The 3-Dimensional Construction of the Average 11-Year-Old Child Face: A Clinical Evaluation and Application

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Purpose: This article describes construction of the average face and its application in the clinical environment.

Subjects and Methods: A total of 72 children, mean age 11.8 years, were selected for the study. Laser-scanned images of the subjects were obtained under a reproducible and controlled environment with 2 Minolta Vivid 900 (Minolta, Osaka, Japan) optical laser-scanning devices assembled as a stereo pair. A set of left and right scanned images was taken for each subject and each scan took an average of 2.5 seconds. These scanned images were processed and merged to form a composite 3-dimensional soft tissue reproduction of the subjects using commercially-available reverse modeling software. The differences in facial morphology were measured using shell deviation color maps. The average face was used to compare differences between male and female groups and 3 subjects with craniofacial anomalies.

Results: The difference between the average male and female face was 0.460 ± 0.353 mm. The areas of greatest deviation were at the zygomatic area and lower jaw line, with the males being more prominent. The results of the surface deviation between the subjects with craniofacial anomalies were significant.

Conclusions: The construction of the average face provides an interesting perspective into measuring changes in groups of patients and also acts as a useful template for the comparison of craniofacial anomalies.

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Orthodontists have been interested in craniofacial morphology for over a century. Evidence suggests that the different types of orthodontic treatment performed on patients alter the facial balance and soft tissue contours of the face (for example: dentofacial orthopedics, extraction treatment, and orthognathic surgery).

The traditional methods of assessing facial and skeletal change have been landmark-based linear measurements, either by direct anthropometrics,[1] radiographic assessments, or, in recent times, 3-dimensional imaging.[2,3] One area that developed from radiographic assessments was the construction of facial templates from lateral cephalograms. The lateral cephalograms of groups of normal cohorts were taken in the various growth studies,[4,5] and templates were used for diagnostic[6] and predictive pur-

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poses[7] to give clinicians an opportunity to identify craniofacial anomalies and to predict the future facial changes for groups of patients. These methods were successful in a time when technology constrained the types of analysis available (eg, evaluating the hard tissue in 2 dimensions).

There seems to be a paradigm shift in recent times[7,8] for clinicians to work from the external soft tissues "inwards" as these features are pertinent and pleasing to the human eye. The advancement in 3-dimensional technology has allowed the capture of facial morphology in an efficient and noninvasive way without the risks of radiation exposure.

This article describes the use of a previously validated laser-scanning device[9] and its use in the construction of the average facial profile for a growth study cohort of 11-year-old children for application in clinical orthodontics.

Subjects and Methods

SUBJECTS

There were 72 children with normal facial features selected from a growth study cohort of 95 children to represent the average face. The sample was made up of 42 boys and 30 girls with a mean age of 11.8 years. All children received no previous orthodontic treatment.

Approval for the study was obtained from the Directors of Education, head teachers, school committees, and the relevant ethics committee. In addition, positive written consent was obtained for the child to be included in the study.

THREE-DIMENSIONAL IMAGING SYSTEM

The laser-scanning system consisting of 2 high-resolution Minolta Vivid VI900 3D cameras (Minolta, Osaka, Japan), with a reported manufacturing accuracy of 0.3 mm, operating as a stereo pair, was used. The technical setup has been previously reported.[9,10] Information was transferred to a reverse modeling software package, Rapidform 2004 PP2 – RF4 (INUS Technology Inc, Seoul, Korea) for analysis. This software provides 9 different 3-dimensional work activities and together allows high quality polygon meshes, accurate freeform Non-Uniform Rationale B-Spline (NURBS) surfaces and geometrically perfect solid models to be created. RF4 generates data as absolute mean shell deviations, standard deviations of the errors during shell overlaps, maximum and minimum range maps, histogram plots, and finally, color maps.

