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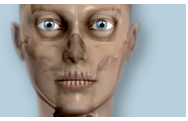

ORIGINAL ARTICLE

J. Koudelová
J. Brůžek
V. Cagáňová
V. Krajíček
J. Velemínská

Development of facial sexual dimorphism in children aged between 12 and 15 years: a three-dimensional longitudinal study

Authors' affiliations:
J. Koudelová, J. Brůžek, V. Cagáňová, V. Krajíček, J. Velemínská, Department of Anthropology and Human Genetics, Faculty of Science, Charles University in Prague, Prague, Czech Republic
J. Brůžek, Laboratoire d'Anthropologie des Populations du Passé et UMR 5809 du CNRS-PACEA, Université Bordeaux I, Talence, France
V. Krajíček, Department of Software and Computer Science, Faculty of Mathematics and Physics, Charles University in Prague, Prague, Czech Republic

Correspondence to:
J. Koudelová
Department of Anthropology and Human Genetics
Faculty of Science
Charles University in Prague
Albertov 6, 128 43 Praha 2, Prague
Czech Republic.
E-mail: spackovajana@email.cz

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Structured Abstract

Objectives – To evaluate sexual dimorphism of facial form and shape and to describe differences between the average female and male face from 12 to 15 years.

Setting and Sample Population – Overall 120 facial scans from healthy Caucasian children (17 boys, 13 girls) were longitudinally evaluated over a 4-year period between the ages of 12 and 15 years.

Materials and Methods – Facial surface scans were obtained using a three-dimensional optical scanner Vectra-3D. Variation in facial shape and form was evaluated using geometric morphometric and statistical methods (DCA, PCA and permutation test). Average faces were superimposed, and the changes were evaluated using colour-coded maps.

Results – There were no significant sex differences ($p > 0.05$) in shape in any age category and no differences in form in the 12- and 13-year-olds, as the female faces were within the area of male variability. From the age of 14, a slight separation occurred, which was statistically confirmed. The differences were mainly associated with size. Generally boys had more prominent eyebrow ridges, more deeply set eyes, a flatter cheek area, and a more prominent nose and chin area.

Conclusion – The development of facial sexual dimorphism during pubertal growth is connected with ontogenetic allometry.

Key words: 3D imaging; dense correspondence analysis; facial morphology; longitudinal growth; sexual dimorphism

Introduction

The human face shows both individual features and features that are characteristic of a specific group according to age, sex,

ethnicity or health (1). The spatial position and relative proportions of each facial component (e.g. eyes, nose, lips, chin) are mostly determined by underlying genes, but different environmental factors also play important roles.

Accurate and complex quantitative evaluation of facial morphology is of great importance in a variety of scientific fields, especially in a number of biomedical disciplines such as orthodontic and maxillofacial surgery, plastic surgery, and genetics. With regard to pre- and post-operative treatment, comparison of facial differences between patients with craniofacial anomalies or syndromes with normative values as well as comparison between different age and sex groups is important in deciding on an appropriate therapeutic course (2–4). For these purposes, the most valuable and informative reference data are those from longitudinal assessments, which best describe the growth patterns during development.

The degree of sexual dimorphism of the human face changes as a function of age (5). The growth rate is not constant throughout ontogenetic development and differences are also apparent between sexes, especially during the pubertal growth spurt, which occurs approximately 2 years earlier in females (6). In females, craniofacial growth is practically completed by about 13 years of age, while craniofacial growth in males continues into early adulthood (7). The presence of sexual dimorphism in adult facial morphology is apparent (8, 9), but the developmental aspects of facial sex differences are not so clear. The generally accepted view is that the sexual dimorphic facial traits became more apparent after 13 years of age and result from different growth trajectories in males and females (7).

Dense correspondence analysis (10) together with 3D surface imaging systems enables objective study of the whole facial surface. The construction of dense correspondences between 3D surfaces is an accurate method used to support clinical assessment of facial morphology, as well as enables identification of the anatomical structure traits characteristic for a specific group of individuals (e.g. sex- or age-specific features) (11, 12).

Using a 3D optical scanning system together with modern geometric morphometric methods, we hypothesized that this longitudinal approach would help to clarify the development of sexual dimorphism of the human face in adolescence. The primary aim of this study was to analyse the facial form and shape variation of males and females aged from 12 to 15 years to identify the sexual dimorphic traits unique to both groups. The second aim was to evaluate the differences between the average female and the average male face in all age categories.

