Palatal surface development from 6 years of age to early adulthood: data modelling using 3D geometric morphometrics

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Research Article

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Abstract

Objectives: The study followed the modelling of postnatal growth of a healthy palate of the Central European (Czech) population sample based on transverse data on sex and age from 6 to 19 years.

Materials and methods: Digitised 3D models of 212 healthy palatal surfaces were evaluated using 3D geometric morphometrics and superprojections. The individuals were grouped based on age (preschool, younger and older school age, younger and older adolescents, young adults) and sex (n=101,   n=111).

Results: Female palatal development was non-linear and was interrupted between the 10–12 years and then proceeded intensively until the age of 15 when it ceased. In contrast, male modelled growth was consistent throughout the follow-up and continued linearly until at least 19 years of age. The palate did not widen further with increasing age, and primarily palatal vaulting and heightening were found. The characteristics and distribution of areas with extensive modelled growth changes were comparable in females and males, as confirmed by the correlation of PC1 and PC2 within modal space and growth trajectories. The extent of sexual dimorphism increased from 15 years of age due to pubertal spurt combined with earlier completion of palatal development in females.

Conclusions: The study showed modelled healthy palatal development from 6 years of age to early adulthood, which might be utilised as reference standards for the Central European population sample.

Clinical relevance: The comparison of normal reference subjects with patients with cranio-maxillo-facial dysmorphologies represents the first step in diagnosing and establishing effective therapy.

Introduction

Palate formation occurs between 6 and 12 weeks of gestation as a strictly regulated process involving specific signalling pathways and transcriptional regulators. The primary palate is created by a fusion of intermaxillary segments with maxillary facial processes, whereas the secondary palate first appears as paired bilateral mounds growing caudally from the medial side of maxillary and medial nasal facial processes. During secondary palate formation, cranial neural crest cells initially migrate to the maxillary process of the first pharyngeal arch, where reciprocal signalling with oral ectoderm controls the process of palatal plates outgrowth [1]. This is followed by elevation and fusion of the two palatal plates, which is associated with the destruction of median epithelial suture [2]. Failure at any stage of this process, and simultaneous presence of various genetic defects, may disrupt palatal plate fusion or development of the first branchial arch and cause craniofacial deformities, including micrognathia, asymmetry, and malocclusion or orofacial clefts [3].

In the postnatal period of life, the palatal grows primarily throughout the entire surface and the suture, increasing palatal width and length [4]. In general, postnatal growth of the palate may be divided into 3 phases according to the mechanism of development: sutural growth, sutural growth combined with bone remodelling and growth by bone remodelling, which predominates in later stages of life [5].

It was determined earlier that palatal width decreases postnatally with increasing age. Using classic morphometric methods, it was reported that the palate in males is generally wider than in females. The most visible changes in palatal width occur from birth to 4 years of age [6]. Only minimal increases in palatal width are noted between 4 and 13 years of age [7], with no evident significant growth changes after this period [6, 8]. Analysis of length measurements also indicated that substantial gains are observed during the first two years of life. Similar to the width is a mild increase in palatal length between 2–13 years of life, while a decrease in both dimensions appears after the age of 13 [9].

The development of the palate is sex specific. The first intersex differences are already visible prenatally when closing the palatal plates proceeds slightly differently in both sexes. The onset of the fusion of palatal plates and their subsequent shift to a horizontal position may be observed in males from the beginning of the 7th gestational week, whereas in females, this process is delayed by approximately one gestational week [10]. This may result in varying incidences of orofacial clefts between sexes [11].

In addition to differences in embryonal development, male and female palates vary in size, shape, period, and intensity of growth. Specifically, other postnatal sexual differences in the palate include larger palatal dimensions in males compared to females, a slower period of growth after the age of 12 years in females compared to males [9], more prominent protraction of the upper alveolar processes relative to the plane of the palate in females [12], variability in number, shape and distribution of the palatal rugae [13] and, the overall shape of the palate [14].

While the embryonic development of the palate is well mapped [15, 16], comprehensive information on the postnatal ontogenetic development of the palate is lacking so far. Although many studies have investigated the changes in palatal dimensions during postnatal life [6–8], these studies were based on classic morphometric methods that cannot fully reflect developmental changes of the entire palatal surface [17].

A complex knowledge of the exact mechanisms by which the entire palatal surface grows is essential for planning orthodontic interventions during childhood and adolescence. Considering the sex and population specificity of the ontogenetic palatal development, its analysis may contribute to establishing standards for palatal defects in the Central European (Czech) population sample. Knowledge of palatal development and morphology may also be useful in forensic science, where palatal sutures may be utilised to estimate the age of individuals. Knowledge of the physiological growth of the palate can be used in plastic surgery, speech therapy, paediatrics, and other medical disciplines as well.

The main objective of the present study is to model the growth of healthy palatal surfaces from 6 years of age to early adulthood in the Central European population sample. The further aim is to evaluate the extent of sexual dimorphism of the palate in the specified age range. Based on these objectives, comparative standards valid for the Central European population sample can be established and utilised in clinical practice. Normal reference subjects and their comparison with patients with palatal and other cranio-maxillo-facial defects represent the first step in diagnosing and determining effective therapy [18].

Materials And Methods

Ethical statement

The Ethics Committee of the Institutional Review Board of the Faculty of Science of Charles University approved this research project. The research was performed in accordance with the ethical standards defined in the 1964 Declaration of Helsinki and its subsequent amendments.

Subjects

A total of 212 participants of Czech origin with a minimum age of 6.2 years and a maximum age of 20.0 years were included in the present study. The exact number of individuals is presented in Table 1. Dental casts were obtained from each subject between 1975–2004. Individuals were divided into the following age groups: preschool-age (T0), younger school-age (T1), older school-age (T2), younger adolescents (T3), older adolescents (T4), and young adults (T5). A more detailed age distribution, including average, minimum and maximum ages, is reported in Table 2. Only healthy individuals without a diagnosed palatal malformation or disease affecting craniofacial morphology were included in subsequent analyses. The selected individuals did not undergo any craniofacial surgery and did not suffer any significant palatal or facial trauma.