DATA CAPTURE TECHNIQUE

A custom-made portable studio facilitated standardized light conditions. The studio was sufficiently compact to fit into a corner of a classroom or medical room without difficulty and house all the necessary equipment. Natural head posture (NHP) was adopted for this study as this has been shown to be clinically reproducible.[11,12] The technique for positioning the patient and image capture has been validated and described elsewhere.[13]

STATISTICAL ANALYSIS

Within RF4, a shell-to-shell deviation map was computed and automatically produced. The results include the maximum and minimum range of shell deviations, the average distance between the 2 shells, and the standard deviation. This function was used to statistically analyze the mean shell deviations and standard deviations for left and right premerged scans in the boy and girl groups. The RF4 features described were also used to measure differences in the shells of whole faces.

The mean shell deviations for left and right scans were tested for normality, and differences between the groups measured were analyzed using the Student's *t* test (SPSS 12.0.1; SPSS, Chicago, IL). *P* values $< .05$ were considered significant.

AVERAGING PROCESS

The average face for a male and female subject at 11.8 years was constructed from the facial meshes of 42 boys and 30 girls. This in-house sub-routine was created from tools available within RF4 and provided the platform for the construction of the average faces. These steps may be summarized as follows:

Prealignment of images by determining the principle axis of rotation (based on computing the tensor of inertia of each 3-dimensional image).
Manual positioning, when necessary, to improve the previous stage.
Best-fit alignment using the in-built algorithm in RF4.
Averaging of co-ordinates of the images normally to a facial template.
Point cloud is triangulated to obtain an average face.
Areas with small holes are filled in.
Color texture is applied.
Standard deviation shells were created.

The averaging process may be represented mathematically as follows:

Each face is considered to be a function $Z = f_k(X, Y)$, where k represents the number of the faces and X, Y, Z represent Cartesian co-ordinates. Therefore, f_k can be defined in tabular form as $[f_k(X_i, Y_j)]$, $i = 0, \ldots, M$, $j = 0, \ldots, N$:

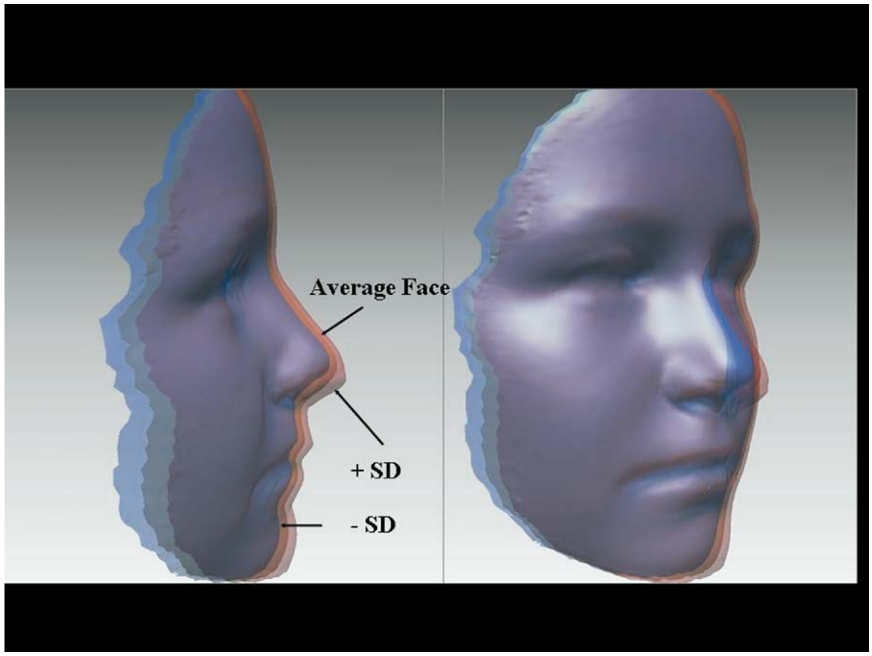

FIGURE 1. The average face when a transparent texture is applied. One standard deviation in the positive and negative directions' shells has also been included to depict the range of the averages.

