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Visualizing three-dimensional facial soft tissue changes following orthognathic surgery

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SUMMARY Laser scanning can be used to visualize the face in three dimensions. These scans can then be processed to enable assessment of facial changes. The aim of this single-centre, prospective, longitudinal, cohort study was to investigate whether four different visualization methods correctly represented facial changes occurring as a result of orthognathic surgery. Twenty-six consecutive orthognathic patients (13 female mandibular advancement and 13 male bimaxillary Class III) were included as well as a control group of 12 non-growing adults (6 males and 6 females). Pre- and post-operative facial laser scans were superimposed and four different visualization methods applied: correspondences with sensitivity to movement, normals, radial, and closest point.

A group of 10 'blinded' observers determined the surgical procedure (if any) that had been performed by applying a specific colour scale to each facial image. The sensitivities and specificities for each visualization method applied to each subject group were determined. The intraobserver repeatability was investigated using Cohen's kappa (κ).

The radial method was found to be superior for identifying mandibular advancement patients (sensitivity/specificity 58.5/92.4 per cent), the normals method for visualization of bimaxillary Class III cases (26.2/99.6 per cent), while the control group was best represented using the closest point (60.0/80.8 per cent). Overall, intraobserver repeatability was good (κ = 0.61). A good level of repeatability was demonstrated in the separate subject groups (mandibular advancement 0.70, bimaxillary Class III 0.70, and controls 0.62). There was no significant difference in the abilities of the four visualization methods to represent facial changes. Each method allowed correct identification of different proportions of the subject groups.

Introduction

Photographs of the face have been used as clinical records for many years. These images, however, have their limitations (Robertson, 1976; Moss *et al.*, 1994b). Small variations in camera angulation can give the illusion of 'improving' or 'worsening' the facial images produced. This problem can be overcome by taking standardized profile and frontal facial views (Robertson, 1976; Ras *et al.*, 1996). However, with a full-face view, the nose is closest to the camera so appears larger, while the ears appear smaller. If such images were used to obtain measurements, the results would be inaccurate. Radiographs have been used along with photographs to visualize the face, but both these techniques produce an image in only two dimensions and expose the patient to irradiation (McCance *et al.*, 1992a; Stoker *et al.*, 1992; Moss *et al.*, 1994a,b).

Two-dimensional (2D) analysis is a crude and unsatisfactory way of analysing the three-dimensional (3D) human face (McCance *et al.*, 1992a; Stoker *et al.*, 1992; Moss *et al.*, 1994a). A 2D assessment of a 3D facial change provides incomplete data and does not account for differences in facial depth and shape (Moss *et al.*, 1994a; Da Silveira *et al.*, 2003). With recent advances in technology, several methods of analysing facial changes in three dimensions have been developed (Da Silveira *et al.*, 2003). These include stereophotogrammetry, cephalometry, moiré topography and contour photography, morphometry, morphanalysis, computed tomography, stereolithography, ultrasonography, and surface laser scanning (Robertson, 1976; Moss *et al.*, 1994a,b; Ras *et al.*, 1996).

Orthognathic surgery requires the teeth and jaws to be manipulated in three planes of space to obtain the most aesthetic, stable, and functional result (Kobayashi *et al.*, 1990; Ayoub *et al.*, 1996; Ferrario *et al.*, 1999; Hajeer *et al.*, 2002; Proffit *et al.*, 2003). Therefore, in order to assess facial changes that occur as a result of orthognathic surgery, 3D images of the pre- and post-operative facial surfaces must be compared. An ideal method for describing these facial changes should be able to record facial soft tissue data, be of sufficient accuracy and precision, be able to produce 3D images, and be easily reproducible (Thomson, 1985). It should accommodate all age groups and not be solely dependent on the skill of a technician. The method should be safe for the patient and the operator, non-invasive, quick, easy, and not too expensive.

