

Article

Palatal Morphology in Artificially Modified Crania: Evidence for Limited Craniofacial Integration

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Featured Application

This study provides insights into the relationship between neurocranial deformation and palatal morphology, with potential applications in dental and craniofacial disciplines. Understanding the relative stability of palatal shape despite significant cranial vault modification may inform clinical approaches in orthodontics, maxillofacial surgery, and craniofacial growth assessment. Additionally, these findings may support the interpretation of morphological variation in both archaeological populations and modern clinical contexts, particularly in cases involving cranial deformities or developmental constraints.

Abstract

Background: Artificial cranial modification (ACM) in pre-Hispanic Andean populations provides a natural model for investigating whether marked deformation of the cranial vault is associated with corresponding changes in palatal morphology and craniofacial integration. **Methods:** Three-dimensional geometric morphometrics was used to quantify neurocranial and palatal shape in 19 Peruvian crania (9 modified, 10 unmodified). Analyses included Generalized Procrustes Analysis, principal component analysis, Procrustes ANOVA, morphological disparity tests, directional asymmetry assessment, and two-block partial least squares (PLS) analysis of neurocranial–palatal covariation. **Results:** Modified crania showed significant neurocranial shape divergence from unmodified individuals, whereas palatal mean shape, principal component scores, and within-group disparity did not differ significantly between groups. Directional asymmetry was significant in both groups, but differences in mean asymmetry between groups were modest. Two-block PLS analysis yielded a first-axis correlation of $r\text{-PLS} = 0.694$; however, this association was not statistically significant ($p = 0.488$), and the RV coefficient indicated only low-to-moderate integration between neurocranial and palatal shape ($RV = 0.341$). **Conclusions:** These findings indicate that pronounced neurocranial deformation is associated with substantial changes in cranial vault morphology but limited alteration of palatal shape. The



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absence of significant neurocranial–palatal covariation suggests that the palate behaves as a comparatively constrained component of the craniofacial complex, supporting a model of partial craniofacial integration during growth.

Keywords: artificial cranial modification; palatal morphology; craniofacial integration; geometric morphometrics; cranial vault deformation; dental anthropology; human anatomy; craniofacial growth; morphometric analysis

1. Introduction

The human skull is a complex anatomical system in which the neurocranium and viscerocranium are structurally connected but only partially integrated in their growth and functional relationships. Within this complex, the palatal arch, formed mainly by the palatine processes of the maxillae and the horizontal plates of the palatine bones, contributes to the roof of the oral cavity and to the separation of the oral and nasal passages, thereby supporting functions such as swallowing, respiration and speech [1,2]. Understanding the relationship between neurocranial and palatal morphology is relevant to studies of craniofacial growth, congenital malformation and functional variation, because these regions are anatomically connected yet developmentally distinct [3–6]. These interactions are also of clinical interest, as disturbances in craniofacial growth contribute to conditions such as cleft palate and craniosynostosis [7–9]. Experimental and clinical studies have shown that masticatory and occlusal forces can influence craniofacial form and bone remodelling, highlighting the broader importance of mechanical factors during growth [10–13]. At the same time, the relationship between craniofacial form, stomatognathic function and posture remains complex, and several aspects of these interactions are still debated or incompletely understood [14–17]. As a result, it remains unclear to what extent marked deformation of the neurocranium is associated with corresponding morphological changes in anatomically connected regions such as the palate. Clarifying this point may improve understanding of craniofacial integration and help contextualize morphological variability observed in developmental and clinical conditions [18–21]. Artificial cranial modification (ACM) provides a useful model for investigating this problem because it induces marked, non-pathological remodeling of the cranial vault during early development. In pre-Hispanic Andean populations, ACM was achieved through sustained external pressure applied during infancy, producing recognizable cranial morphotypes, including annular and tabular forms, without directly targeting the palate or other facial structures. This makes ACM particularly informative for testing whether extreme neurocranial deformation is accompanied by corresponding changes in palatal morphology, or whether the palate remains comparatively conserved despite major alteration of the cranial vault. Previous studies have shown that artificial cranial modification can affect craniofacial morphology beyond the cranial vault, with reported changes in cranial base configuration, facial projection, orbital morphology, zygomatic shape, and maxillofacial proportions [22–25]. However, these effects are not fully consistent across populations, deformation types, and analytical approaches, and the evidence is generally stronger for the cranial base and midface than for the palate specifically [23,24,26]. In particular, much of the available literature has focused on broad facial dimensions or regional craniofacial landmarks, whereas the palate has received comparatively limited and less systematic 3D investigation [25,26]. Moreover, because the cranial vault and palate are anatomically connected but developmentally and functionally distinct, facial changes cannot be assumed to imply equivalent palatal remodeling. It remains unclear whether palatal variation associated with ACM represents a direct and

coordinated component of craniofacial remodeling, an indirect developmental response, or only a limited change despite marked vault deformation. Studies that jointly quantify neurocranial and palatal shape in three dimensions, distinguish among ACM morphotypes, include unmodified comparative individuals, and assess directional asymmetry and shape covariation are still limited [25,26].

In the present study, high-resolution three-dimensional geometric morphometrics was used to analyse neurocranial and palatal morphology in a sample of pre-Hispanic Peruvian crania, including individuals with annular or tabular ACM and unmodified controls (Figure 1). The aims were: (1) to assess whether modified and unmodified crania differ in palatal shape; (2) to evaluate whether ACM is associated with changes in palatal directional asymmetry; and (3) to evaluate the degree of covariation between neurocranial and palatal shape and to compare the morphometric response of these two anatomical regions to ACM. Rather than assuming a priori functional compensation, this study tests whether marked vault deformation is mirrored by detectable palatal variation and whether neurocranial and palatal morphology covary in a coordinated manner, thereby providing new evidence on the degree of craniofacial integration between these anatomical regions.

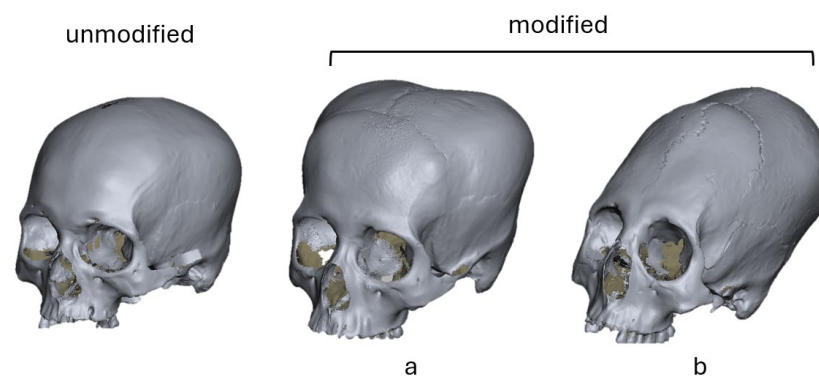


Figure 1. Virtual elaboration of cranial sample subdivided into unmodified skull and modified: (a) tabular type, (b) annular type.

Artificial Cranial Modification in Pre-Hispanic Peru

Pre-Hispanic populations of Peru are renowned for artificial cranial modification (ACM), one of the most distinctive and extensively documented practices in the Andean archaeological record [27,28]. ACM involved intentional reshaping of the cranial vault during early infancy, when cranial bones remain plastic and deformable. The practice was widespread among groups such as the Paracas, Nazca and Inca and was performed using boards, bindings or headaddresses that exerted sustained pressure on the infant skull to produce permanent cranial forms [22,29,30].