Kau et al. 3-Dimensional Average Face Construction. J Oral Maxillofac Surg 2006.

$$Z_{ij}^{k} = fk\left(X_i,\ Y_j\right) \quad k = 1, \ldots, K \text{ (number of faces)} \quad i = 0, \ldots, M \quad j = 0, \ldots, N \tag{1}$$

The mathematical formula for the average face may be defined as:

$$Z_{ij}^{ave} = \frac{1}{K}\sum_{k=1}^{k} Z_{ij}^{k} \tag{2}$$

The output of the averaging algorithm gives a point cloud reading of (X_i, Y_j and Z_{ij}). Once this is completed the point cloud is triangulated to obtain an average facial surface.

Standard deviation faces were created after the average point $Z_{ij\ (Average)}$ was created and were calculated based on the formulas below. These faces can be illustrated diagrammatically (Fig 1).

$$Z_{ij}^{ave+1SD} = Z_{ij}^{ave} + \frac{1}{K_{ij}-1}\sqrt{\sum_{K=1}^{K_{ij}}\left(Z_{ij}^{ave} - Z_{ij}\right)} \tag{3}$$

$$Z_{ij}^{ave-1SD} = Z_{ij}^{ave} - \frac{1}{K_{ij}-1}\sqrt{\sum_{K=1}^{K_{ij}}\left(Z_{ij}^{ave} - Z_{ij}\right)} \tag{4}$$

Following the averaging process, each average face is further improved by removing possible mesh defects and by filling in small holes, using the inbuilt tools within Rapidform 2004. Each average face is given a colored surface texture.

CLINICAL EVALUATION

The average faces, for boys and girls, were evaluated to determine facial differences between gender groups. Furthermore, gender-specific averages for males and females were overlaid individually for subjects presenting with craniofacial anomalies using the iterative closest point algorithm. In this study, 1 subject in each of the following categories was presented:

A female, aged 11.8 years, with a unilateral right cleft lip and palate (Subject BO).

A male, aged 11.9 years, with Binders Syndrome (Subject OW).

A male, aged 11.9 years, with significant left-sided asymmetry (Subject SW).

Results

There were 72 normal subjects and 3 with craniofacial anomalies analyzed and compared. The mean ages for the normal subjects were 11.8 years and the rest were 11.9 years of age.

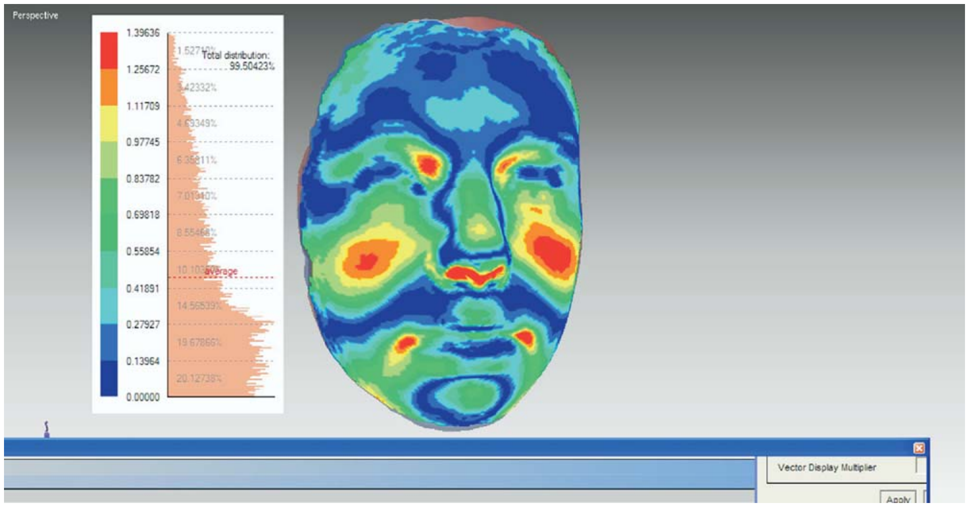

FIGURE 2. Differences in facial morphlogy between males and females. The colored areas depict positive facial differences. The zygomatic and lower mandibular areas show difference.

