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The use of three-dimensional imaging in orthodontics*

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SUMMARY The article illustrates the value of three-dimensional imaging of the face and jaws in the diagnosis and treatment of patients. The applications of programs that have been written for the analysis of facial form are also described, including registration and prediction. The use of the Procrustes analysis is demonstrated in groups of children and adults to differentiate between male and female facial morphology. The use of scanning in forensic science is also described. The application of surface shape analysis to groups of monozygotic and dizygotic twins and to family studies to detect those areas that are genetically determined from those areas, which are not, is illustrated.

Introduction

This article traces the way in which three-dimensional (3D) imaging has developed, its usefulness today, and the way in which it may develop in the future.

The Greek sculptors realized the 3D nature of the skull and Polyklietos emphasized the measurements of the various parts. The artist, Durer, also noted the 3D nature of the head and showed how if the proportions changed, so did head shape (Olds, 1993). He was also the first person to utilize faceting to demonstrate the 3D nature of the face, a system that is used today to visualize the face. George Northcroft who was interested in the development of the face and took plaster casts of his son to record the 3D changes with growth from 6 to 21 years of age. Later further records were taken at 75, 82, and 88 years of age (Moss, 1989). These records illustrated the changes in the soft tissues and the dentition over that period of time. Broadbent (1931) used radiographs to record the 3D nature of the head using a combination of lateral and antero-posterior radiographs.

These attempts at imaging the face in three dimensions were invasive, so the challenge was to produce a system of non-invasive 3D measurement, which could be utilized for orthodontics. The initial pilot system used fanned beams of low-grade laser light projected onto the face, the surface of which distorted the line and this distortion was recorded (Arridge *et al.*, 1985; Moss *et al.*, 1987, 1989). Computerized tomography (CT), ultrasound, and magnetic resonance imaging (MRI) were included in the investigations and development.

CT imaging

Since the 1980s, the quality and speed of CT imaging has changed dramatically. Now with improved techniques and imaging programs it is possible to produce images, which can be rotated and cut at any level. An example is shown in Figure 1. The accuracy of the imaging is excellent and can be used to manufacture models for surgery using stereo lithographic techniques.

Prostheses for surgical implantation can be manufactured and these can be fitted in less time, and can be custom-made with the screws situated in the exact position where there is sufficient bone. For cranioplasties, a model is milled out of the area that is to be replaced and the quality of the bone around the periphery is assessed. This enables the screws to be placed in the correct area where the bone is of sufficient thickness to hold a screw. An area of bone where there is no defect is then mirrored to the deficient site to provide the correct contour and a prosthesis is constructed to this shape. Custom-made cranioplasties have reduced the duration of surgery by up to 4 hours (Sauret *et al.*, 2002).

Another area where CT imaging is of great value is in the production of ear prostheses in patients with hemifacial microsomia (Watson *et al.*, 1993). To construct such a prosthesis, a scan is taken and the position of the ear is ascertained by mirror imaging the unaffected side and then positioning it over the bone at the correct level. The positions of the osseointegrated implants are then marked where there is the correct depth of bone and where there is sufficient thickness of the prosthesis for attachment of the framework. If the thickness of bone and the position of the ear are correct, a template is made with the marks for the implants in their correct position. The template is taken to the theatre to be used at the time of surgery and the ear is then milled out and an exact replica made with a framework on the inside of the ear, which enables the patient to attach it to the implants. Once the implants have healed a framework for attachment of the ear can be fixed (Figure 2). These procedures have also reduced operating time and produced excellent results.

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MRI

MRI is good for 3D imaging of soft tissues but the accuracy of the data is not sufficient for precision milling of prostheses, as it does not differentiate between air and bone. However, for soft tissues it is excellent, and can be useful in imaging temporomandibular joints. It is also useful in the management of tumours of the head and neck region and for imaging the brain for neurological problems.

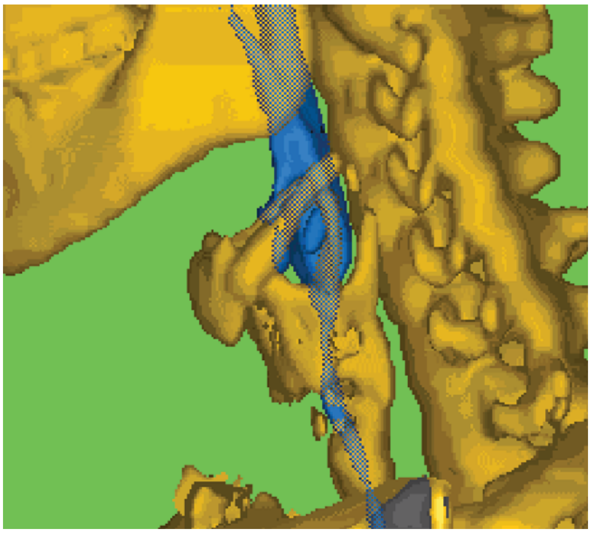

Figure 1 A computed tomographic scan thresholded showing the soft tissues of the nasopharynx, the hyoid, and the larynx, with the associated hard tissues of the spine and jaw.