Subjects and methods

The sample consisted of children from a high school in Kladno and an elementary school in Prague, Czech Republic, who were longitudinally studied between the ages of 12 and 15 years of age from 2009 to 2012 at approximately the same time of the year. Mean age of the subjects was 12.4 years for boys and 12.3 years for girls at the start of the study. The parents of all children were previously informed about the 3D optical scanning procedures and had given their consent to the investigation. The inclusion criteria of the study were Central European origin, body mass index (BMI) within the normal range (13) and absence of craniofacial anomalies, facial trauma or previous orthodontic treatment. Overall, 120 facial scans from 30 children (17 boys, 13 girls) from the original sample of 45 subjects were included in the study because only subjects with a complete series of scans were included.

Scanning and image processing

Three-dimensional facial images were taken using a high-resolution optical scanner Vectra-3D (Canfield Scientific, Inc., Fairfield, NJ, USA) based on stereophotogrammetric technology. The subjects were scanned sitting on a chair. They were instructed to look directly to the front and to relax their face with lips together if possible. The capture time was 2 ms which minimized changes in position or facial expression. The model was imported into RapidForm 2006

software (INUS Technology Inc., Seoul, Korea) for further processing. Finally, each facial model was composed of a triangulated surface mesh with different numbers of vertices.

Dense correspondence analysis

Prior to any other surface-based methods and analysis (i.e. facial averaging, principal component analysis), standardization of all facial models was performed. A dense correspondence algorithm (11, 12) was used to convert all the surface models into polygonal meshes with the same number of vertices by finding mutual correspondences between all facial models.

The first step of dense correspondence analysis (DCA) was to manually place nine reference landmarks on each facial model. One model was selected as the base mesh, and the other models were aligned to it on the basis of 9 reference landmarks (right exocanthion, left exocanthion, right endocanthion, left endocanthion, nasion, pronasale, right cheilion, left cheilion and pogonion). Generalized Procrustes analysis (GPA) was used to register the landmarks by removing translational and rotational (14) differences from the data. GPA enables either normalizing the models to equal sizes or preserving the size. The mean position of each landmark was computed. Each surface model was then warped into the mean position of the reference landmarks using the thin-plate spline (TPS) technique (14). Correspondences between the vertices of the base mesh and points in other meshes were found based on the closest point principle. Finally, all the surface models were unwrapped back to their original position by inverse TPS taking the points of correspondence with them. In this way, all of the surface meshes had the same number of vertices, which could be used as landmarks for further analysis. DCA is part of the subroutine of in-house Morphome3cs software (http://cgg.mff.cuni.cz/trac/morpho).

Facial averaging

The average facial shell for each specific group was created using the tools available within Morphome3cs software (including DCA, GPA without normalizing the size). Finally, four average male facial shells and four female facial shells, one each at ages 12, 13, 14 and 15, were constructed. The average faces were then imported to RapidForm 2006, where morphologic differences between all pairs of sex-specific faces were compared using a specialized superimposition technique, which has been used and described previously (15). The parameters used in our study were colour deviation maps and histogram plots, which were used to visualize and quantify areas of difference between two average facial shells. In each age category, the average female face was used as the initial (reference) shell. Generally, the more protrusive parts of the female faces were represented in red. The parts which were situated more deeply, compared to the male faces, were in blue and vice versa. The tolerance level was set at 0.5 mm, and areas with deviation below this threshold were represented in black and were considered to be similar.

Shape and form analysis

Principal component analysis (PCA) was used to explore the relationships between groups of males and females in each age category and also to analyse their variability. PCA was performed both with and without normalizing size to evaluate the variability of facial shape and form. The study was mainly focused on those components that distinguish males and females in each age category in the best possible way, that is those that most markedly exhibit sexual dimorphism. The analysis was supplemented by PCA scatter plot, which was used to visually represent variation among the individuals in the sample for a selected pair of principal components (PCs).

Multivariate permutation testing of PCA scores (16) was used to assess statistically significant differences in facial shape and form between the groups. The significance level was set at 0.05. The broken-stick criterion (17) was used to determine the number of statistically significant components included in the analysis. PCA and

permutation testing were performed in Morphome3cs.