Kau et al. 3-Dimensional Average Face Construction. J Oral Maxillofac Surg 2006.

RELIABILITY VALUES AND COMPARISONS OF AVERAGE FACES

The mean shell deviation values for the left and right scans for males and females were 0.324 ± 0.124 mm and 0.308 ± 0.706 mm, respectively. Each of these data sets were tested for normality and found to be normally distributed. Paired *t* tests showed that there was no statistical difference between the 2 groups of subjects, indicating that the subject groups were comparable.

The difference between the average male and female face was 0.460 ± 0.353 mm. The areas of greatest deviation were at the zygomatic area and lower jaw line. These areas were more prominent in boys (Fig 2).

CLINICAL EVALUATION OF THE SEX-SPECIFIC AVERAGE FACE WITH SUBJECTS WITH CRANIOFACIAL ANOMALIES

The mean difference between Subject BO and the average female face was 1.886 ± 2.147 mm; 60.1% of the deviation between the faces was in the region of the cleft site. The volume of the defect was $3.79 \times 10_6$ uL.

The mean difference between Subject OW and the average male face was 2.412 ± 2.617 uL; 63.7% of deviation of the between the faces was in the region of the mid face.

The mean difference between Subject SW and the average male face was 1.412 ± 1.715 mm; 45.5% of the deviation between the faces was in the region of the asymmetric mandible. The volume of the defect was $2.76 \times 10_6$ uL.

Discussion and Clinical Applications

This article describes the technique required to construct an average face from a cohort of 11.8-year-old children. In addition, the average face was used as a template from which subjects with craniofacial anomalies could be compared to those with normal facial morphology.

Three-dimensional average faces have been described previously in the literature. Hutton et al built dense surface models from 421 facial scans of subjects aged 1 to 80 years old.[14] In their study, the faces were aligned based arbitrarily on 10 surface landmarks before a hybrid combination of iterative closest point and active shape-fitting algorithms were applied. The final dense surface model was used to assist in the diagnosis of Noonan's Syndrome.[15]

Average faces have also been described by Israil and Moss.[16] They used average faces to compare treatment changes among extraction versus nonextraction[16] cohorts and also cross-sectional growth changes among children.[17] However, the process of averaging faces was not mentioned.

The average face constructed in this study represents the true variation in facial morphology in a cohort of children. This method does not rely on mathematical manipulation to construct an average surface mesh and is age and gender specific. In the cases where averages were compared to subjects with craniofacial anomalies, a number of interesting findings may be presented.

In the case of BO, who presents with a right unilateral cleft lip and palate, the 3-dimensional severity of the defect corresponds well with the location of