3D model acquisition

The dental casts were scanned using a Roland LPX-250 3D laser scanner (Roland DG, Hamamatsu, Japan) with a resolution of 200 µm. High-resolution 3D models of the palate represented by triangular meshes were obtained with Dr. Picza 3 software (Roland DG, Hamamatsu, Japan). The 3D models were further modified in Pixform (Roland DG, Hamamatsu, Japan) and Rapidform XOS 2006 (INUS technology Inc., Seoul, South Korea) software. Using these software, teeth and other unnecessary parts of the palate were manually removed from the 3D models. Furthermore, minor errors in the surface model were corrected by filling holes in triangular mesh caused by insufficient scanning of problematic parts of the palate. Finally, each palatal model was smoothed and decimated to a surface mesh with 26k triangles.

3D model processing

All further statistical processing of the 3D models was completed in Morphome3cs Software (http://www.morphome3cs.com/). Before statistical evaluation of the data, it was crucial to apply coherent point drift-dense correspondence analysis (CPD-DCA), a modification of the original dense correspondence analysis (DCA) algorithm [19], to ensure the vertex homology. The modified algorithm was utilised to create homologous representations of palatal surfaces, expressed by verticals and triangles with the same index defining the same anatomical characteristics.

To obtain vertex homology, four landmarks were first applied to the 3D palatal models. In the present study, the following landmarks were utilised: the landmark between the central incisors at the incisive papilla (1), the centre of the palatal margin of alveolar processes of the first permanent molars (2, 3), the centre of the palatal arch at the junction of the line passing through landmarks 2 and 3 with the perpendicular line intersecting the landmark 1 (4). These landmarks were used for rigid pre-alignment, which accelerated convergence in the next stage of CPD-DCA. Before data evaluation, measurement error was determined to be 0.11 mm after reusing landmarks on five randomly selected 3D palatal models, according to von Cramon-Taubadel et al. [20].

After that, one surface topology (base mesh) was randomly selected to which all other surface models (floating meshes) were aligned based on landmarks. An automatic non-rigid registration algorithm was then used to attach this base mesh to every other surface homologous to the base mesh. In later stages, landmarks were no longer used in the 3D models. Since the deformation of the floating meshes in the CPD-DCA analysis was accomplished by aligning the vertices of the triangles at the closest point to the base mesh surface, CPD-DCA achieved a more accurate surface assignment than the original DCA analysis [21].

Eventually, generalised Procrustes analysis (GPA) was used to rigidly align homologous surface representations by removing translational and rotational differences from the data. Using GPA, the 3D models were not normalised to the same size; therefore, the palatal form was examined with the original size in all subsequent morphometric analyses.

Statistical analyses

Principal component analysis (PCA) was applied to the vertex coordinate matrix to quantify the variability while reducing the dimensionality of the vectors using a linear transformation. The principal components (PC) represented uncorrelated and independent variables that explained the morphological variability of presented samples with minimal loss of information. The PCs and their percentage contribution to the distribution of variables were visualised in a scree plot, from which PCs containing adequate information about the variability of the samples may be determined. The only PCs that were positioned on the scree plot according to the broken-stick rule of thumb [22] and simultaneously explained more than 10 % of the total variability (PC1 and PC2) were included in the data analysis.

The main outcome of PCA was a graphical representation of the PC scores using a scatter plot with confidence ellipses defining the region of the plot where each individual is 95 % probable to occur. The scatter plot expressed the differences in form variability between analysed age groups, with black arrows indicating the direction of the growth trajectory for the sexes. Each point on the scatter plot depicted a specific individual, and its position was determined within the modal space of PC1 and PC2. In addition, it was possible to observe changes in the form of the average 3D palatal models, which varied interactively as a function of movement into positive or negative PCs. This detailed visualisation contributed to a more efficient evaluation of the morphological differences between PCs.

Using superprojection, visualisations of differences between age groups (modelling of palatal growth changes) in each observed age and sex category were created. The superprojection resulted in colour-coded maps, including the superposition of the younger group's mean palate with the older group's mean palate (modelling of growth changes in age groups) or the mean female palate with the mean male palate (sexual dimorphism). The colour-coded maps further depicted average differences on the base mesh and indicated the distance between two points on the polygonal grid.

There were modelling growth changes within each age group by colour-coded maps containing red, blue, and green shades. Palatal areas marked with red and other warm colours showed positive growth changes (protrusion). Conversely, the region of palates that were coloured blue and other cool colour tones indicated areas of negative growth (retrusion). The green colour represented areas where no differences in palatal form were observed between all studied groups. A red-blue-white colour scale was used to show sexual differences, where the blue area indicated more pronounced areas in males, while the red colour corresponded to the more protrusive regions of the female palate. In the case of white colour, no sexual differences were observed.

To visualise modelled growth changes more accurately in each age group, a compare group function was utilised, resulting in an overlap of two palates with different colouration and transparency. This function manifested the average younger palate (orange) superimposed on the average older palate (green). The mixed orange-green colour indicated the overlapping of the younger and older palate.

A statistically significant difference between age groups and sexual differences between the palatal surfaces were expressed using a per-vertex t-test based on the two-sample t-test. The per-vertex t-test evaluated the shell distance differences between all homologous vertices of the polygon networks forming the 3D models of the palate. This method resulted in a shell distance significance map. Shades of blue on significance maps were provided by significance level (p-value), with the darkest blue region manifesting the most significant modelled growth differences. The palatal areas marked in white showed no statistical significance [23].

Results

Palatal variability from childhood to early adulthood

The PCA was utilised to visualise the form variability of palatal segments in healthy subjects with different sex and age distributions (Fig. 1). Modelled growth differences in palatal variability in each group were expressed by the first two principal components, which explained 62.2 % of the total variability. The rest of the variability (37.8 %) was dispersed in the remaining PCs, with the amount of explained variability decreasing very rapidly.

A closer look at the distribution of individuals in modal space expressed that the most considerable variability was observed in males at younger school-age and females at older school-age and younger adolescence. The effect of PCs on palatal variability and its changes related to age and sex of the analysed individuals were then assessed in more detail. The PC1 strongly correlated with the palatal size and development. The palates located in the modal space towards the positive values of PC1 were small, short, relatively broad, and deepened in the medial part of the palate. In contrast, palates situated in negative PC1 values were visibly large, long, relatively narrow, and high in the posterior part of the palate. Conversely, the height in the medial part of the palate decreased, resulting in an overall rounding of the palate.

