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Original article

Morphometric covariation between palatal shape and skeletal pattern in Class II growing subjects

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Summary

Objectives: To evaluate the patterns of covariation between palatal and craniofacial morphology in Class II subjects in the early mixed dentition by means of geometric morphometrics.
Methods: A cross-sectional sample of 85 Class II subjects (44 females, 41 males; mean age 8.7 years ± 0.8) was collected retrospectively according to the following inclusion criteria: European ancestry (white), Class II skeletal relationship, Class II division 1 dental relationship, early mixed dentition, and prepubertal skeletal maturation. Pre-treatment digital 3D maxillary dental casts and lateral cephalograms were available. Landmarks and semilandmarks were digitized (239 on the palate and 121 on the cephalogram) and geometric morphometric methods (GMM) were applied. Procrustes analysis and principal component analysis (PCA) were performed to reveal the main patterns of palatal shape and craniofacial skeletal shape variation. Two-block partial least squares analysis (PLS) assessed patterns of covariation between palatal morphology and craniofacial morphology.
Results: For the morphology of the palate, the first principal component (PC1) described variation in all three dimensions. For the morphology of the craniofacial complex, PC1 showed shape variation mainly in the vertical direction. Palatal shape and craniofacial shape covaried significantly (RV coefficient: 0.199). PLS1 accounted for more than 64 per cent of total covariation and related divergence of the craniofacial complex to palatal height and width. The more a Class II subject tended towards high-angle divergence, the narrower and higher was the palate.
Conclusions: Class II high-angle patients tended to have narrower and higher palates, while Class II low-angle patients were related to wider and more shallow palates.

Introduction

Numerous studies (1–3) in the literature have analyzed the dental and skeletal components of Class II malocclusion in order to improve orthodontic diagnosis and treatment planning. It has been pointed out that Class II malocclusion is a complex clinical entity that entails a combination of different three-dimensional features such as mandibular deficiency and transverse discrepancy due to a narrow maxillary arch (2, 4, 5–10).

In particular, Bishara *et al.* (6) and Baccetti *et al.* (7) evaluated longitudinally, with direct measurements on dental casts, the growth trends in Class II malocclusion and found a reduction of the maxillary intermolar width at all the three stages of dental development, i.e. deciduous, mixed, and permanent dentition. Posterior transverse discrepancy is maintained or worsens in the transition from the deciduous to the mixed dentition.

On the other hand, Vasquez *et al.* (11) and Marinelli *et al.* (10) analyzed two Class II subgroups (maxillary protrusion group and mandibular retrusion group) with respect to subjects with normal occlusion. Marinelli *et al.* (10) pointed out that Class II malocclusion with mandibular retrusion was associated with reduced maxillary intercanine and intermolar widths, while Vasquez *et al.* (11) found that Class II malocclusion with maxillary protrusion showed no deficiency in transverse dentoskeletal relationships.

No data are available with regard to morphological covariation of the palatal shape and skeletal pattern in children with Class II malocclusion. This covariation can be assessed with morphometric analysis. Geometric morphometrics (GMM) was proposed in the literature as a different method of comprehensive evaluation of shape that can communicate even complex morphological changes much more effectively than coefficients that result from traditional morphometric analysis (12). Visualizing shape changes is important to understand morphological variation, as GMM is used to address an increasingly varied range of questions about evolution and development of organisms (13).

The aim of this cross-sectional study, therefore, was to evaluate the patterns of covariation between palatal and craniofacial morphology in Class II subjects in the early mixed dentition by means of GMM.

Materials and methods

A sample of 85 Class II subjects (44 females and 41 males) with a mean age of 8.7 years ± 0.8, was collected retrospectively from the archives of the Departments of Orthodontics of the Universities of Rome "Tor Vergata" and Florence.