Optical surface scanning

Optical surface scanning was first tested in 1981 to produce a non-invasive 3D image of the face. The system was modified, improved, and re-tested (Arridge *et al.*, 1985; Moss *et al.*, 1987; Aung *et al.*, 1995). Since that time, the system has also been developed to scan models of the teeth (Stern and Moss, 1994). In 1996, the hand-held scanner was designed to make the system mobile (McCallum *et al.*, 1996). This can be used for scanning many parts of the body. The recent introduction of a probe that records the 3D co-ordinates of any point means that many of the hard tissue points used by Farkas (1994) can now be recorded. Many recent scanners, which take instant pictures, have the problem of the scarcity of data at the periphery of the scan which makes joining of the two scans difficult and not very accurate. In contrast, the hand-held scanner overcomes this problem and can collect over 120 000 points around the head. It is important to have sufficient data over all the surfaces for the analysis of changes in facial morphology, and especially of surface shape changes.

The data

Over the years, the value of the 3D system in the diagnosis and management of patients has been demonstrated. 3D material has been obtained on various types of craniofacial anomalies: cleft palate, hemifacial microsomia, and cherubism (Moss and Janes, 1984; Moss *et al.*, 1990, 1996, McCance *et al.*, 1997a,b,c,d). Craniofacial patients who

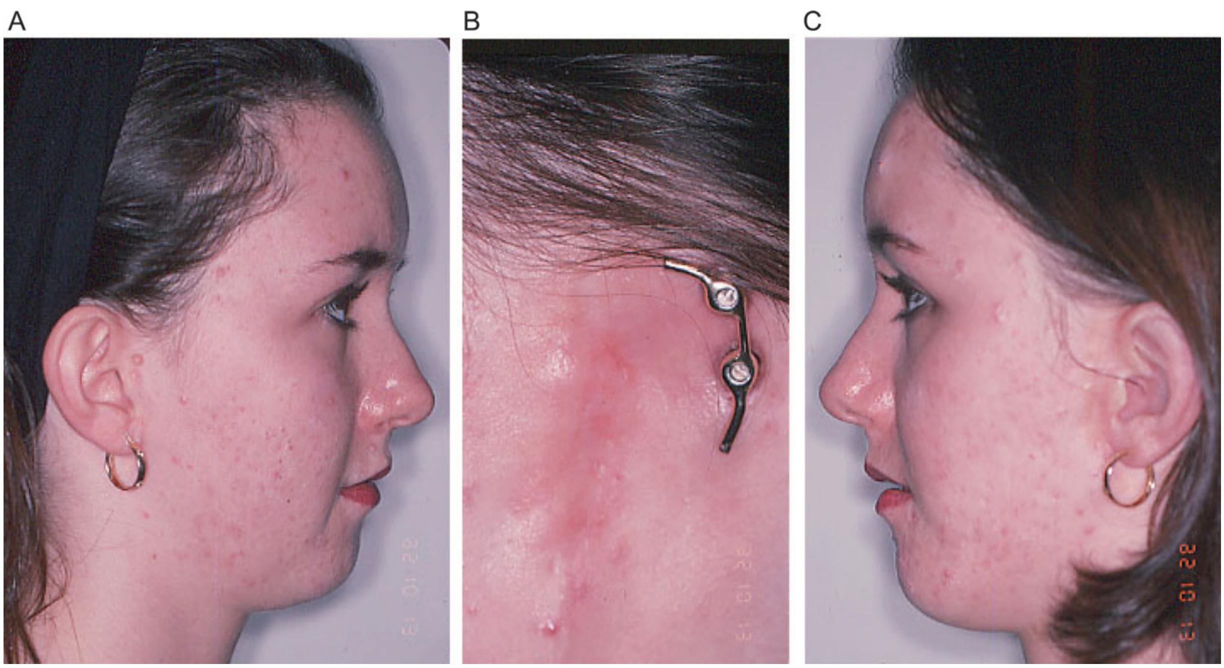

Figure 2 The ears of a patient with hemifacial microsomia. (A) The normal right ear. (B) The implants with the attachment for the ear. (C) The left ear with the prosthesis.

have been treated surgically have been recorded before and after treatment (Moss *et al.*, 1987, 1991; McCance *et al.*, 1994) and there is also a large database of patients who have undergone various types of orthodontic treatment (Moss *et al.*, 1997). A database of untreated children and adults divided into males and females provides useful control group data (Nute and Moss, 2000). A group of untreated Class II patients and a collection of twins and families for genetic studies provide further useful information.

Programs for the analysis of 3D data

Mark and measure. This program enables the operator to mark points on the surface of the face to obtain 3D co-ordinates and then measure the distances between them. It can also be used to calculate angles, areas, and volumes. The cursor shows the horizontal and vertical profiles at the point on the face and is therefore useful in defining points on the surface.

In order to illustrate the value of the program, a series of patients at different ages were analysed to distinguish between the facial forms of males and females. In the adult, it is easy to identify males and females, but how early in life is it possible to distinguish between them by looking at facial morphology? To test the differences between males and females at different ages, the scans of forty-three 5- to 6-year olds, forty-one 11-year olds, and forty-two 17-year-old patients were selected together with a random group of 131 adults from Ireland. The facial surfaces of the subjects were recorded in three dimensions using either a fixed laser scanner (Moss *et al.*, 1987) or a hand-held scanner (McCallum *et al.*, 1996, 1998) and between 60 000 and 120 000 points were recorded on each patient.