When monitoring PC2, it was evident that it primarily contained information about the overall shape of the palate. With negative values of PC2, the palate shortened and relatively widened, while the height of the palate increased, resulting in a marked vaulting, and flattening of the palate. On the opposite, movement to positive values within the modal space caused a considerable elongation of the palate. Simultaneously, there was an apparent decrease in palatal height in the medial region and an increase in palatal height in the posterior region, resulting in flattening in the anterior part of the palate.

The dependence of PC1 and PC2 expressed in the scatter plot reflected the modelled growth of the palate from the youngest to the oldest age group regardless of sex. The youngest age group was situated in positive PC1 and negative PC2 values. The palates of younger individuals were thus characterised by smaller size in the anteroposterior dimension, and they were short and relatively wide simultaneously. With increasing age, there was a marked shift of individuals into negative PC1 and positive PC2 values, which meant that the palates became larger. At the same time, their height decreased in the medial palatal region relative to other dimensions. The palatal height in the posterior part of the palate increased, leading to a distinct palatal flattening. These developmental trends were also confirmed by visualised growth trajectories (black arrows) with stronger modelled growth intensity in males.

Modelling of palatal growth changes in females

Different age groups were visualised using superimposition through colour-coded maps and shall distance significance maps. The modelled growth changes from 6 years of age to early adulthood in females and subsequently in males were depicted.

When the palates of preschool-age and younger school-age females were compared, significant changes were localised in the posterior part of the palate. The palate of the older group of females was higher and elongated posteriorly in this area (Fig. 2A).

In the second comparison between younger school-age and older school-age female, the main significant differences were situated in the medial area of the palate. The palate of the older school-age females became more flattened and concave in this region. Smaller areas of significant changes also occurred anteriorly and posteriorly. These changes indicated an increase in the palatal length and height in the posterior part of the palate in the older group of females (Fig. 2B).

Comparing older school-age females and younger adolescents showed almost no significant differences. Only small areas of significant differences were localised in the lateral part of the alveolar processes. According to the colour-coded maps, the palate of the older group of females was slightly longer and higher posteriorly. Areas or alveolar processes were moderately more vaulted. This difference contributed to the greater palatal height of the older group of females (Fig. 2C).

The greatest differences were shown in the comparison of the younger adolescents and older adolescents. In this comparison, the trends from the previous comparison continued, with the largest differences localised in the same areas, but they were much more pronounced and significant. The palate was longer and higher. Palatal height becomes greater in the posterior part of the palate. Alveolar processes were more vaulted, mainly in the posterior part of the palate. This resulted in greater posterior palatal height in the older group of females (Fig. 2D).

The last comparison of the older adolescents and young adult females revealed almost no significant changes. Colour-coded maps also showed no differences that might represent changes in palatal development (Fig. 2E).

Modelling of palatal growth changes in males

In the case of males, almost no significant differences were observed when comparing the youngest groups of individuals (preschool-age and younger school-age). Colour-coded maps indicated only slight changes. The palate became longer and higher in the posterior area. Alveolar processes were slightly more vaulted in the older groups of males (Fig. 3A).

The second comparison between younger and older school-age males also showed almost no significant changes. Color-coded maps again depicted more vaulted alveolar processes and slight prolongation of the anterior and the posterior palatal areas. The height of the posterior part of the palate became slightly greater in older school-age males (Fig. 3B).

The comparison of older school-age and younger adolescent males displayed significant differences, mainly in the posterior area of the palate. The palate was longer and higher in this area in younger adolescent males. The medial area of the palate was more concave and flattened (Fig. 3C).

The same trends were visible in comparison to younger and older adolescent males. The palate became longer and higher in the posterior palatal part. The medial area was again more flattened and concave in the older groups of individuals. However, there was a difference between the previous comparisons. In this comparison, the posterior part of the alveolar processes was more vaulted, which accounted for the greater palatal height of older adolescents than younger adolescents. The comparison of these two groups of males showed the greatest significant differences, and therefore it indicated the greatest changes in palatal development (Fig. 3D).

The last comparison of older adolescents and young adult males also showed large areas of significant differences. There were similar trends to the previous comparison, except that the changes in alveolar processes were much more expressed not only in the posterior parts of the palate, but also in the whole lateral palatal parts that were more vaulted. Palatal height and length in the posterior area were again greater in the oldest group of individuals (Fig. 3E).

Modelling of palatal growth changes throughout the follow-up

The whole time period was divided into two parts: prepubertal age (differences between preschool-age and younger adolescents) and post-pubertal age (differences between younger adolescents and young adults), differences between males and females in timing and characters of modelled growth changes were visible. In prepubertal females, the main changes involved the posterior part of the palate, which became lengthier and more extensive. The same trends were apparent in males but slightly less pronounced (Fig. 4A).

On the contrary, the differences were more pronounced in males than females in the post-pubertal age period. In males, elongation, and enlargement of the posterior part of the palate continued to appear. Differences were also evident in the lateral parts of the palate, where alveolar processes were more vaulted. The medial area flattened and became more concave. In females, the differences were similar and significant but not as strongly expressed. This was particularly evident in the case of palatal length, which only changed slightly (seen in superimpositions). Just the height of the female palate increased posteriorly (Fig. 4B).

The overall comparison of preschool-age individuals with young adults indicated general modelled growth changes occurring during the follow-up period. Although the localisation and characteristic of the differences between preschool-age and young adults were similar in sexes, superprojections clearly showed greater differences in males than in females. The male palate became longer, higher, and more flattened in the medial area than the female (Fig. 4C).

Sexual dimorphism of palatal development

The most significant differences between males and females in all investigated age categories were found in older adolescents and young adulthood (Fig. 5). In the preschool-age period, significant differences between males and females were located in the lateral parts of the palate. Alveolar processes were more vaulted in females, and the palatal width was more significant in males. The palatal height was slightly greater in the medial area in females (Fig. 5A).

