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The application of 3D geometric morphometrics and laser surface scanning to investigate the standardization of cranial vault modification in the Andes

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ABSTRACT

Cranial vault modification and the social significance of permanent body modification have long been an important topic of interest in Andean archaeology. While previous studies have enriched our understanding of these practices among prehistoric Andean populations, the introduction of 3D surface scanners and geometric morphometric methods in archaeology enable us to examine head-shaping practices in novel ways. In this pilot study, we used a NextEngine 3D Laser Surface Scanner to generate high resolution models of artificially modified crania from four archaeological sites dating to the Archaic (2300–1600 BCE), Formative (500 CE), late Middle Horizon/early Late Intermediate period (LIP) (750–1100 CE) in Chile and late LIP crania (circa 1350 CE) from central, highland Peru. Landmarks were recorded on the 3D digital models of crania and these data were analyzed to assess variation in vault shape within and between the samples. Results of the PCA analysis showed graphical separation of the annular, tabular erect, and some tabular oblique types even when gross morphological assessments proved challenging. We documented marked variation within the general modification type traditionally identified as tabular oblique, which suggests more detailed classifications within this type are needed. We also investigated how standardized (i.e., similar) particular cranial modification types were at each site, and results show that the coastal sites of Morro 1 and Playa Miller 7, and the highlands Huari-Vegachayoc Moqo site show higher levels of standardization than the other four samples. This study highlights the utility of 3D imaging and geometric morphometric methods for straightforward, objective assessments of cranial modification and levels of standardization within sites and within particular modification types. This has implications for understanding the broader social and cultural significance of this practice, such as whether there were shared cultural norms about how a head should be modified, which could have led to highly uniform modification practices and head shapes in the Andes.

1. Introduction

Ancient forms of body modification have received considerable attention in archaeology. For example, cranial vault modification (CVM), which originated independently around the world, appears to have been common among prehistoric populations throughout the Americas (Tiesler, 2014), and especially in the Andean highlands and coastal regions of South America (Dembo and Imbelloni, 1938; Dingwall, 1931; Gertszen, 1993; Gertszen and Gertszen, 1995; Tubbs et al., 2006). On the South American continent, ancient cranial modification forms have been described and documented throughout Argentina (e.g., Perez, 2007), Brazil (e.g., Mendonça de Souza et al., 2008; Okumura, 2014), Chile (e.g., Boston, 2012; Gertszen, 1993; Manríquez et al., 2006; Rhode and Arriaza, 2006; Salazar et al., 2014; Torres-Rouff and Knudsen, 2007), Ecuador (e.g., Munizaga, 1976), and Peru (e.g., Blom et al., 1998; Hoshower et al., 1995; Pomeroy et al., 2010; Torres-Rouff, 2002; Verano et al., 1999). Some of the earliest examples of cranial modification in the Andes have been observed among the La Galgada highlanders of Peru (Grieder, 1988) and the Chinchorro of northern Chile (Munizaga, 1987) dating to around 5000 years BP. Cranial modification practices were eventually prohibited by the Toledan reforms of the sixteenth century, in large part because it was perceived as an idolatrous act in which the head shapes were meant to mimic the principal mountain deity of particular ethnic groups (Ulloa Mogollan, 1965[1586]).

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Although no written documentation is available for the prehistoric period in the Andes, Colonial chroniclers, el Inca Garcilaso de la Vega and Bernabé Cobo, offer some insights into the technique underlying this practice through their descriptions of head modification apparatuses that were applied to infants and young children (Cobo, 1979[1653]; Garcilaso de la Vega, 1966[1609] as cited in Torres-Rouff, 2003). The Spanish and Andean chroniclers also tried to explain the social meanings associated with this form of corporal modification, noting that different head forms were a way to discern village affiliation, linguistic group, and cultural groups more broadly. Using gross visual assessments, recent studies of CVM in the Andes have explored whether the practice was a corporal marker of gender, social, ethnic, or occupational identity (e.g., Blom, 2005; Blom et al., 1998; Lozada Cerna, 1998; Torres-Rouff, 2002), noting that ethnic or cultural affiliation (which could be tied to occupation) was a key factor in affecting which cranial modification style would be imposed upon an infant. Through this work, it has become clear that particular body modification practices, including cranial modification, were a powerful and permanent way to make and mark social identity in the ancient Andean world (Tung, 2007).