The inclusion criteria for the selection of subjects were the following: European ancestry (white), Class II skeletal relationship (ANB greater than 4 degrees, Wits appraisal greater than 2 mm), Class II division 1 dental relationships (full Class II or end-to-end molar relationship and overjet greater than 5 mm), early mixed dentition, prepubertal skeletal maturation (CS1–CS2) (14), good quality of pretreatment records (study casts and lateral cephalograms with reference ruler). Time discrepancy between lateral cephalograms and study casts was set within 6 months.

Exclusion criteria included Class II division 2 dental relationships, pubertal and postpubertal subjects (older than CS3), deciduous and permanent dentition, previous orthodontic treatment, sucking habits or mouth breathing, lateral crossbite and lateral functional shift, multiple and/or advanced caries, tooth agenesis, supernumerary teeth, cleft lip and/or palate, and other genetic diseases.

This project was approved by the Ethical Committee of the University of Rome "Tor Vergata" (Protocol number: 126/16) and informed consent was obtained from the patients' parents.

For each subject, digital 3D maxillary dental casts and lateral cephalograms were available before treatment. Maxillary casts were scanned using an intraoral scanner Carestream (CS3500, Carestream Dental LLC, Carestream Health, Rochester, New York, USA) with a manufacturer's reported accuracy of 30 µm. Lateral cephalograms were scanned at a resolution of 150 dpi and scaled to life size. To study comprehensively palatal shape and craniofacial skeletal structures, three-dimensional GMM was applied (15–17). Viewbox 4 software (dHAL software, Kifissia, Greece) was used to digitize the cast and cephalogram of each subject.

On each digital cast, three curves were drawn and a total of 239 landmarks were digitized (Figure 1) (18). The boundaries of the palate were defined as: the midsagittal suture (9 points), a perimeter curve of the dental arch passing apical to the gingival sulci of each tooth (21 points) and a posterior curve passing from distal of the first permanent molars, perpendicular to the midsagittal line (9 points). The remaining points (semilandmarks) were placed uniformly on the palatal surface within the confines delimited by the three curves.

For the evaluation of the shape of the craniofacial skeletal complex, we drew 15 continuous curves (Table 1) with 121 points, 14 of them being fixed cephalometric landmarks (Figure 2). The remaining landmarks were semilandmarks, initially placed at equidistant distances along the curves. The averages of all the datasets (palatal and skeletal) were calculated, and used as a fixed reference (Procrustes average) to allow all semilandmarks to slide and become more homologous from subject to subject in order to minimize the thin-plate spline (TPS) bending energy (15, 19, 20). This procedure was repeated two times.

All digitizations of radiographs and study casts were performed by the same operator and analyzed using the Generalized Procrustes method.

Statistical analysis

To determine the reliability of the method, 20 maxillary casts and 20 lateral cephalograms were randomly selected and re-digitized by the same operator 10 days after the first digitization. Random error was expressed as the distance between repeated digitizations in shape space compared with the total variance of the sample (12). Procrustes analysis was applied and principal component analysis (PCA) was performed to reveal the main patterns of palatal shape variation and of craniofacial skeletal shape variation. Two-block partial least squares analysis (PLS) was performed for the whole sample in order to assess any pattern of covariation between palatal morphology and craniofacial morphology. The analysis was conducted with Viewbox 4 (PCA) and MorphoJ software (PLS) and covariation strength was evaluated by the RV coefficient of Escoufier (21) (10 000 permutations) as a scalar measure of the strength of association between the coordinates of two sets of landmarks (22).

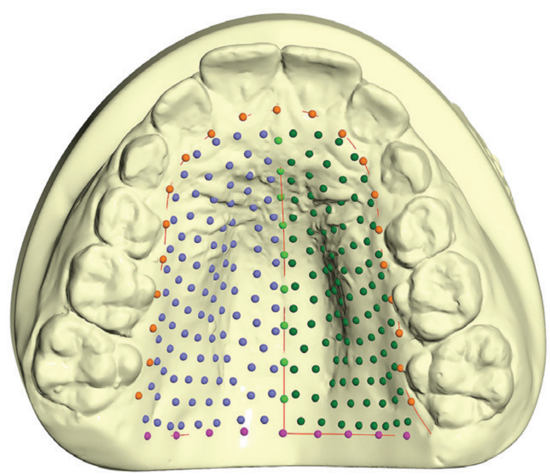

Figure 1. The three curves drawn on the digital casts. Green points: midsagittal suture; orange: perimeter of the dental arch on margin; pink: posterior border tangent to the distal surface of permanent first molars; dark green and blue: semilandmarks on the palatal surface.