Almost the same differences occurred in the younger school-age group. Alveolar processes were more vaulted, and the palate was higher in females than in males, but these differences were not significant (Fig. 5B).

The pattern of sexual dimorphism changed in the older school-age group. Palatal height in the medial area was significantly greater in males than in females. On the contrary, the posterior area was slightly higher in females, and their palate was broader and less peaked than the male palate in this area (Fig. 5C).

Younger adolescents manifested significant differences in the posterior area of alveolar processes. These were more vaulted in females than in males, and male palates were broader in this area. The medial and posterior area of the female palate was again higher, but this difference was not significant (Fig. 5D).

Vast areas of significant differences between males and females were evident in the older adolescents. The greatest differences were localised in lateral parts of the palate. The male palate was wider than the female palate, and the female alveolar processes were more vaulted throughout the entire palatal length. The second significant difference occurred in the medial area. The female palate was higher in this region (Fig. 5E).

More vast areas of significant differences between males and females were detected, but the pattern of sexual dimorphism changed in young adults. Significant differences were localised in the palate’s anterior and posterior parts. The male palate was longer and higher posteriorly than the female palate in this age group (Fig. 5F).

Discussion

To the best of our knowledge, most previous studies evaluated the palates of children, adolescents or adults with morphological defects or malformation. At the same time, analyses of the healthy palatal development during childhood or adulthood are so far lacking. In addition, previous studies dealing with the morphology and development of the healthy palate were conducted using classic morphometric methods to assess linear palatal dimensions [7, 9, 24]. Yet, analyses of the whole palatal volume and surface were more robust to size and shape differences than linear measurements [25]. The current study is, therefore, the first one focusing on the children, adolescents, and early adults of the Central European (Czech) population sample as well as considering the entire 3D palatal surface using geometric morphometrics and superprojections. Using these advanced methods, it was possible not only to determine how the whole palate changes the size and variability, but also to follow the direction and intensity of modelled growth in different regions of the palate.

Studies describing palatal variability in the healthy Central European population sample are not yet fully available. The present data might contribute to the development of norms that could be used to compare patients with craniofacial dysmorphologies, including orofacial clefts [26, 27]. In our set of individuals, the most considerable variability was observed in females of older school-age and younger adolescence, accompanied by only minimal movement of individuals within the modal space. This indicated that the female palates did not change markedly during this period compared to the same age groups in males, leading to a slowing and gradual cessation of the modelled palatal growth. The observed slowing of palatal development after the age of 15 in females was consistent with the study by Ferrario et al. [28], where the slowing was noted in overall facial growth.

The modelled growth of the palate in females stopped after the age of 15. According to the present results, the palatal development in females was completed earlier than in males, where it continued at least up to 19 years of age. In this respect, the present research agreed with the study of Jelinek et al. [29], where it was confirmed that the female maxilla barely grows after 15 years, while in males, the modelled growth stopped after 17 years of age. In line with this, the study of Melsen [4] confirmed that the growth of the female palate, according to the activity of osteoblasts in the suture region of the palate, is finished after 15 years.

The palatal development associated with changes in its dimensions proceeded linearly from the youngest to the oldest age category in males, with the largest modelled growth changes occurring between 12 and 15 years of age. In contrast, the development of the female palate did not follow a linear pattern, mainly due to an earlier cessation of development after the age of 15 years, with the most extensive modelled growth changes observed between younger and older adolescence. Consistent with Šmahel [30], the most significant palatal growth changes at this age corresponded to the largest growth rate during the pubertal spurt (females aged 12 years and males aged 14 years).

Linear development in females was interrupted by a temporary slowing of the modelled palatal growth between 10 and 12 years, where almost no significant changes were evident throughout the palatal surface. This was consistent with the findings of Ferrario et al. [28], reporting a significant decrease in facial development rate in females after the age of 11 years. It was hypothesised that the temporary slowing of palatal development might correspond to the overall stabilisation of maxillary growth after rapid development between the ages of 5 and 11 years due to eruption of the permanent dentition [31]. This did not agree with the fact that in males, the permanent dentition was only slightly delayed compared with females; however, no temporary deceleration of the modelled growth was noted.

When the modelled changes in morphology over the entire follow-up period were observed, it was evident that the increase in palatal width occurred in the present cohort of individuals at younger ages up to approximately 12 years of age. This agreed with the results of many studies [6, 7], which reported that the palatal growth in width ceases between the ages of 12 and 13 years, and therefore only nonsignificant changes were noted. Nevertheless, the most significant changes in the lateral palatal regions might be apparent in females between the younger and older adolescents. This was due to the vaulting of the palate, which mainly increased palatal height. The most significant changes for males in the lateral palatal regions were visible between the older adolescents and young adults. The alveolar processes enlarged and convex, causing an increase in palatal height, while the palatal width remained unchanged.

The first significant signs of sexual dimorphism in the lateral and medial region of the palate started to appear in the present group of individuals at the age of 15 years. They were mainly affected by the disproportion in modelled linear growth between females and males. Jelinek et al. [29] observed manifestations of sexual dimorphism as early as around 12 years of age. This minor discrepancy between our studies might be caused by the wider age intervals between the analysed groups.

Females in the older age ranges (15 and 19 years) presented a less deepened (less high) palate in the transverse palatine suture and a shorter palate in its posterior part than age-matched males as per our outcomes. According to Ursi et al. [32], these morphological changes were presumably attributed to gonadal changes during ongoing pubertal development combined with a delayed growth spurt in males. The presence of sexual dimorphism in palatal length and height was also in line with Bigoni et al. [12].

The results of this study might be utilised in clinical practice as reference data for comparison and subsequent diagnosis and treatment of individuals with negatively affected craniofacial morphology. In addition, our data, and their modelling by geometric morphometrics and superprojections, could be useful in monitoring modelled growth patterns, and their application might lead to improved treatment protocols for children, adolescents, and young adults with cranio-maxillo-facial abnormalities.

