

Use of 3-dimensional surface acquisition to study facial morphology in 5 populations

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Introduction: The aim of this study was to assess the use of 3-dimensional facial averages for determining morphologic differences from various population groups. **Methods:** We recruited 473 subjects from 5 populations. Three-dimensional images of the subjects were obtained in a reproducible and controlled environment with a commercially available stereo-photogrammetric camera capture system. Minolta VI-900 (Konica Minolta, Tokyo, Japan) and 3dMDface (3dMD LLC, Atlanta, Ga) systems were used. Each image was obtained as a facial mesh and orientated along a triangulated axis. All faces were overlaid, one on top of the other, and a complex mathematical algorithm was performed until average composite faces of 1 man and 1 woman were achieved for each subgroup. These average facial composites were superimposed based on a previously validated superimposition method, and the facial differences were quantified. **Results:** Distinct facial differences were observed among the groups. The linear differences between surface shells ranged from 0.37 to 1.00 mm for the male groups. The linear differences ranged from 0.28 and 0.87 mm for the women. The color histograms showed that the similarities in facial shells between the subgroups by sex ranged from 26.70% to 70.39% for men and 36.09% to 79.83% for women. The average linear distance from the signed color histograms for the male subgroups ranged from -6.30 to 4.44 mm. The female subgroups ranged from -6.32 to 4.25 mm. **Conclusions:** Average faces can be efficiently and effectively created from a sample of 3-dimensional faces. Average faces can be used to compare differences in facial morphologies for various populations and sexes. Facial morphologic differences were greatest when totally different ethnic variations were compared. Facial morphologic similarities were present in comparable groups, but there were large variations in concentrated areas of the face. (Am J Orthod Dentofacial Orthop 2010;137:S56.e1-S56.e9)

The use of 3-dimensional (3D) imaging in orthodontics has accelerated over the past 3 decades.¹⁻³ Traditional 2-dimensional modes for records have been replaced by 3D images used to diagnose malocclusions.

Although frontal and lateral cephalometric radiographs, panoramic radiographs, and intraoral and extraoral photographs are still used, more emphasis has been placed on the 3D virtual image^{4,5} and soft-tissue esthetics.⁶

In the past, study models have been the main 3D records routinely used by practicing orthodontists, allowing them to examine malocclusions from many viewpoints. Current virtual technologies have enhanced the digitization of 3D models and added value for the clinician.⁷

The paradigm shift in treatment philosophies also means that many clinicians have started to plan from the external profile, placing importance on the soft tissues of the face largely to determine the limitations of orthodontic treatment. From the perspectives of function, stability, and esthetics, the orthodontist must plan treatment within the patient's limits of soft-tissue adaptation and contours.⁸ With new developments in technology, many clinicians have shifted toward digital computer-based records for quicker results, easier organization, the ability to enlarge and enhance images, and ease of sharing this information with patients and colleagues.

Three-dimensional images of the facial soft tissues can give the clinician this same information with a

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more accurate representation of facial morphologies⁹⁻¹¹ and can be useful to better understand, compare,^{3,12} and predict treatment outcomes before and after orthodontic treatment.¹³⁻¹⁵ In addition, some 3D soft-tissue models have been used to estimate growth changes.^{16,17}

Some applications of 3D imaging in orthodontics include pretreatment and posttreatment orthodontic assessment of dentoskeletal relationships and facial esthetics, auditing orthodontic outcomes with regard to soft and hard tissues, 3D treatment planning, and 3D soft-tissue and hard-tissue predictions. Three-dimensional fabricated custom archwires, and archiving 3D facial, skeletal, and dental records for in-treatment planning, research, and other medical and legal purposes are some other benefits of 3D models in orthodontics.¹⁸

To date, little work has been done with 3D imaging tools in the analysis of the facial morphologies of various populations. This study was carried out to determine whether there are differences in the facial morphologies of subjects from different populations.

MATERIAL AND METHODS

Subjects were recruited from 5 countries: Hungary (Hun); United Kingdom, Wales (Wel); United States, Houston, Tex (Hou); Slovenia (Slo); and Egypt (Egy). All participants were students at dental schools. They were invited to participate in the study if they met the following inclusion criteria: (1) ethnic descent or native of their country or state, (2) between the ages of 18 and 30 years, (3) normal Class I malocclusion with no adverse skeletal deviation, (4) normal body mass index value, and (5) no gross craniofacial anomalies.