Results

Analysis of facial form

First, variability of facial form in boys and girls aged 12–15 was evaluated in the pooled sample. Table 1 shows a summary of the statistically significant PCA components according to the broken-stick criterion, which explained from 62.5% to 72.2% of variability. However, sexual differences in each age category (Fig. 1) were best characterized using the first two components (PC1 and PC2), which together were responsible for more than 50% of the total variability in facial form (specifically 53.4%, 55%, 55.3% and 52.4%, respectively, from age 12 to age 15). PCA scatter plots (Fig. 1) show the relationship between PC1 and PC2 components and allow visualization of the distribution within each age and sex subgroup. Generally, the variation of facial form was greater in boys in all age categories with the exception of 14-year-old subjects, where variability was similar for both sexes. The PCA scatter plots further showed a high degree of overlap in the distribution of individuals in the 12- and 13-year-old groups, indicating that boys and girls were indistinguishable in these age categories. In the 14-year-old group, PC1 slightly separated boys and girls, and in the 15-year-old group, the separation became much more evident.

The results of a multivariate permutation test of PCA scores are shown in Table 2. Statistically significant differences in facial form between boys and girls were found only in the 14- and 15-year-old categories.

Superimposition was used to evaluate differences between the average male face and the average female face from 12 to 15 years. Visual comparisons are shown as colour-coded maps together with histogram plots, which display objective differences between paired average faces (Fig. 2). A decrease in the black areas was apparent (from 36.08% at age 12 to 18.34% at age 15) which indicated increased highlighting of sexual differences with age. Comparison of the average faces from the lateral view shows that the lower third of the average male face is longer in all age categories compared to females (Fig. 2). As a result, female faces appear to have relatively more protruding lower lips and anterior parts of the chin (in colour-coded maps), but in fact, these areas were situated within the supramental concavity of average male faces.

Table 1. **Principal component analysis components of facial form and shape of boys and girls aged 12–15 according to the broken-stick criterion**

Age categories	12 years		13 years		14 years		15 years	
	% of variability		% of variability		% of variability		% of variability	
Number of components	Form	Shape	Form	Shape	Form	Shape	Form	Shape
1	38.4	25.0	41.5	19.7	39.2	25.1	34.2	24.5
2	15.0	12.9	13.5	16.2	16.1	14.7	18.3	15.6
3	8.9	11.5	8.2	12.2	9.6	13.8	10.0	11.6
4	6.6	8.9	5.5	8.9	7.3	10.1		9.2
5		7.5		7.0				7.2
6		6.7		6.1				
7				5.7				
∑	68.9	72.5	68.7	75.8	72.2	63.7	62.5	68.0