Conclusions

The present study analysed the palatal development, its variability and sexual dimorphism in the Central European (Czech) children and adolescents aged 6–19 years. Using the methods of geometric morphometrics and superprojections, the modelled age- and sex-related changes in the morphology of the entire palatal surface were investigated. As a result of the chosen methodology, it was feasible to track individual morphological changes' direction and intensity and locate them directly on the palatal surface.

Based on the performed analyses, the following conclusions were reached by the results:

1. PC1 correlated with modelled growth and associated palatal size changes during childhood and adolescence in the age range 6–19 years. The PC2 provided information on the overall shape of the palate and its changes during maturation. The correlation of PC1 and PC2 reflected the modelled growth of the palate from the youngest to the oldest age group regardless of sex, which was confirmed as well by the growth trajectories.
2. The modelled linear growth of the female palate was temporarily interrupted between the older school-age and younger adolescents. The modelled growth changes in females were observed primarily between younger and older adolescents (12–15 years). After the age of 15 years, palatal morphology did not change considerably.
3. In males, a continuous pattern of palatal development was evident throughout the study period. In contrast to females, modelled growth changes did not stop at 15 years and instead continued linearly until at least young adulthood (19 years).
4. The localisation and characteristics of modelled growth changes between preschool children and young adults were similar with larger intensity in males. Overall, the palate did not visibly widen in the post-pubertal period, and a marked vaulting of the palate was found.
5. Sexual dimorphism was evident at all studied ages; however, it was most significant in the older adolescent group (15 years), where the male palate was wider in the lateral region and higher in the medial region of the palate.
6. In the oldest age group of young adults, the pattern of sexual dimorphism slightly decreased and modified. It was realised in the form of a longer male palate, which was higher in the posterior and anterior parts compared to the female palate.

In conclusion, the results of this study might provide a reference for comparative studies examining the palate of Central European individuals suffering from cranio-maxillo-facial abnormalities.

Declarations

Compliance with ethical standards

Conflict of interest

Lenka Kožejová Jaklová declares that she has no conflict of interest.

Jana Velemínská declares that she has no conflict of interest.

Ján Dupej declares that he has no conflict of interest.

Tomáš Moravec declares that he has no conflict of interest.

Šárka Bejdová declares that she has no conflict of interest.

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Ethical approval

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. The study was approved by the IRB Charles University, Faculty of Science (No. 2022/13).

Author contributions

Lenka Kožejová Jaklová drafted and revised the manuscript, analysed, visualised, and interpreted the data.

Jana Velemínská proposed the experimental design of the study, critically revised the manuscript, and participated in data analysis and interpretation.

Ján Dupej contributed to the application of statistical, mathematical, and computational techniques in data analysis and interpretation.

Tomáš Moravec edited and processed the data, participated in data collection, visualization, analysis, and interpretation.

Šárka Bejdová provided critical revision of the manuscript, agreed on the final study design, and participated in data visualization, interpretation, and analysis.

All authors read and approved the final version of the manuscript.

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Tables

Table 1. The total number of subjects used in the present study. F: females, M: males.

	T0	T1	T2	T3	T4	T5	summary
F	11	12	19	20	24	25	**111**
M	11	12	15	23	22	18	**101**
summary	**22**	**24**	**34**	**43**	**46**	**43**	**212**

Table 2. Age distribution of individuals in each analysed group. F: females, M: males.

	F			M		
age (years)	**average**	**minimum**	**maximum**	**average**	**minimum**	**maximum**
T0	6.7	6.2	7.0	6.7	6.4	7.0
T1	7.7	7.2	8.1	7.6	7.1	8.3
T2	9.9	10.6	9.5	9.8	9.6	10.1
T3	11.6	11.2	11.9	11.3	11.0	11.9
T4	14.7	14.1	15.2	14.6	14.2	15.0
T5	18.7	17.5	19.4	18.5	17.1	20.0