Two predominant forms of modification are recognised: the tabular type, which flattens the forehead and occiput while expanding the parietals, and the annular type, which acts circumferentially through bandaging to alter vault shape [22,31,32]. These forms were associated with social identity, status and religious beliefs, serving as visible markers of group membership and social differentiation [28,33–35]. Decisions regarding ACM were typically made within the family and required technical expertise to obtain the desired form without causing overt harm [28,29,31,32]. Osteoarchaeological studies indicate that modified crania occur across all age classes and do not show significant sex-based differences in frequency or patterning [28,29,31–33]. Although generally not associated with severe neurological impairment, it may be accompanied by morphological changes extending beyond the cranial vault, including facial asymmetry and possible effects on anatomically related craniofacial structures [22]. This makes ACM a valuable

model for investigating how early, externally induced neurocranial remodeling may relate to palatal morphology.

2. Materials and Methods

This study analysed 19 adult crania (Table 1) from pre-Hispanic Peruvian contexts curated in the osteological collection of the Museum of Anthropology and Ethnology of the University of Florence [30,36–38]. All analyses and digital acquisitions described below were conducted under the authorization of the responsible institutions and in accordance with their ethical and curatorial policies for the study of human remains, with particular attention to the respectful treatment of historically marginalized and Indigenous communities. Specimen selection was based on the identification of morphological traits attributable to artificial cranial modification (ACM), following the classification criteria proposed by Torres-Rouff [29,31,32]. Nine crania displaying clear evidence of ACM were selected, together with ten unmodified individuals showing no evidence of taphonomic distortion, cultural modification other than ACM, congenital anomalies, or pathological conditions, including systemic diseases known to affect skeletal growth and craniofacial development, that could confound the morphological comparisons. The final sample size ($n = 19$) reflects the strict application of these inclusion criteria to the available archaeological collection. Specimens were included only when both the neurocranial and palatal regions were sufficiently preserved for high-resolution 3D digitisation and reliable landmark placement. This selection strategy was intended to minimise variation related to taphonomic deformation, pathological alteration, and incomplete preservation, thereby improving the comparability of specimens and reducing potential confounding factors in the assessment of neurocranial–palatal morphological relationships.

Table 1. Sex distribution and group characterization of the pre-Hispanic Peruvian crania curated at the Museum of Anthropology and Ethnology, University of Florence. Sex was assessed by cranial features of the specimen [38].

Code	Sex
1798	male
2250	male
2251	male
2252	female
2253	male
2254	male
2255	male
2258	male
2259	female
2264	male
2268	male
2270	female
2275	male
2283	male
2297	male
2318	female
3034	female
4080	female
4713	indeterminate
6150	indeterminate

The analysis focused on two anatomical regions: the neurocranium and the palate. The neurocranium was selected because ACM directly alters vault morphology through externally imposed mechanical shaping during growth [26,38,39]. The palate was selected

because it is anatomically connected to the craniofacial complex and is developmentally sensitive to functional and spatial influences, including tongue posture and craniofacial configuration [40,41]. Comparing these two regions makes it possible to test whether marked neurocranial deformation is associated with corresponding variation in palatal morphology and to evaluate the degree of covariation between these craniofacial components. The mandible was not included because its morphology is strongly influenced by factors that are not the focus of the present study, including subsistence-related variation and masticatory behaviour, which may obscure patterns specifically related to neurocranial–palatal relationships [42]. The present study therefore focuses on the relationship between neurocranial modification and palatal morphology. The crania were digitised using an Artec Eva S Spider 3D scanner (Artec 3D, Senningerberg, Luxembourg), which employs structured-light technology and captures surface details with an accuracy of approximately 0.05 mm and a resolution of 0.1 mm (Artec 3D, 2025). This system enabled the generation of high-resolution three-dimensional models suitable for geometric morphometric analysis. Point-cloud acquisition and alignment were performed using Artec Studio 12 Professional software (version 12; Artec 3D, Senningerberg, Luxembourg). Digital meshes were subsequently post-processed at the Laboratory of Nuclear Imaging and Computed Tomography (LINC), University of Ferrara, using PMOD 2021 software. PMOD was used to correct digitisation artefacts and improve mesh quality prior to landmark acquisition. Morphometric data were collected in Viewbox 4 (dHAL Software), which supports three-dimensional landmark-based geometric morphometric analyses [43–45].

2.1. Geometric Morphometric and Asymmetry Analysis

The study sample comprised 19 Peruvian crania, divided into two groups (modified and unmodified). For palatal analyses, 41 landmarks were digitised per specimen, including fixed anatomical landmarks, curve semilandmarks and surface semilandmarks, in order to capture both discrete anatomical points and continuous morphological features of the palatal vault (Figure 2).

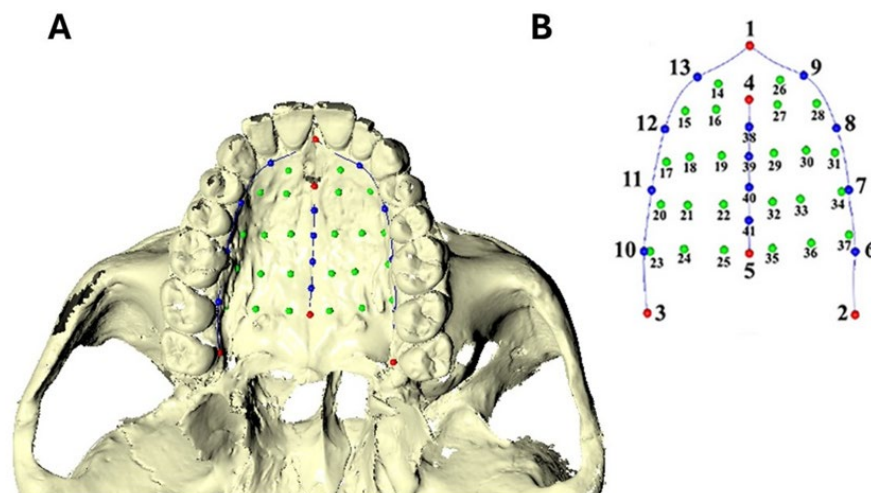


Figure 2. Digital skull (A) and template structure (B) showing digitized landmarks on the palatal arch: fixed anatomical landmarks (red), curve semilandmarks (blue), and surface semilandmarks (green) (procedure published by Oxilia et al. [46]).

For whole-cranium analyses, a configuration of 286 landmarks (fixed landmarks plus curve and surface semilandmarks) was recorded (Figure 3 and Table 2). Landmarking protocols followed previously validated procedures: Oxilia et al. [46] for the palate and Oxilia et al. [47] for the neurocranial surfaces. All landmark configurations were digitised by the same observer using standardised landmark definitions and template-based proto-

cols. Meshes were inspected and post-processed before landmark acquisition to minimise artefacts that could affect landmark placement. For both anatomical regions, landmark coordinates were assembled into three-dimensional arrays ($k \times m \times n$) for subsequent processing in R.

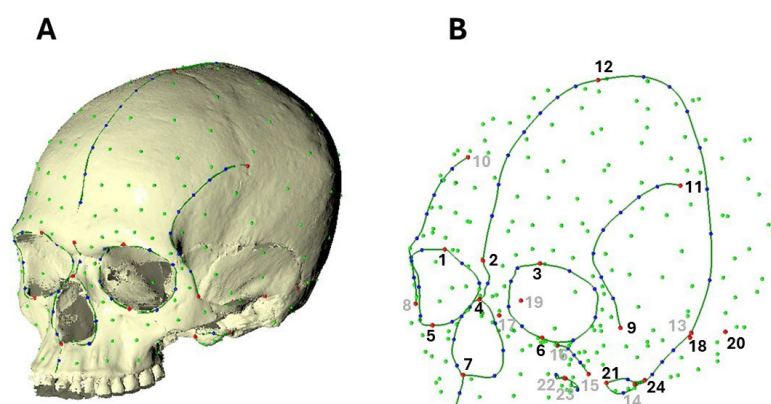


Figure 3. Digital skull (A) and template structure (B) showing the digitized landmarks on the skull shape: fixed anatomical landmarks (red), curve semilandmarks (blue), and surface semilandmarks (green).