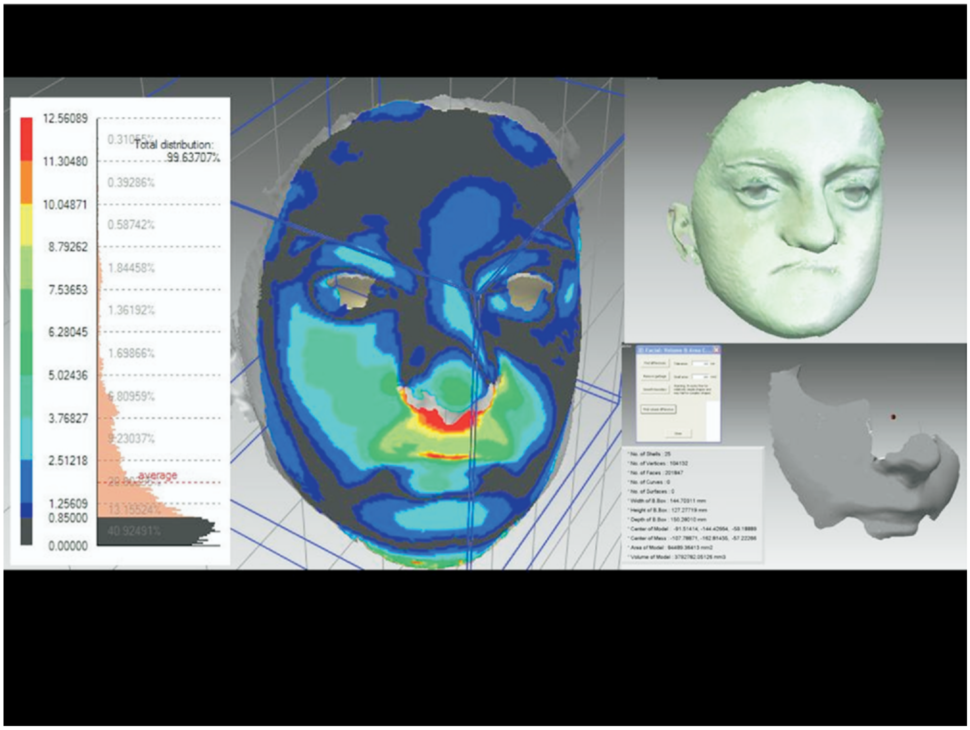

FIGURE 3. Subject BO. *A*, The shell deviation map indicating the differences between the average face shell and the subject. The black areas indicate the areas of reproducibility and the colored areas the shell-to-shell deviation present. The defect is asymmetrical in shape and corresponds well to the clinical problem. *B*, Soft tissue surface shell of the patient. *C*, The volumetric and shape analysis of the defect.

Kau et al. 3-Dimensional Average Face Construction. J Oral Maxillofac Surg 2006.

the anomaly (ie, the right side). One interesting observation noted is the asymmetric shape defect and the potential complications that clinicians would need to address during treatment. For example, any form of treatment to advance the maxilla would require an asymmetric rotational component, to compensate for the greater defect on the right side (Fig 3). In addition, all treatment would need to produce a soft tissue movement equivalent to 8 mm in an anterior direction.

Subject OW presents with Binder's Syndrome, a form of mid-facial dysplasia. The comparison of his facial scan to the average face shows up the deficiency well (Fig 4). This deficiency relates not only to the maxilla but the whole of the mid-facial complex. Some methods to treat this condition have focused on protracting the maxillary complex with face mask therapy. The facial differences in this case, however, illustrate that not only the maxilla is deficient, but the nasal bridge and mid-facial complex. This will certainly require a Le Fort II procedure and increases the morbidity and risks of the treatment.

Finally, in the case of SW, the subject presents with left-sided asymmetry (Fig 5). The diagnostic application of the 3-dimensional facial scan may help the clinician determine if surgery should be performed or whether a hybrid functional appliance should be attempted as the child continues to grow. The obvious choice in this case is that surgery will be required in the future. The facial scans and deviation maps are also an excellent means for the clinician to communicate information to the parent, and help to explain the challenges in treatment.

No discussion is complete without pointing out the limitations of the study, and these relate to the sample size of the patients with craniofacial anomalies. Although the current facial meshes of the sample fit very well, a larger sample is required to determine if the average face can be used successfully.

There is a tremendous potential for the method described above to be applied to different samples based on age, gender, and facial condition. Three-dimensional laser-based imaging is an efficient and noninvasive method to capture facial morphology. Further research will need to be carried out to optimize the use of these average facial meshes.

The following conclusions may be drawn from this study:

The average face, specific to age and gender, can be efficiently and effectively created from a sample of 3-dimensional faces.

