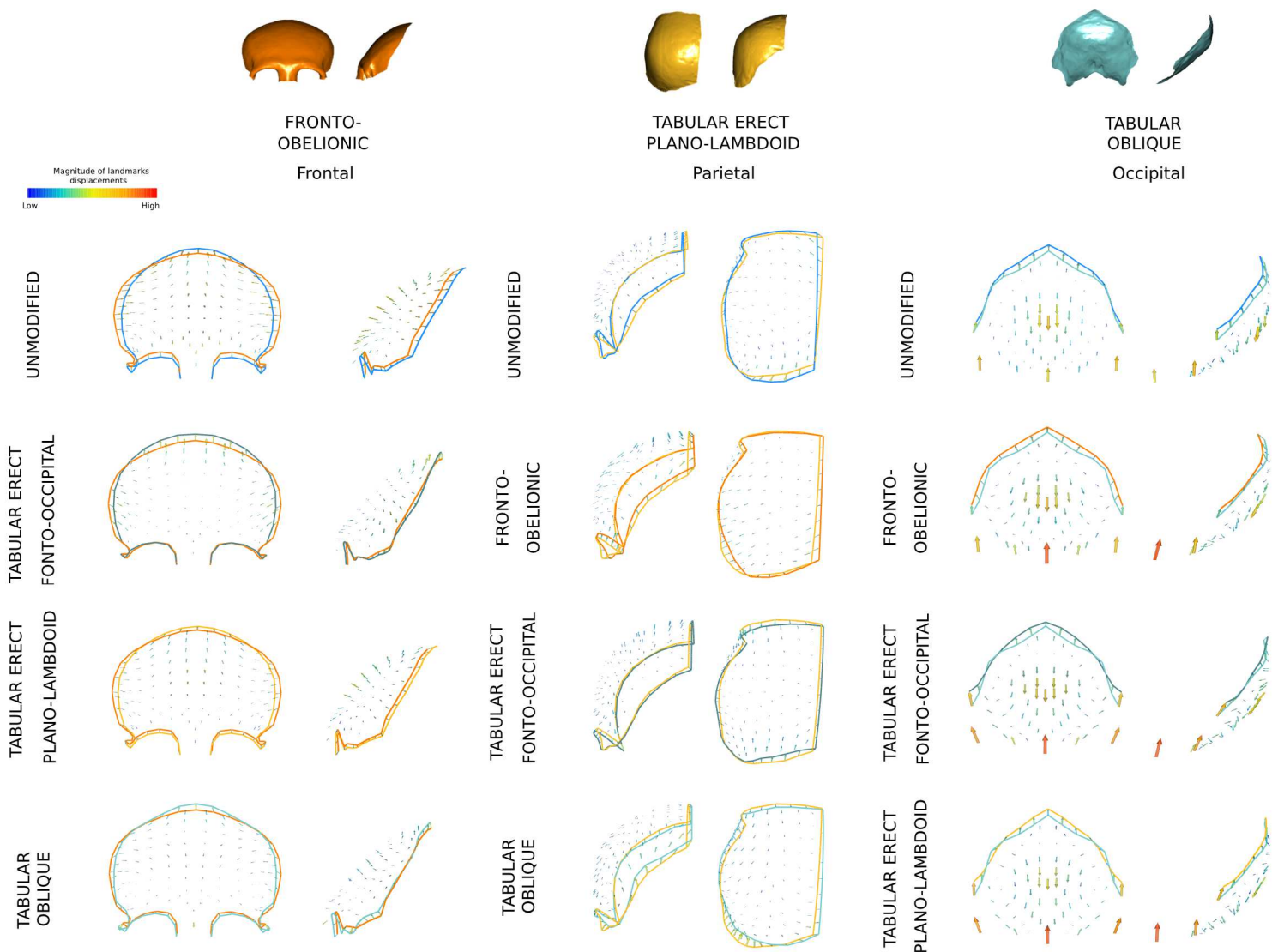
Figure 5 describes the calvaria bones' mean shape of each ACM variant (except for the TO variant, which is represented by one individual). Figures 6 and 7 and SI Figures 1, 2 and 3 illustrate the calvaria bones' shape changes between groups. For the frontal bone, the flattening degree of the frontal squama distinguishes ACM from the Unmodified group (Figure 5). However, in the case of TEPL ACM, the morphological differences of the frontal bone observed between the Unmodified and the TEPL groups are more tenuous (Figure 4.a). Thus, some difficulties can be encountered when looking to differentiate those forms from the physiological variation if the analyses are exclusively based on visual examinations. When comparing the parietal bones of every ACM variant to the Unmodified group (Figures 5 and 6), the important protrusion of the lateral parietal region is a pattern shared among all types. For all ACM variants, the parietal bosses move backward and laterally when compared to the Unmodified group (Figure 6). Furthermore, ACM affects the lambdoid suture and its surroundings, and is characterized by their stretching laterally and inferiorly. The occipital bone of the Unmodified group (Figure 5) has a narrower and rounder shape than that of all ACM types, which shows a certain amount of bone flattening (differentially localized according to the ACM variant considered) associated with a broadened shape (Figure SI 3).