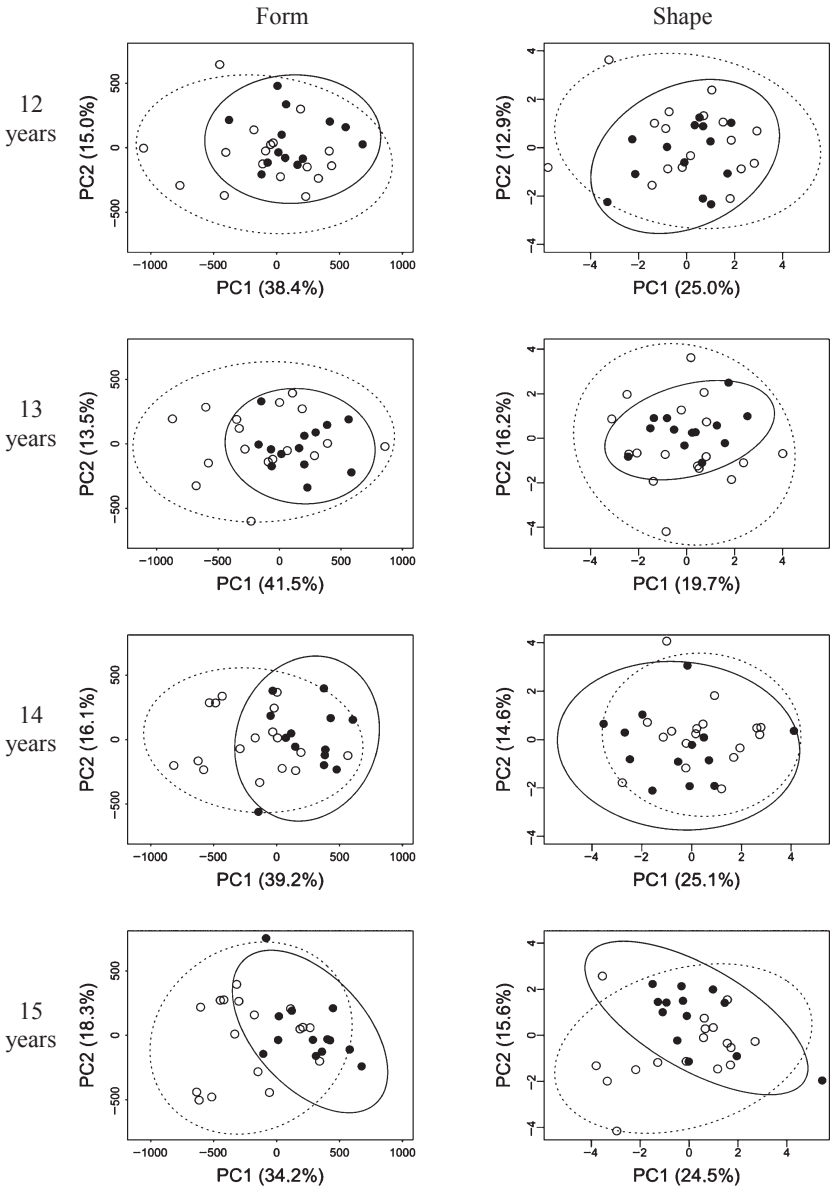

Fig. 1. Scatter plots of the PC scores of boys and girls with respect to form (left) and shape (right). The *x*-axes are the first components (PC1) and the *y*-axes are the second components (PC2). The white points represent boys, and the black circles represent girls. The confidence ellipses include 95% of the individuals in each subgroup.

In the 12-year-old group, the upper third of the average female face was longer compared to males. The female face tended to have a more anteriorly situated eye region. In contrast, males showed more marked protrusion of the lateral part of the forehead and the eyebrow ridges, as well as the nostril region, philtrum and upper lip.

In the 13-year-old group, the upper third of the average female face was still slightly longer and was also more protrusive in the central part of the forehead. The deeper situated eye region in males became more obvious compared to age 12, and the central sections of the cheeks were more prominent in girls. The boys had on average a larger and more protruding nose tip, nostrils, area below the nose, upper lip and areas around the corners of the mouth. The chin region showed more marked protrusion compared to age 12. These differences can be seen more clearly in profile view (Fig. 2).

In 14-year-old girls, there were no apparent differences compared to the previous age category, except for a more protruding cheek region, which became more evident and enlarged in downward projection. There was a visible increase in nose prominence connected with a downward shift of both upper and lower lips in boys.

In the 15-year-old category, the sexual dimorphic differences in favour of girls were again apparent in the eye region and the cheeks. The greater and more protrusive parts of the face in favour of boys were the forehead (except the central part), eyebrow ridges including the glabellar area, the entire nasal region, upper lip and mandibular area.

Table 2. **Comparison of facial shape and form differences between males and females using permutation tests**

Age category	Number of components*		*p*-value	
	Form	Shape	Form	Shape
12	4	6	0.188	0.230
13	3	7	0.122	0.333
14	4	4	0.019	0.136
15	3	5	0.003	0.109

*Number of components included to the analysis according to the broken-stick criterion.

Analysis of facial shape

In this study, only variability in the facial shape was evaluated, because no significant sexual dimorphism in shape was found. Table 1 shows a summary of those PCA components which corresponded to the broken-stick criterion. These components explained from 63.7% to 75.8% of variability in total facial shape. PC1 and PC2 described on average 38.4% of the total variability (specifically 37.9%, 35.9%, 39.7% and 40.1% at ages 12 to 15). PCA scatter plots (Fig. 1) show