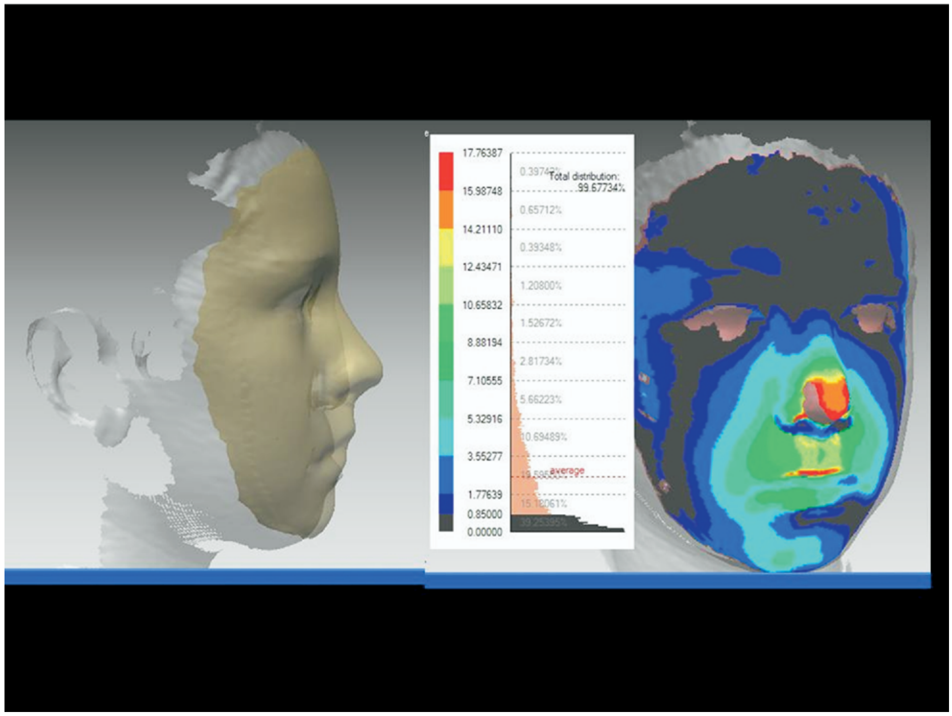

FIGURE 4. Subject OW. *A*, The average male face and the subject presented as a transparent surface texture. Note that the difference lies only in the mid-facial region and corresponds very well with the clinical presentation. *B*, The shell-to-shell deviation map showing the distribution of the size of the defect.

Kau et al. 3-Dimensional Average Face Construction. J Oral Maxillofac Surg 2006.