The use of new scientific techniques has enabled researchers to revisit Andean archaeological questions in a variety of ways, ranging from 3D analyses of artifacts and skeletal morphology, to ancient DNA analysis of nuclear DNA, to the use of drones and photogrammetry for mapping archaeological sites in 3D (e.g., Fehren-Schmitz et al., 2015; Kuzminsky, 2013; Poulson et al., 2013; Wernke et al., 2014). Among these, we will focus here on the application of 3D laser surface scanning technology and analyses that explore cranial morphological variation with a level of precision that moves beyond traditional assessments (e.g., Fehren-Schmitz et al., 2015; Kuzminsky, 2013). Building on previous research that has utilized gross visual assessments, linear measurements and angles obtained by calipers, and 2D approaches to the study of cranial vault modification, our study aims to utilize modern geometric morphometric techniques to explore variation in cranial modification forms between and within particular categories of cranial modification in the Andes. Although there are bioarchaeological standards using gross observations to classify crania into particular modification styles, the growing number of studies on cranial modification in the Andes is revealing a wider array of modification forms (e.g., Pomeroy et al. 2010; Torres-Rouff, 2002; Velasco, 2016), necessitating an improved methodology to more adequately document the differences within and between types.

We suggest that 3D scanning and morphometric analyses as described here will provide those clearer data, which will allow researchers to examine the diachronic and geographic uniformity of shape, or lack thereof, among artificially modified crania. Using 3D techniques, we document cranial modification forms and examine how similar (i.e., how standardized) particular modification types are at each site (e.g., how much variability is there within the tabular oblique type?). We also compare the differences between the samples to evaluate whether certain groups have more standardized norms and practices regarding head modification. Those insights may thus enable us to investigate broader questions about this Andean practice that were not documented by chroniclers, such as whether a specialist class with standardized techniques conducted the head modifications on infants. If specialists were tasked with this important job, there may be greater standardization within one type of cranial modification style (e.g., annular type). Standardized forms may also suggest that the notion of an ideal head shape was strongly reinforced and taught to mothers and caregivers to ensure community norms about how cranial modification was performed, whether through the use of cloth bindings around the head, boards strategically placed on the head, and/or pressure of the head against portable cribs, known as *kiraw*. In contrast, greater variability within a cranial modification type may suggest the absence of a specialized class responsible for modifying heads; instead, family members, or other non-specialists, may have modified the heads of infants, leading to greater variability within one modification type.

1.1. Cranial modification types

In the Andes, two general types of cranial modification are typically recognized: annular and tabular (Blom, 2005; Dembo and Imbelloni, 1938; Torres-Rouff, 2002). Annular modification uses cloth bindings and rope to elongate the skull posterior-superiorly with little to no lateral expansion of the parietal bosses, and the tabular form alters the head with boards and bindings, resulting in two major subcategories: tabular erect (flattened cranium from front to back with bulging parietals; the occipital bone is flattened, at a 90° angle with the basicranium) and tabular oblique which gives the head an elongated (posterior-superiorly) appearance by flattening the anterior and posterior aspects of the head, with an occipital bone that forms an obtuse angle with the basicranium (Fig. 1). Additional differences within the tabular form of modification include cases where only one aspect of the skull is flattened: frontal flattening, lambdoidal flattening, and occipital flattening, the latter of which can occur unintentionally when an infant is placed for extended periods on his/her back in a cradle board or on some other restrictive device with a solid surface.