Facial changes as a result of orthognathic surgery can be assessed relatively easily using pre- and post-operative 3D facial surface laser scans. The two scans must be accurately superimposed and measurements taken between them. There are several possible methods to measure the differences between the scans. In this study, four different visualization techniques were used to analyse and describe the post-surgical facial differences in two patient groups who had undergone orthognathic surgery.

The aim of this single-centre, prospective, longitudinal, cohort study was to test the hypothesis that all four of the visualization techniques under investigation would correctly represent the expected surgical changes. In turn, this would allow the correct identification of the specific orthognathic surgical procedure performed on each subject by a group of inexperienced observers.

Subjects and methods

Ethical approval for this study was sought and gained from the Leeds (West) Research Ethics Committee. Since June 1999, all Leeds Teaching Hospitals National Health Service Trust surgical-orthodontic patients under the care of a single consultant orthodontist (DOM) have had a minimum of two 3D facial laser scans taken. A Cyberware laser scanner 3030HRC (Cyberware Inc., Monterey, California, USA) was used, which is an infrared laser with a maximum output of 1 mW at 780 nm. It is a Class I laser product so is eye-safe and has an automatic cut-out after 30 seconds. The patients were scanned on the day of their admission to hospital for surgery and again 4 months post-operatively. The scans were repeated immediately if evidence of distortion was seen on the screened image. A consecutive group of 16 female subjects (age range 16–37 years) who underwent mandibular advancement surgery and 13 male subjects (age range 18–28 years) who underwent bimaxillary Skeletal III surgery were selected. Each group was composed entirely of patients of the same gender to eliminate the varying facial characteristics found between the genders. Patients with significant facial asymmetry, who required asymmetrical jaw movement at surgery to correct their dentofacial midline discrepancies, were excluded from the study.

The control group consisted of six male and six female non-growing adults (age range 21–29 years) who had not undergone orthognathic surgery. These subjects were scanned twice within an interval of 2 weeks in order to assess the possible errors of the various visualization methods.

A total of 41 pre- and post-operative scans were analysed. Each pair of scans underwent the same regimen. This method has been previously described (Guest *et al.*, 2001a). Each facial scan was converted to a triangular surface mesh. The facial points were then reduced to 15 per cent of their original number in order to reduce the size of the data file and speed up computation, without distorting the geometry.

To compare the scans taken at different time periods, the scans were superimposed to locate the areas on the face where changes had occurred. This process is called ‘registration’. In order to register the scans, an unchanged area of the face was aligned. The forehead was used because it has been found to remain unchanged as a result of routine orthognathic surgery or natural growth beyond 9 years of age (McCance *et al.*, 1992a, 1997a; Moss *et al.*, 1994a). On all the pre-operative scans, the forehead region of the face was extracted. This area consisted of the forehead following the hairline superiorly and laterally, with the inferior margin just below the superior border of the orbits and across the bridge of the nose. This region was then converted into a triangular mesh and reduced to 15 per cent of the original points. The forehead region of each subject was registered using the iterative closest point (ICP) rigid registration algorithm (Guest *et al.*, 2001a,b) to the whole face of the post-operative scan. The registered scans for each subject were then analysed using four visualization techniques: correspondences with sensitivity to movement (CSM), normals, radial, and closest point. With CSM, the displacement vector indicates the direction and distance between points on the two scans which are matched because they have the most similar surface curvedness, shape, and relative angle (Guest *et al.*, 2001a). For the normals technique, a perpendicular (normal) line is constructed from points on the pre-operative surface. The amount and direction of movement are determined from points on the pre-operative scan to where the line intersects the post-operative scan (Figure 1A). The radial method involves constructing a line from the centroid of the pre-operative scan to the point of intersection with the surface of both scans. The distance between the intersections can be quantified and the direction of the vector from the pre-operative scan can also be determined (Figure 1B). Closest point is a simple concept: it literally measures the distance and direction of the closest point on the post-operative scan from each point on the pre-operative scan (Figure 1C).