Table 2. Landmarks and semilandmarks (sml = semilandmark) of the skull shape configuration.

Landmark n.	Name
1	Superior orbital notch_dx
2	Glabella
3	Superior orbital notch_sx
4	Rhinion
5	Orbitale dx
6	Orbitale sx
7	Nasospinal
8	Jungale sx
9	Jungale dx
10	Stephanion dx
11	Stephanion sx
12	Bregma
13	Inion
14	Opisthion
15	Basin
16	Basisphenoid
17	Porion dx
18	Porion sx
19	Asterion dx
20	Asterion sx
21	left anterior occipital condyle
22	right anterior occipital condyle
23	right anterior occipital condyle
24	left anterior occipital condyle

2.2. Statistical Analysis

Landmark configurations for the neurocranium and palate were aligned separately using Generalized Procrustes Analysis (GPA) with the `gpgen` function in the `geomorph` package [48], allowing semilandmarks to slide by minimising bending energy. Prior to testing morphological differences between groups, the potential influence of biological sex on palatal and neurocranial shape was evaluated through a permutational Procrustes ANOVA (`procD.lm`, 9999 permutations) including sex as the first covariate to account for its effect

before testing for the group factor and the group $\times$ sex interaction. To account for two individuals of indeterminate sex, four assignment scenarios were considered: (1) excluding indeterminate individuals from the analysis; (2) assigning both as male; (3) assigning both as female; and (4) using alternating assignments (individual 4713 as male, individual 6150 as female). Given the absence of a significant effect of sex or group $\times$ sex interaction across all scenarios, sex was not included in subsequent analyses, which focused exclusively on the contrast between artificially modified and unmodified individuals. To identify major axes of shape variation, Principal Component Analysis (PCA) was performed on the Procrustes-aligned coordinates. Mean shape differences between modified and unmodified individuals were tested using permutational Procrustes ANOVA (procD.lm, 9999 permutations). Morphological disparity within groups was quantified as Procrustes variance and evaluated by permutation (9999 iterations), while multivariate dispersion was compared using the betadisper function in the vegan package. Directional asymmetry (DA) of the palate was assessed using the bilateral-symmetry model in geomorph to partition shape variance and identify systematic side effects. Differences in the magnitude of global directional asymmetry between modified and unmodified individuals were evaluated using a permutation test based on the mean landmark-wise DA values. Morphological integration between the neurocranium and the palate was investigated via two-block partial least squares (PLS) analysis and the RV coefficient [49,50]; statistical significance of the PLS correlation was assessed through 9999 permutations. All statistical procedures were conducted in R (v. 4.4.1) [51] using the packages geomorph [48] and vegan [52].

3. Results

Prior to the main morphological comparisons, the influence of biological sex on palatal shape was assessed across four assignment scenarios for two individuals of indeterminate sex (Table 3). Given the absence of significant sex effects or group $\times$ sex interactions across all assignment scenarios (all $p > 0.28$), subsequent analyses focused on the contrast between artificially modified and unmodified individuals without further stratification by sex.

Table 3. Sensitivity analysis for the effect of biological sex on palatal shape (permutational Procrustes ANOVA, 9999 permutations).

Scenario	N (F/M)	Model	Effect	Df	F	p
1—Known sex only (indet excluded)	5 F/12 M	shape ~ sex	sex	1	0.705	0.639
		shape ~ sex + group	sex	1	0.683	0.663
			group	1	0.528	0.802
		shape ~ sex * group	sex	1	0.662	0.686
			group	1	0.512	0.819
			sex:group	1	0.565	0.744
2—Indet $\rightarrow$ male	5 F/14 M	shape ~ sex	sex	1	0.594	0.748
		shape ~ sex + group	sex	1	0.586	0.756
			group	1	0.765	0.571
		shape ~ sex * group	sex	1	0.566	0.777
			group	1	0.739	0.590
			sex:group	1	0.460	0.853
3—Indet $\rightarrow$ female	7 F/12 M	shape ~ sex	sex	1	1.202	0.284
		shape ~ sex + group	sex	1	1.170	0.301
			group	1	0.545	0.795
		shape ~ sex * group	sex	1	1.159	0.310
			group	1	0.539	0.799
			sex:group	1	0.844	0.509
4—Indet alternated (4713 = M, 6150 = F)	6 F/13 M	shape ~ sex	sex	1	0.895	0.464
		shape ~ sex + group	sex	1	0.876	0.482

Table 3. Cont.

Scenario	N (F/M)	Model	Effect	Df	F	p
		shape ~ sex * group	group	1	0.648	0.685
			sex	1	0.861	0.495
			group	1	0.637	0.696
			sex:group	1	0.730	0.601

F = female; M = male. All models include shape as dependent variable. Group = modified vs. unmodified. The asterisk indicates the inclusion of the main effects of sex and group, as well as their interaction term (sex:group).

The first three principal components (PCs) from the PCA of palatal shape accounted for 72.1% of the total variance (PC1: 38.7%; PC2: 23.2%; PC3: 10.2%). In the PC1–PC2 morphospace, modified and unmodified individuals exhibited broad overlap with no clear separation (Figure 4A). Permutational Procrustes ANOVA confirmed that differences in mean palatal shape between the two groups were not statistically significant ($F = 0.839$; $p = 0.511$). Similarly, no significant difference was found in morphological disparity (modified Procrustes variance = 0.00947; unmodified = 0.00986; $p = 0.889$).

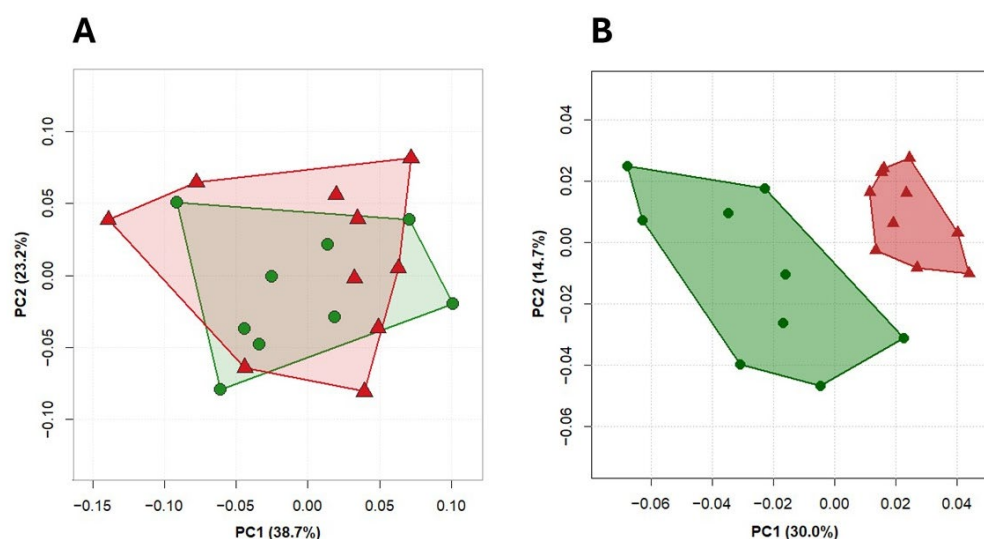


Figure 4. Principal Component Analysis (PCA) plots comparing two groups, “modified” (green circles and polygons) and “unmodified” (red triangles and polygons), for (A) palatal vault shape and (B) cranial shape.