Figures

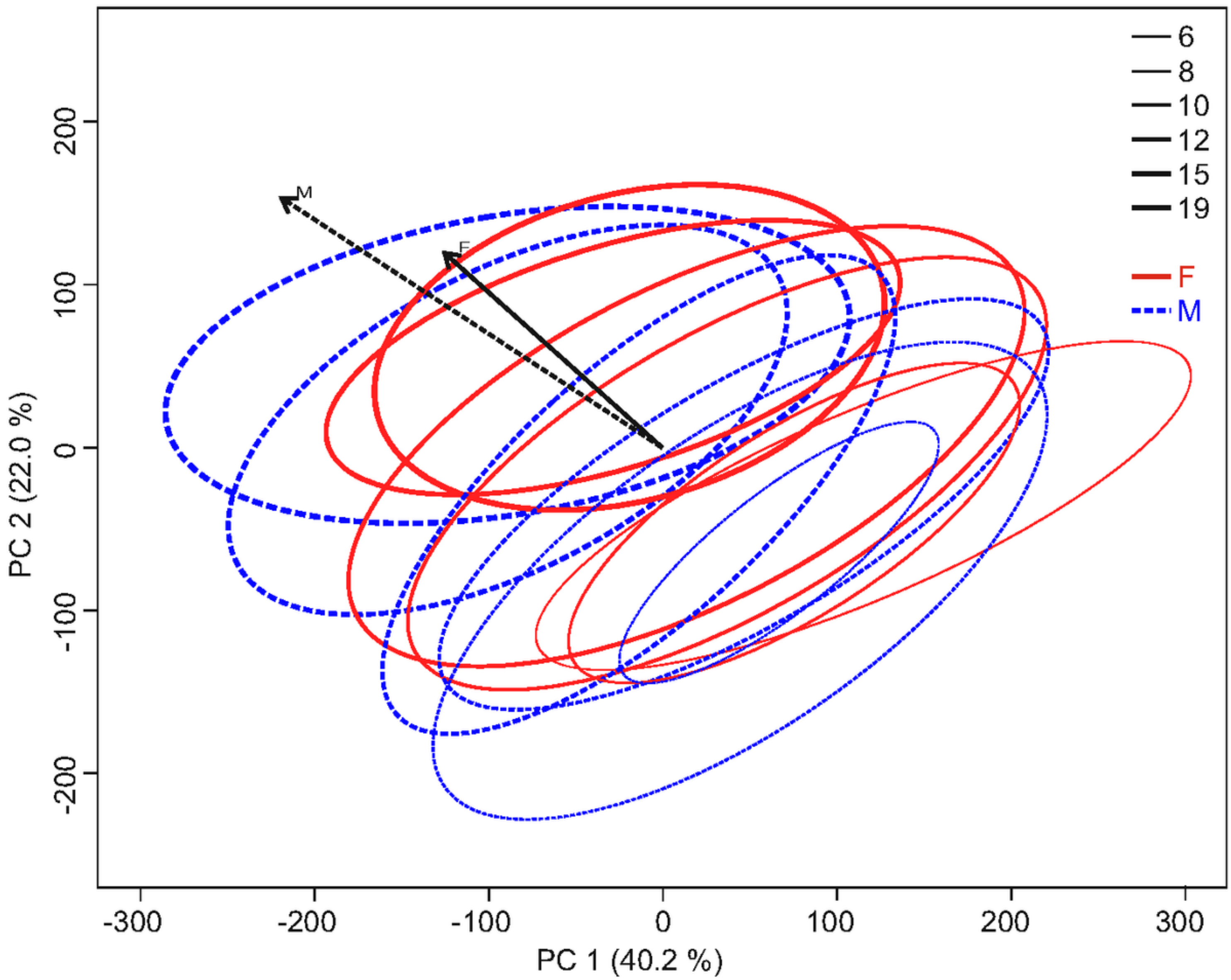

Figure 1

Scatter plot indicating the dependence of the principal components (PC1 and PC2) contributing to the 62.2 % of palatal form variability in females and males in all age categories. Confidence ellipses for the groups at the 95% level are included in the scatter plot. The solid line describes female's confidant ellipses, while the dashed line shows male's variability. The boldness of the line widens concomitantly with increasing age. Black arrows represent the growth trajectories of females (solid line) and males (dashed line).

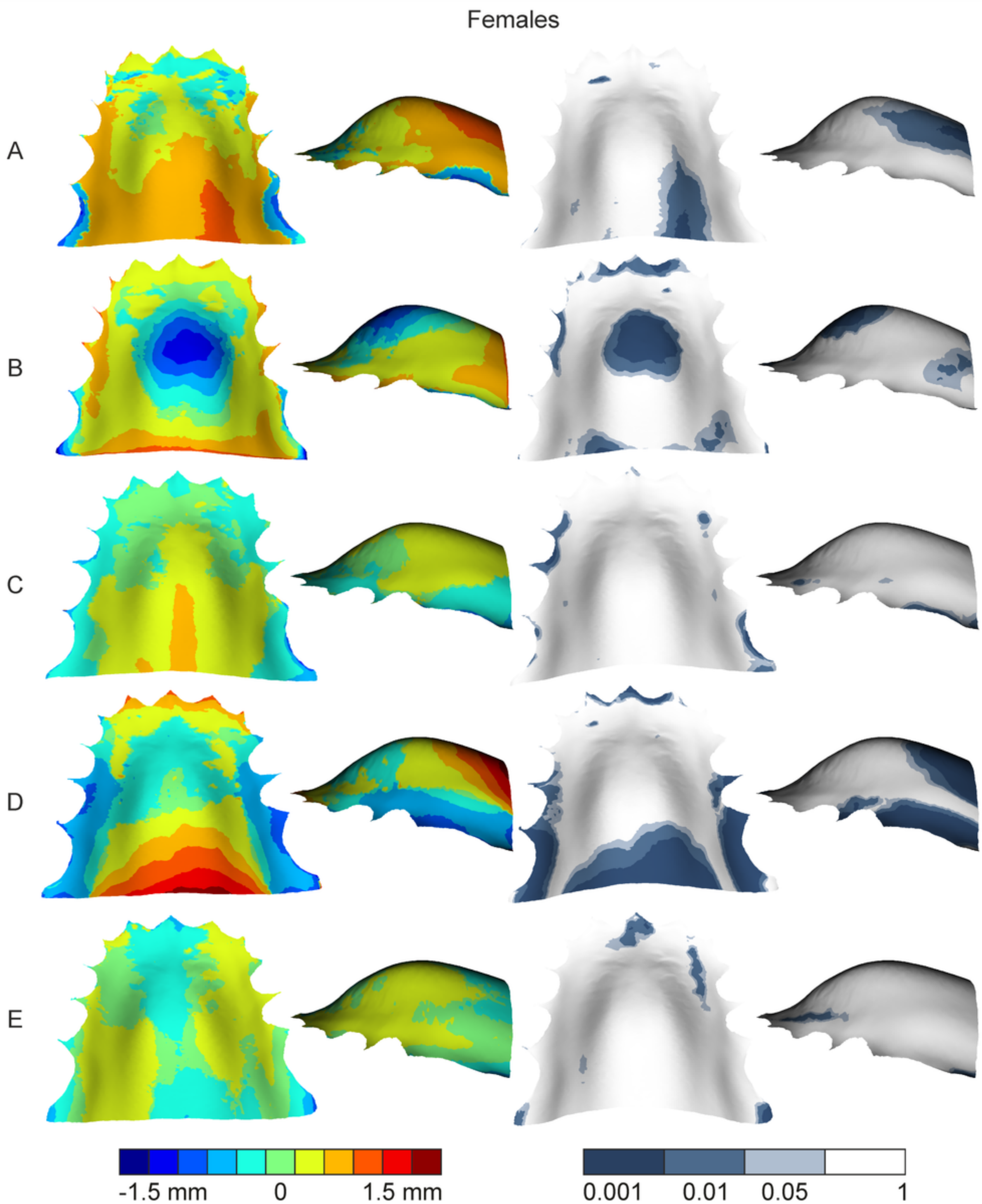

Figure 2

Colour-coded maps (left) and shall distance significance maps (right) representing modelled growth changes in palatal form and the most significant areas on the palate in females. Modelled growth changes were observed between the following age groups: A) T0 and T1, B) T1 and T2, C) T2 and T3, D) T3 and T4, and E) T4 and T5.