2. Archaeological background

The modified crania come from four prehistoric sites in the Andes (Fig. 2): the sites of Morro 1, Playa Miller 7, and Azapa-140 in northern Chile and the site of Huari in central, highland Peru. The samples cover several millennia of prehistory, beginning with Archaic-period hunting, foraging, and fishing communities of the northern Chile coast, to increased sedentism, social complexity, and the introduction of irrigated farming, animal husbandry, and ceramic technology within Andean communities during the Formative period. The Late Intermediate period is difficult to generalize given the variety of local and regional changes that occurred along the coast of northern Chile and in the Ayacucho basin of Peru, but northern Chile is often characterized as a time of continued social change and economic specialization among sedentary agricultural societies who emphasized textile production, large-scale feasting, metallurgy, and ceramic production. These activities continued in the Ayacucho basin too, but the quality and quantity of textiles, metallurgy, and polychrome ceramics greatly decreased relative to preceding eras. Although there is clear evidence of violence during the Archaic period in northern Chile (e.g., Arriaza et al., 2008), bioarchaeological and archaeological data available for later periods, particularly the Late Intermediate period, indicates a time of increased warfare and other types of violence combined with social upheaval as evidenced by the emergence of defensive architectural structures in several areas of the central Andean highlands (see Arkush and Tung, 2013; Tung, 2014).

The Morro 1 site (2300–1600 BCE) in northern Chile is located in the modern city of Arica located a few kilometers south of the Peruvian border. Archaeological excavations conducted at Morro 1, combined with recent isotope studies, indicate that this hunter-gatherer-fisher group associated with the Chinchorro tradition, was likely sedentary or semi-sedentary, subsisting primarily on marine foods from the Pacific Ocean located approximately 0.5 km from the site (Arriaza et al., 2008; Poulson et al., 2013; Standen and Santoro, 2004; Sutter and Mertz, 2004). Perhaps the most intriguing and complex of these is the emergence of extensive mummification practices among the Archaic-period Chinchorro culture in northern Chile, who artificially mummified the bodies of adults and children and deposited them in simple, shallow burials (possibly familial units).

The site of Playa Miller 7 (1000 BCE–750 CE) is a Formative period site located approximately 0.5 km from the coast and represents some of the earliest forms of cultivation practices and sand-tempered pottery associated with this time sequence (Focacci, 1974; Sutter and Mertz, 2004; Watson et al., 2013). Recent research suggests that the individuals living at this site continued to exploit marine resources given their close proximity to the Pacific shoreline (Watson et al., 2010). The elaborate mummification practices of the Chinchorro during Archaic

Fig. 1. Examples of three intentionally-modified crania: one classified as tabular oblique on the left (from the site of Morro 1, northern Chile), annular in the middle (from the site of Monqachayoq, Peruvian highlands), and tabular erect on the right (from the site of Azapa-140, northern Chile).

period completely disappeared during the Formative, and were replaced with subterranean shafts and tumuli that contained funerary bundles and a variety of grave goods reflecting maritime and agricultural lifeways (Díaz-Zorita Bonilla et al., 2016). The late Formative period is also a time of social and cultural change, as archaeological evidence shows the arrival of foreign groups from the Tiwanaku region (see Díaz-Zorita Bonilla et al., 2016 for a summary).

The site of Azapa-140 is associated with the Maitas-Chiribaya culture in the Azapa Valley located 25 km from the coast. Radiocarbon dates and cultural artifacts indicate that the site was occupied during the Middle Horizon and the early Late Intermediate period (750–1100 CE) (Sutter and Mertz, 2004). Burials at the site of Azapa-140 were interred in sandy cavities in the seated position along with a variety of local ceramics, textiles, and other grave goods (Sutter, 2005). Tiwanaku influence declined during this period, and was replaced by local developments that involved the intensification of irrigated farming and standardized ceramic and textile production. Animal husbandry and camelid caravans were important during this period, resulting in an expansion of trade and caravan traffic through this region of northern Chile (Valenzuela et al., 2015). As Sutter (2005) notes, cemetery analyses of grade goods for this time period suggest there was ethnic diversity within the Azapa Valley, albeit weakly correlated with the style of cranial vault modification.