Once all four visualization techniques had been applied to each pair of scans, the amount and direction of movement that occurred after surgery was displayed on the post-operative scan, represented using a colour millimetric scale (Figure 2). Warm colours (yellow, orange, red) represented ‘backwards’ or ‘negative’ movement and cold colours (green, blue, purple) ‘forward’ or ‘positive’ movement (Moss *et al.*, 1994a; McCance *et al.*, 1997a; Guest *et al.*, 2001a). In areas where there had been no change, the original neutral colour of the scan remained.

The four visualization images for each of the 41 subjects were randomly displayed to 10 trainee orthodontists (six females and four males; age range 28–32 years) at Leeds Dental Institute. The observers were ‘blinded’ and unaware as to whether or not the subject had undergone surgical-orthodontic correction. Working independently, each observer recorded the direction of movement of nine different parts of the face for each laser scan image examined as depicted by the colour millimetric scale. The nine facial areas were the nasal, paranasal, orbit, forehead, cheekbone, upper lip, lower lip, chin, and mandibular body regions. The options for the direction of movement were forwards, backwards, none, and ‘do not know’. From these observations, the

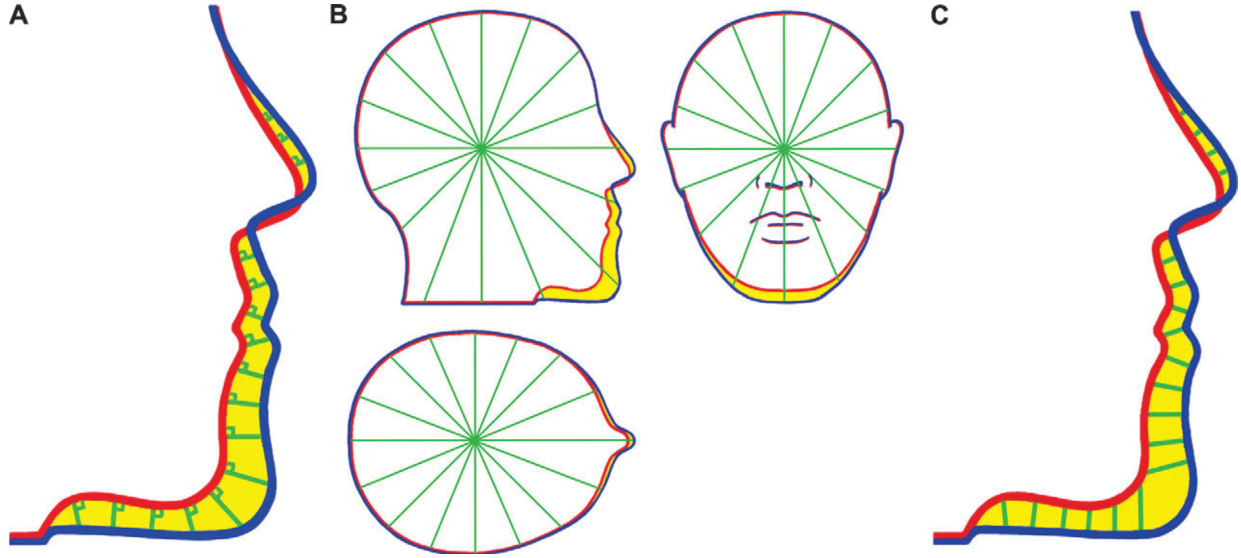

Figure 1 Diagrammatic representation of the normals (A), radial (B), and closest point (C) visualization techniques. The pre- and post-operative facial surfaces are shown with lines indicating how measurements are taken.