The influence of biological sex on neurocranial shape was assessed across four assignment scenarios for two individuals of indeterminate sex (Table 4). Sex had no significant effect on neurocranial shape, and no significant group $\times$ sex interaction was detected in any scenario ($p > 0.11$ in all cases). Once biological sex was excluded as a covariate, all subsequent analyses focused exclusively on the contrast between artificially modified and unmodified individuals.

The first two principal components accounted for 44.7% of total cranial shape variance (PC1: 30.0%; PC2: 14.7%; Figure 4B). Mean cranial shape differed significantly between modified and unmodified individuals (Procrustes ANOVA: $F = 4.75$, $Z = 3.27$, $R^2 = 0.218$, $p < 0.001$). Morphological disparity was also significantly higher in modified individuals (Procrustes variance = 0.00293) than in unmodified individuals (0.00227; $p = 0.00065$). The first PLS axis showed an r-PLS correlation of 0.694 and accounted for 45.17% of the total covariation between neurocranial and palatal shape (Figure 5). However, this association was not statistically significant ($Z = 0.036$, $p = 0.488$; 9999 permutations). The RV coefficient was 0.341.

Table 4. Sensitivity analysis for the effect of biological sex on cranial shape (permutational Procrustes ANOVA, 9999 permutations).

Scenario	N (F/M)	Model	Effect	Df	F	p
1—Known sex only (indet excluded)	5 F/12 M	shape ~ sex	sex	1	0.761	0.6785
		shape ~ sex + group	sex	1	0.892	0.5252
			group	1	3.570	0.0005
		shape ~ sex * group	sex	1	0.916	0.5011
			group	1	3.669	0.0004
			sex:group	1	1.387	0.1545
2—Indet → male	5 F/14 M	shape ~ sex	sex	1	0.590	0.8766
		shape ~ sex + group	sex	1	0.713	0.7424
			group	1	4.543	0.0001
		shape ~ sex * group	sex	1	0.732	0.7192
			group	1	4.663	0.0001
			sex:group	1	1.423	0.1297
3—Indet → female	7 F/12 M	shape ~ sex	sex	1	1.263	0.2151
		shape ~ sex + group	sex	1	1.485	0.1234
			group	1	3.981	0.0001
		shape ~ sex * group	sex	1	1.502	0.1179
			group	1	4.029	0.0001
			sex:group	1	1.192	0.2528
4—Indet alternated (4713 = M, 6150 = F)	6 F/13 M	shape ~ sex	sex	1	1.014	0.3955
		shape ~ sex + group	sex	1	1.218	0.2418
			group	1	4.424	0.0001
		shape ~ sex * group	sex	1	1.247	0.2272
			group	1	4.527	0.0001
			sex:group	1	1.373	0.1571

The asterisk indicates the inclusion of the main effects of sex and group, as well as their interaction term (sex:group).

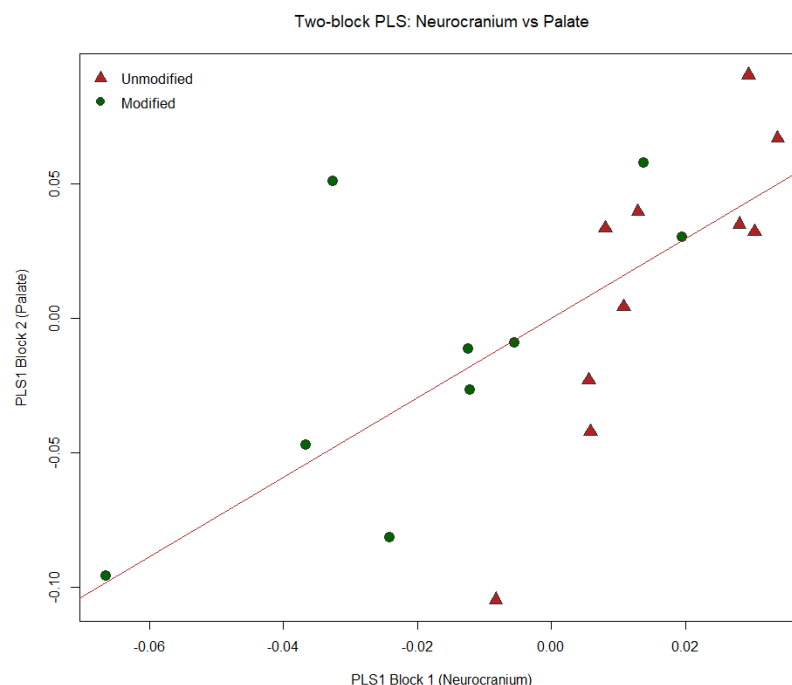


Figure 5. Two-block partial least squares (PLS) analysis of neurocranial and palatal shape. Scatterplot of the first PLS scores for the neurocranium (Block 1) and palate (Block 2). Red triangles represent unmodified individuals and green circles represent modified individuals. The red line indicates the linear regression. The first PLS axis showed an r -PLS correlation of 0.694 ($p = 0.488$; 9999 permutations) and accounted for 45.17% of total covariation; the RV coefficient was 0.341.

Directional Asymmetry of the Palate

Directional asymmetry was assessed separately in modified and unmodified individual. A significant side effect was detected in both groups, indicating systematic left–right differences in palatal shape (modified: $p = 0.0001$; unmodified: $p = 0.0002$; Tables 5 and 6). In both groups, the individual component accounted for the largest proportion of palatal shape variance.

Table 5. Analysis of variance results for directional asymmetry (DA) in individuals with modified neurocrania.

Effect	Df	SS	Rsq	F	Z	Pr(>F)	Percent Variance
ind	8	0.136957	0.62882	5.1512	5.8277	0.0001	62.88%
side	1	0.054257	0.24911	16.3255	2.7371	0.0001	24.91%
ind:side	8	0.026588	0.12207				12.21%
Total	17	0.217802					100%

Note: Df, degrees of freedom; SS, sums of squares; Rsq, coefficient of determination; F, F-ratio; Z, effect size; Pr(>F), permutation-based p -value (10,000 iterations).

Table 6. Analysis of variance results for directional asymmetry (DA) in unmodified individuals.

Effect	Df	SS	Rsq	F	Z	Pr(>F)	Percent Variance
ind	9	0.176696	0.75889	9.3320	6.1227	0.0001	75.89%
side	1	0.037205	0.15979	17.6840	3.7908	0.0002	15.98%
ind:side	9	0.018934	0.08132				8.13%
Total	19	0.232835					100%

Mean landmark-wise directional asymmetry was higher in modified individuals (0.0146) than in unmodified individuals (0.0116), with a between-group difference of 0.0030; this difference was not statistically significant (global permutation test: $p = 0.103$; Table 7).

Table 7. Comparison of global palatal directional asymmetry between modified and unmodified individuals.

Metric	Value
Mean DA (modified)	0.0146
Mean DA (unmodified)	0.0116
Difference (modified – unmodified)	0.0030
Global permutation p -value	0.103

4. Discussion

4.1. Differential Morphometric Responses of the Neurocranium and Palate

This study showed contrasting morphometric responses to artificial cranial modification (ACM) in the neurocranial and palate. Modified and unmodified individuals differed significantly in mean neurocranial shape, whereas no significant between-group difference was detected in mean palatal shape. These findings indicate that, in the present sample, the morphological effects of ACM were more pronounced in the neurocranium than in the palatal vault. The absence of detectable differences in mean palatal shape reflects the partial developmental and functional constraint of the palatal region. This interpretation is compatible with the functional matrix perspective [53], according to which craniofacial form is influenced by functional demands related to mastication, swallowing, occlusion, and airway patency. However, these mechanisms were not directly assessed in the present study and should therefore be regarded as possible explanatory frameworks rather than demonstrated processes. Given the limited sample size, subtle palatal effects cannot be

excluded; nevertheless, the results do not support a detectable displacement of average palatal form associated with ACM in this sample.