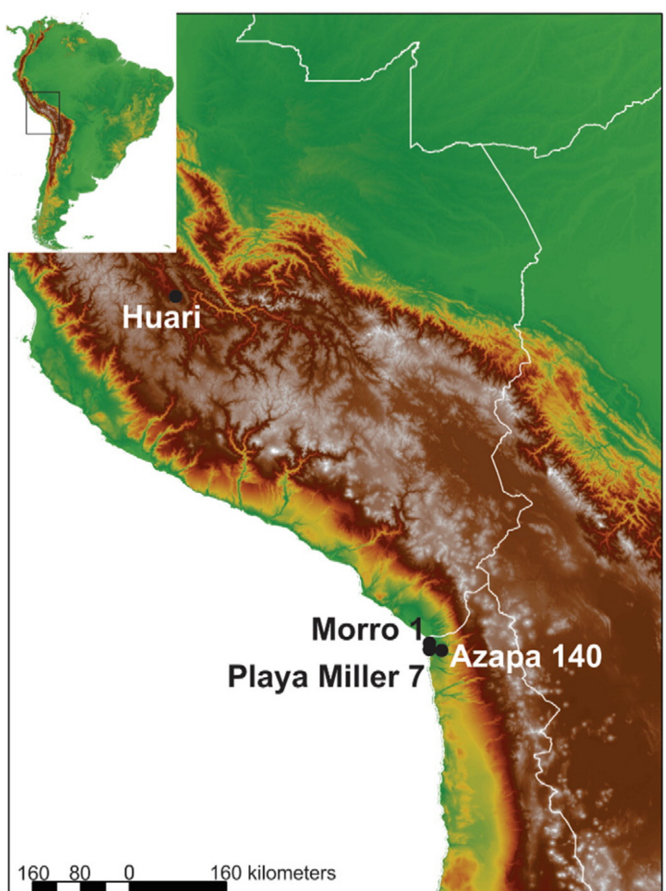

Fig. 2. Map of Peru and Chile where from which the samples were derived. The Chile sites include Morro 1 and Playa Miller 7 along the coast, and Azapa-140 in the Azapa Valley. The Huari site (and location of the two samples Vegachayoq Moqo and Monqachayoq) is located in the highlands of central Peru.

The Peruvian samples derive from two sectors (Monqachayoq and Vegachayoq Moqo) at the site of Huari in the Ayacucho Basin. Huari was the capital of the Wari Empire in the Middle Horizon (600-1000/1100 CE), and parts of the site were reused in the subsequent Late Intermediate period (LIP, 1100-1400 CE), after the decline of Wari. Twenty AMS dates show that the Monqachayoq and Vegachayoc Moqo samples correspond to the second half of the Late Intermediate period, 1270–1390 CE (Tung, 2008; Tung et al., 2013). These two sectors were excavated in the 1980s, and they are located only 150 m apart. Both of these sectors have D-shaped structures, which were important ritual spaces in earlier Wari times, and those D-shaped rooms are adjacent to mortuary spaces (niches at Vegachayoq Moqo and massive underground tombs at Monqachayoq). The post-Wari (late LIP) human remains were not deposited in the formal mortuary places; rather, in the case of Vegachayoq Moqo, the commingled skeletonized bodies were dumped in a trench outside of the perimeter wall that surrounded the D-shaped structure (González Carre et al., 1996). At Monqachayoq, the commingled skeletal parts were deposited in underground galleries that were adjacent to the formal, Wari elite tombs, which were 18 m east of the D-shaped structure (Benavides, 1991; Tung, 2014).

The human remains from the two sectors represent at least 240 individuals, but they were commingled because the bodies were dismembered, as evidenced by cut marks, and many had suffered sublethal and lethal cranial fractures from violent blows to the head (Tung, 2008, 2014). The perimortem trauma made it particularly difficult to perform 3D scans because large portions of the cranium were missing as a result of the massive fracturing; thus, those crania are not included in this analysis. These post-Wari individuals appear to be massacre victims (Tung 2008, 2014), but the stable oxygen isotope ratios from the dentition indicate that the individuals are from the local Ayacucho Basin (Tung et al., 2016) and strontium isotope ratios from a preliminary sample of nine individuals from Vegachayoq Moqo further undergird the interpretation that they are local (Tung, n.d.). In other words, these are not individuals from a variety of distant locales, though they could be from different, local villages surrounding the site of Huari.

3. Materials and methods

Fifty-six adult crania from the archaeological sites described above were selected for this study (Table 1, Fig. 2).

Age-at-death estimations for the crania were based on dental eruption, fusion of the spheno-occipital synchondrosis, dental attrition, and cranial suture closure more generally (Buikstra and Ubelaker, 1994). Sex estimations were based on cranial morphology (Buikstra and Ubelaker, 1994). The crania selected for analysis were determined by the completeness of the cranial vault, which had to be complete enough to allow for the collection of the landmarks used in this study. These

Table 1
List of samples (pooled adult males and females) from four sites and chronological periods.