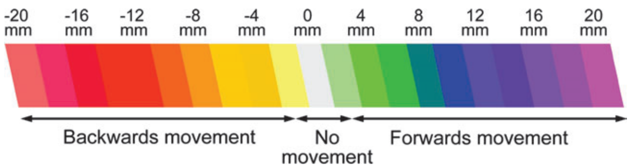

Figure 2 Colour millimetric scale used by the observers to determine the direction of facial movement in the subjects.

observers were asked to state which operation (if any) each subject had undergone. The available options were maxillary advancement only, maxillary impaction only, mandibular advancement only, mandibular setback only, bimaxillary Class II surgery, bimaxillary Class III surgery, none (i.e. control), and do not know. All nine facial regions needed to be studied in order for the observers to decide which surgical procedure had been performed. For the purposes of this investigation, only the responses for the surgical procedure performed were analysed. The responses from the observers were then compared with the procedure the subjects were known to have undergone and the sensitivity and specificity of each visualization method for correctly identifying the members of each patient group were calculated.

Sensitivity is the proportion of patients who were correctly identified as either having undergone mandibular advancement or bimaxillary Class III surgery or being a control subject, i.e. true-positive results (Altman, 1997). Specificity is the proportion of subjects who were correctly identified as not having undergone a particular procedure, i.e. true-negative results. The confidence intervals for the sensitivities and specificities were calculated to give an indication of the interobserver agreement (reproducibility).

The proportion of responses from the observers that were termed do not know for each subject group and each visualization method were determined to enable an overall assessment of how many of the scans could not be interpreted at all.

Two weeks later, the images were randomly reordered and the same group of observers repeated the process. This enabled an assessment of repeatability (intraobserver agreement) to be calculated using the chance-corrected proportional agreement of Cohen's (κ) kappa (Altman, 1997).

Results

Three subjects were removed from the study sample because the registration process failed. Therefore, the number of subjects was reduced to a total of 38: 13 mandibular advancement patients, 13 bimaxillary Class III patients, and 12 controls who had not undergone any intervention.

The coloured images produced displayed facial changes with varying degrees of accuracy, leading to some being well-interpreted by the observers (Figure 3A) and some being poorly interpreted (Figure 3B).

For mandibular advancement patients, the radial visualization method was found to be superior for representing the facial changes that occurred, i.e. had the highest specificity, and closest point was poorest, i.e. had the lowest specificity (Table 1). The bimaxillary Class III patients were correctly identified less often. For these subjects, the normals technique was the most superior method for representing the facial changes that occurred, with closest point being the poorest. The closest point method was most superior for correctly identifying the control subjects, and radial was poorest. When the three subject groups were combined, CSM was the visualization method that most often correctly identified a member of any