**FIGURE 5** Mean shapes of each group for the frontal, parietal and occipital bones.



**FIGURE 6** Morphological differences between the frontal, parietal and occipital mean shapes of the Unmodified group and each ACM type. The differences are illustrated as landmarks displacements. The arrows represent the displacements from a mean shape (column) to another (row). Arrows with small lengths and cold colors indicate low morphological differences. Arrows with large lengths and warm colors indicate large morphological differences. The magnitude of the heatmaps (i.e., the minimum and maximum values) have been standardized on the minimal and maximal Procrustes distances observed when comparing the mean shapes of the five groups for each bone separately.



**FIGURE 7** Morphological differences between the frontal (for the Fronto-Obelionic group), the parietal (for the Tabular-Erect Plano-Lambdoid group) and the occipital (for the Tabular Oblique group) mean shapes and all other groups. The differences are illustrated as landmarks displacements. The arrows represent the displacements from a mean shape (column) to another (row). Arrows with small lengths and cold colors indicate low morphological differences. Arrows with large lengths and warm colors indicate large morphological differences. The magnitude of the heatmaps (i.e., the minimum and maximum values) have been standardized on the minimal and maximal Procrustes distances observed when comparing the mean shapes of the five groups for each bone separately.

In some cases, certain bones exhibit shape features specific to some types of ACM and allow their differentiation from the other ACM variants. The within-group variation observed for the frontal bone of the FO group indicates a distinct shape when compared to the other groups. The frontal bone of the FO ACM displays a marked flattening, a shortened length of the frontal squama associated with a more retracted position of the glabellar region and the orbital rims (Figure 7). These features distinguish FO ACM from the Unmodified group and the

TEPL ACM, which show a rounded frontal squama and a more protruding glabellar region (Figures 5 and 7). The differences are more subtle in regards with the two other types of ACM that both involve a flattening of the frontal bone. The evaluation of the shape differences between the FO and the TO ACMs demonstrates that the degree of flattening is lower for the FO group than for the TO one. In comparison with the TEFO group, the FO one shares a similar flattened morphology. Compared to the TEFO and TO groups, the FO one is mainly characterized by an important degree of lateral protrusion that affects the region of the temporal lines and the lateral sections of the coronal suture combined with a reduced height of the frontal squama (Figure 5 and 7).

The measures of morphological differences (SI Table 2b) and the distribution pattern of variation within the TEPL variant for the parietal bone (Figure 4.k), also point to specific shape features. First, the parietal shape is broadened (Figure 5); likewise the other individuals belonging to any ACM groups. Yet, they differ from the FO and TO parietal mean shapes because the bulging of the TEPL mean shape is less prominent than these two groups (Figure 7). The TEPL also shows higher parietal bosses oriented more anteriorly than these two groups. Finally, the differences between the TEPL and the TEFO are subtle, as they seem to relate to small variations in the lateral protrusion of the parietal bone (Figure 7). When compared to the Unmodified group, the morphological differences concern similar regions. However, they express this characteristic with lower intensity among the TEPL group. Differentiating those forms via a visual examination is a difficult process that should be addressed using complementary analyses (e.g., using linear measurements).