Site. Label	Time Period	Annular	Tabular Erect	Tabular Oblique	Unmodified	Male	Female
Morro 1, northern Chile Coast. Morro 1	Archaic, 2300–1600 BCE	0	3	10	0	7	6
Playa Miller 7 northern Chile Coast. Playa Miller 7	Formative, 500 CE	2	1	12	0	8	7
Azapa 140, northern Chile Valley. AZ-140	Middle Horizon–early Late Intermediate Period, 750–1100 CE	0	1	9	0	4	6
Monqachayoq-Huari, Ayacucho Basin, central highland Peru. Monq	Late Intermediate Period, ca. 1350 CE	3	0	7	1	7	4
Vegachayoq Moqo-Huari, Ayacucho Basin, central highland Peru. Vega	Late Intermediate Period, ca. 1350 CE	0	0	7	0	4	3
	Total	5	5	45	1	30	26

crania were classified by location and time period to examine the variation among cranial types within and between sites, as well as any potential diachronic differences.

Previous research examining sex-based differences in modified crania among Andean populations in Chile suggests that cranial modification practices were not performed differently according to the biological sex of the individual (e.g., Torres-Rouff, 2002). Other studies also suggest no significant sex differences have been found among individuals with modified crania in central Peru (Okumura, 2014:19; but see Kurin, 2012). Thus, male and female crania were pooled together in this study to maximize the sample size of complete tabular crania, and ensure that the number of landmarks were at least four times greater than the total number of individuals to increase statistical power. However, the sex distribution is roughly the same in all sites (Table 1), so sex differences, if present, will not affect the conclusions based on the comparisons between sites. Gross visual assessments were made of all of the crania to determine whether they could be categorized as annular, tabular, or unmodified. The majority of modified crania were classified as tabular; specifically, 45 crania were tabular oblique, five were tabular erect, and five were annular. One unmodified cranium from the site of Monqachayoq was included to evaluate how it compared to the modified crania.

A NextEngine 3D laser scanner was used to create high resolution digital models for the analyses (Fig. 1). Each cranium was placed on a turntable attached to the laser scanner and laptop. The models were assembled from 18 individual scans using ScanStudio Software (version 1.3.2), and following the scanning criteria outlined in Kuzminsky (2013) and Kuzminsky and Gardiner (2012). Stratovan Checkpoint software was used to generate a series of landmark coordinate data with two replicates for each cranium (Appendix 1) comprised of 10 anatomical midline and paired landmarks on the vault. Anatomical landmarks and descriptions are listed in Table 2, as described in Buikstra and Ubelaker (1994) and von Cramon-Taubadel (2011).

Analyses were conducted with MorphoJ (Klingenberg, 2011) and R (R Core Team, 2014). The replicate x,y,z coordinate data were first subjected to geometric morphometric procedures (GM) widely used in phylogenetic studies of 2D and 3D data that allow for the exploration of morphological variation of biological organisms within and between groups (Zelditch et al., 2012). MorphoJ software was used to perform a Procrustes fit that removes variation in scale, position, and orientation, and to check for any potential outliers that may have occurred as the result of digitizing error. Based on the Procrustes variables, Principal Components Analyses (PCA) generated from the correlation matrix were used to explore the morphological affinities among individuals. Two PCAs were performed: the first explored all the individuals to see how cranial deformation segregated in the morphospace. The second PCA focused only on crania classified as tabular oblique, which was the largest sample, to explore differences that existed among sites in this modification category. In both cases, morphological affinities were illustrated graphically according to the first two principal components. To explore the amount of variation present in each site, we performed a Relethford-Blangero analysis (Relethford and Blangero, 1990), which compares the expected variance within each site with the expected variance based on the R-matrix calculated from these data. The results of this analysis were represented graphically in a scatterplot with the expected variance represented as a regression line. Both PCA and RB analyses were performed in R (R Core Team, 2016) with functions written by MH.

