Characterization of the very young child's palatal vault growth pattern: how do its size and shape evolve?

F. Remy[1], Y. Godio-Raboutet[2], G. Captier[4], P. Burgart[3], P. Bonnaure[3], L. Thollon[2], L. Guyot[5]

[1] Aix-Marseille University, University Gustave Eiffel, LBA, Marseille,France - YooMed, Montpellier, France
[2]Aix-Marseille University, University Gustave Eiffel, LBA, Marseille,France
[3]YooMed, Montpellier, France
[4]Department of Plastic Pediatric Surgery, Lapeyronie Hospital, Montpellier University, Montpellier, France
[5] Aix-Marseille University, University Gustave Eiffel, LBA, Marseille,France - Department of Oral-Maxillofacial, Plastic and Reconstructive Surgery, A.P.-H.M., Conception Hospital, Marseille, France

e-mail: floriane.remy.ymd@gmail.com

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Abstract

Aim This study aimed to characterise the palatal vault evolution during the first years of life, both in terms of shape and size.

Materials and methods The study sample was composed of 168 healthy children aged less than 4 years. Twenty-one measurements of distances and 6 angles were taken from 7 fixed landmarks set on the palatal vaults 3D surfaces reconstructed from CT-scans. To analyse only the shape evolution, the "size-free" log-shape ratio of those measurements were computed and the global shape of the palatal vault and their transversal curve were plotted. Statistical analyses were performed to highlight the shape and size differences separately.

Results Three main groups were identified, reflecting the development of the deciduous dentition. Within the first two groups, additional morphological distinctions were observed, explained by age. Within the third group, three subgroups were identified, each composed of individuals aged approximately the same but distinct in terms of sex. Aside from a global increase in the palatal dimensions, observed mostly before the eruption of all deciduous teeth, this growth pattern was characterized by the progressive deepening of the vault and increasing of the posterior relief. An asymmetry was also observed for older individuals.

Conclusions The shape and size evolution of the palatal vault during the first years of life was not only correlated with deciduous dentition development. We assumed that the progressive orofacial muscles activation and tongue movements in the oral cavity may also explain these results as they induced strains on the palatal vault, warping it in various ways.

KEYWORDS Growth, Palate, Morphometry, Deciduous dentition development, Functional strains

Introduction

Besides genetic and hormonal factors, the biomechanical strains associated with functional stimuli may influence the oral cavity growth pattern. Among these functional factors, the tongue movements involved during sucking, deglutition, mastication or phonation affect the palate size. Indeed, several studies showed the correlation between the palate size and respiratory disorders in children, as upper airway obstruction is often associated with mouth breathing and high palates [Kusumaningrum et al. 2019]. Finally, depending on whether the child is mainly bottle- or breast-fed [Warren and Bishara, 2002], if she/he presents some oral habits as the use of a dummy or finger sucking [Aznar et al., 2006], or according to the dietary diversification rhythm – that is the age from which the child begins to eat soft (puree) or solid (pieces) food – [Sato et al., 2005], the tongue movements in the oral cavity and the oro-facial muscular activation pattern may differ, and so the child's palatal vault may present various shapes. Thus, an abnormality in the palatal vault form may be associated with speech, sucking, masticatory and/or breathing functional disorders.

To identify such an abnormality, the first necessary step is to define what is "normal". As highlighted in a recent systematic review, most studies evaluate the palate dimensions only, taken from dental landmarks marked on the gums or the cusps, grooves or pits of the teeth [Berwig et al., 2018]. Usually, the palate dimensions are defined through its length, its depth and its width (i.e. its sagittal, vertical and transverse dimensions, respectively). These dimensions can be measured directly within the child's mouth, on the plaster cast of her/his dental arch or on medical images.

However, study of the palate dimensions only may be restrictive as its growth pattern may also be characterised by morphological changes. This distinction between size and shape was defined by Needham [1950] who highlighted the importance to evaluate these two components separately. Various methods have been developed to only consider the geometric conformation effects, that is morphological differences: the Procruste superimposition technique, the surface sliding semi-landmarks or the Mosimann's log shape ratio are some of these.

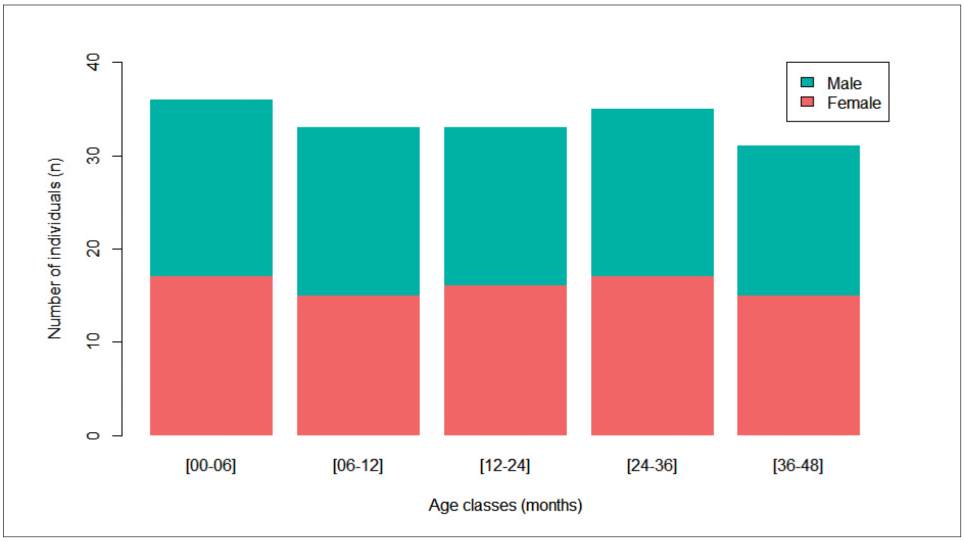
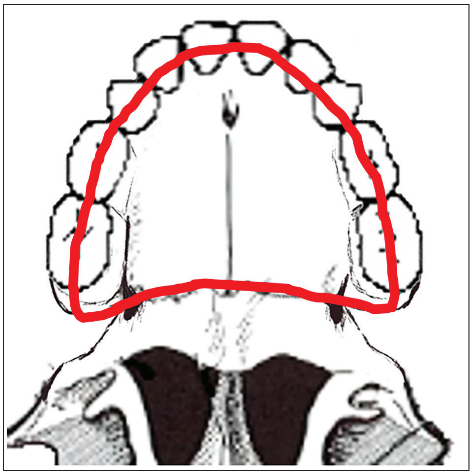