Table 1. Description of the curves of the craniofacial complex (some points are common between curves)

Curves	Description	N° Points
Porion	External auditory meatus	4
External frontal nasal	External cortical plate of frontal bone and nasal bone	12
Sella–Basion	From tuberculum sellae to posterior clinoid process, dorsum sellae, along clivus, to Basion	11
Endocranial frontal	From frontal sinus, along roof of orbit and planum sphenoidale, to anterior clinoid processes	7
Internal frontal–Sella	Internal cortical plate of frontal bone, along the cribriform plate of the ethmoid, the superior surface of the sphenoid body, to tuberculum sellae	10
Sphenoethmoidal	From fronto-sphenoethmoidal suture to Basion, along the anterior border of the body and the greater wings of the sphenoid bone and the exocranial surface of basioccipital	6
Orbit	Anterior border of the zygomatic bone, terminating at Orbitale	5
Zygomaticomaxillary	From the posterior margin of frontal process of the zygomatic bone to the zygomatic process of the maxilla	10
Maxilla 1	From PNS anteriorly along the nasal floor, around ANS, and inferiorly along the alveolar process to supradentale	13
Maxilla 2	From PNS, along the outline of the palate, to the cervix of the maxillary incisors	9
PTM1	External surface of maxillary tuberosity	5
PTM2	Anterior surface of the pterygoid process of sphenoid bone	5
Mandible	From infradentale, along the external outline of the mandible around the condyle, to the anterior neck of the condyle	25
Symphysis	The lingual cortical plate of the symphysis	6
Anterior ramus	Anterior border of ramus from the level of the palate to the distal of the first mandibular molar	4

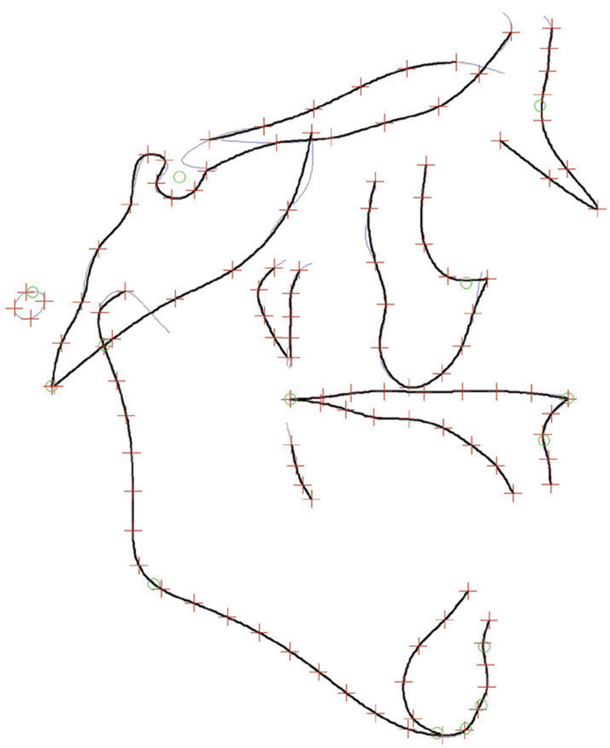

Figure 2. Fixed landmarks (green circles) and sliding semilandmarks (red crosses) used to describe the craniofacial skeletal complex.

Results

Mean random error of the 20 repeated digitizations, expressed, as a percentage of total shape variance (12) was 6.4 and 8.7 per cent for maxillary casts and lateral cephalograms, respectively.