The internal variation of the TO group could not be investigated because of its sample size of one individual. Nevertheless, when compared to individuals belonging to other groups the TO individual displays a specific occipital shape that is not reported in the other comparisons. The TO occipital shows a very high degree of specificity as evidenced by its unique morphology (Figure 5) and by its important amount of shape variation when it is compared to occipital bones from other ACM groups (no mean Procrustes distance is less than 0.14; SI Table 2c; Figure 4.o). Important increases in length and flattening of the nuchal area are the most noticeable criteria accounting for the specific occipital shape of this variant (Figure 5 and 7). In combination with these characteristic features, we also observe that the superior part of the occipital squama is reduced substantially, and the occipital eminence occupies a much higher position, closer to lambda (Figure 7). A downward motion of the asterionic region is also observed and results in its displacement inferiorly and anteriorly.



#### 4. DISCUSSION

This study has provided, for the first time, information on the shape features of isolated calvaria bones that pertain to instances of ACM. Besides evaluating the potential of using isolated calvaria bones to identify and differentiate ACM, it also reveals valuable information relative to the techniques employed to produce certain ACM variants. These results question the homogeneity of one specific group: the Tabular Erect Fronto-Occipital variant.

Our results demonstrate that isolated bones may provide valuable information that can help to identify individuals with ACM from those that have never undergone any form of ACM during their lifetime. Calvaria bones that have undergone ACM exhibit characteristic flattening and broadening morphology, when compared to the natural shape variation of the Unmodified group. In addition, under certain conditions our results support the assumption, that some ACM variants can be characterized based on isolated calvaria bones.. The frontal bone is the most informative element to characterize the Fronto-Obelionic (FO) type. The combination of a flatter and broader morphology seems to be specific to this variant. The Tabular Erect Plano-Lambdoid (TEPL) type displays a parietal shape that can be distinguished from the other variants through the identification of laterally expanded parietal bosses as well as via their anterior position. Finally, the elongated shape of the nuchal portion of the occipital bone, characterizes the Tabular Oblique (TO) type. This morphology is highly specific to this type and has never been observed in any of the other ACM variants considered here. These results are important for the context of western and central Mesoamerican archaeology where in-depth investigations on the evolution and diversity of ACM practices are sometimes limited by bone preservation. However, the methodological framework presented here could easily be applied to other archeological contexts across the Americas. Such research would permit a clearer understanding of the spread and evolution of ACM practices on a continental scale. For example, the technique outlined here may be extremely valuable when applied to the archeology of the Maya area, where poor bone preservation has substantially limited the study of ACM (e.g., Danforth, 1994; Wright, 1997; Cucina et al., 2002).

While the patterns of variation within and between groups have revealed some specificities among certain variants, they have also brought information on standardization of ACM techniques and the manner in which they were performed. The FO variant shows within-

group values similar to that of the control group for the three calvaria bones considered in this study. This reinforces that this technique was standardized (Natahi et al., 2019). When comparing the occipital shape differences within the FO group to those quantified between groups, the weakest differences were recorded for the FO – Unmodified comparison and the highest for the FO – TEFO comparison. This suggests that the shape of the occipital bone in individuals with FO ACM is closer to that of individuals with no modification than to any of the ACM groups. The occipital shape variation observed for the Unmodified – FO comparison differs slightly from the variation recorded for the FO within-group. These results show that the occipital bone underwent a modification process important enough to distinguish it from the physiological variation; yet not as marked as the reported case of TO ACM. Therefore, it strengthens the assumption of Pereira (1999) that FO variant is distinct from the two major types (i.e., Tabular Erect and Tabular Oblique) usually encountered in the context of Mesoamerican archaeology (Romano, 1974; Tiesler, 2014; Tiesler & Serrano, 2018). Moreover, it proves that an element of the cranial device (e.g., such as a pad or a bandage) had also exerted a constraint with lower intensity on the nuchal part of the occipital bone for this variant. Consequently, these lines of evidence are consistent with the conclusions reached by Pereira (1999, 2018) that such a modification process would be obtained through the implementation of constraining elements localized on the frontal squama and in the obelionic and nuchal regions.