FIG. 1 Composition of the total study sample divided by age groups (in months) and sex



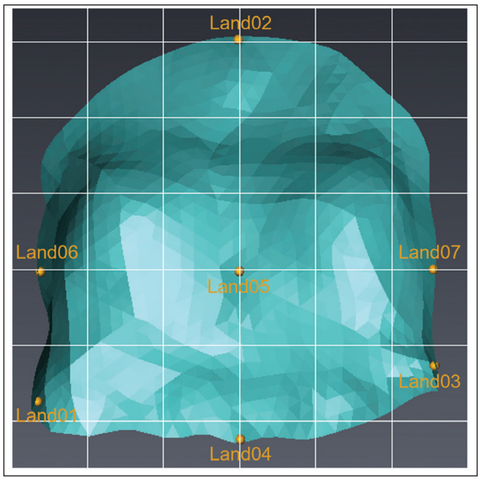


FIG. 2 The bony palatal vault 3D surface was reconstructed from a virtual line intersecting the alveolar process in its middle to the transversal palatal suture (red line, inferior view). Teeth were excluded from the reconstructions

FIG. 3 Illustration of the 7 fixed landmarks positioned on the 3D mandibular models with the help on a homogeneous grid set in transparency (inferior view)

Name	Definition
Land01	Point of intersection between the right and posterior borders of the palatal vault
Land02	Most anterior point on the medial line of the palatal vault
Land03	Point of intersection between the left and posterior borders of the palatal vault
Land04	Most posterior point on the medial line of the palatal vault
Land05	Lowest point on the medial line of the palatal vault
Land06	Projection of Land05 on the right border of the palatal vault
Land07	Projection of Land05 on the left border of the palatal vault

TABLE 1 Name and definition of the 7 fixed landmarks set on the 3D palatal vault models

The present study aimed to use these morphometric tools to characterise the palatal vault size and shape evolution during the first years of life of healthy children. As demonstrated for the mandible in a previous study [Remy et al., 2019], we believe that this evolution is correlated to the development stages of the child' orofacial abilities. If such an interaction is observed, this would justify the relevance of myofunctional therapies to correct abnormality in the palatal vault and the associated speech, sucking, masticatory and/or breathing functional disorders [Garliner and Gables, 1982; Koletsi et al., 2018].

Materials and Methods

The study sample

Previous studies highlighted that the highest growth rates for the mandible occur during the first years of life [Smartt et al., 2005; Remy et al., 2019]. Thus, the total study sample, illustrated in Figure 1, was composed of 168 children aged less than 4 years. The sex-ratio was balanced (48% of girls for 52% of boys).

Children showing trauma or any pathology affecting their maxillofacial morphology or growth were not selected.

3D models of these children's bony palatal vault surface were reconstructed from CT-scan collected during a previous study [Remy et al., 2019], with Avizo® software (Avizo® Standard Edition 7.1.0, Visualization Sciences Group, SAS). Those 3D surfaces were reconstructed from a virtual line intersecting the alveolar process in its middle to the transversal palatal suture. (Figure 2). Teeth were excluded from the reconstructions.

Biometric data collection

Seven landmarks were set on the 3D palatal vault models with Avizo® as defined in Table 1 and illustrated in Figure 3. A homogeneous grid pattern was set in transparency on the models to help in the placement of these landmarks. Except for the lowest point on the medial line of the palatal vault (Land05), all these landmarks were positioned by placing the 3D models in an inferior view (Figure 3). Regarding

Name	Definition	Reference landmarks
L_max	Maximal length of the palatal vault	Land02 – Land04
L_max_l	Maximal length of the left part of the palatal vault	Land02 – Land03
L_max_r	Maximal length of the right part of the palatal vault	Land02 – Land01
L_ant	Length of the anterior part of the palatal vault	Land02 – Land05
L_ant_l	Length of the left anterior part of the palatal vault	Land02 – Land07
L_ant_r	Length of the right anterior part of the palatal vault	Land02 – Land06
L_post	Length of the posterior part of the palatal vault	Land05 – Land04
L_post_l	Length of the left posterior part of the palatal vault	Land05 – Land03
L_post_r	Length of the right posterior part of the palatal vault	Land05 – Land01
W_med	Width of the medial part of the palatal vault	Land06 – Land07
W_med_l	Width of the left medial part of the palatal vault	Land05 – Land07
W_med_r	Width of the right medial part of the palatal vault	Land06 – Land05
W_post	Width of the posterior part of the palatal vault	Land01 – Land03
W_post_l	Width of the left posterior part of the palatal vault	Land04 – Land03
W_post_r	Width of the right posterior part of the palatal vault	Land01 – Land04
SmallDiag01_l	Diagonal measurement between Land03 and Land05	Land03 – Land05
SmallDiag02_l	Diagonal measurement between Land04 and Land07	Land04 – Land07
SmallDiag01_r	Diagonal measurement between Land01 and Land05	Land01 – Land05
SmallDiag02_r	Diagonal measurement between Land04 and Land06	Land04 – Land06
BigDiag_01	Diagonal measurement between Land03 and Land06	Land03 – Land06
BigDiag_02	Diagonal measurement between Land01 and Land07	Land01 – Land07
A_ant	Angle of the anterior part of the palatal vault	
A_med	Transversal angle of the medial part of the palatal vault	
A_post	Transversal angle of the posterior part of the palatal vault	
A_left	Sagittal angle of the left part of the palatal vault	
A_right	Sagittal angle of the right part of the palatal vault	
A_anteropost	Sagittal angle of medial part of the palatal vault	

TABLE 2 Name, definition, and reference landmarks of the 27 measurements collected on the 3D palatal vault models

the Land05, it was identified by placing the 3D models in a posterior view.