4. Results

Fig. 3 shows the scatterplot of the individuals according to the first two Principal Components (39.64% of the variance explained) extracted from the complete dataset. In this analysis, crania have been color-coded according to the type of modification that was initially ascribed based on gross observation. There is a clear segregation between the annular, and tabular erect crania, with annular types generally falling on the right side of the scatterplot and tabular erect forms falling along the lower left quadrant; all but one tabular erect individual falls on the negative side of both PCs. The crania that were classified as tabular oblique in gross observation exhibit considerable variation of shape. This dispersion appears to be reflected in the variation that exists within this category. The cranium classified as unmodified falls within the range of variation for the tabular oblique crania, and is mostly closely situated near those that were classified as having light to moderate forms of modification.

Fig. 4 shows the morphological affinities of the individuals with tabular oblique deformation according to the first two Principal Components (39.63% of variance explained) from this dataset. Individuals in the scatterplot are color coded by site of origin. Looking only at the centroids (as illustrated by the position of the text labels), Azapa-140 falls primarily along the negative side of PC1, being considerably separate

Table 2
List of landmarks used in the study. Descriptions are from Buikstra and Ubelaker (1994) and von Cramon Taubadel (2011).

Landmark	Description
1. Nasion	The point of intersection between the frontonasal suture and the midsagittal plane
2. Bregma	The ectocranial midline point where the coronal and sagittal sutures intersect
3. Lambda	The ectocranial midline point where the sagittal and lambdoidal sutures intersect
4. Inion	The point where the superior nuchal lines merge in the external occipital protuberance
5. Krotaphion L 6. Krotaphion R	Most posterior extent of the sphenoparietal suture
7. Asterion L 8. Asterion R	The point where the lambdoid, parietomastoid and occipitomastoid sutures meet
9. Opisthion	The midline point at the posterior margin of the foramen magnum
10. Basion	The midline point on the anterior margin of the foramen magnum

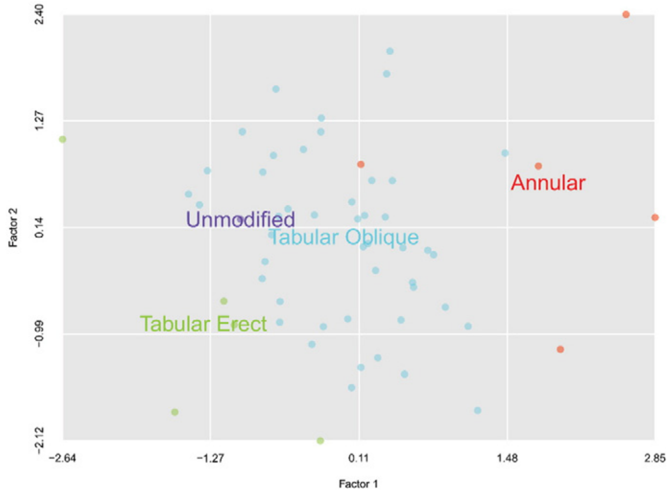

Fig. 3. Morphological affinities of individuals according to the first two Principal Components extracted from the complete dataset. The text labels mark the position of the centroid (average) morphology in each group.

from the remaining sites. Playa Miller 7, Morro 1, and Monqachayoc, fall in the positive range on both axes, respectively. Vegachayoq Moqo falls along the negative side of PC2. However, when the individual dispersion in each site is taken into account, there is significant overlap among sites, which suggest that the average differences in cranial shape among tabular oblique individuals is less pronounced.

Fig. 5 shows the results of the expected and observed variances among tabular oblique individuals, according to the Relethford-Blangero analysis. In this graph, sites above the regression line have within group observed variance that is larger than would be expected given the average genetic distance (Rii) of the site, while sites below the line have lower variance than expected. This analysis corroborates the pattern observed in the previous PCA (Fig. 4), and show that Monqachayoq and Azapa-140 have a higher within-group variance than the other sites included in the study (Vegachayoq Moqo, Morro 1, and Playa Miller 7). Of the sites with lower than expected variance, Morro 1 has remarkably low variance, being the farthest from the regression line. At Azapa-140 and Monqachayoq, in contrast, there is more intra-site variability in the tabular oblique style. From a methodological perspective, the variability detected at Monqachayoq and Azapa-140 may also reveal the need to subdivide cranial modification types further, such as slight tabular oblique or frontal modification.