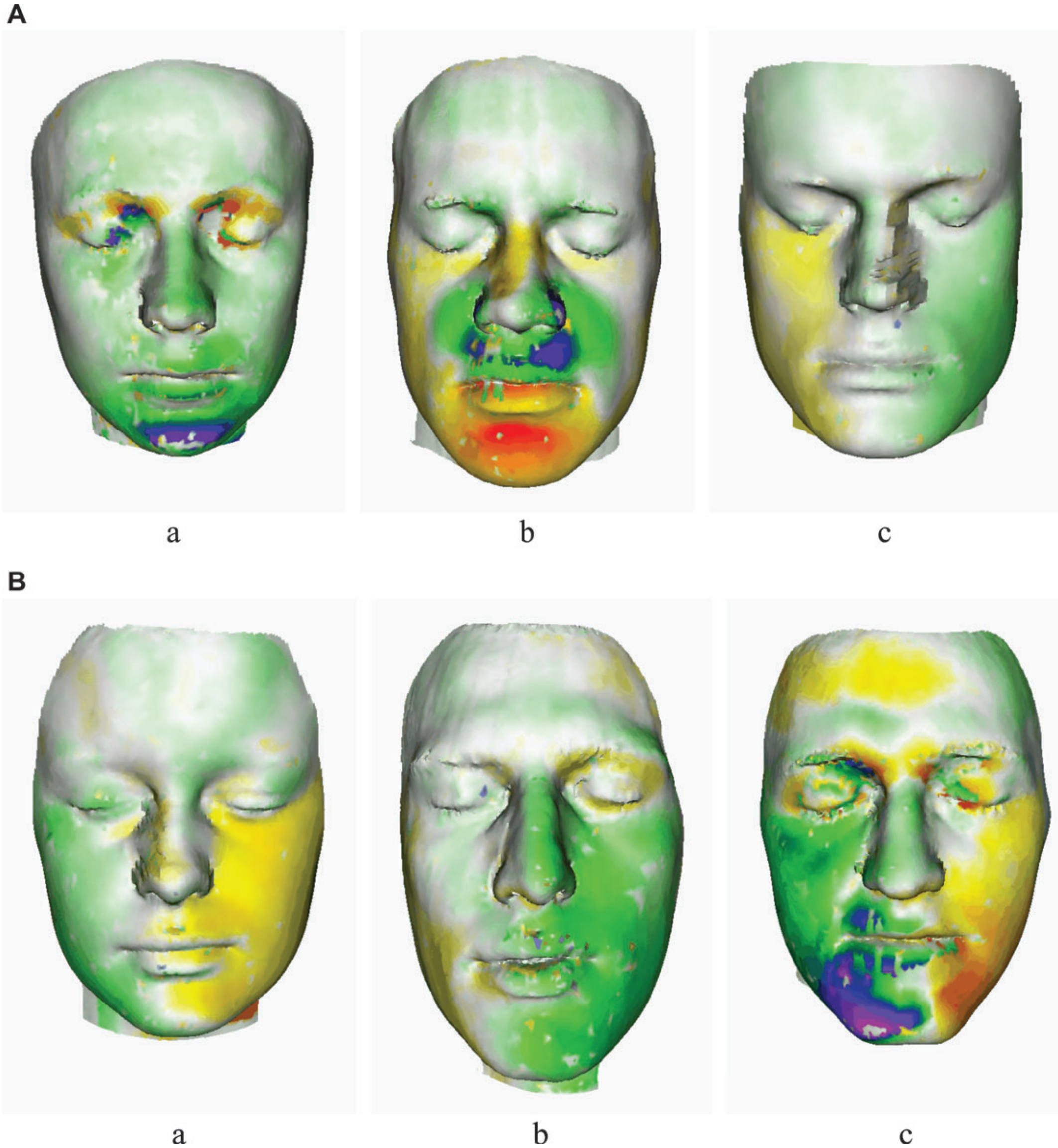

Figure 3 Examples of well (A) and poorly (B) interpreted facial images (a, mandibular advancement patient—closest point method; b, bimaxillary Class III patient—closest point method; and c, control subject—radial method).

of the three groups, followed by the normals, closest point, and then the radial method.

The specificity for the identification of each subject group with each visualization method was above 80 per cent (Table 1). In fact, for the identification of bimaxillary Class III patients, the specificity for CSM, radial, and closest point was 100 per cent i.e. ideal. Normals had only slightly less specificity at 99.6 per cent. For the mandibular advancement group, CSM had the greatest specificity and radial, the least. The highest specificity for the control group was with the radial visualization method, while the closest point had the lowest specificity.

At times, the observers could not tell which orthognathic procedure had been performed in each of the patient groups when the facial changes were represented using each of the four visualization methods (Table 2). The highest percentage of 'do not know' responses was in the control group using the radial visualization method and the lowest in the mandibular advancement group when the closest point visualization method was used.

Intraobserver agreement demonstrated a Cohen's κ value between 0.61 and 0.70 for each individual subject group as well as the three subject groups combined (Table 3).

Discussion

Mandibular advancement patients were identified more accurately using the radial visualization method, bimaxillary Class III patients when the normals method was applied, and closest point for the control subjects. When the three

Table 1 Sensitivities and specificities of the correspondences with sensitivity to movement (CSM), normals, radial, and closest point visualization methods for identifying each subject group. The standard errors (SEs) and 95 per cent confidence intervals (CIs) are also shown.