To analyse the size evolution of those palatal vaults, 21 Euclidean distances and 6 angles were computed from those 7 landmarks (Table 2). These measurements illustrated the sagittal, vertical and transverse dimensions of the palatal vaults.

To visualize shape differences, without consideration of any proportions increase (i.e. the geometric conformation effect), the "size-free" log-shape ratio of those measurements were computed according to Mosimann's formula

$$logShapeRatio(u_n) = log\left[\frac{u_n}{(\prod_{k=1}^{n} u_k)^{(1/n)}}\right]$$

where u was the measurement and n was the number of measurements.

To represent the global palatal morphology, a set of one hundred (100) 3D surface sliding semi-landmarks was also extracted from the 7 landmarks with the statistical software RStudio (version 3.6.1, RStudio Team, 2019. Integrated Development for R. RStudio, PBC, Boston, MA].

A set of 3D surface sliding semi-landmarks is defined as a set of equidistant points automatically set on the 3D surface of an object according to a nearest neighbor method between each previously defined landmark.

Finally, on Avizo®, 2D sliding semi-landmarks were extracted to plot the transversal curve of the palatal vault, placed along a line intersecting the lowest point on the medial line of the palatal vault (Land05) and its projections on the palate lateral borders (Land06 and Land07).

Statistical analyses

Statistical analyses were performed with RStudio, with a significance threshold set to 5%.

To identify some morphological differences within the studied period, we performed a Principal Component Analysis (PCA) and a clustering method around centroids on the log-shape ratio of the measurements, for the total sample. The clustering results were interpreted by analysing the composition of these subgroups in terms of age spread, sex-ratio and number of erupted teeth.

The morphological differences that distinguished the identified subgroups were illustrated by a color map got from the superimposition of their morphotype (i.e. the palatal vault model characterised by the average landmark coordinates of a given group). Likewise, the mean transversal curves of these identified subgroups were drawn and compared.

Significant differences according to sex and laterality within the raw measurements were evaluated for each identified subgroup. Likewise, we compared each subgroup to better understand how they differ, this time in terms of size. Since the Shapiro-Wilk test did not verified the normality of the variables' distribution for the identified subgroups, and considering their size, non-parametric tests were used.

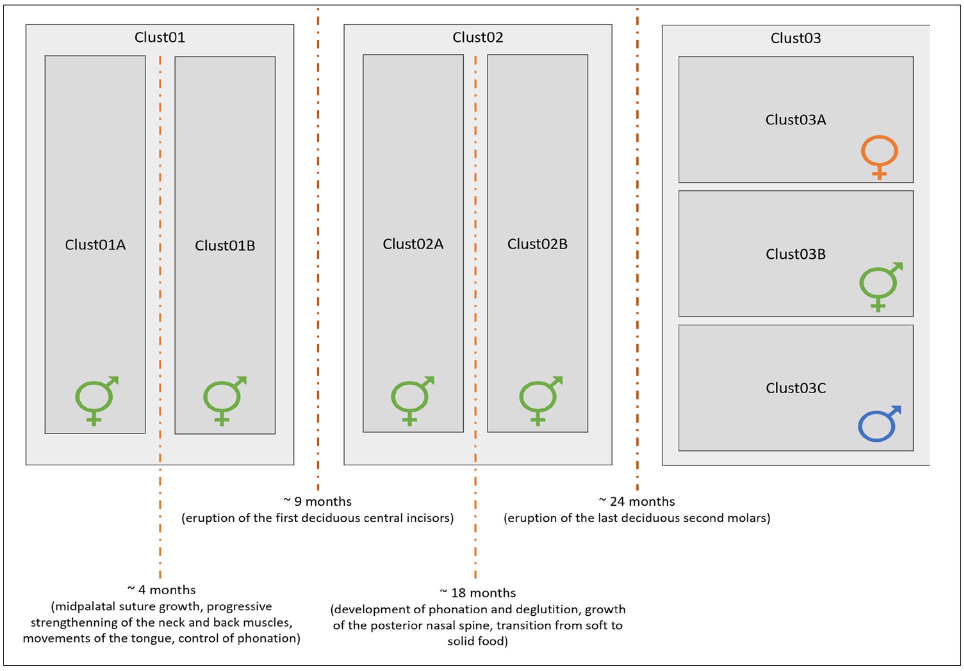


FIG. 4 Summary of the clustering results, interpreted from the observation of the subgroups identified by the analysis. The vertical lines illustrate the age separation between the identified clusters

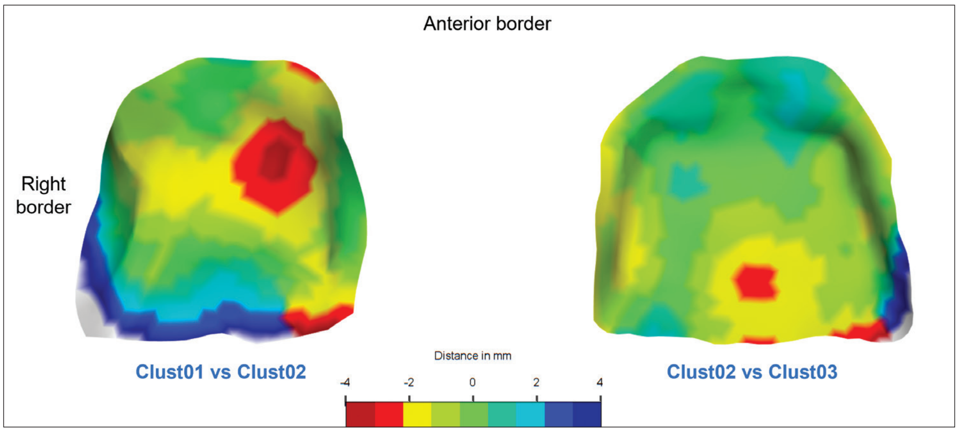


FIG. 5 Color mapping of the morphological differences get from the superimposition of the identified groups morphotypes: Clust01 vs. Clust02 on the left and Clust02 vs. Clust03 on the right (inferior view). The color scale illustrates the amount of differences between the two superimposed morphotypes

Results

The results of the Principal Component Analysis and the clustering method are displayed in Figure 4. As we can see, three main groups were identified, named respectively Clust01, Clust02 and Clust03. The first two groups (Clust01 vs. Clust02) separated from each other around 9 months old, that is when the deciduous dentition began to develop. The distinction between Clust02 and Clust03 happened around 24 months, that is when the deciduous dentition was complete and the last second molars were progressively erupting.