On each scan, the points shown in Table 1 were identified, marked, and the x, y, and z co-ordinates recorded for statistical analysis using the Mark and Measure program. The majority of the points were standard anthropometric points as described by Farkas (1994) and their identification was aided by the display of the vertical and horizontal profiles at each point and calculated using a surface fitting method. The points marked were of the types described by Bookstein (1991). Type 1 landmarks show the juxtaposition or intersection of tissues, type 2 the points of extremity of maximum curvatures, and type 3 the points of inflection (Hennessy and Moss, 2001).

Statistical shape analysis of landmark sets. Geometric morphometrics was used to analyse the sets of landmark co-ordinates. These were analysed directly, following suitable scaling and alignment, rather than using the conventional analysis of inter-landmark distances and angles. Size was first removed by scaling and the measurement recorded for separate analysis. The scaled landmarks were then aligned by rotation and translation and the distances between the landmark sets were minimized by generalized Procrustes analysis (GPA) to produce a mean shape for the sample.

Table 1 The list of points on the surface of the face that were identified and marked for the Procrustes analysis. Type refers to Bookstein's (1991) definition of the surface point.

Name	Type	Locating profile
Soft tissue nasion	2	Shape index
Pronasale	3	Conventional
Sublabiale	2	Gaussian
Pogonion	3	Conventional
Right inner canthus	2	Conventional
Left inner canthus	2	Conventional
Right outer canthus	2	Conventional
Left outer canthus	2	Conventional
Right alar crest	1	Conventional
Left alar crest	1	Conventional
Subnasale	1	Conventional
Right alar	3	Conventional
Left alar	3	Conventional
Right columella breakpoint	3	Conventional
Left columella breakpoint	3	Conventional
Right crista philtrum	1/2	Conventional
Left crista philtrum	1/2	Conventional
Labiale superius	1/2	Conventional
Labiale inferius	1/2	Conventional
Stomion	1	Conventional
Right cheilion	1	Conventional
Left cheilion	1	Conventional
Right tragion	2	Conventional
Left tragion	2	Conventional

Subtraction of the Procrustes mean from Procrustes-registered co-ordinates generated the Procrustes residuals. Statistical analysis was applied to the co-ordinates in the tangent plane at the Procrustes mean and the results were visualized, and expressed both numerically and visually. A detailed explanation of the analytical method has been reported by Hennessy *et al.* (2002) where the same method was used to determine sexual dimorphism of a control group using the same 24 landmarks. The reproducibility of the method is described and the data below reproduced with permission. The other groups described have been recorded and analysed in the same way.

The analysis consists of removing size by scaling the landmark sets to unit size as they record both size and shape. The GPA is used to bring into alignment, via translation and rotation, the scaled landmark co-ordinates recording facial shape. Goodall's F-test (Goodall, 1991), which is a non-parametric test for overall shape difference between two groups that takes into account all the variances was then applied. Principal component analysis (PCA) is carried out on the transformed landmark co-ordinates to establish the main sources of shape variability in the sample and the principal component scores are then subjected to logistic regression to compute the shape differences. This result is a statistical model of the differences between the male and female groups. The output of this model is a statistic, R^2, which describes the proportion of variance explained by the model, and 3D graphics are used to visualize the warped mean shape of the sample which illustrates the shape variability that best distinguishes males from females. The Procrustes mean co-ordinates are added to the Procrustes residual co-ordinates, each multiplied by beta coefficients, which are generated by the regression analysis and by an arbitrary scaling factor. The greater the scaling factor, the more the shape is warped from the Procrustes mean and the sign of the scaling factor determines whether the Procrustes mean is warped in the male or female direction. The positions of the mean shapes of the female and male subgroups can also be superimposed and the warping can be adjusted to approximate multiple group means difference.

Results

PCA of Procrustes co-ordinates

PCA divides the total variance into component parts. The first of these, PC1, has the greatest variance, the second the next greatest, etc. This analysis generated 16 PCs with an eigenvalue exceeding the mean value which described the total shape variance. These 16 PCs, which explained 91.8 per cent of the overall sample variance in craniofacial shape, were used for subsequent analysis.

Logistic regression

The full logistic regression model contained no significant predictors but stepwise regression yielded a parsimonious model with PCs 2, 3, 4, 5, 6, 9, and 14, contributing significantly and independently to this discriminant model. The PCs used are those with an eigenvalue > mean eigenvalue. The parsimonious model for the adult data set had a R^2 value of 0.58 and correctly classified 92.7 per cent of the females and 77.6 per cent of the males.

Visualization of logistic regression

An orthogonal view of the logistic regression visualization for the adult group (n = 131) is shown in Figure 3A (Hennessy *et al.*, 2002) in terms of the 24 landmarks of the Procrustes mean over all subjects, compared with those same 24 landmarks for a hypothetical specimen lying along the discriminating axis in the female direction, representing the characteristics which the regression model identifies as distinguishing females. Vectors are drawn at each landmark between mean and hypothetical specimens and the vector lengths correspond, approximately, to the difference between the male and female group means exaggerated by a factor of 10.