The sample size was determined from the parameters of the changes of the nose, which is normally unaffected by orthodontic treatment and shows the greatest variance. With the likely change of 3 mm overall during the postgrowth period (>15 years) and a 2.8-mm standard deviation, a power of 0.85 with significance of 0.05 required a sample size of 35 in each sex group.

Ethical approval and informed consent for this study were obtained from the relevant institutional review boards and the participants in the study.

Two main imaging systems, Minolta VI-900 (laser scanning) (Konica Minolta, Tokyo, Japan) and 3dMDface (stereo-photogrammetric) (3dMD LLC, Atlanta, Ga), were used in this study.

The laser scanning system consisted of 2 high-resolution 3D cameras, with a reported accuracy of 0.1 mm, operating as a stereo pair. Each camera emits an eye-safe class I laser, 690 nm at 30 mW, with an object-to-scanner distance of 600 to 2500 mm (depending on lense type) and

a fast mode scan time of 0.3 seconds. The system uses a half-frame transfer charge-coupled device and can acquire 307,000 data points. The scanner's output data are 640 × 480 pixels for 3D and red, green, and blue color data. Data were recorded on a desktop work station, and, for surface capture, a Minolta medium-range lens with a focal length of 14.5 mm was used. The cameras were placed 1350 mm from the subjects. The scanners were controlled with multi-scan software (Cebas Computer, GmBH, Eppelheim, Germany), and data coordinates were saved in a software file format (vivid file). Validation of the system had been previously carried out.^{19,20}

The 3dMDface system was a structured light system with a combination of stereo-photogrammetry (a technique used to acquire 3D objects from stereoscopic images) and the structured light technique; it was also portable.¹³ This system uses a multi-camera configuration, with 3 cameras on each side (1 color and 2 infrared) that capture photo-realistic quality pictures. A random light pattern is projected onto a subject, and an image is captured with several synchronized digital cameras set at various angles in an optimum configuration. This system can capture full facial images from ear to ear and under the chin in 1.5 ms at the highest resolution. The accuracy is less than 0.5 mm, according to the manufacturer, and the quoted clinical accuracy is 1.5% of the total observed variance.²¹ Three-dimensional surface images captured by surface acquisition systems are highly repeatable, and 3D landmark data can be acquired with high precision.^{2,22}

Natural head posture was used for all subjects, because it is clinically reproducible.²³ The subjects sat on the adjustable chair and were asked to look into a mirror with horizontal and vertical lines marked on it. They were asked to level their eyes to the horizontal line and adjust the midline of their faces to line up with the vertical line. Adjustments to seating heights were made to assist them in achieving natural head posture. They were asked to swallow hard and keep their jaws relaxed just before the images were taken. Each image acquisition took 1.5 ms.

Completed 3D facial images were then imported into a reverse-modeling software program (Rapidform 2006, INUS Technology, Seoul, Korea) (RF6) for analysis. This software provided different 3D work activities that included 3D scan data processing; polygon cleaning, editing, and optimization (a process of improving the surface shell and mesh); rapid prototyping work preparation; curve modeling and editing; freeform inspection and geometric dimensioning and tolerance; and customized application developments in VB, VBA, C++, and JAVA.