Two other subgroups were identified within Clust01, named respectively Clust01A and Clust01B. The composition of these subgroups in terms of sex was equivalent (proportion of girls vs. boys for Clust01A = 57-43% / for Clust01B = 50-50% – p value > 0.05) but differed in age (mean ± sd for Clust01A = 2.9 ±3 months / for Clust01B = 6.6 ±6.1 months – p value = 0.01).

Likewise, Clust02 was composed of two smaller subgroups: Clust02A and Clust02B, also similar distinct in terms of sex (proportion of girls vs. boys for Clust02A = 46-54% / for Clust02B = 36-64% – p value > 0.05) but distinct in age (mean ± sd for Clust02A = 14.8 ±11.6 months / for Clust02B = 20.47 ±9.9 months – p value = 0.008).

Finally, Clust03 may be also divided in three additional subgroups: Clust03A, Clust03B and Clust03C. This time, these subgroups gathered individuals of the same age (mean ± sd for Clust03A = 31.6 ±10.7 months / for Clust03B = 32.8 ±11.5 months / for Clust03C = 37.7 ± 6.8 months – p value > 0.05). Moreover, Clust03A and Clust03C differ regarding their proportion of girls and boys as the first was mainly composed of girls (77% – p value = 0.03) whereas there was a majority of boys in the second (71% – p value = 0.02). Clust03B gathered as many girls as boys (41/59% – p value > 0.05).

The morphometric differences between the groups and subgroups identified during the clustering analysis, are illustrated in Figure 5 and Figure 6. These morphometric differences were illustrated as color map get from the superimposition of the morphotypes of these groups and subgroups. In Figure 7, we compared the profile of their transversal curve.

When comparing the morphotypes of the three main groups (Clust01, Clust02 and Clust03), we can see that the main morphological differences concerned the anterior border which was more straight-lined – less curved – in Clust02 and continue to extend in Clust03. Between Clust01 and Clust02, the posterior border also became more lengthened, and a relief appeared in its medial part between Clust02 and Clust03. Besides, when comparing the transversal curves of the palatal vault of these

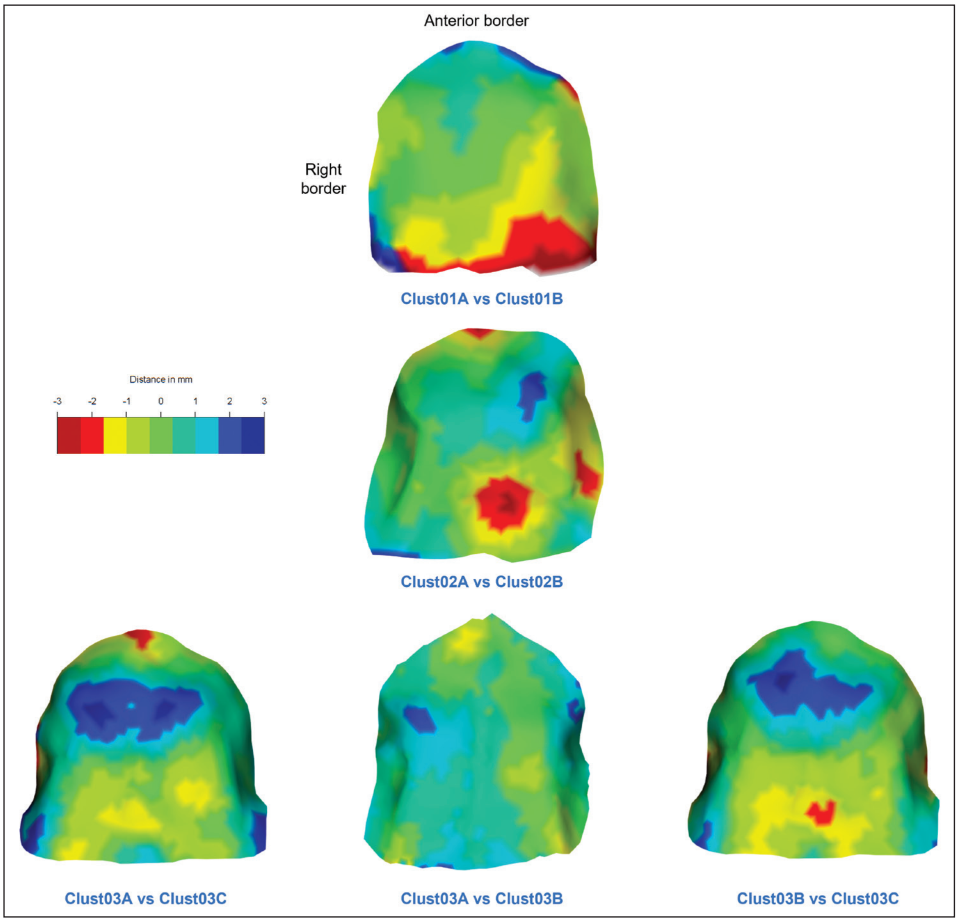


FIG. 6 Superimposition of the morphotypes of the subgroups identified within the three main groups Clust01 (at the top), Clust02 (on the middle) and Clust03 (at the bottom) and the color mapping associated illustrating their morphological differences (inferior view). The color scale indicates the regions the most concerned by morphological differences