In general terms, the female face is wider and the eyes are more lateral and anterior, with nasion being posteriorly positioned. The nose is smaller, narrower, and less protrusive. The distance between the lower and upper margins of the lips is greater, and the upper lip is located more posteriorly. The mouth width is similar but the chin point, pogonion, is situated more posteriorly.

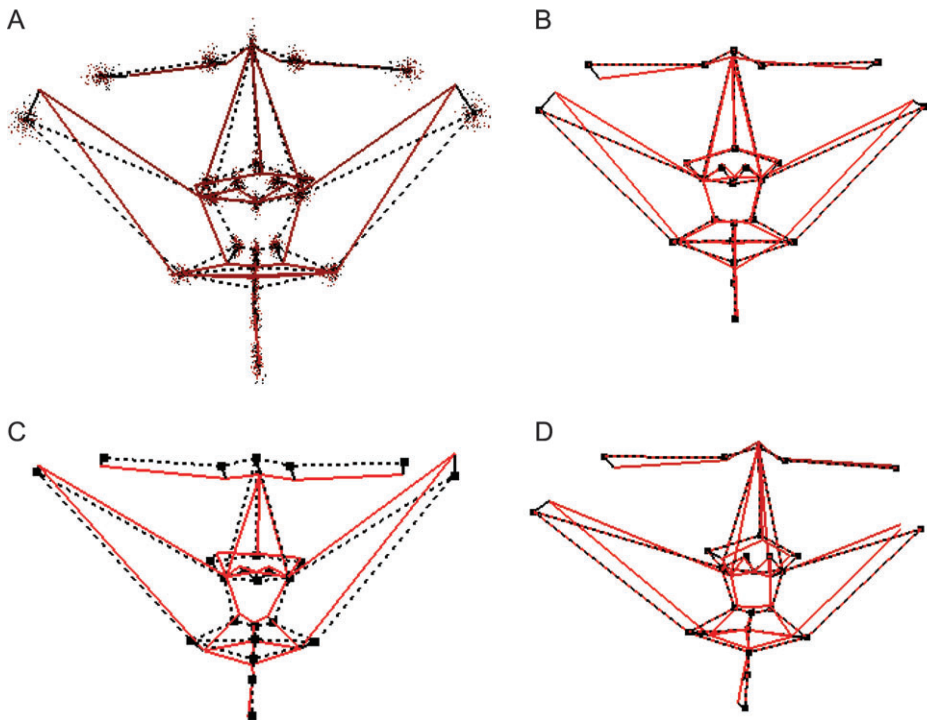

Figure 3 Procrustes analysis of (A) 131 adults showing the spread of the points analysed. (B) The 5- to 6-year-old group. (C) The 11-year-old group. (D) The 17-year-old group. These diagrams can be rotated and viewed from any angle. The males are shown in red.

A similar analysis has been applied to the groups of males and females 5–6, 11, and 17 years of age and the results of these analyses are shown in Figure 3. There were statistically significant differences between males and females at all ages. At 5–6 years $P = 0.002$, at 11 years $P = 0.004$, and at 17 years $P = 0.007$. The difference between males and females was similar at all ages. At each age, when size is removed and shape is considered, there is a difference between males and females and the differences are the same as those found in the adult sample. This would indicate that at 5–6 years of age, the differences between males and females are present with the eyes being more forward and lateral in the female and nasion more posteriorly positioned.

Registration

The registration program enables accurate superimposition of similar areas on two overlaid scans to demonstrate the surface differences in colour. Warm colours, from green to bright red, are positive changes and negative changes are from blue to purple. The colour change can be adjusted so that the scans can be evaluated using different values.

The benefit is that growth of an individual can be monitored in three dimensions using a method which is non-invasive and which can be repeated every few weeks so that orthodontic treatment might be started at the most appropriate time. A patient who has a developing Class III malocclusion was monitored over a period of time in order to assess the direction of growth and the rate of change (Figure 4). The rate of change in the growth of the jaw can be assessed and compared with either the previous scan or the average for that particular age. Registration of the scans indicated that there was downward growth of the jaw by +6 mm and forward growth of the nose lips and chin of 2–3 mm between 14 and 15 years of age.

From the database of scans of subjects with a Class I skeletal pattern who had not undergone orthodontic treatment, average scans have been produced for each age from 5 to 18 years divided into males and females. The value of these groups is that it allows comparison with the faces of other patients and can establish whether there is abnormal growth for their age group in any part of the face. The difference between the patient at 16 years of age and the norm for that age is shown in Figure 5. It can be seen that the midface is deficient by 3–4 mm when compared with the norm and that the mandible is excessive by 6–7 mm. Registration thus allows comparison of patients before treatment with the norm for that age to detect the amount of difference between them and to determine exactly where the problem might be (Figure 6).