Procrustes superimposition and PCA

For the morphology of the palate, the first four principal components (PCs) of the maxillary casts (variance explained: PC1 = 42%; PC2 = 16.1%; PC3 =9.9%; PC4 = 5.3%) were considered to be statistically meaningful (at least 5% of total shape variability) and explained 73.3 per cent of total shape variability. Supplementary Figure 1 shows the plot of the palatal shape. The PC with the largest variance (PC1) described morphological variation in all three dimensions of space. Low values were associated to a wide, shallow and short palate, while high values corresponded to a narrow, high, and long palate. PC2 showed shape variation mainly in palatal height (Figure 3).

For the morphology of the craniofacial complex, the first five PCs were considered to be statistically meaningful (variance explained: PC1 = 21.7%; PC2 = 13.4%; PC3 =8.2%; PC4 = 6.4%; PC5 = 6.1%) and explained 55.8 per cent of the total shape variability. Supplementary Figure 2 shows the sample distribution in the shape space after Procrustes superimposition. The most significant principal component (PC1) described skeletal shape variation in the vertical direction. High values were associated to a high-angle skeletal pattern while low values to a low-angle skeletal pattern. PC2 was related to the sagittal position of the maxilla and the mandible with respect to the cranial base (Class II malocclusion with mandibular retrusion or maxillary protrusion) (Figure 4).

When the whole sample was considered in the same shape space, no statistically significant differences were found between males versus females. The evaluation was performed by permutation tests (10 000 repetitions) using the Procrustes distance between group means as the test criterion (males versus females, palatal morphology: P = 0.44; males versus females, craniofacial morphology: P = 0.54).

Two-block partial least square analysis: covariation

PLS analysis evaluated covariance between the palatal and craniofacial components.

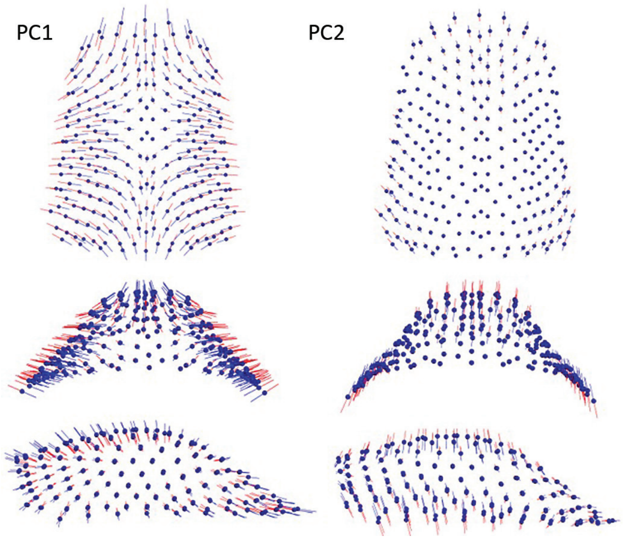

Figure 3. Graphic depiction of the first two PCs (principal components) of the palate from the three views. Red line: –3 Standard Deviation, blue line: +3 Standard Deviation.

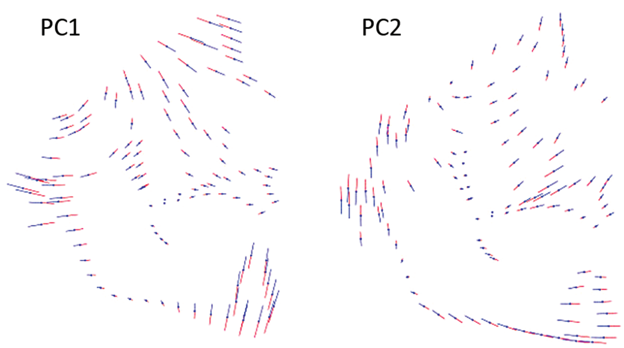

Figure 4. Graphic depiction of the first two PCs (principal components) of the craniofacial complex. Red line: –3 Standard Deviation, blue line: +3 Standard Deviation.