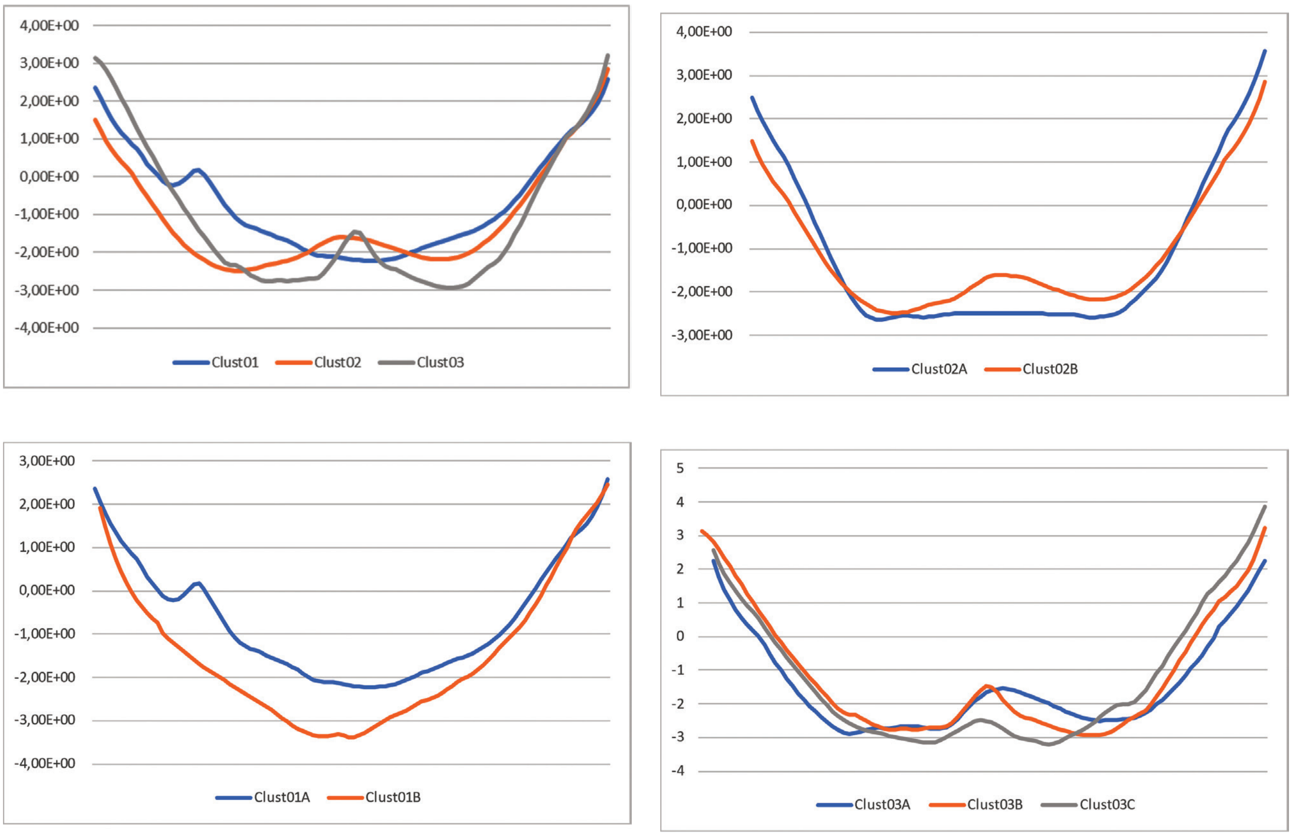


FIG. 7 Superimposition of the transversal curves of the mean palatal vault of each identified groups (Clust01 vs. Clust02 vs. Clust03, at the top), and subgroups (Clust01A vs. Clust01B, Clust02A vs. Clust02B and Clust03A vs. Clust03B vs. Clust03C from top to bottom, respectively)

three main groups, we can observe a more marked "m-shape" profile for Clust03.

When comparing the morphotypes identified within the main Clust01 and Clust02 groups (i.e. Clust01A vs. Clust01B and Clust02A vs. Clust02B respectively), we found the same morphological distinctions: a deepening of the palatal vault, mostly because of the lengthening of its anterior border which also became progressively more straight-line. Moreover, a relief appeared in the medial part of the posterior border within Clust02. This evolution in the vault profile was also observed when comparing the transversal curves.

Regarding the three subgroups identified within Clust03, we first compared the two subgroups composed of either a majority of girls or boys (i.e. Clust03A and Clust03C respectively) to analyze the sexual dimorphism. As we can see, the boy's morphotype had a deeper but less wide palatal vault, but both had a transversal curve with a "m-shape" profile. When comparing Clust03C with Clust03B (i.e., respectively, the boys' vs. the mixed-gender subgroups), we can see that Clust03B presented a transversal curve with a more marked "m-shape" profile. The boys' subgroup (Clust03C) also had a more vaulted anterior part. Regarding the differences between Clust03A and Clust03B (i.e., respectively, the girls' vs. the mixed-gender subgroups), they were minors but concerned the whole palate, Clust03B being more massive.

Regarding the analysis of the raw measurements, interestingly, the morphological sexual dimorphism observed from the clustering analysis was confirmed as significant differences in size were only found for Clust03 (Table 3). Considering the disproportion between girls and boys within the subgroups, we performed this analysis only for the three main groups (Clust01, Clust02 and Clust03).

While no morphological asymmetry was observed for any subgroup, the statistical tests showed differences between left and right raw measurements for Clust01B, Clust02A and Clust03C (Table 4).