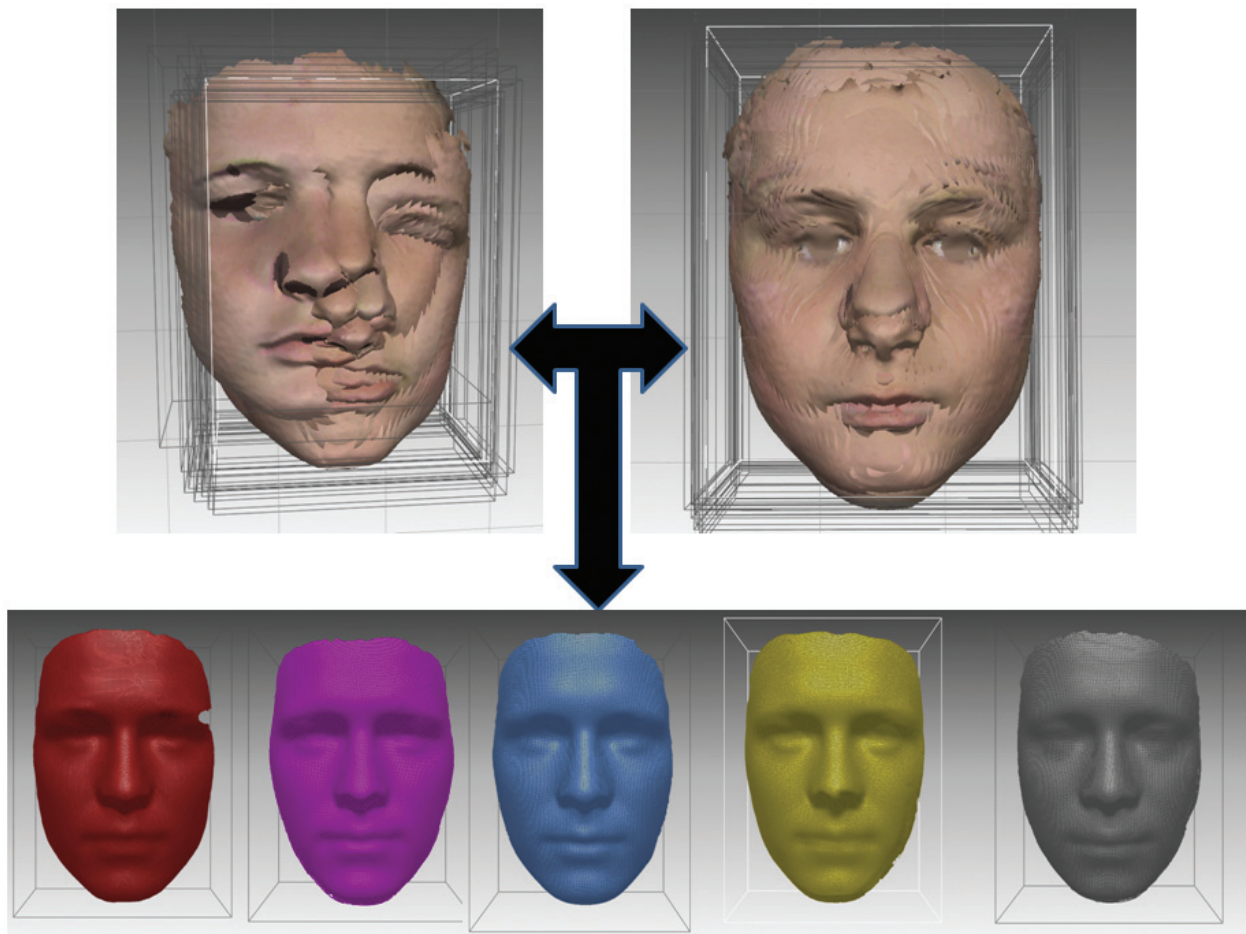


Fig 1. Three-dimensional process detailing the alignment of shells along the center of mass, fine registration, and final averaging process.

Together, these functions allowed high-quality polygon meshes, accurate freeform nonuniform rationale b-spline (NURBS) surfaces, and geometrically perfect solid models to be created. RF6 generated data as absolute mean shell deviations, standard deviations of errors during shell-to-shell overlaps, maximum and minimum range maps, histogram plots, and color maps.

The initial file formats imported into RF6 had a semirough image texture because of the irregularity of the surface contours and how light was reflected off the surfaces of different objects. Further data processing was carried out by a custom software subroutine to obtain a workable image that preserved shape, surface, and volume.²⁴ The images were checked individually, and unwanted areas that could not be automatically removed were done so manually by dividing the unwanted areas from the main shell before proceeding to the next stage. Surface meshes with “defects” or “holes” were filled in automatically by

RF6. Finally, a composite whole face for each subject was generated.

The faces were constructed to represent the averages and their variations based on the facial morphologies of the different study populations. The average facial constructs were made by using a previously validated software subroutine from tools in RF6. The steps required to produce an average face were reported previously and are summarized as follows and illustrated in Figure 1²⁵: (1) prealignment of images by determining the principal axes of rotation, based on computing the tensor of inertia of each 3D image (mathematical method of locating the center point of the shell); (2) manual positioning, when necessary, to improve the previous stage; (3) best-fit alignment by using the built-in algorithm in RF6; (4) averaging of z-coordinates of the images based on normals to a facial template; (5) point cloud triangulated to obtain an average face (multiple points stitched together to create a surface); (6) the average face improved by