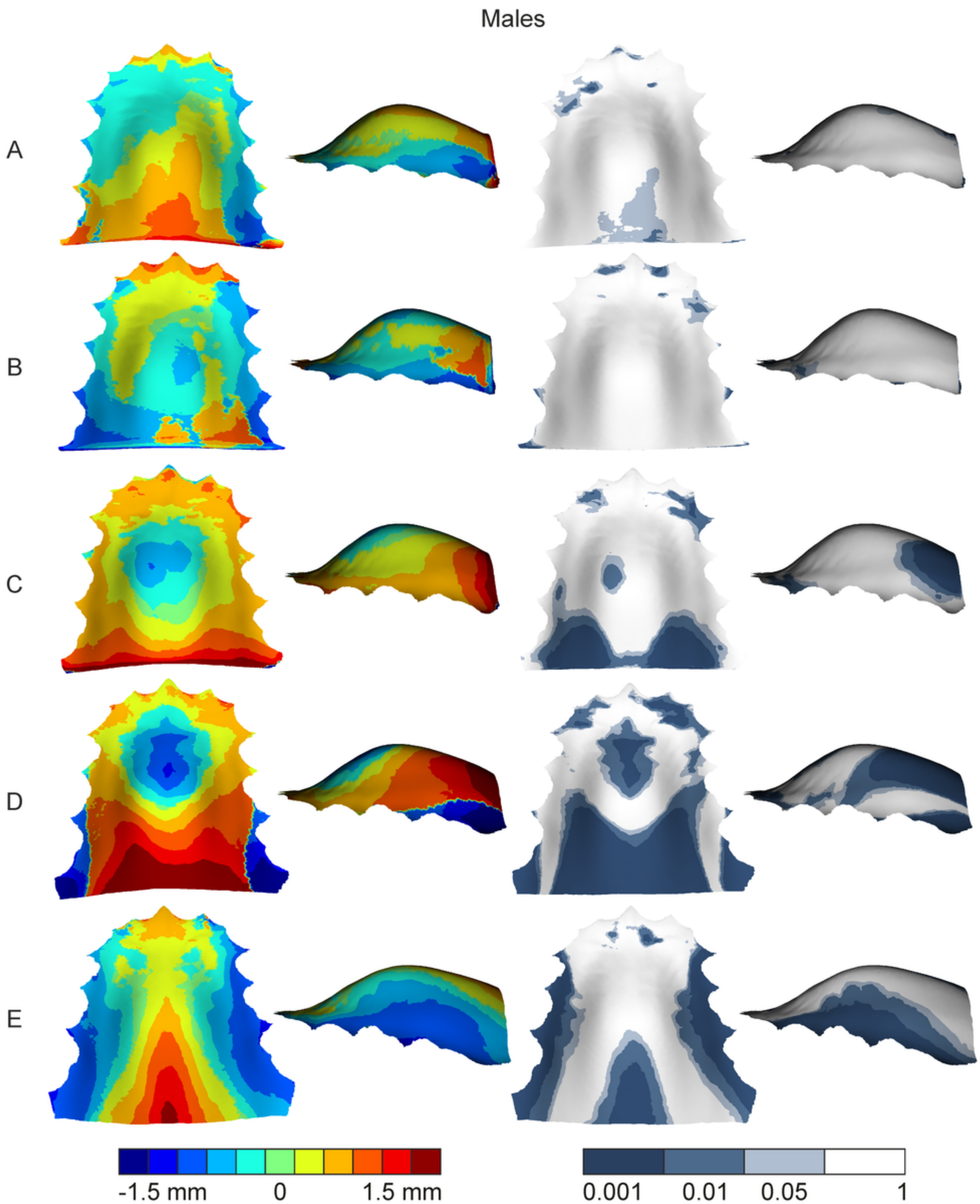

Figure 3

Colour-coded maps (left) and shall distance significance maps (right) illustrate modelled growth changes in palatal form and males' most highly significant palatal regions. Modelled growth changes were monitored between the following age groups: A) T0 and T1, B) T1 and T2, C) T2 and T3, D) T3 and T4, and E) T4 and T5.