In our group, palatal shape and craniofacial shape covaried significantly (RV coefficient: 0.199, $P < 0.0001$, 10 000 permutations). PLS1 accounted for more than 64 per cent of the total covariation and related the divergence of the craniofacial complex to the palatal height and width. The more a Class II subject tended towards high-angle divergence the narrower and higher was the palate. On the contrary, the closer the subject was to the low-angle end of the spectrum, the shallower and wider was the palate (Figure 5).

The remaining singular values were much smaller and not statistically significant.

Discussion

This study aimed to assess covariation between palatal and craniofacial morphology in Class II subjects in early mixed dentition by means of GMM. Previous studies (10, 11) evaluated the relationship between the craniofacial complex and the palate in Class II patients by using conventional two-dimensional measurements on cephalometric radiographs and dental casts. Most authors (2, 4, 7) agree that maxillary constriction is a distinctive occlusal feature of Class II malocclusion from the early mixed dentition. Tollaro *et al.*

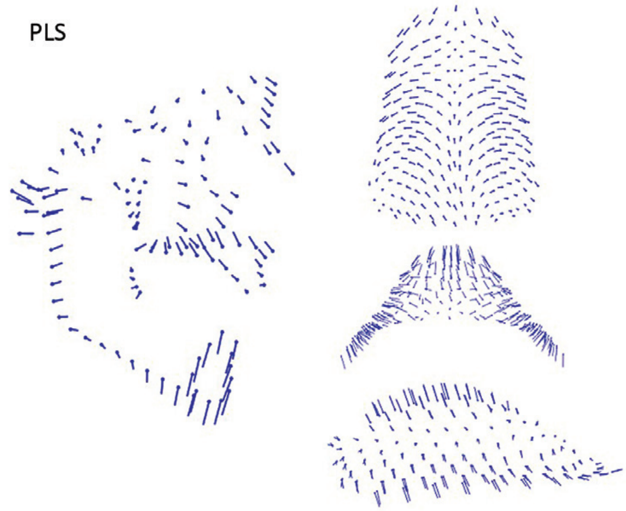

Figure 5. Graphic depiction of the first component (PLS1: partial least square 1).

(2) stated that the posterior transverse interarch discrepancy due to a reduced intermolar width could be considered as a possible cause of functional mandibular retrusion inducing a backward position of the mandible itself. Alarashi *et al.* (4) pointed out by means of TPS analysis that subjects with Class II malocclusion in the mixed dentition present shape differences in craniofacial configurations with constriction of the maxilla at both the skeletal and dentoalveolar levels and a narrowing of the base of the nose. However, a limitation of these studies is the lack of three-dimensional analysis that would allow evaluation of the interaction between transverse, sagittal, and vertical factors.

To our knowledge, this is the first attempt to assess shape covariation between the palate and the craniofacial complex, specifically in a Class II orthodontic population. A more general orthodontic population was studied by Parcha *et al.* (18) using the same methodology. To evaluate and visualize morphological variation and covariation, we applied the methods of geometric morphometrics (13, 15).

All subjects with Class II occlusal relationship were included in the study group irrespective of the skeletal basis of their jaw relationship (maxillary protrusion versus mandibular retrusion). Such a differentiation is debatable and difficult to achieve using conventional cephalometric measurements (23); in any case, we considered the inter-jaw relationship more relevant to the covariation studied here than the relationship of each jaw to the cranial base, or any other reference structure. As recommended by Parcha *et al.* (18), subjects with unilateral crossbite, tooth agenesis, and impacted teeth were excluded to avoid their potential impact on palatal shape and asymmetry. The palatal vault was assessed up to the gingival margin in order to eliminate the influence of dental inclination and position on the alveolar bone (18, 24). Another exclusion criterion was the mouth-breathing pattern. The influence of breathing mode on craniofacial growth has been widely debated, as prolonged mouth breathing in growing subjects could lead to different palatal and craniofacial morphologies due to muscular and postural alterations (24). In fact, variations of the muscles of mastication can affect craniofacial characteristics in Class II growing children and can be one of the possible causes of the reported variation of treatment results with functional appliances (25, 26).