Using the same program, it is possible to compare the change in the surfaces of the faces of patients before and

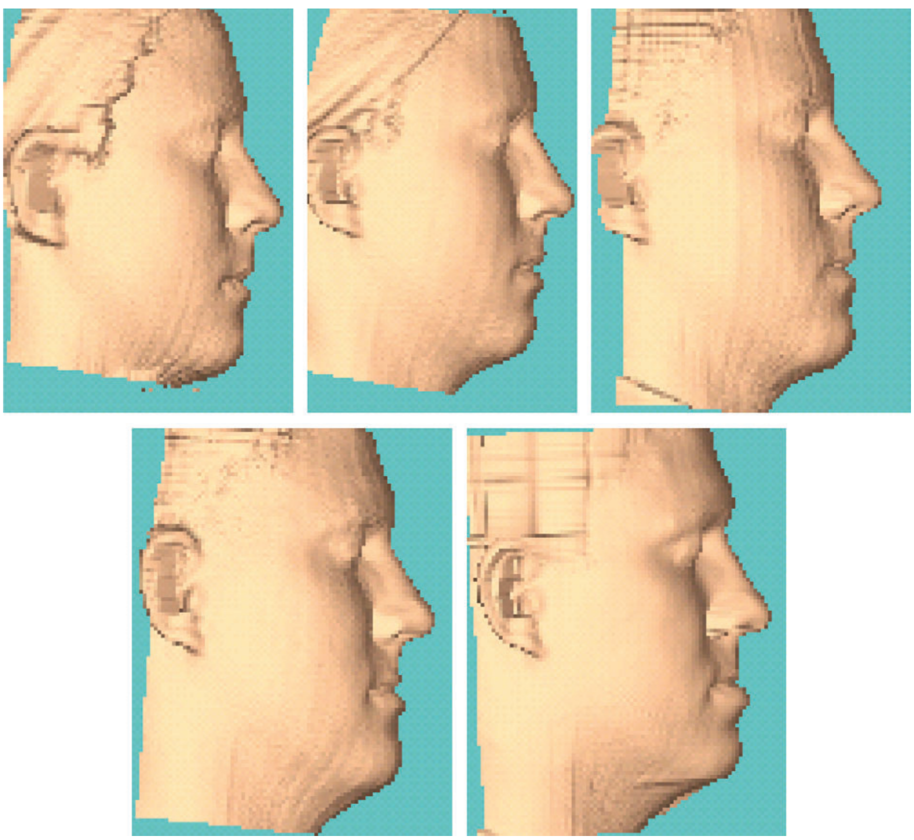

Figure 4 Scans of a patient with a developing Class III malocclusion.

after treatment. Similarly, groups of patients can be averaged to show 'average' improvement with therapy. At the end of treatment, it is possible to see the effects of treatment in an individual and to establish exactly what changes there have been in terms of facial form. It is then possible to compare this with the norm for that age to see if treatment has 'normalized' the facial features.

Forensic science

In forensic science, optical surface scanning has proved valuable in assisting in identification by building faces over dry skulls that have been found. When human remains have been buried or left for some time, the soft tissues disintegrate and all that remains for identification purposes are the hard tissues of the skeleton, with the result that identification is difficult or impossible. Programs have been written using the depth of soft tissues over the underlying bone from CT scans, which can be used to determine the position of the surface of the soft tissues relative to the bone surface (Vanezis *et al*., 1989). The surface of the skull is optically scanned and the program used to build up the surface details for identification purposes. This is a considerable saving on the time and cost of the routine method of an artist building up the surface in clay in order to give an artistic representation of the facial form.

Optical surface scanning has also proved useful in identifying suspected criminals from video footage or photographs. The suspected criminal is scanned in three dimensions and as the scanner has the ability to move the image into any position, it enables the operator to move the scan into the exact position of the photograph and to mathematically compare the profile shape. In this way, the suspect can be either identified or eliminated from the investigation (Linney and Coombes, 1998).

In medicine, optical surface scanning has been used as a means of studying certain diseases such as investigations into the developmental model of schizophrenia (Waddington *et al*., 1999; Hennessy *et al*., 2002). It has also been used to