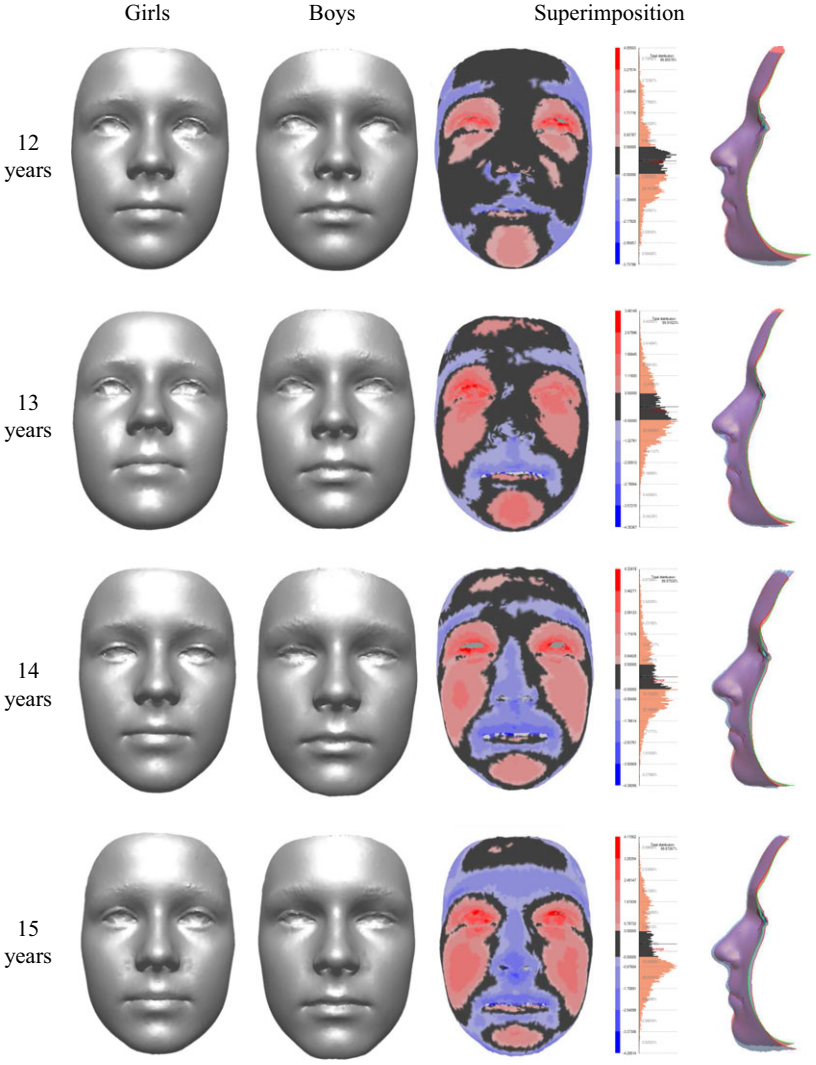

Fig. 2. Average facial shells for girls (left) and boys (centre) in each age category and their superimposition within the same age category. Superimposition is represented by colour deviation maps, supplemented with histogram plots and lateral views of transparent facial surfaces (right). The histogram plots show the differences in the colour maps. The more protrusive parts of the average female faces are represented in red, while the parts which are situated more deeply, compared to male faces, are coloured blue and vice versa in males. Black represents the areas below the tolerance level of 0.5 mm. The percentages of black areas were 36.08%, 31.21%, 24.73% and 18.34% at ages 12, 13, 14 and 15.

the relationship between the first and second components and visualize the distribution within each subgroup. Generally, variability in facial shape was greater in boys in all age categories with the exception of 14-year-old subjects, where the variability was similar for both sexes. The PCA scatter plots further show a high degree of overlap in the distribution of individuals at ages 12, 13 and 14 and indicate no overall shape differences. In the 15-year-old group, PC1 slightly separated boys and girls.

The results of multivariate permutation testing of PCA scores are shown in Table 2. No statistically significant differences in facial shape between boys and girls were found in any age category, so visual evaluation of facial shape was not performed.

Overall, statistically significant sexual differences in facial morphology were found only in the 14- and 15-year-old categories with respect to form, while facial shape differences were not observed in any age category.

Discussion

In the present longitudinal study, a 3D optical scanning system and its applications together with modern geometric morphometric methods (GMM) were used to describe the development of facial sexual dimorphism in children between 12 and 15 years of age. Previous longitudinal studies describing the sex-related facial differences during growth were mostly based on direct linear measurement of the face (18) or on X-ray films (19, 20). These studies provide valuable information about the growth of individual dimensions, but fail to capture the essence of the face as a three-dimensional structure. The 3D imaging systems used in our study overcome some of the limitations of such 2D methods, because salient features of the facial form as a whole are overlooked (21).

Variation in facial shape and form

According to the distribution of individuals, no clear differences in variation between the two sexes were found in any of the observed age categories with respect to facial shape (Fig. 1). Previous cross-sectional studies of soft-tissue facial surfaces showed no significant differences in overall facial shape in the 8- to 12-year-old group (22) and slight but non-significant differences in the shape of the lower facial third during puberty (23). This is in contrast to a longitudinal craniofacial study carried out by Bulygina et al. (24), who found that differences in facial shape occur from age 12, when growth trajectories in males and females exhibit some degree of divergence.

In terms of facial form, the separation of both sexes was observed from 14 years of age and became more apparent in the 15-year-old age category, which was confirmed statistically. This sex differentiation was obtained using the first component (PC1), which is usually interpreted as a measure of size, while all the other components are interpreted as measures of shape and this association between size and shape during growth is connected with ontogenetic allometry (25). Facial form therefore more closely reflects the development of facial sexual dimorphism than facial shape.