An important finding was that subjects with Class II malocclusion showed differences in the morphology of the palate not only in width, but also in the vertical dimension. As shown in Figure 3, morphological variation in the palate occurs in all three dimensions of space; we noted that a wide palate was associated with a shallow palatal shape, and conversely, a narrow palate was related to a high palatal vault.

Regarding the craniofacial complex (Figure 4), the most significant morphological variability referred to the vertical and not the sagittal plane, as reported by previous authors (10, 11). Thus, the first principal component described the variation in the vertical and not in the sagittal dimension, spanning the 'high-angle' to 'low-angle' skeletal pattern spectrum. Moreover, when studying the pattern of covariation, a statistically significant relation between the divergence of the craniofacial complex and the shape of the palate was found; Class II patients with increased vertical dimension tended to have a narrower and higher palate (Figure 5). The PLS1 component correlated a narrow maxillary arch to a hyperdivergent skeletal pattern and a wide palate to a hypodivergent skeletal pattern. The tendency to develop a transverse deficiency of the maxillary arch is more easily recognizable in Class II subjects with high-angle mandibular pattern. These results are in agreement with previous studies that reported a strong relationship between arch forms, craniofacial growth pattern, and muscle activity (27–29). Parcha *et al.* (18) analyzing the palatal morphology and its relationship to skeletal pattern in a general orthodontic population found a similar covariation pattern. High and narrow palatal vaults were mainly related to a hyperdivergent skeletal pattern while shallow and wide palates to a hypodivergent one.

Some amount of shape covariation between the palate and the craniofacial complex was expected because the face and cranium are considered to consist of separate functional and anatomical modules that are nevertheless integrated due to spatial constraints (30–32). The palate is a particularly interesting structure as it is situated in the central region of the face representing the boundary between the nasal and oral cavity, each of these dedicated to different functions. Assuming that function dictates anatomy, as asserted by the functional matrix hypothesis (33, 34), the shape of the palate may be determined by functional demands acting upon it from opposing directions. Interestingly, the nasal and oral functional matrices seem to be relatively independent, as evidenced by their different ontogenetic growth trajectories and the lack of strong morphological integration (30, 35). The palate, being an interfacing structure, is expected to be related to both the oral and the nasal cavity shape and, in extension, to the whole facial region. It is difficult to comment on the degree of covariation found here, as very few data are available regarding the extent of integration within the craniofacial complex. Cephalometric studies investigating the covariation of the cranial base and face show similarly modest correlation values (31, 36, 37). Our study included the oral surface of the palate only; it would be interesting to examine the covariation between the nasal and oral surfaces, as well as the anterior and posterior regions, as different levels of integration may be expected (38).

Many interacting factors must be considered in the aetiology of Class II malocclusion in the early mixed dentition, such as muscle function and the close correlation between the transverse and vertical dimension. The clinician should be aware of this relationship and as a consequence should pay attention to both discrepancies in the diagnostic process of Class II malocclusion. Subjects with Class II malocclusion and a high-angle mandibular pattern may more often require orthopaedic maxillary expansion. Such patients tend to have weak muscle function (28) so training of muscle activity to control the increased vertical dimension may also be advisable.

A limitation of this study was the use of two-dimensional cephalometric radiographs, which ignore the transverse dimension of the craniofacial complex. Additionally, the sample was selected based on dental relationships and a limited number of conventional cephalometric measurements that may not be sufficient to ensure skeletal homogeneity (23).

Conclusions

Palatal and craniofacial morphology in a Class II population in early mixed dentition showed a statistically significant covariation: Class II high-angle patients tended to have narrower and higher palates, while Class II low-angle patients were related to wider and more shallow palates.

Supplementary material

Supplementary material is available at *European Journal of Orthodontics* online.

Conflict of interest

None to declare.

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