4.2. Palatal Directional Asymmetry Patterns

Palatal directional asymmetry (DA) patterns should be interpreted within the framework of craniofacial modularity and integration, where partially distinct modules such as neurocranium, cranial base, and facial skeleton, that covary to preserve structural and functional equilibrium [54–56]. Although DA was significant in both groups, the difference between modified and unmodified individuals was statistically non-significant. This suggests that ACM may have altered craniofacial loading conditions without producing a uniform remodeling of the palate or a discrete shift in average asymmetry. Mechanistically, palatal form reflects a balance between intrinsic trajectories and functional demands, including occlusal forces, tongue posture, and muscle activity [55,57–60]. Other potential pathways involving velopharyngeal, glossopalatal, lingual, or cranio-cervical relationships might be considered [19,61–71], but as these were not directly measured, they remain hypotheses for future research.

4.3. Stability of Mean Palatal Morphology

The absence of statistically significant mean palatal shape differences may also reflect the multifactorial development of the palatal complex. During early craniofacial growth, cranial and palatal sutures may contribute to the transmission and redistribution of mechanical influences across the craniofacial skeleton [22,55,72]. Palatal morphology is also shaped by maxillary growth, dental development and eruption, and changes in the adjacent oral and nasal cavities [53,55,73–77]. These factors may contribute to the relative preservation of average palatal shape despite marked neurocranial remodeling; however, they were not directly assessed in the present study.

4.4. Covariation Between Neurocranial and Palatal Shape

Two-block partial least squares analysis showed an r-PLS correlation of 0.694 along the first covariation axis; however, this association was not statistically significant. The RV coefficient was 0.341. Thus, the present data do not provide evidence of significant overall covariation between neurocranial and palatal shape. Although ACM was associated with marked neurocranial differences, corresponding coordinated changes in palatal shape were not detected in this sample.

4.5. Evolutionary–Anatomical Perspective on Craniofacial Modularity

From an evolutionary–anatomical perspective, the contrasting responses of the neurocranium and palate observed in this sample are consistent with a model of a partial and region-specific craniofacial integration. Craniofacial structures do not necessarily respond uniformly to developmental or environmental perturbations, as their growth is regulated by partly distinct developmental trajectories and patterns of covariation. Previous developmental and comparative research has highlighted the temporally dynamic organisation of human craniofacial development, as well as regional differences in skull-base and facial integration [78–80]. In this context, the marked plasticity of the neurocranial vault and the absence of detectable mean palatal shape differences may reflect differential sensitivity among craniofacial components. Comparative evidence further suggests that oral, facial, and neurocranial regions may follow distinct developmental trajectories and may be subjected to unequal constraints and heterochronic processes [81]. Although the present study does not directly test evolutionary mechanisms or developmental timing, the observed pattern provides a comparative framework in which neurocranial–palatal relationships can be interpreted as partial rather than uniform across the craniofacial complex.

4.6. Comparative Relevance for Clinical Craniofacial Research

Although the present findings cannot be directly extrapolated to pathological conditions, they may have cautious comparative relevance for clinical craniofacial research. The absence of significant neurocranial–palatal covariation in this sample indicates that marked morphological change in one craniofacial region is not necessarily accompanied by proportionate change in another. This observation is consistent with clinical morphometric evidence showing that craniofacial integration and modularity may be reorganized, rather than uniformly disrupted, in individuals with cleft lip and palate [82]. Likewise, biomechanical studies of early postnatal craniofacial growth have highlighted region-specific responses to functional loading across the developing skull [83]. These comparisons should be interpreted cautiously, as neither clinical conditions nor developmental loading were assessed in the present study. Nevertheless, they support a broader framework in which neurocranial and stomatognathic regions may show unequal sensitivity to developmental perturbations.

4.7. Limitations and Future Directions

Several limitations should be acknowledged. First, the sample size was limited by the strict inclusion criteria applied to the available archaeological collection, which may have reduced statistical power, particularly for integration analyses and the detection of subtle between-group effects. Accordingly, non-significant findings should not be interpreted as definitive evidence of the absence of an effect, as type II error cannot be excluded. Second, the study was based exclusively on skeletal morphology and could not directly assess muscular, occlusal, airway, or postural mechanisms. Third, the archaeological nature of the material limited control over developmental timing and other life-history factor variables. In addition, although landmark placement followed established geometric morphometric protocols, a formal assessment of intra- or interobserver error was not performed. Future studies combining larger samples with 3D morphometrics, dental and developmental information, functional data and formal assessment of landmarking reproducibility will help clarify the mechanisms underlying differential craniofacial responses to ACM.

5. Conclusions

This study demonstrates a clear dissociation in the morphometric response of the neurocranium and the palate to artificial cranial modification (ACM). While culturally-mediated forces induce marked neurocranial remodeling, the palatal arch maintains a comparatively stable phenotype. This finding provides significant insights into human craniofacial modularity, suggesting that anatomical structures directly involved in vital functions (such as respiration and mastication) operate within more constrained developmental limits than the cranial vault. From an anatomical and evolutionary perspective, these results support a model of partial and region-specific integration, where different cranial modules exhibit unequal degrees of plasticity in response to external perturbations. For the field of craniofacial research and clinical medicine, this study offers a cautious but informative comparative framework. It reinforces the principle that substantial remodeling in one cranial region does not necessarily predict proportionate alterations in adjacent components, a concept that may be relevant for understanding region-specific sensitivity in both developmental and pathological contexts.