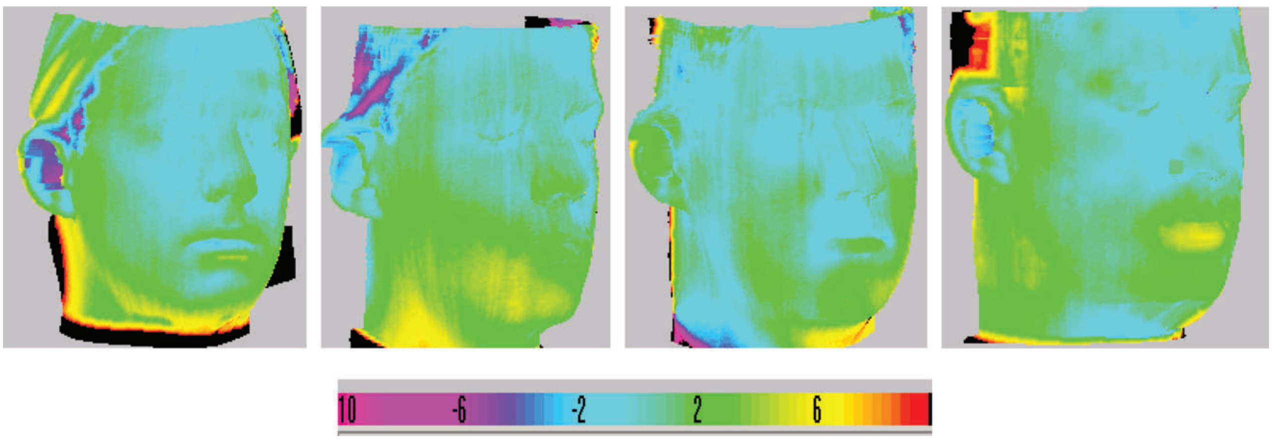

Figure 5 The registrations of the scans of the patient in Figure 4 showing the changes with growth from 12 to 16 years. The scale is in millimetres and positive colours are towards the observer.

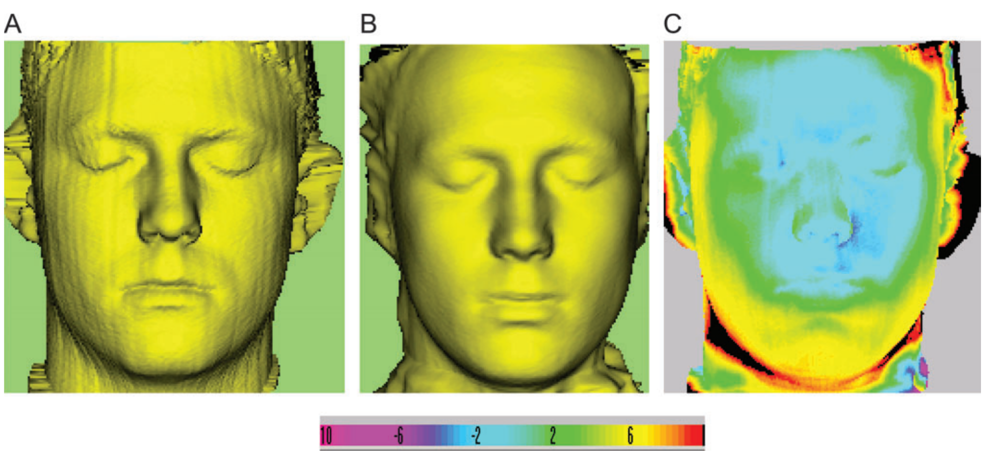

Figure 6 (A) The scan at 16 years of the patient in Figure 4 (left) and (B) the average scan for a group of normal 16-year-old males. (C) Registration of the two scans indicates the differences. The scale is in millimetres and positive colours are towards the observer.

identify changes in facial morphology as a result of drug therapy. The increasing usefulness of optical surface scanning is due to the various analytical programs that have been written to analyse data.

Prediction of jaw surgery

Programs may also demonstrate the change in the surface of the face following movement of the jaws after orthognathic surgery (Moss *et al.*, 1988). The scan is loaded and the area of anticipated change identified. Markers are then placed over the facial surface and those markers where change is anticipated are altered depending on the amount of surgical movement that is to be undertaken using the ratio of bone to surface movement which has been calculated in certain types of surgery (McCance *et al.*, 1993). The amount of movement of the surface is then recorded and the computer warps the surface to illustrate the amount of jaw movement that has been indicated. The image can be viewed from any aspect, thus it is possible to allow the patient to see the potential 3D effects of surgery before it is undertaken. The effect of surgery on the Class III patient shown in Figure 4 is the result of moving the upper and lower jaws the amount that they deviate from the normal for that age (Figure 7).

Analysis of surface shape

Besl and Jain (1986) carried out pioneering work in the field of computer vision by applying differential geometry for calculating curvature. Modifications of their ideas have been used to study the effects of surgery on the facial soft tissues (Coombes *et al.*, 1991). Koenderink and van Doorn (1992) introduced the shape index (SI) and curvedness to bridge the practices of observation and measurement and provide links to the statistically well-founded methods of shape space. These methods have been applied to the face (Ismail *et al.*, 2002; Moss *et al.*, 2003).

For each scan, the Gaussian (K) and mean (H) curvatures of each data point were calculated. This method allowed a description of the surface, which was independent of the surface orientation (rotation and translation), and was thus the same from any viewpoint. A 3D-rendered face can be segmented into nine surface types via SI values. The points on the face are colour coded according to the surface type to which they belong in order to produce a surface type image which is a readily understandable way of displaying the data. The nine different surface shapes distinguished by their colour are spherical cap (red), dome (pink), ridge (green), saddle ridge (dark blue), saddle (light blue), saddle rut (brown), rut (dark grey), trough (light grey), and spherical cup (white).

The convex surface types are effective at segmenting the face into regions of anatomical significance. Most noticeable are the regions of ridge shape, which act as markers of, where the soft tissues pass over, underlying skeletal structures. They provide adequate segmentation of the zygomas, the superior margins of the mandible, the ridge of the nose, the alars, and the superior margins of the orbits. The spherical cap and dome identify the tips of the nose and chin and the saddle ridge the nasal bridge. The saddle locates the lateral margins of the alars, the labiomental fold, and the nasolabial furrow. Overall wide ranges of facial features are located by data-driven segmentation.