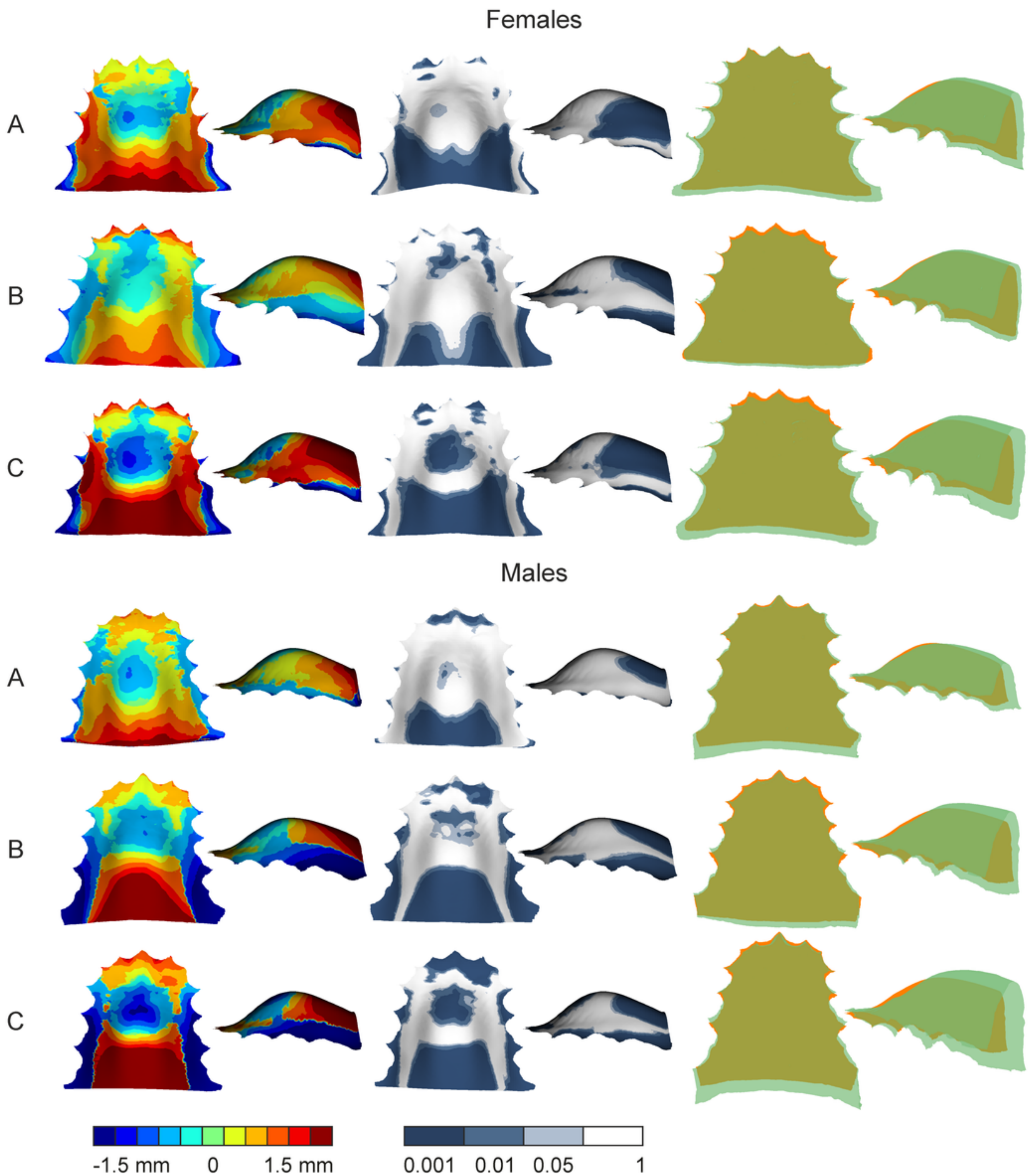

Figure 4

Colour-coded maps (left), shall distance significance maps (middle), and superimpositions (right) visualising modelled growth differences and their significance in females and males at A) prepubertal age (modelled growth differences between T0 and T3), B) post-pubertal age (modelled growth differences between T3 and T5), and C) throughout the analysed period (modelled growth differences between T0 and T5).

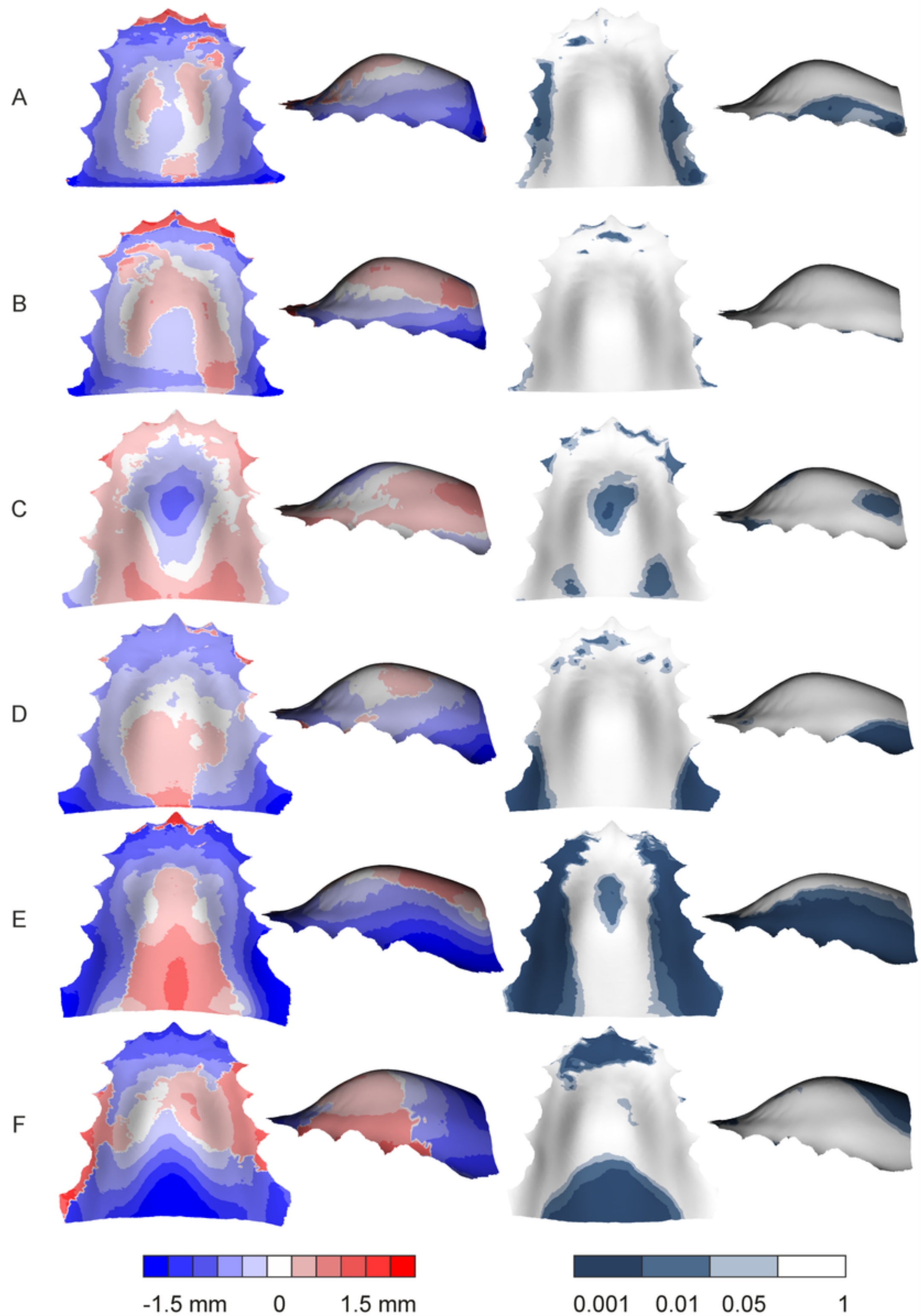

Figure 5

Colour-coded maps (left) and shell distance significance maps (right) depicting sexual dimorphism of the palatal form. Sexual dimorphism was assessed in the following age groups: A) T0, B) T1, C) T2, D) T3, E) T4, and F) T5.