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References

1. Enlow, D.H.; Hans, M.G. *Essentials of Facial Growth*, 2nd ed.; Needham Press: Needham, MA, USA, 2008; 303p.
2. Sperber, G.H.; Guttman, G.D.; Sperber, S.M. *Craniofacial Embryogenetics and Development*; PMPH-USA: Hamilton, ON, Canada, 2010; 250p.
3. Mossey, P.A. The heritability of malocclusion: Part 2. The influence of genetics in malocclusion. *Br. J. Orthod.* **1999**, *26*, 195–203. [[CrossRef](#)]
4. Jansen van Rensburg, G.J.; Wilke, D.N.; Kok, S. Human skull shape and masticatory induced stress: Objective comparison through the use of non-rigid registration. *Int. J. Numer. Methods Biomed. Eng.* **2012**, *28*, 170–185. [[CrossRef](#)]
5. Kiliaridis, S.; Engström, C.; Thilander, B. The relationship between masticatory function and craniofacial morphology. I. A cephalometric longitudinal analysis in the growing rat fed a soft diet. *Eur. J. Orthod.* **1985**, *7*, 273–283. [[CrossRef](#)] [[PubMed](#)]
6. Du, W.; Bhojwani, A.; Hu, J.K. FAcEts of mechanical regulation in the morphogenesis of craniofacial structures. *Int. J. Oral Sci.* **2021**, *13*, 4. [[CrossRef](#)] [[PubMed](#)]
7. Wehby, G.L.; Cassell, C.H. The impact of orofacial clefts on quality of life and healthcare use and costs. *Oral Dis.* **2010**, *16*, 3–10. [[CrossRef](#)] [[PubMed](#)]
8. Tarnow, P.; Kölby, L.; Maltese, G.; Söfteland, M.B.; Lewén, A.; Nilsson, P.; Enblad, P.; Nowinski, D. Incidence of non-syndromic and syndromic craniosynostosis in Sweden. *J. Craniofac. Surg.* **2022**, *33*, 1517–1520. [[CrossRef](#)] [[PubMed](#)]
9. Mai, C.T.; Isenburg, J.L.; Canfield, M.A.; Meyer, R.E.; Correa, A.; Alverson, C.J.; Lupo, P.J.; Riehle-Colarusso, T.; Cho, S.J.; Aggarwal, D.; et al. National population estimates for major birth defects, 2010–2014. *Birth Defects Res.* **2019**, *111*, 1420–1435. [[CrossRef](#)] [[PubMed](#)]
10. Lieberman, D.E.; McBratney, B.M.; Krovitz, G. The evolution and development of cranial form in Homo sapiens. *Proc. Natl. Acad. Sci. USA* **2002**, *99*, 1134–1139. [[CrossRef](#)] [[PubMed](#)]
11. Toro-Ibacache, V.; Zapata Muñoz, V.; O'Higgins, P. The relationship between skull morphology, masticatory muscle force and cranial skeletal deformation during biting. *Ann. Anat.* **2016**, *203*, 59–68. [[CrossRef](#)] [[PubMed](#)]
12. Liang, C.; Profico, A.; Buzi, C.; Khonsari, R.H.; Johnson, D.; O'Higgins, P.; Moazen, M. Normal human craniofacial growth and development from 0 to 4 years. *Sci. Rep.* **2023**, *13*, 9641. [[CrossRef](#)] [[PubMed](#)]
13. Song, Y.; Jiao, Y.; Liu, Y.; Guo, L. Role of masticatory force in modulating jawbone immunity and bone homeostasis: A review. *Int. J. Mol. Sci.* **2025**, *26*, 4478. [[CrossRef](#)] [[PubMed](#)]
14. Cuccia, A.; Caradonna, C. The relationship between the stomatognathic system and body posture. *Clinics* **2009**, *64*, 61–66. [[CrossRef](#)] [[PubMed](#)]
15. Ioniță, C.; Petre, A.E.; Cononov, R.S.; Covaleov, A.; Mitoiu, B.I.; Nica, A.S. Methods of postural analysis in connection with the stomatognathic system: A systematic review. *J. Med. Life* **2023**, *16*, 507–514. [[CrossRef](#)] [[PubMed](#)]
16. Fadillioglu, C.; Kanus, L.; Möhler, F.; Ringhof, S.; Hellmann, D.; Stein, T. Influence of controlled stomatognathic motor activity on sway, control and stability of the center of mass during dynamic steady-state balance—An uncontrolled manifold analysis. *Front. Hum. Neurosci.* **2022**, *16*, 868828. [[CrossRef](#)] [[PubMed](#)]
17. Manfredini, D.; Castroflorio, T.; Perinetti, G.; Guarda-Nardini, L. Dental occlusion, body posture and temporomandibular disorders: Where we are now and where we are heading for. *J. Oral Rehabil.* **2012**, *39*, 463–471. [[CrossRef](#)] [[PubMed](#)]

18. Sfondrini, M.F.; Gallo, S.; Pascadopoli, M.; Licari, A.; Marseglia, G.L.; Gandini, P.; Turcato, B.; Nardi, M.G.; Scribante, A. The knowledge of orthodontic and craniofacial growth amongst Italian pediatric medical residents for early diagnosis in growing patients: A cross-sectional study. *J. Clin. Pediatr. Dent.* **2023**, *47*, 64–73. [\[CrossRef\]](#) [\[PubMed\]](#)
19. Jamilian, A.; Ferati, K.; Palermo, A.; Mancini, A.; Rotolo, R.P. Craniofacial development of the child. *Eur. J. Musculoskel. Dis.* **2022**, *11*, 89–95. Available online: <https://www.labpublishers.com/ejmd/craniofacial-development-of-the-child/> (accessed on 18 August 2026).
20. Savarirayan, R.; Tunkel, D.E.; Sterni, L.M.; Bober, M.B.; Cho, T.J.; Goldberg, M.J.; Hoover-Fong, J.; Irving, M.; Kamps, S.E.; Mackenzie, W.G.; et al. Best practice guidelines in managing the craniofacial aspects of skeletal dysplasia. *Orphanet J. Rare Dis.* **2021**, *16*, 31. [\[CrossRef\]](#) [\[PubMed\]](#)
21. Knigge, R.P.; Hardin, A.M.; Middleton, K.M.; McNulty, K.P.; Oh, H.S.; Valiathan, M.; Duren, D.L.; Sherwood, R.J. Craniofacial growth and morphology among intersecting clinical categories. *Anat. Rec.* **2022**, *305*, 2175–2206. [\[CrossRef\]](#) [\[PubMed\]](#)
22. Anton, S.C. Intentional cranial vault deformation and induced changes of the cranial base and face. *Am. J. Phys. Anthropol.* **1989**, *79*, 253–267. [\[CrossRef\]](#) [\[PubMed\]](#)
23. Kohn, L.A.P.; Leigh, S.R.; Jacobs, S.C.; Cheverud, J.M. Effects of annular cranial vault modification on the cranial base and face. *Am. J. Phys. Anthropol.* **1993**, *90*, 147–158. [\[CrossRef\]](#) [\[PubMed\]](#)
24. Friess, M.; Baylac, M. Exploring artificial cranial deformation using elliptic Fourier analysis of Procrustes aligned outlines. *Am. J. Phys. Anthropol.* **2003**, *122*, 11–22. [\[CrossRef\]](#) [\[PubMed\]](#)
25. Jimenez, P.; Martinez-Insua, A.; Franco-Vazquez, J.; Otero-Cepeda, J.L.; Santana, U. Maxillary changes and occlusal traits in crania with artificial fronto-occipital deformation. *Am. J. Phys. Anthropol.* **2012**, *147*, 40–51. [\[CrossRef\]](#) [\[PubMed\]](#)
26. Püschel, T.A.; Friess, M.; Manríquez, G. Morphological consequences of artificial cranial deformation: Modularity and integration. *PLoS ONE* **2020**, *15*, e0227362. [\[CrossRef\]](#) [\[PubMed\]](#)
27. Marino, R., Jr.; Gonzales-Portillo, M. Preconquest Peruvian neurosurgeons: A study of Inca and pre-Columbian trephination and the art of medicine in ancient Peru. *Neurosurgery* **2000**, *47*, 940–950. [\[CrossRef\]](#) [\[PubMed\]](#)
28. Andrushko, V.A. Revelations of ancient head shape: Cranial modification in the Cuzco region of Peru, Early Horizon to Inca Imperial Period. *Am. J. Phys. Anthropol.* **2021**, *175*, 95–105. [\[CrossRef\]](#) [\[PubMed\]](#)
29. Torres-Rouff, C. Cranial modification and the shapes of heads across the Andes. *Int. J. Paleopathol.* **2020**, *29*, 94–101. [\[CrossRef\]](#) [\[PubMed\]](#)
30. Mantegazza, P. Sulle antichità peruviane donate dal Comm. Prof. Ernesto Mazzei al Museo Nazionale d’Antropologia. *Arch. Antropol. Etnol.* **1884**, *14*, 405–410.
31. Torres-Rouff, C. Cranial vault modification and ethnicity in Middle Horizon San Pedro de Atacama, Chile. *Curr. Anthropol.* **2002**, *43*, 163–171. [\[CrossRef\]](#) [\[PubMed\]](#)
32. Torres-Rouff, C. *Shaping Identity: Cranial Vault Modification in the Pre-Columbian Andes*; University of California: Santa Barbara, CA, USA, 2003.
33. Blom, D.E. Embodying Borders: Human Body Modification and Diversity in Tiwanaku Society. *J. Anthropol. Archaeol.* **2005**, *24*, 1–24. [\[CrossRef\]](#)
34. Verano, J.W. Trepanation in prehistoric South America: Geographic and temporal trends over 2,000 years. In *Trepanation: History, Discovery, Theory*; Arnott, R., Finger, S., Smith, C., Eds.; CRC Press: Boca Raton, FL, USA, 2003; pp. 223–236.
35. Andrushko, V.A.; Verano, J.W. Prehistoric trepanation in the Cuzco region of Peru: A view into an ancient Andean practice. *Am. J. Phys. Anthropol.* **2008**, *137*, 4–13. [\[CrossRef\]](#) [\[PubMed\]](#)
36. Giglioli, E.H. An important archaeological collection formed in Central and South America, principally in Guatemala and Peru. *Int. Arch. Ethnogr.* **1892**, *5*, 89–91.
37. Giglioli, E.H. Notes on some remarkable specimens of old Peruvian ‘Ars Plumaria’, in the Mazzei collection. *Int. Arch. Ethnogr.* **1894**, *7*, 221–226.
38. Mori, T.; Riga, A.; Dionisio, G.; Bigoni, F.; Moggi-Cecchi, J. Cranial modification and trepanation in pre-Hispanic collections from Peru in the Museum of Anthropology and Ethnology, Florence, Italy. *Med. Hist.* **2022**, *6*, e2022002. Available online: <https://mattioli1885journals.com/index.php/MedHistor/article/view/12218> (accessed on 18 August 2026).
39. Mori, T.; Sparacello, V.S.; Riga, A.; Ciappi, G.; Ferrari, D.; Seghi, F.; Di Vincenzo, F.; Zavattaro, M.; Pasquinelli, F.; Carpi, R.; et al. Early European evidence of artificial cranial modification from the Italian Late Upper Palaeolithic Arene Candide Cave. *Sci. Rep.* **2025**, *15*, 27792. [\[CrossRef\]](#) [\[PubMed\]](#)
40. Primožic, J.; Farčnik, F.; Perinetti, G.; Richmond, S.; Ovsenik, M. The association of tongue posture with the dentoalveolar maxillary and mandibular morphology in Class III malocclusion: A controlled study. *Eur. J. Orthod.* **2013**, *35*, 388–393. [\[CrossRef\]](#) [\[PubMed\]](#)
41. Solow, B.; Tallgren, A. Head posture and craniofacial morphology. *Am. J. Phys. Anthropol.* **1976**, *44*, 417–435. [\[CrossRef\]](#) [\[PubMed\]](#)
42. Von Cramon-Taubadel, N. Global human mandibular variation reflects differences in agricultural and hunter-gatherer subsistence strategies. *Proc. Natl. Acad. Sci. USA* **2011**, *108*, 19546–19551. [\[CrossRef\]](#) [\[PubMed\]](#)