These programs have been used to identify differences in the shape of the face due to treatment (Ismail *et al.*, 2002; Moss *et al.*, 2003). One other area in which these programs are proving useful is in facial genetics where attempts are being made to determine which features of the face are inherited and which are environmentally affected.

Genetics

Analysis of over 1000 adults showed that the areas of the face that seemed to be most genetically determined were the brow ridges, the nose, the region around nasion, and the chin (McCulley, 2000). In order to observe if differences exist between monozygotic twins, who have the same genetic basis, and dizygotic twins, who have a similar genetic pool, 10 pairs of monozygotic twins (five male and five female, mean age 11.9 years) and 10 pairs of same-gender dizygotic twins (three male and seven female, mean age 12.1 years) were scanned using the fixed optical surface scanner. The dizygotic twins analysed were of the same gender to eliminate some of the differences between males and females when comparing each pair.

The scanned data were subjected to analysis of surface shape; segmenting the face into the nine basic surface shapes calculating the HK and SI values and the twins were then compared. When the faces of the monozygotic twins were segmented into the nine surface shapes, it was found that in the region of the brows, bridge of the nose, and infraorbital ridges that the surfaces were very similar in shape but for the lower part of the face in the cheeks, chin, and lips there were considerable differences (Figure 8A,B). However, when the faces of dizygotic twins were subjected to the same analysis, the areas around the eyes are different in shape and that the lower part of the face is also different (Figure 8C,D). The

Figure 7 The patient in Figure 4 correcting the upper and lower jaws to predict the changes that surgery would have made to the facial contours. The upper and lower jaws have been moved the amount that they deviated from normal.

three areas that seem to be of genetic importance are the brow ridges, nasion, and infraorbital margins. The chin was of less significance. Although this was a very small study it has been suggested that by looking at a large population the chin might be genetically important (McCulley, 2000).

Family data

Surface shape analysis of twins indicated that certain areas of the face seem to be more genetically determined than others. This finding has prompted the collection of data from families, in order to see if certain surface shapes would be associated with parents and whether those shapes might be seen in family members. Families have been recorded using the optical surface scanner and the data analysed using surface shape analysis of the area around the nose and eyes. In order to obtain detailed information of the shape of the surface in the nasal region, the area was scanned using 265 lines from the right to the left inner canthus. One such family is shown in Figure 9. The bridge of the nose of the parents is of a different shape, as is the tip of the nose. As the shapes of these areas are different in the parents, the scans of the children were then examined to see if these shapes could also be identified in the children. The bridge of parent 1 is seen in child 5, whereas the shape of the bridge of the nose of parent 2 is seen in children 3 and 4. The shape of the nose along its midline is similar to parent 2 in children 4 and 5, whereas child 3 is similar to parent 1. The tip of the nose in parent 2 is similar to child 5. The intercanthal areas of parent 2 are similar to child 3 and also to some extent in children 3 and 4. The shape of the lateral aspect of the nose is similar in parent 2 and child 5. Analysis of the DNA in the various members of the family may give same clue as to which genes are responsible for nose and face shape.

Optical surface scanning provides a helpful tool both for diagnosis and monitoring the effects of treatment and growth. It is also useful for predicting and analysing results of treatment.

Ultrasound

Ultrasound is improving rapidly and resulting in some excellent 3D images of the face and underlying structures. The work has now progressed so that images can be displayed adding the fourth dimension—time. Recently, the lips have been recorded four dimensionally and the movements of the muscles of the lips have been demonstrated (Deng *et al.*, 2000). Ultimately, non-invasive ultrasound may provide an image of the hard tissues of the teeth and jaws, thus dispensing with radiation.

Conclusion

The advances in 3D imaging of the face and skull enable the results of treatment to be viewed from any perspective and to analyse the changes that have occurred.