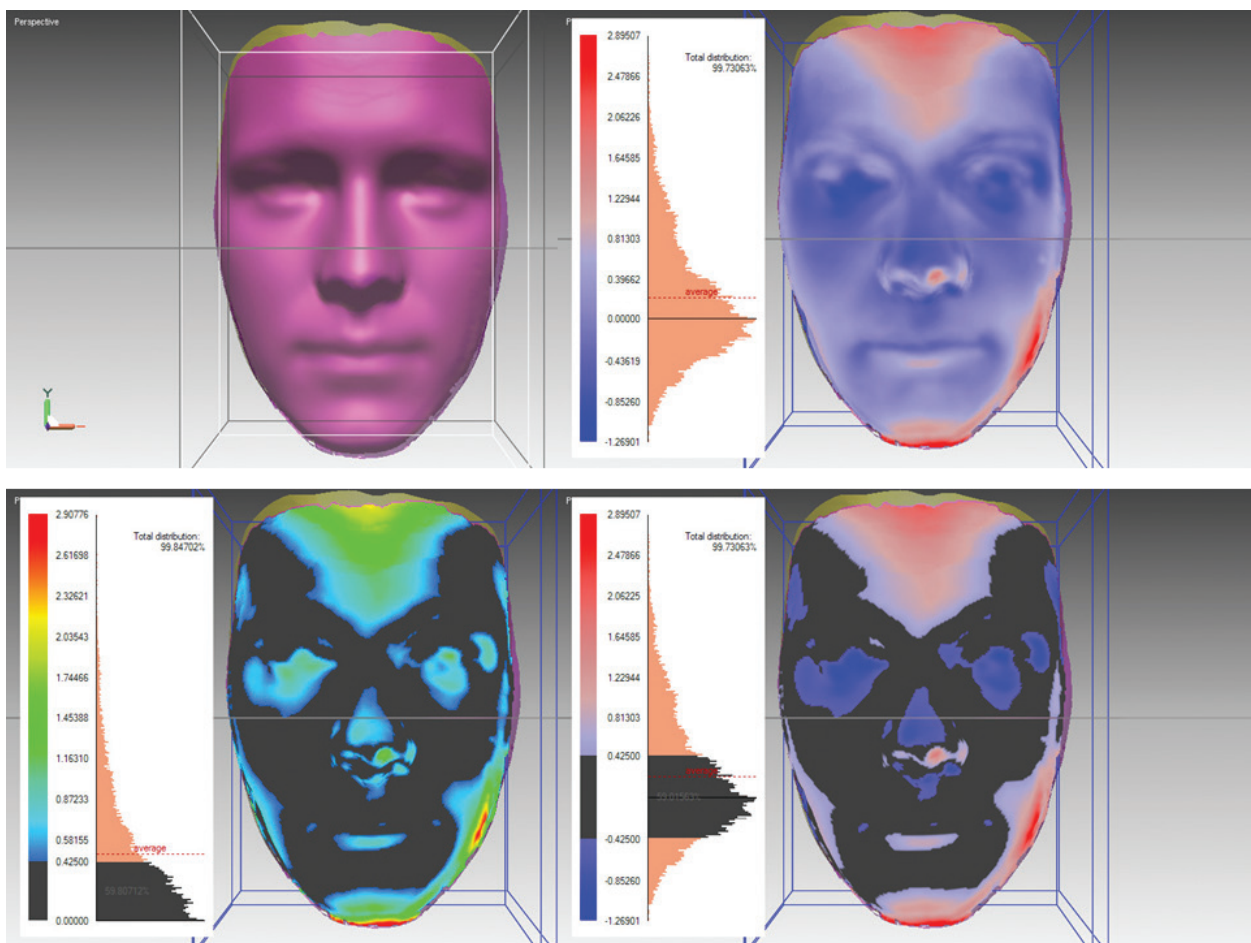


Fig 2. Three-dimensional extraction of data (clockwise from the top left): superimposition of 2 average shells (Hou and Wei), color map indicating the range of differences, color map with tolerance at 0.425 mm showing a 59.01% similarity between shells, and color map showing the mean difference between 2 shells as 0.48 ± 0.46 mm.

filling in small holes and removing possible mesh defects; (7) color texture applied; and (8) shells with 1 positive and 1 negative standard deviation created.