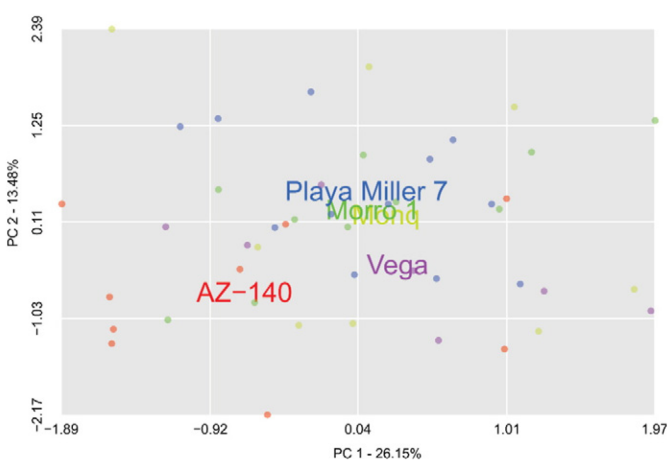

Fig. 4. Morphological affinities of individuals according to the first two Principal Components extracted from the tabular oblique dataset. The text labels mark the position of the centroid (average) morphology in each group.

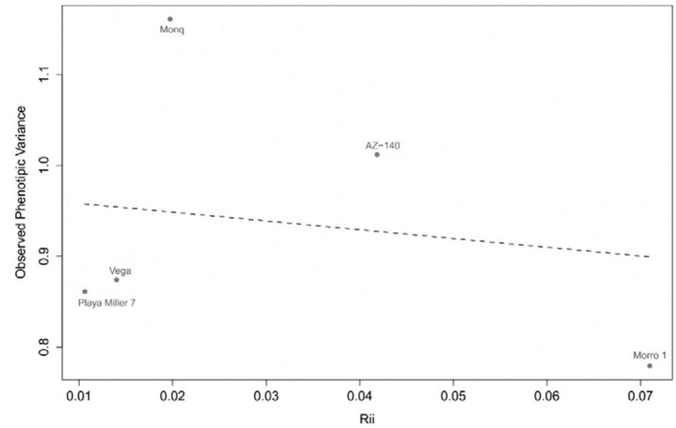

Fig. 5. Regression between observed and expected phenotypic distance, according to the Relethford-Blangero analysis.

5. Discussion and conclusions

While 2D geometric morphometric techniques have been effectively applied to the study of cranial vault modification (e.g., Manríquez et al., 2006; Manríquez et al., 2011; Perez, 2007; Salazar et al., 2014), here we used portable NextEngine laser scanners to create high-resolution 3D digital images from which 3D landmark data could be obtained for geometric morphometric analyses. The incorporation of the 3D data allowed us to document the differences in standardization within a particular CVM type over time and between different regions in the Andes. Our results show that the morphometric approach, even with the use of only 10 cranial landmarks, can discern between annular and tabular erect types of modification. Our assessments also documented the range of variation within the type that is typically referred to as tabular oblique, a variation that could have been produced by varying degrees of severity in frontal and lambdoidal flattening. It also highlights the possible need for a different category of cranial modification type, or at least the recognition of slight tabular oblique, which others have done in studies of northern Chilean populations (Torres-Rouff, 2002). This has not gone unnoticed in other areas of Mesoamerica and South America, where researchers have tried to address ways of categorizing this variation through the creation of more detailed diagrams that aid in visual assessments (e.g., Tiesler, 2014; see also Weiss (1961) for critiques of diagrams used to describe Peruvian vault styles). Because researchers often find certain types of modification difficult to categorize visually, especially when pad or binding impressions are not obviously visible or the modification is only slight, we suggest that these morphometric procedures can aid in distinguishing between unmodified and modified crania (also see Perez, 2007). They also serve as a preliminary step in 3D morphological biological assessments of Andean populations. Further, the variation documented within the traditionally labeled tabular oblique type occurs not just between archaeological sites, but within them, indicating that the standardization of cranial modification types within a particular population warrants further study.