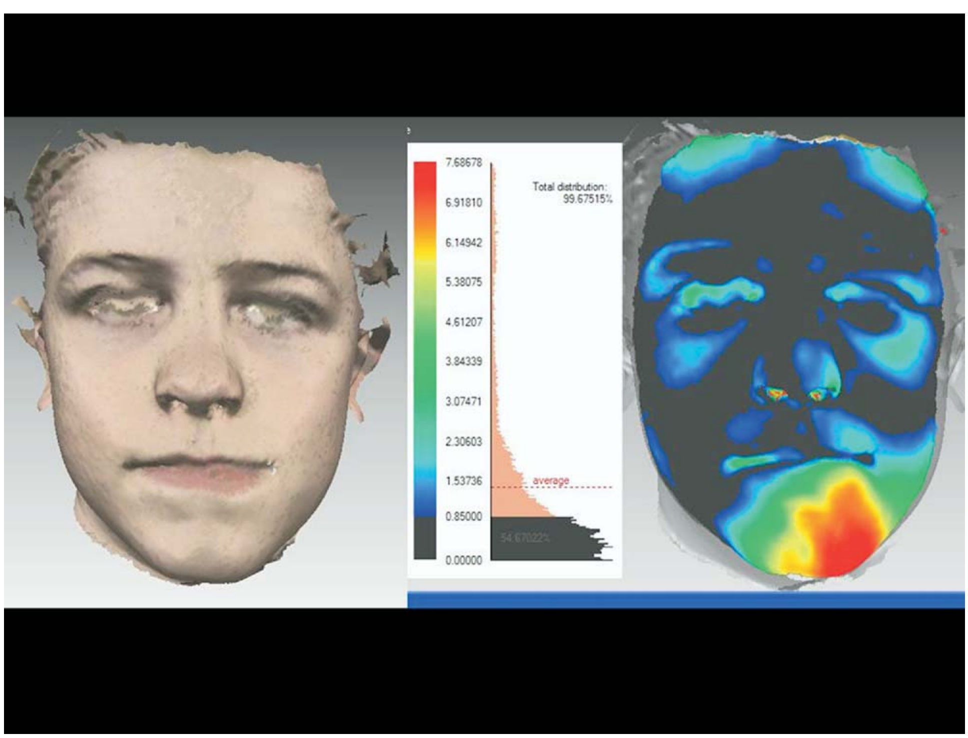

FIGURE 5. Subject SW. *A*, 3D facial scan showing the left-sided asymmetry. *B*, Color deviation map showing the extent of the asymmetry and the direction it seems to be pointed as shown by the concentration of red areas.

Kau et al. 3-Dimensional Average Face Construction. J Oral Maxillofac Surg 2006.

The average face may be used to compare differences in facial morphologies for different gender groups.

The average face may be used to compare differences in facial morphologies in patients with craniofacial anomalies.

References

1. Farkas L: Anthropometry of the Head and Face. New York, NY, Raven Press, 1994
2. Ayoub AF, Siebert P, Moos KF, et al: A vision-based three-dimensional capture system for maxillofacial assessment and surgical planning. Br J Oral Maxillofac Surg 36:353, 1998
3. Moss JP, Linney AD, Lowey MN: The use of three-dimensional techniques in facial esthetics. Semin Orthod 1:94, 1995
4. Broadbent BHS, Broadbent BHJ, Golden WH: Bolton Standards of Dentofacial Developmental Growth. St. Louis, MO, CV Mosby, 1975
5. Riolo ML, Moyers RE, McNamara JA, et al: An Atlas of Craniofacial Growth (Vol 2). Ann Arbor, MI, Needham Press, 1979
6. Jacobson A: The proportionate template as a diagnostic aid. Am J Orthod 75:156, 1979
7. Holdaway RA: A soft tissue cephalometric analysis and it use in orthodontic treatment planning. Part 1. Am J Orthod 84:1, 1983
8. Arnett GW, Bergman RT: Facial keys to orthodontic diagnosis and treatment planning. Part 1. Am J Orthod Dentofacial Orthop 103:299, 1993
9. Kau CH, Zhurov AI, Knox J, et al: The validity and reliability of a portable 3-dimensional laser scanner for field studies, *in* Giuliani R, Galliani E: 7th European Craniofacial Congress. Bologna, Italy, Monduzzi Editore International Proceedings Division, 2004, pp 41-45
10. Kau CH, Zhurov AI, Scheer R, et al: The feasibility of measuring three-dimensional facial morphology in children. Orthod Craniofac Res 7:198, 2004
11. Chiu CS, Clark RK: Reproducibility of natural head position. J Dent 19:130, 1991
12. Kau CH, Hartles FR, Knox J, et al: Natural head posture for measuring three-dimensional soft tissue morphology, *in* Middleton J, Shrive MG, Jones ML (eds): Computer Methods in Biomechanics and Biomedical Engineering – 5, Cardiff, UK, FIRST Numerics Ltd, 2005
13. Kau CH, Richmond S, Zhurov AI, et al: Reliability of measuring facial morphology using a 3-dimensional laser scanning system. Am J Orthod Dentofacial Orthop 128:424, 2005
14. Hutton TJ, Buxton BF, Hammond P: Dense surface point distribution models of the human face, *in* IEEE Workshop on Mathematical Methods in Biomedical Image Analysis. Kauai, Hawaii, 2001, pp 153–160.
15. Hammond P, Hutton TJ, Allanson JE, et al: 3D analysis of facial morphology. Am J Med Genet A 126:339, 2004
16. Ismail SF, Moss JP: The three-dimensional effects of orthodontic treatment on the facial soft tissues—A preliminary study. Br Dent J 192:104, 2002
17. Nute SJ, Moss JP: Three-dimensional facial growth studied by optical surface scanning. J Orthod 27:31, 2000