Ten average facial shells of male and female representations from each population group were created. Each sex-specific face was superimposed on a population-specific sex template, by using a specialized superimposition technique to compare morphologic differences between each one.²⁶ This was done until all possible combinations were made. The method of superimposition used a systematic process involving manually aligning 5 points of the facial scans (2 points on the inner canthus of the eyes, 2 points on the outer commissure of the lips, and 1 point on the nasal tip) and then fine registration, with the RF6 determining the best fit of the 2 scans.

The parameters used in this study were linear measurements, color histograms, and surface areas and shapes.

Linear measurements representing the mean differences between 2 surface shells were recorded in millimeters. This value represented the sum total of all differences recorded between the overlapping surfaces of 2 shells, and the value could be used as an indicator of the best fit between 2 shells. Furthermore, it could also show the changes in surface fit or regions of change on the full faces.

Color deviation maps, as previously mentioned, were produced by using the software tool RF6 Plus Pack 2. The color maps indicated the areas of change between the average facial shells. Blue areas showed negative changes, and red areas showed positive changes.

Surface areas and shapes were automatically generated by RF6. These shapes were obtained when a previous tolerance of 0.425 mm was applied to the paired surface shells studied. The areas that corresponded to

Table I. Demographic and sex information for the 5 populations

	United Kingdom (Wales)	Hungary	Slovenia	United States (Houston, Tex)	Egypt	Total
Men	50	50	43	50	36	229
Women	50	50	44	50	50	244
Total	100	100	87	100	86	473

Table II. Surface differences for the women in millimeters

Comparison	Mean (mm)	SD (mm)	Minimum (mm)	Maximum (mm)
Wel-Hou	0.28	0.34	-3.40	1.28
Hun-Slo	0.46	0.44	-0.88	2.45
Wel-Hun	0.47	0.38	-2.16	1.45
Hou-Hun	0.55	0.59	-1.99	3.81
Wel-Slo	0.64	0.50	-2.02	2.56
Wel-Egy	0.70	0.79	-3.41	1.27
Hou-Slo	0.75	0.70	-2.02	4.25
Hou-Egy	0.75	0.68	-4.20	2.04
Hun-Egy	0.83	0.90	-4.21	3.64
Slo-Egy	0.87	1.27	-6.32	3.65

Table III. Surface differences for the men in millimeters

Comparison	Mean (mm)	SD (mm)	Minimum (mm)	Maximum (mm)
Wel-Slo	0.37	0.41	-1.41	2.53
Hou-Hun	0.44	0.41	-1.98	2.07
Wel-Hun	0.45	0.38	-1.61	2.13
Wel-Hou	0.47	0.46	-1.18	2.42
Wel-Slo	0.47	0.40	-1.71	2.20
Hou-Slo	0.48	0.47	-2.00	4.44
Wel-Egy	0.69	0.81	-4.88	2.30
Slo-Egy	0.75	0.78	-4.15	2.41
Hun-Egy	0.91	0.79	-4.39	2.66
Hou-Egy	1.00	1.01	-6.30	2.41

0.425 mm were deemed to be similar surfaces, whereas surface areas above this tolerance showed up as surface shapes and color deviations.

These methods are described in Figure 2.

RESULTS

The final sample included 473 subjects (244 men, 229 women). A detailed breakdown of the groups is given in Table I. The mean ages for the male and female subjects were 23.5 and 25.2 years, respectively.

The surface shells for each average subgroup were superimposed by using a previously denoted superimposition technique.²² A total of 10 pairs were established for each of male and female set. The results of the study are presented as follows.

Distinct differences in the absolute linear measurements between surface shells were noted in the

sex-specific subgroups. The linear differences ranged from 0.37 mm (Wel-Slo) to 1.00 mm (Hou-Egy) for the male groups. The linear differences ranged from 0.28 (Wel-Hou) and 0.87 mm (Slo-Egy) for the female groups. The results in ascending order of the mean values are shown in Tables II and III.

Differences were also noted between the facial shells of the subgroups when color histograms were used; these results are given in Figure 3. The color histograms showed that the similarities in facial shells between the sex subgroups ranged from 26.70% (Hun-Egy) to 70.39% (Wel-Slo) for the men and 36.09% (Hou-Egy) to 79.83% (Wel-Hou) for the women. The average linear distance from the signed color histograms for the male subgroups ranged from -6.30 mm (Hou-Egy) to 4.44 mm (Hou-Slo). The female subgroups ranged from -6.32 mm (Slo-Egy) to 4.25 mm (Hou-Slo) (Tables II and III).