43. Gunz, P.; Mitteroecker, P.; Bookstein, F.L. Semilandmarks in three dimensions. In *Modern Morphometrics in Physical Anthropology*; Slice, D.E., Ed.; Springer: New York, NY, USA, 2005; pp. 73–98.
44. Mitteroecker, P.; Gunz, P. Advances in geometric morphometrics. *Evol. Biol.* **2009**, *36*, 235–247. [[CrossRef](#)]
45. Oxilia, G.; Tomasella, M.; Cecere, A. Dental morphology in restorative dentistry: A pilot study on morphological consistency and variability in human upper first molars. *Dent. J.* **2025**, *13*, 122. [[CrossRef](#)] [[PubMed](#)]
46. Oxilia, G.; Menghi Sartorio, J.C.; Bortolini, E.; Zampirolo, G.; Papini, A.; Boggioni, M.; Martini, S.; Marciani, F.; Arrighi, S.; Figus, C.; et al. Exploring directional and fluctuating asymmetry in the human palate during growth. *Am. J. Phys. Anthropol.* **2021**, *175*, 847–864. [[CrossRef](#)] [[PubMed](#)]
47. Oxilia, G.; Mussi, M.; Chiriu, D.; Pisu, F.A.; Marini, E.; Melis, R.T. Virtual analysis of a concretioned skullcap from S'Ormu e S'Orku, an Early Holocene Mesolithic site of Sardinia. *Am. J. Biol. Anthropol.* **2025**, *187*, e70065. [[CrossRef](#)] [[PubMed](#)]
48. Adams, D.C.; Collyer, M.L.; Kaliontzopoulou, A.; Baken, E.K. Geomorph: Software for Geometric Morphometric Analyses. R Package Version 4.0.8. 2024. Available online: <https://cran.r-project.org/package=geomorph> (accessed on 10 July 2026).
49. Rohlf, F.J.; Corti, M. Use of two-block partial least-squares to study covariation in shape. *Syst. Biol.* **2000**, *49*, 740–753. [[CrossRef](#)] [[PubMed](#)]
50. Robert, P.; Escoufier, Y. A unifying tool for linear multivariate statistical methods: The RV-coefficient. *J. R. Stat. Soc. Ser. C Appl. Stat.* **1976**, *25*, 257–265. [[CrossRef](#)]
51. R Core Team. *R: A Language and Environment for Statistical Computing*; R Foundation for Statistical Computing: Vienna, Austria, 2024. Available online: <https://www.R-project.org/> (accessed on 10 July 2026).
52. Oksanen, J.; Simpson, G.L.; Blanchet, F.G.; Kindt, R.; Legendre, P.; Minchin, P.R.; O'Hara, R.B.; Solymos, P.; Stevens, M.H.H.; Szoecs, E.; et al. *Vegan: Community Ecology Package*. R Package Version 2.6-4. 2022. Available online: <https://cran.r-project.org/package=vegan> (accessed on 10 July 2026).
53. Moss, M.L. The functional matrix. In *Vistas in Orthodontics*; Krauss, B.S., Jordan, R.E., Eds.; Lea and Febiger: Philadelphia, PA, USA, 1962; pp. 85–97.
54. Klingenberg, C.P. Cranial integration and modularity: Insights into evolution and development from morphometric data. *Hystrix* **2013**, *24*, 43–58. [[CrossRef](#)]
55. Bastir, M.; Rosas, A.; O'Higgins, P. Craniofacial levels and the morphological maturation of the human skull. *J. Anat.* **2006**, *209*, 637–654. [[CrossRef](#)] [[PubMed](#)]
56. Gkantidis, N.; Halazonetis, D.J. Morphological integration between the cranial base and the face in children and adults. *J. Anat.* **2011**, *218*, 426–438. [[CrossRef](#)] [[PubMed](#)]
57. Šidlauskienė, M.; Papievis, V.; Šidlauskas, A.; Šidlauskas, M.; Juzėnas, S.; Lopatienė, K. Genetic and environmental impact on variation in the palatal dimensions in permanent dentition: A twin study. *Sci. Rep.* **2024**, *14*, 19785. [[CrossRef](#)] [[PubMed](#)]
58. Yan, F.; Jia, P.; Yoshioka, H.; Suzuki, A.; Iwata, J.; Zhao, Z. A developmental stage-specific network approach for studying dynamic co-regulation of transcription factors and microRNAs during craniofacial development. *Development* **2020**, *147*, dev192948. [[CrossRef](#)] [[PubMed](#)]
59. Lowe, A.A. Correlations between orofacial muscle activity and craniofacial morphology in a sample of control and anterior open-bite subjects. *Am. J. Orthod.* **1980**, *78*, 89–98. [[CrossRef](#)] [[PubMed](#)]
60. Kurihara-Okawa, K.; Okawa, J.; Nihara, J.; Takahashi, K.; Hori, K.; Nagasaki, T.; Fukui, T.; Ono, T.; Saito, I. Tongue pressure production and orofacial muscle activities during swallowing are related to palatal morphology in individuals with normal occlusion. *Clin. Investig. Orthod.* **2024**, *83*, 61–69. [[CrossRef](#)]
61. Ishijima, K.; Sando, I.; Balaban, C.D.; Miura, M.; Takasaki, K. Functional anatomy of levator veli palatini muscle and tensor veli palatini muscle in association with eustachian tube cartilage. *Ann. Otol. Rhinol. Laryngol.* **2002**, *111*, 530–536. [[CrossRef](#)] [[PubMed](#)]
62. Mehra, S.; Saxena, S.; Pansotra, S.; Puri, J.; Mohammed, K.; Saha, S.; Gupta, S.; Kumar, S. Correlation between tongue morphology and dental arch dimensions in skeletal Class I and Class II malocclusions: A cephalometric study. *Cureus* **2025**, *17*, e80946. [[CrossRef](#)] [[PubMed](#)]
63. Bourdiol, P.; Mishellany-Dutour, A.; Abou-El-Karam, S.; Nicolas, E.; Woda, A. Is the tongue position influenced by the palatal vault dimensions? *J. Oral Rehabil.* **2010**, *37*, 100–106. [[CrossRef](#)] [[PubMed](#)]
64. Hutchinson, E.F.; Kieser, J.A.; Kramer, B. Morphometric growth relationships of the immature human mandible and tongue. *Eur. J. Oral Sci.* **2014**, *122*, 181–189. [[CrossRef](#)] [[PubMed](#)]
65. Khan, Y.S.; Fakoya, A.O.; Bordoni, B. *Anatomy, Head and Neck: Suprahyoid Muscle*. In *StatPearls [Internet]*; StatPearls Publishing: Treasure Island, FL, USA, 2025.
66. Moreira, R.S.; Sgrott, E.A.; Stuker, H.; Alonso, L.G.; Smith, R.L. Palatal asymmetry during development: An anatomical study. *Clin. Anat.* **2008**, *21*, 398–404. [[CrossRef](#)] [[PubMed](#)]
67. Peng, H.; Liu, W.; Yang, L.; Yan, P.; Zhong, W.; Gao, X.; Song, J. Cranio-cervical posture in patients with skeletal malocclusion and its correlation with craniofacial morphology during different growth periods. *Sci. Rep.* **2024**, *14*, 5280. [[CrossRef](#)] [[PubMed](#)]