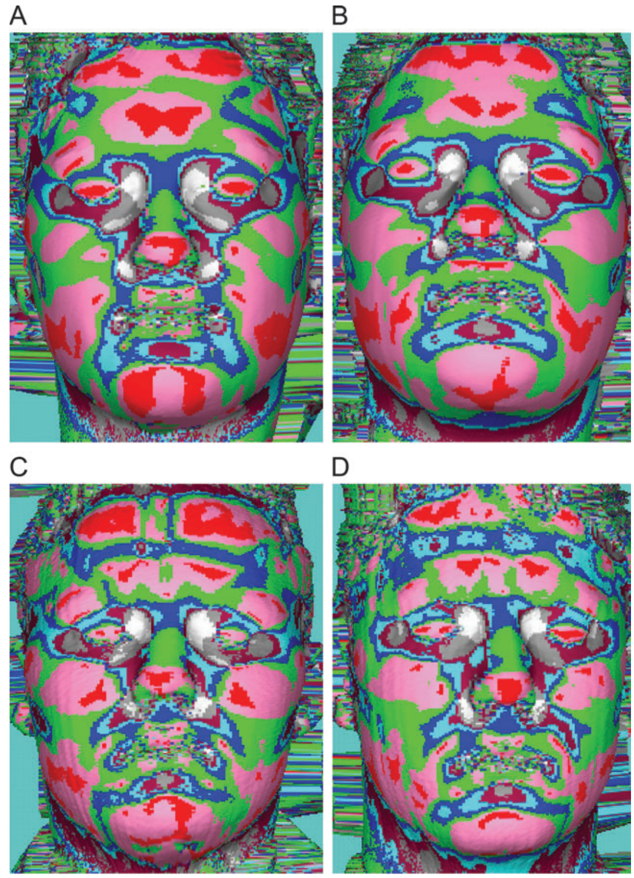

Figure 8 The faces of monozygotic (A and B) and dizygotic (C and D) twins segmented to show the surface shapes. For the monozygotic twins, the brow ridges and the area of nasion are similar. The chin is different as are the lips and cheeks but the infraorbital ridges are of a similar shape. For the dizygotic twins, the areas around the nasion and infraorbital ridges are different as are the brow ridges.

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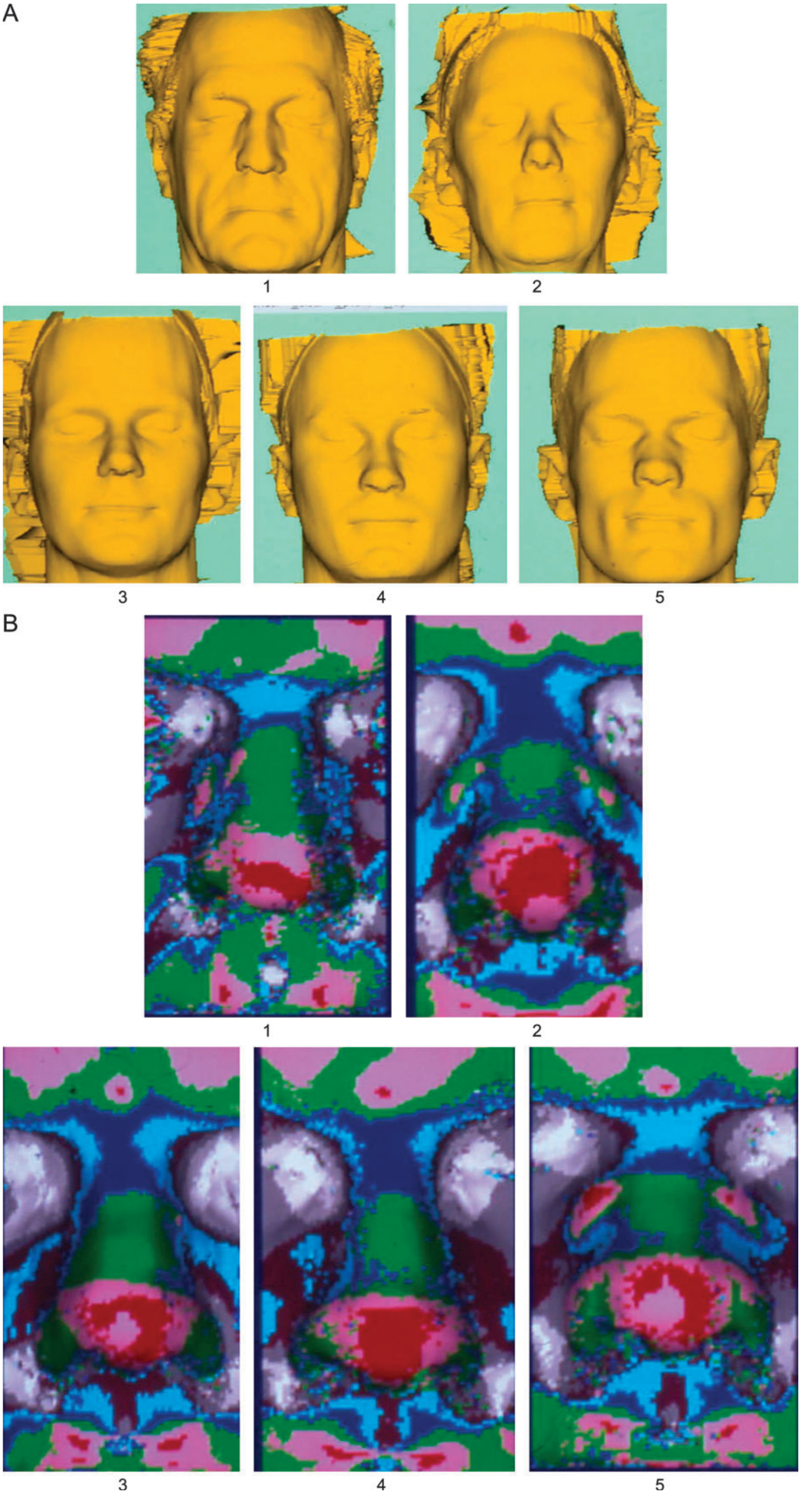

Figure 9 (A) The surface scans of one family. The parents (1 and 2), the children are a female (3) aged 35 years, a male (4) aged 33 years, and a male (5) of 30 years. (B) The scans of the nose region analysed by surface shape. The parents (1 and 2) and the children (3, 4, and 5).

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