The TEPL variant results from the implementation of a constraining element in the posterior section of the occipital bone, which prevents brain growth in that direction. While barely noticeable via a visual examination, we have demonstrated here that the frontal bone for this variant presents a shape that differs slightly from the Unmodified group. This information is valuable regarding the nature of the cephalic device employed to produce this variant. The TEPL variant is thought to be induced by the process of cradleboarding (e.g., Dembo & Imbelloni, 1938; Tiesler, 2014). Dembo and Imbelloni (1938) have identified forms similar to ours since they have observed both anterior and posterior compression planes among individuals exhibiting it. More specifically, they proposed that the head of the newborn was maintained by a system tying the frontal bone back to the cradleboard. Such a system, as documented for the southwest of the United States of America (e.g., Piper, 2002) would result in a slightly modified curvature of the frontal squama and would explain the variation we have documented here.

The TEPL group considered here expresses a within-group variation distribution and values similar to that of the control group for the frontal and parietal bones. However, the group variation for the occipital bone is bimodal with very high Procrustes distances. It indicates that very different occipital shapes co-exist within that cluster and questions whether or not this practice was standardized. Such a result is consistent with the hypothesis that these variants were produced via cradleboarding. Random phenomena such as the infant's head movements are likely to occur daily and may explain the discrepancies of occipital shapes observed here. The consistency of the within-group variation for the parietal bone compared to the bimodal distribution of the occipital variation is of interest. It suggests that the parietal shapes within this group are similar while the occipital ones differ greatly. This result implies that differential constraints localized in the posterior part of the skull can result in similar responses in other region (i.e., the parietal bones). Whether those forms have been produced by different cradleboarding techniques or by random events that occurred during the life of the infant (e.g., head movements, sleep position), is currently unknown. However, future studies could compare the occipital shape variation of the TEPL type to that of children with positional plagiocephaly (with a specific focus on the lateralization) in order to decipher the underlying causes of such shape variation .

The within-group variations of the frontal, parietal and occipital bones observed for the Tabular Erect Fronto-Occipital (TEFO) group exhibit a bimodal distribution. Furthermore, several comparisons with other groups have also shown a bimodal distribution. Except for the variation measured between the TEFO and the TO individual for the occipital bone and the variation between the TEFO and the Unmodified groups for the parietal bone, the within-group variation of the TEFO group is always roughly equal to or greater than the between group variation.

These results indicate important shape differences within this group. It is composed of four individuals, one of which expresses a different shape to the others. This questions the homogeneity of the technique employed to produce their forms and highlights the limitations that current classification systems have to face. Future work, encompassing larger sample sizes, should focus on the variation recorded within each variant in order to disentangle whether cases like the TEFO variant actually forms a homogenous class ensuing from similar techniques of ACM.

The purpose of this study was to investigate the shape variation of the calvaria bones among individuals with ACM independent of how asymmetric they are, as the asymmetric

component of all landmark configurations was removed. Nevertheless, ACM is reported to cause important amount of asymmetry in the entire cranium (Neumann, 1942; Romano, 1974; Kohn et al., 1995; Tiesler, 1998; Clark et al., 2007; Pomeroy et al., 2010). Some authors have identified that in certain ACM cases, flattening can affect separately the right or left posterior portions of the skull (Kohn et al., 1995; Tiesler, 1998; Natahi et al., 2019). As asymmetry was excluded here, further studies should evaluate the extent to which it can complicate the assessment of ACMs based only on calvaria bones.

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