68. Naderi, M.H.; Biria, M.; Shahbazi, S.; Kousha, S.; Dalaie, K.; Behnaz, M. Estimating and comparing the duration of adolescent growth peak in skeletal Class I and III subjects using cervical vertebral maturation method. *Prog. Orthod.* **2022**, *23*, 25. [[CrossRef](#)] [[PubMed](#)]
69. Yamazaki, Y.; Tohara, H.; Hara, K.; Nakane, A.; Wakasugi, Y.; Yamaguchi, K.; Minakuchi, S. Excessive anterior cervical muscle tone affects hyoid bone kinetics during swallowing in adults. *Clin. Interv. Aging* **2017**, *12*, 1903–1910. [[CrossRef](#)] [[PubMed](#)]
70. Ulman-Macón, D.; Fernández-de-Las-Peñas, C.; Angulo-Díaz-Parreño, S.; Arias-Buría, J.L.; Mesa-Jiménez, J.A. Morphological changes of the suboccipital musculature in women with myofascial temporomandibular pain: A case-control study. *Life* **2023**, *13*, 1159. [[CrossRef](#)] [[PubMed](#)]
71. Westersund, C.D.; Scholten, J.; Turner, R.J. Relationship between craniocervical orientation and center of force of occlusion in adults. *Cranio* **2017**, *35*, 283–289. [[CrossRef](#)] [[PubMed](#)]
72. Oxilia, G.; Bortolini, E.; Martini, S.; Papini, A.; Boggioni, M.; Buti, L.; Figus, C.; Sorrentino, R.; Townsend, G.; Kaidonis, J.; et al. The physiological linkage between molar inclination and dental macrowear pattern. *Am. J. Phys. Anthropol.* **2018**, *166*, 941–951. [[CrossRef](#)] [[PubMed](#)]
73. Madeline, L.; Elster, A. Suture closure in the human chondrocranium: CT assessment. *Radiology* **1995**, *196*, 747–756. [[CrossRef](#)] [[PubMed](#)]
74. Hallett, S.A.; Ono, W.; Franceschi, R.T.; Ono, N. Cranial base synchondrosis: Chondrocytes at the hub. *Int. J. Mol. Sci.* **2022**, *23*, 7817. [[CrossRef](#)] [[PubMed](#)]
75. Vu, G.H.; Xu, W.; Go, B.C.; Humphries, L.S.; Kalmar, C.L.; Taylor, J.A.; Bartlett, S.P.; Vossough, A.; Nah-Cederquist, H.-D.; Swanson, J.W. Physiologic timeline of cranial-base suture and synchondrosis closure. *Plast. Reconstr. Surg.* **2021**, *148*, 973e–982e. [[CrossRef](#)] [[PubMed](#)]
76. Bassed, R.; Briggs, C.; Drummer, O.H. Analysis of time of closure of the spheno-occipital synchondrosis using computed tomography. *Forensic Sci. Int.* **2010**, *200*, 161–164. [[CrossRef](#)] [[PubMed](#)]
77. Kolpakova-Hart, E.; McBratney-Owen, B.; Hou, B.; Fukai, N.; Nicolae, C.; Zhou, J.; Olsen, B.R. Growth of cranial synchondroses and sutures requires polycystin-1. *Dev. Biol.* **2008**, *321*, 407–419. [[CrossRef](#)] [[PubMed](#)]
78. Srivastava, D.; Singh, H.; Mishra, S.; Sharma, P.; Kapoor, P.; Chandra, L. Facial asymmetry revisited: Part I—Diagnosis and treatment planning. *J. Oral Biol. Craniofac. Res.* **2018**, *8*, 7–14. [[CrossRef](#)] [[PubMed](#)]
79. Rajderkar, S.S.; Paraiso, K.; Amaral, M.L.; Kosicki, M.; Cook, L.E.; Darbellay, F.; Spurrell, C.H.; Osterwalder, M.; Zhu, Y.; Wu, H.; et al. Dynamic enhancer landscapes in human craniofacial development. *Nat. Commun.* **2024**, *15*, 2030. [[CrossRef](#)] [[PubMed](#)]
80. Raoul-Duval, J.; Ganet, A.; Benichi, S.; Baixe, P.; Cornillon, C.; Eschapasse, L.; Geoffroy, M.; Paternoster, G.; James, S.; Laporte, S.; et al. Geometric growth of the normal human craniocervical junction from 0 to 18 years old. *J. Anat.* **2024**, *245*, 842–863. [[CrossRef](#)] [[PubMed](#)]
81. Cook, L.E.; Feigin, C.Y.; Hills, J.D.; Vespasiani, D.M.; Pask, A.J.; Gallego Romero, I. Gene regulatory dynamics during craniofacial development in a carnivorous marsupial. *eLife* **2025**, *14*, RP103592. [[CrossRef](#)]
82. Sumardi, S.; Kuijpers-Jagtman, A.M.; Latief, B.S.; Wellens, H.L.L.; Fudalej, P.S. Craniofacial integration and modularity in untreated cleft lip and palate. *Clin. Oral Investig.* **2025**, *29*, 218. [[CrossRef](#)] [[PubMed](#)]
83. Liang, C.; Landi, F.; Çetin, I.E.; Profico, A.; Buzi, C.; Dutel, H.; Khonsari, R.H.; O'Higgins, P.; Moazen, M. Functional adaptation of the infant craniofacial system to mechanical loadings arising from masticatory forces. *Proc. R. Soc. B* **2024**, *291*, 20240654. [[CrossRef](#)] [[PubMed](#)]

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