Beyond the utility of 3D laser scanning and geometric morphometric methods for the analysis of cranial vault modification, our study allowed us to investigate whether a particular CVM type (tabular oblique) was highly standardized within and between sites in the Andes. We found lower variance (i.e., greater standardization of the practice) among three groups: the Chinchorro (Morro 1) and Playa Miller 7 samples from northern Chile, and the Vegachayoc Moqo sample from the Peruvian highlands. The Chilean sites are associated with two of the earliest two time periods—Morro 1, a coastal community associated with the Chinchorro fishing-hunting-gathering people, and Playa Miller 7, a coastal Formative period site associated with incipient agriculture and marine subsistence. The lower variance (and greater standardization) within these two Chilean sites could be attributed to a particular technique specialization, including the tools (pads and bindings) used to conduct the technique, the placement of these devices on the infant's head, the time at which the process begins in an infant's life, and the length of time these devices are left on the head. It is also worth considering that there were fewer external cultural and biological influences in this region of northern Chile during the Archaic and Formative periods, which may suggest that the greater standardization that we have documented with Morro 1 and Playa Miller 7 could be attributed to a more homogenous biological population whose cultural and social developments were likely to be local, rather than from Tiwanaku and other outside polities, whose arrival and cultural impact only occurs at the end of the Formative period and thereafter in this region of Chile.

The difference in variance between the Vegachayoq Moqo and Monqachayoc samples is indeed intriguing because, although they are different burial groups separated by 150 m and several stone walls, they were recovered from the same site (Huari) and time period (ca. 1350 CE). Cranial modification forms at Vegachayoq Moqo suggests greater standardization, while Monqachayoc shows far less standardization. It may be possible that individuals interred at Vegachayoc Moqo and Monqachayoc represent distinct ethnic groups or social classes,[1] each of whom may have had different notions regarding how cranial modification techniques were implemented. It is also possible that Monqachayoq simply had people from different neighboring sites, leading to more variability in cranial modification forms. As the aDNA data show, they are from the same biological population (Kemp et al., 2009), and as the stable oxygen and strontium isotope data show, they are from the local Ayacucho Basin (or from an area with similar oxygen and strontium isotope ratios). However, those who were buried together at Monqachayoq could have spent their childhoods at different, local villages near the site of Huari, and then moved to Huari later in life or were forcibly brought there before their deaths. The ideal of a sloping (tabular oblique) shaped head may have been differently enacted at those different village sites. In all, these findings are important because they suggest that the two post-Wari massacre groups at Huari may have been comprised of different community populations, or that the Vegachayoq Moqo group was one community, and the Monqachayoq group was comprised of several communities. This is still unknown, but these new cranial modification data provide new insights into the composition of the victim profiles.

Greater standardization in the Vegachayoq Moqo, Morro 1, and Playa Miller 7 groups may suggest (albeit tentatively) that there were strong cultural norms about ideal modified head forms and standardized ways of achieving that modified shape. These standardized ideals could have been carried out by family members or a specialist class, and if so, the low level of variability in cranial modification could suggest that these ideals were widely adopted and knowledge about how to modify an infant's head in a particular way was equitably shared throughout the community. The chronologically later sites of Azapa-140 and Monqachayoc show higher than expected variance; this could perhaps indicate that they had less stringent norms about standardizing cranial modification types, and that families used a variety of tools and techniques to modify an infant's head, leading to variation in the cranial modification forms. In the case of the Monqachayoq sample, it could be that they come from several different communities, as noted above. While these preliminary data can only hint at these possibilities, we hope to further test these ideas through the study of more geographically and temporally diverse samples from the Andes.

This study has demonstrated that 3D laser scanners can aid in classifying modified crania. The 3D visualization and analytical methods we used in this study provide quantitative assessments of diachronic and geographical variation among prehispanic Andean populations. The classification systems designed for gross visual assessments by Dembo and Imbelloni (1938), for example, are often of limited use because of the array of modification styles. This makes it challenging to address broader archaeological questions about the practice itself. The application of these methods allows researchers to address these limitations and examine the variability within and between cultural groups. Lastly, this study provides a starting point for addressing broader cultural questions about past Andean lifeways, such as cultural notions about the permanent modification of infant's heads.

[1] There were no grave goods buried with any of the commingled individuals recovered from Vegachayoq Moqo and Monqachayoq, making it difficult to identify different social classes.

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Appendix 1

List of individuals by site and the digitized data for each variable (with replicates). Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.jasrep.2016.11.007.

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