At last, Table 5 resumed the statistical tests performed to com-

MEASUREMENTS	Clust01	Clust02	Clust03	
L_max	0.60	0.97	0.52	
	Left	0.54	0.73	0.55
	Right	0.51	0.36	0.87
L_ant	0.33	1.00	0.81	
	Left	0.29	0.43	1.00
	Right	0.21	0.57	0.96
L_post	0.49	0.77	0.90	
	Left	0.95	0.62	0.62
	Right	0.84	0.15	0.78
W_med	0.12	0.17	<0.05 girls<boys	
	Left	0.12	<0.05 girls<boys	0.96
	Right	0.07	<0.05 girls<boys	0.48
W_post	0.55	0.50	<0.05 girls<boys	
	Left	0.71	<0.05 girls<boys	0.30
	Right	0.28	0.23	0.78
SmallDiag01	Left	0.67	0.19	0.62
	Right	0.55	<0.05 girls<boys	0.78
SmallDiag02	Left	0.34	0.74	0.16
	Right	0.38	0.59	0.25
BigDiag01	Left	0.52	0.12	0.55
	Right	0.45	<0.05 girls<boys	0.70
A_ant	0.74	0.46	<0.05 girls<boys	
A_med	0.78	0.59	0.16	
A_post	<0.05 girls>boys	0.11	0.27	
A_left	0.51	0.36	0.16	
A_right	0.99	0.25	0.17	
A_anteropost	0.17	0.20	<0.05 girls>boys	

TABLE 3 P.values associated to the two.sided Wilcoxon tests evaluating the significance of the differences according to sex for each identified group. Please, refer to Table 2 for the measurements abbreviations. Shaded cases highlight p.values < 5%

MEASUREMENTS	Clust01	Clust01A	Clust01B	Clust02	Clust02A	Clust02B	Clust03	Clust03A	Clust03B	Clust03C
L_max	0.26	<0.05 left<right	0.68	0.18	0.10	0.67	<0.05 left<right	0.19	0.84	<0.05 left<right
L_ant	0.08	0.92	<0.05 left>right	<0.05 left>right	<0.05 left>right	0.13	0.20	0.31	0.87	0.23
L_post	0.13	0.06	0.70	<0.05 left<right	<0.05 left<right	0.07	<0.05 left<right	0.12	0.41	<0.05 left<right
W_med	0.12	0.79	<0.05 left>right	<0.05 left>right	0.07	0.06	0.09	0.43	0.18	0.43
W_post	<0.05 left>right	0.29	<0.05 left>right	<0.05 left>right	<0.05 left>right	<0.05 left>right	<0.05 left<right	0.75	<0.05 left>right	0.11
SmallDiag01	0.90	0.13	0.11	0.15	0.39	0.30	0.11	0.46	0.20	<0.05 left<right
SmallDiag02	0.59	0.06	0.39	0.59	0.31	0.87	<0.05 left>right	0.40	0.90	<0.05 left<right

TABLE 4. P.values associated to the two.sided Wilcoxon tests evaluating the significance of the differences according to laterality for each identified group and subgroup. Please, refer to Table 2 for the measurements abbreviations. Shaded cases highlight p.values < 5%

MEASUREMENTS	Clust01 VS Clust02	Clust02 VS Clust03	Clust01A VS Clust01B	Clust02A VS Clust02B	Clust03A VS Clust03B	Clust03B VS Clust03C	Clust03A VS Clust03C	
L_max	<0.05 Clust01<Clust02	<0.05 Clust02<Clust03	<0.05 Clust01A<Clust01B	<0.05 Clust02A<Clust02B	0.41	0.07	0.37	
	Left	<0.05 Clust01<Clust02	<0.05 Clust02<Clust03	<0.05 Clust01A<Clust01B	<0.05 Clust02A<Clust02B	0.34	0.08	0.68
	Right	<0.05 Clust01<Clust02	<0.05 Clust02<Clust03	<0.05 Clust01A<Clust01B	<0.05 Clust02A<Clust02B	0.56	0.79	0.82
L_ant	<0.05 Clust01<Clust02	0.65	0.07	<0.05 Clust02A<Clust02B	<0.05 Clust03A<Clust03B	<0.05 Clust03B>Clust03C	0.14	
	Left	<0.05 Clust01<Clust02	0.63	0.23	<0.05 Clust02A<Clust02B	<0.05 Clust03A<Clust03B	<0.05 Clust03B>Clust03C	0.84
	Right	<0.05 Clust01<Clust02	0.50	0.35	<0.05 Clust02A<Clust02B	<0.05 Clust03A<Clust03B	<0.05 Clust03B>Clust03C	1.00
L_post	<0.05 Clust01<Clust02	<0.05 Clust02<Clust03	<0.05 Clust01A<Clust01B	0.73	0.42	<0.05 Clust03B<Clust03C	0.42	
	Left	<0.05 Clust01<Clust02	<0.05 Clust02<Clust03	<0.05 Clust01A<Clust01B	<0.05 Clust02A<Clust02B	0.31	0.36	0.79
	Right	<0.05 Clust01<Clust02	<0.05 Clust02<Clust03	<0.05 Clust01A<Clust01B	0.64	0.11	<0.05 Clust03B<Clust03C	0.27
W_med	<0.05 Clust01<Clust02	0.62	0.84	<0.05 Clust02A<Clust02B	<0.05 Clust03A<Clust03B	0.93	<0.05 Clust03A<Clust03C	
	Left	<0.05 Clust01<Clust02	0.28	0.67	<0.05 Clust02A<Clust02B	<0.05 Clust03A<Clust03B	0.54	<0.05 Clust03A<Clust03C
	Right	<0.05 Clust01<Clust02	0.18	0.93	<0.05 Clust02A<Clust02B	<0.05 Clust03A<Clust03B	0.19	<0.05 Clust03A<Clust03C
W_post	<0.05 Clust01<Clust02	<0.05 Clust02<Clust03	0.88	<0.05 Clust02A<Clust02B	<0.05 Clust03A<Clust03B	0.16	<0.05 Clust03A<Clust03C	
	Left	<0.05 Clust01<Clust02	<0.05 Clust02<Clust03	0.46	<0.05 Clust02A<Clust02B	<0.05 Clust03A<Clust03B	0.60	<0.05 Clust03A<Clust03C
	Right	<0.05 Clust01<Clust02	<0.05 Clust02<Clust03	0.75	<0.05 Clust02A<Clust02B	<0.05 Clust03A<Clust03B	0.26	<0.05 Clust03A<Clust03C
SmallDiag01	Left	<0.05 Clust01<Clust02	<0.05 Clust02<Clust03	<0.05 Clust01A<Clust01B	<0.05 Clust02A<Clust02B	0.27	<0.05 Clust03B<Clust03C	<0.05 Clust03A<Clust03C
	Right	<0.05 Clust01<Clust02	<0.05 Clust02<Clust03	<0.05 Clust01A<Clust01B	<0.05 Clust02A<Clust02B	0.80	<0.05 Clust03B<Clust03C	<0.05 Clust03A<Clust03C
SmallDiag02	Left	<0.05 Clust01<Clust02	<0.05 Clust02<Clust03	<0.05 Clust01A<Clust01B	<0.05 Clust02A<Clust02B	0.48	0.33	0.14
	Right	<0.05 Clust01<Clust02	<0.05 Clust02<Clust03	<0.05 Clust01A<Clust01B	<0.05 Clust02A<Clust02B	0.46	0.12	0.07
BigDiag01	Left	<0.05 Clust01<Clust02	<0.05 Clust02<Clust03	0.23	<0.05 Clust02A<Clust02B	<0.05 Clust03A<Clust03B	0.46	<0.05 Clust03B<Clust03C
	Right	<0.05 Clust01<Clust02	<0.05 Clust02<Clust03	0.59	<0.05 Clust02A<Clust02B	<0.05 Clust03A<Clust03B	<0.05 Clust03B<Clust03C	<0.05 Clust03B<Clust03C
A_ant	<0.05 Clust01>Clust02	0.48	0.06	0.96	0.16	<0.05 Clust03B<Clust03C	<0.05 Clust03B<Clust03C	
A_med	<0.05 Clust01>Clust02	<0.05 Clust02>Clust03	0.26	0.90	0.71	<0.05 Clust03B>Clust03C	<0.05 Clust03A>Clust03C	
A_post	0.18	0.09	0.08	0.39	0.60	0.56	0.62	
A_left	<0.05 Clust01<Clust02	0.47	0.07	<0.05 Clust02A>Clust02B	0.44	0.07	<0.05 Clust03A>Clust03C	
A_right	<0.05 Clust01<Clust02	0.35	0.89	<0.05 Clust02A>Clust02B	0.19	0.36	<0.05 Clust03A>Clust03C	
A_anteropost	0.26	<0.05 Clust02<Clust03	0.57	0.11	0.60	<0.05 Clust03B>Clust03C	<0.05 Clust03A>Clust03C	