Sex differences in various facial parts

In terms of the upper third of the face, the average female faces were found to have a larger forehead in the lateral view in the 12- and 13-year-old age groups. These findings correspond with those of several previous studies (23, 26). The most noticeable differences in this area were found in the eyebrow ridges. Their lateral parts were more prominent in boys from 12 years of age and the prominence increased with age up to 15 years, when the prominence extended up to the glabellar area. In a slightly older age group (15.5 years), prominence of the eyebrow ridges was observed only in the lateral areas (27). In association with the more prominent supraorbital part, eyes were situated more deeply in relation to the facial plane in boys compared to girls in all age categories. One possible explanation is that sinus enlargement in conjunction with size differences in certain areas of the orbit might cause this difference in the prominence of

the glabella and eyebrow ridges (9). Deeply situated eyes in males were also found in the study population aged 15.5 years (27), as well as in adult facial morphology (8).

In the middle third of the face, differences were mainly evident in the cheeks and nose. The cheeks were protruded more in girls, which corresponding with the increase in facial (buccal) fat during puberty, which is generally much more evident in females (28). On the other hand, males had flatter cheeks in all age categories, probably due to their wider frontal and zygomatic processes (29). The most distinctive differences were observed in the nasal region. While in the 12-year-old group, no or minimal sex-related differences were found, each part of the nose subsequently enlarged with age. These results correspond with previous 2D (30) and 3D studies (27, 31). According to the hypothesis of Rosas and Bastir (32), the size of the nose and nostril soft tissues could be important in meeting the greater oxygen requirements of males.

Overall, elongation of the nose also affected the area of the philtrum and upper lip, which were more prominent in boys in all age categories, with prominence increasing with age. The same results have also been described in similar studies (27, 31). In younger age groups (below 12 years), a fuller and more prominent upper lip was found in girls (22). We also observed a greater prominence of the lower lip vermillion area in girls in all age categories and a more prominent lower lip in boys from 14 years. These differences could be observed in the lateral view (Fig. 2). If male and female average faces were ideally superimposed according to the lip area, the whole lower lip would be more prominent in boys. A more prominent lower lip in boys has also been described in the slightly older age group (15.5) (27). After 13 years of age, an overall elongation of the lower face in boys occurred, but due to the shift of the compared parts, female faces appeared to have a relatively more protruding anterior part of the chin, but from the lateral point of view, these parts were situated within the male supramental concavity. Lengthening of the lower face was mainly due to pubertal growth of the mandible, which has been described in previous studies (24, 33). One of the reasons for the more prominent mandibular region is that the male muscles, which are stronger compared to female muscles, produce greater forces that affect mandibular growth (34).

Increasing size and shape (form) of facial features during puberty is associated with a high testosterone-to-oestrogen ratio (T/E ratio) (35). Direct measurement of plasma testosterone levels in boys during puberty shows its increase with age, which results in larger and more robust male faces compared to girls with mild sexual ontogenetic allometric divergence (36). The onset of puberty occurs about 2 years earlier in females and the growth spurt slows down at about 13 years of age (7, 24), while male growth peaks at 15 years of age (37), so males take longer to achieve full facial development and their features appear more distinct (36).

Conclusions

1. Facial sexual dimorphism became more evident during pubertal growth (from 12 to 15 years). Significant sexual differences in facial form were found, but only in the 14- and 15-year-old categories.
2. No significant sexual differences in facial shape were found between 12 and 15 years.
3. The variability of facial form was greater in boys at ages 12 and 13; the female faces were within the variability of the male faces, indicating that boys and girls are indistinguishable in these age categories. At age 14, a slight separation between boys and girls was found and this separation became more evident at age 15.
4. Three-dimensional surface-based analysis together with geometric morphometric methods provides a qualitative and quantitative non-invasive technique for studying facial morphology.

Clinical relevance

Sexual dimorphism of facial morphology is clearly present in adults, but the developmental

aspects are not so clear. In this longitudinal study, a three-dimensional optical scanning system and its applications together with modern geometric morphometric methods (DCA, PCA) were used to provide a detailed analysis of the facial surface as a whole, leading to a better understanding of differences between the two sexes during pubertal growth. Knowledge of the longitudinal development of sexual dimorphism is beneficial for evaluation of different facial anomalies and syndromes as well as orthodontics or plastic surgery.

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