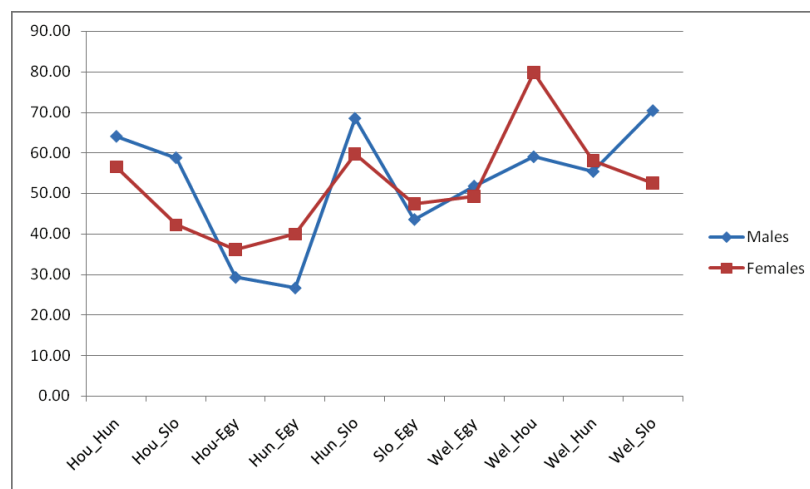


Fig 3. Graphic representation of the percentage similarities for comparisons between populations according to sex.

Surface area and shape differences between the subgroups were illustrated by the color histograms and surface mapping (Figs 4 and 5). Surface area comparisons between the Egyptian and all other templates varied the most for both male and female faces. These discrepancies were most notably seen in the nose, maxilla, mandible, and chin areas. The least variability was in the Wel-Slo template for the men and the Wel-Hou template for the women.

DISCUSSION

This study describes the technique required to construct 3D facial averages from 5 populations around the world. In addition, the 3D average faces were used as templates to compare the morphologic differences between the sex-specific populations.

Three-dimensional average faces have been described previously in the literature and are an excellent basis to understand complex 3D data sets.^{25,26} The use of facial templates has been demonstrated to robustly represent populations; the uniqueness was best illustrated by the distinct differences between male and female averages.^{27,28} Furthermore, Hutton et al²⁹ built dense surface models from 421 facial scans of subjects from 1 to 80 years old. It was noted in those faces that a difference in methodology was represented. Faces were aligned, based on 10 surface landmarks before a combination of complex algorithms was applied to the faces. The final dense surface model was used to help diagnose people with Noonan's syndrome.³⁰ Average faces have also been described to compare treatment changes between extraction and nonextraction groups³¹ and also

cross-sectional growth changes in children.¹⁷ The average templates presented here capture the probable variations in a representative population data set.

Previous studies on male facial averages of 2 ethnic groups (Japanese and European) showed distinct differences: in the orbital and cheek regions and, to a lesser extent, in the jaw area. The authors postulated that the Japanese male face was flatter than the European male face.²⁸

From comparing the linear measurements between subgroups, we were able to first determine that each average face was fundamentally different and unique. The ranges in the linear measurements, color histograms, and surface areas indicated that some facial averages were more similar, but, in others, the morphologic differences were much greater. This was most apparent when 2 totally different ethnic groups were studied (Egyptian vs Europeans).

The differences in mean values of surfaces were small, but the amounts of variability (maximum and minimum variations) were high and concentrated in regions of the face. This was not unexpected, since the subgroups were different and had to be treated as separate entities. The color histograms best indicated these differences. For example, when European faces were compared with Egyptian faces, most of the differences were in the foreheads (Egyptians had flatter, sloping foreheads), stronger malars, and smaller chins (Egyptians tended to have more bimaxillary protrusion). The analysis of European and North American populations showed greater similarities, reflected in the higher similarity percentages (Fig 3). Even though these similar percentages were higher,



Fig 4. Three-dimensional morphologic analysis of female variations. The color maps depict the areas of differences (blue and red) and the areas of similarities (black).

the differences were more concentrated in areas of the face where orthodontic treatment might have an impact. For example, Slovenian women were more Class III compared with Welsh or Houston women (Fig 4), and Hungarian men tended to be more Class II compared with Houston men (Fig 5).