TABLE 5 P.values associated to the two.sided Wilcoxon tests evaluating the significance of the differences between each identified group and subgroup. Please, refer to Table 2 for the measurements abbreviations. Shaded cases highlight p.values < 5%

pare the raw measurements of each identified group and subgroup. These analyses highlighted that size differences were found mostly between Clust01/Clust02 and Clust02A/02B, that is at the beginning and at the end of the development of the decidual dentition. The differences between Clust02/Clust03 and Clust01A/01B concerned the maximal length and posterior dimensions of the palatal vault. Regarding Clust03, the differences inside this group occurred both in the width (Clust03A), the anterior length (Clust03B) and the angles (Clust03C) of the palatal vault.

Discussion

The morphometric growth pattern of the very young child's palatal vault

This study aimed to evaluate the growth pattern and morphological variability of the palatal vault during the first years of life of healthy children. Usually, this issue was addressed through the analysis of distances measured between dental or anatomical landmarks and collected either directly into the child's mouth or on palatal casts. However, such measurements give more information about tooth movements rather than morphological bone growth and cannot be used for younger toothless individuals. Moreover, as observed by Berwig et al. [2018] in their systematic review of the literature, those study mostly collect measurements on the transverse dimensions of the palate, at the expense of vertical or sagittal measurements.

As we focused on this early growth period, where the deciduous dentition is progressively erupting, we decided to rather use measurements depicting the global form of the palatal vault, independently from dental landmarks. To study the size evolution and shape variability of the palatal vault separately, both the raw measurements and their log-shape ratio were analysed.

With this methodology, we identified three main groups separated from each other around 9 months and 2 years old. Thus, the main morphological evolution of the palatal vault highlighted in this study reflected the beginning and the end of the deciduous dentition development. This morphological distinction was mostly explained by the progressive deepening of the palatal vault, with the anterior border becoming more lengthened and straight-lined. Yet, this anterior border corresponds to the emplacement of the central incisors, which are the first deciduous teeth to erupt. This evolution was also observed in terms of size with a significant increase of raw measurements, mostly during the eruption of the first teeth. When the deciduous dentition was complete, the size differences mostly occurred in the posterior part of the palatal vault. Thus, we may emphasise that during the first three years of life, the palatal vault dimensions increased to create the necessary space for the developing dentition. This increase in size more important during the first year of life and then slowed down is in concordance with previous studies [Laowansiri et al., 2013; Bauer et al., 2017] and is in keeping with the decreasing rates already observed during the prenatal period, in fetuses [Hermann et al., 2015].

Aside from this global evolution, we also observed some morphological distinctions within these three periods. Before the beginning of teeth development, two other subgroups were identified, with a separation occurring around 4 months old. These morphological distinctions mimic those observed with Clust01 vs. Clust02: the anterior border began to lengthen, and the palatal vault was already deeper for Clust01B. In terms of size, the differences were mostly expressed in the maximal length and posterior dimensions of the palatal vault. Thus, the form of the palatal vault evolves during the first year of life not only to create sufficient space for the developing teeth buds, but in response to other strains. Ewers et al. [1968] observed that during the perinatal period, growth was very active at the midpalatal suture, so the palate width rapidly increased.This period around 4 months of age is also characterized by the progressive strengthening of the neck and back muscles so the child can rest seat with his/her head straight [Onis, 2006]. Yet, in the sitting position, the tongue moves backward due to gravity, creating new strains on the posterior part of the palate. It is also around this age that infants gain control over their phonation, producing speech-like vocalizations called cooing [Ramsdell et al., 2019]. Finally, this period may coincide for some infants with a transition from breast- to bottle-feeding as the postnatal maternity leave lasts 10 weeks in France. Yet, the development of speech and bottle-feeding imply an activation of the orofacial muscles as the tongue, here again producing strains against the palatal vault, so expanding it [Mirchandani et al., 2021]. However, as we did not collect any information about the dietary and growth pattern of the analyzed children, these hypotheses remain to be assessed in further studies.