Most available data concerning facial soft tissues, particularly profiles, in orthodontics have been obtained from cephalometric data, with additional material from a few 3D studies. It was shown in previous cephalometric studies that ethnic variations should be applied in orthodontics.^{32,33} In recent years, 3D surface acquisition imaging systems have been gaining popularity and have proved to be an accurate and reliable way to capture facial soft tissues.³⁴

In this study, facial averages were used to compare the facial morphologic differences between 5 populations, representing their respective variations. Although populations of white descent showed the

greatest similarities, they had distinct facial morphologic differences. Each population has unique differences, particularly in different regions of the face. Furthermore, when a totally different ethnic population was included, large variations were observed.

Some authors have also commented on the prominence of the nose as a defining factor in population differences.³⁵ Others have stated that the soft-tissue drape differs considerably between 2 similar groups of North American children, and the relationship of the soft tissues should be considered seriously.³⁶

The importance of these findings, especially in orthodontics, implies that baselines for facial morphologic norms for each population might be required soon. Studies such as these can help to formulate normative data bases that clinicians can use when predicting treatment for specific populations.² If the facial averages truly represent the norms for each population, then the soft-tissue profile as the final treatment outcome might need to be studied in

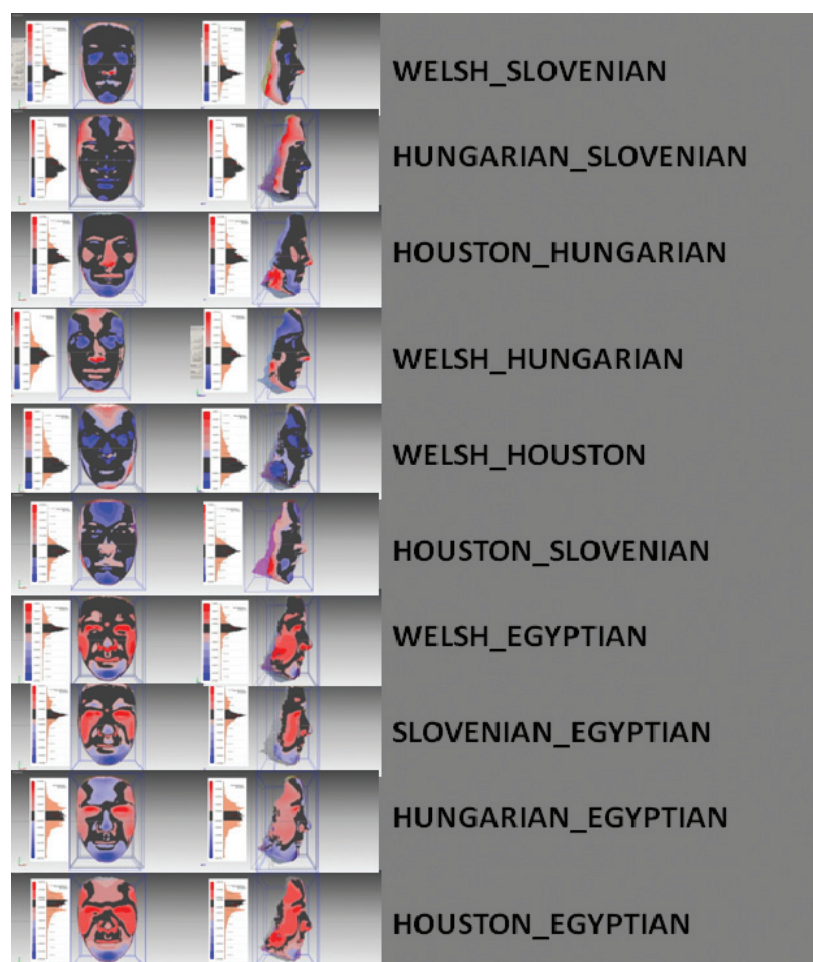


Fig 5. Three-dimensional morphologic analysis of male variations. The color maps depict the areas of differences (*blue and red*) and the areas of similarities (*black*).

greater detail. This study also demonstrated that subgroups of populations differ according to their specific group. Therefore, as in traditional cephalometrics, normative values might need to be readdressed to create new 3D norms.

CONCLUSIONS

The following conclusions can be drawn from this study.

1. Average faces can be efficiently and effectively created from a sample of 3D faces.
2. Average faces can be used to compare differences in facial morphologies of various populations and sexes.
3. Facial morphologic differences were greatest when totally different ethnic variations were compared.
4. Facial morphologic similarities were present in comparable groups, but there were large variations in concentrated areas of the face.

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