Regarding the decidual dentition development period (i.e. Clust02), two other subgroups were also identified, separated from each other around 18 months of age, that is when all teeth are usually erupted, except the second molars. The morphological differences between those two subgroups globally concern the palatal vault which still progressively deepens and the anterior border which continued to become more straight-lined than curved. We also noted a progressively more marked "m-shape" profile of the palatal vault transversal curve as the posterior part was flatter in Clust02A compared to Clust02B. This posterior protuberance, which became larger with growth, may correspond to the insertion site of the palatine aponeurosis, a thin, firm fibrous lamella which supports the muscles responsible of the movements of the soft palate and the Eustachian tube [Granick and Jacob, 2010]. Yet, this early growth period is characterised with the progressive development of speech and deglutition, increasingly activating the soft palate [Kahrilas, 1993]. Likewise, several studies demonstrated the important growth rates of the Eustachian tube during this period of eruption of deciduous dentition [Pagano et al., 2017]. Thus, we hypothesise that these muscular solicitations generate strains on the insertion point of the palatine aponeurosis on the posterior border of palatal vault, creating this relief. This posterior protuberance may also be the consequence of an activation of the medial palatal suture by the growth of the posterior nasal spine, whereas the horizontal lamellae of palatine bones were thinner [Captier et al., 2006; Park et al., 2016].

In terms of size, the whole palatal vault dimensions increased, most certainly because of the functional strains associated with the deciduous dentition development and the still ongoing activation of the orofacial muscles (tongue, lips and masticatory muscles), more and more solicited with the transition from soft to solid food. Here again, the literature also demonstrated a progressive decrease of growth at the midpalatal suture during the first years of life, but still a widening of the palate with appositional growth at the alveolar margins, an increase in height and a lengthening until later in the child's life [Cunningham et al., 2016]. Interestingly, our analysis performed on the raw measurements also highlighted an asymmetry for the Clust02A subgroup, that is during a period which may coincide with the progressive introduction of hard pieces of food into the child's diet. Indeed, some studies reported the existence of a chewing side preference induced with food solid texture [Zamanlu et al., 2012]. This asymmetry was also observed within the Clust03C subgroup (i.e. subgroup of boys with complete deciduous dentition). This may correspond with a study by Lysell et al. [1969] who reported significant asymmetry in emergence of the deciduous dentition among boys.

Finally, once all deciduous teeth were fully erupted (i.e. within Clust03), three additional subgroups were identified. This time, this morphological distinction cannot be explained by age. However, they were distinct in terms of sex as Clust03A was mostly composed of girls whereas Clust03C mostly gathered boys. Regarding Clust03B, it included approximately as many boys as girls. This sexual dimorphism was also observed in terms of size as significant differences of the raw measurements between the two sexes were only found for this Clust03 group, where boys had bigger palatal vault dimensions than girls. This result is consistent with the literature [Berwig et al., 2018; Garcia Rincon et al., 2020]. Anyway, the main morphological differences were located within the anterior border, which was more curved in boys, and in the posterior part presenting more or less relief in its medial part.

Limitations

This study aimed to characterise the growth pattern of the palatal vault in young children. However, its material was cross-sectional: the sample included individuals of various age groups. Thus, the inter-individual variability may explain the presented results. To confirm our findings, the study should be performed on individuals observed at various times throughout the growth period. However, this may be challenging since it would require exposing healthy children to ionising radiations for no medical reason.

In this study, we discussed the possible role of bottle- or breastfeeding, mastication, the locomotor development, or speech on the highlighted morphological growth pattern of the palatal vault. This hypothesis cannot be confirmed as we did not have access to any of this information for the analysed subjects. However, numerous studies tend to demonstrate this correlation between the volume of the tongue, masticatory muscle insertions, dentition development, non-nutritive habits, mouth-breathing, and maxillofacial growth [Moss, 1960; Warren and Bishara, 2002; Liu et al., 2008; Kusumaningrum et al., 2019].

Conclusion

The morphometric methodology presented in this study, based on the analysis of both raw measurements and their log shape-ratio, helped us better understand the variability of the palatal vault size and shape separately during the first years of life of healthy children. As for the mandible [Remy et al., 2019], aside from the deciduous dentition development, the progressive activation of the orofacial muscles dedicated to sucking, phonation, deglutition, breathing, mastication, etc., also participate in the morphological growth pattern of the palatal vault as it implies specific strains on the bone, warping it in various ways.

These results are interesting from a clinical perspective as they imply that the palatal vault morphometrics can be corrected with myofunctional therapeutic strategies: by acting on the swallowing pattern, the tongue posture, oral habits, breathing patterns [Garliner and Gables, 1982]. Because training methods seem to be less efficient than intraoral appliances to provide such a muscular solicitation [Koletsi et al., 2018], one challenge for the future would be to develop new solutions to correct – or even prevent – palatal vault abnormalities through the activation of orofacial muscles. For instance, considering their association with malocclusion [Zardetto et al., 2002], new "breast-like" pacifiers or feeding bottles may be developed in the future, benefiting from these data on the evolution of the shape and size of healthy children' palatal vault.

Thus, this Orofacial Myofunction Rehabilitation (OMR) strategy may be an efficient alternative solution to more invasive intra-oral treatments to correct the earliest as possible the maxillary growth. Indeed, most of the time, maxillary constriction is treated during the mixed dentition period (i.e. between 6–12 years old), through maxillary expansion by fixed or removable appliances. Yet, according to the literature, it seems that these orthodontic treatments have little to no clinical implication [Alsawaf et al., 2022].

Data Availability Statement

The data underlying this article will be shared on reasonable request to the corresponding au-thor.

Conflict of Interest statement

Authors have no conflict of interest to declare.

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