Visualization method	Subject group	Sensitivity/ specificity (%)	SE of sensitivity/ specificity	95% CI for sensitivity/ specificity (%)
CSM	Mandibular advancement	57.7/97.6	0.043/0.010	49.2–66.2/95.7–99.5
	Bimaxillary Class III	21.5/100	0.036/0	14.5–28.6/100–100
	Control	55.8/86.2	0.045/0.021	46.9–64.7/82.0–90.4
Normals	Mandibular advancement	56.9/97.2	0.043/0.010	48.4–65.4/95.2–99.2
	Bimaxillary Class III	26.2/99.6	0.039/0.004	18.6–33.7/98.8–100.0
	Control	42.5/92.3	0.043/0.017	34.0–51.0/89.1–95.5
Radial	Mandibular advancement	58.5/92.4	0.066/0.017	45.6–71.4/89.1–95.7
	Bimaxillary Class III	23.8/100	0.037/0	16.5–31.2/100–100
	Control	27.5/95.8	0.041/0.012	19.5–35.5/93.3–98.2
Closest point	Mandibular advancement	50.8/96.0	0.044/0.012	42.2–59.4/93.6–98.4
	Bimaxillary Class III	20.0/100	0.035/0	13.1–26.9/100–100
	Control	60.0/80.8	0.045/0.024	51.2–68.8/76.0–85.6

Table 2 Percentage of responses from observers classified as 'do not know'.

Surgery performed	Visualization method			
	Correspondences with sensitivity to movement	Normals	Radial	Closest point
Mandibular advancement	20.8	20.8	23.1	12.3
Bimaxillary Class III	38.5	31.5	33.8	36.2
None	36.7	32.5	39.2	23.3
Overall	31.8	28.2	31.8	23.9

groups were combined, the subjects were well-identified using CSM. Therefore, no method was significantly better than the other for identifying any of the subject groups. All the sensitivity values were low with an accuracy range of 20–60 per cent.

For all groups represented by each of the four visualization methods, specificity was higher than sensitivity. Therefore, there were more false-positive results than false-negative results. This indicates that each method was good at excluding those subjects who were not members of a particular group but less effective at identifying those subjects who belonged to a particular group.

McCance *et al.* (1992a,b, 1993, 1997a,b) preferred the use of the radial visualization method. In previous studies, they found it to be a suitable way to visualize the facial changes that occur as a result of orthognathic surgery in Class I, II, and III patients. This agrees with some of the results from the present study, which showed superior results for skeletal Class II patients undergoing mandibular advancement. However, there are also some conflicting comparisons. McCance *et al.* (1992b) found that bimaxillary Class III surgery was correctly represented using the radial method. This study, however, demonstrated that the normals visualization method was superior for this specific group of patients.

The proportion of subjects correctly identified varied greatly between groups as well as between visualization methods. One reason for this variation may be due to errors in the initial scan registration process. Some of the facial images were found to display an apparent degree of rotation with one vertical half of the face being warm coloured and the other cold coloured. This indicates that the pre-and post-operative scans may not have been correctly aligned during the registration process. This may have been because the forehead area, which was used to register the scans, may have had insufficient unique shape characteristics. This may have led to the scans being rotated slightly from their true registration position. One possible way to overcome this in the future would be to use landmarks on the forehead to register the two scans. In the past, in order to analyse facial changes, researchers have identified and located landmarks on facial images and compared their positions, in terms of 3D co-ordinates, at various time intervals (McCance *et al.*, 1992a,b, 1993, 1997a; Moss *et al.*, 1994a; Ferrario *et al.*, 1999; Guest *et al.*, 2001a; Da Silveira *et al.*, 2003). To assess any changes, accurate identification of the landmarks is essential (Coward *et al.*, 1997). However, the identification of some landmarks depends significantly on the experience of the operator. In addition, the positions of some facial landmarks are dependent on the exact orientation of the head.

McCance *et al.* (1992a,b, 1993, 1997a,b) have previously used landmarks to match pre- and post-operative scans. In several of their studies, they found that five landmarks were adequate to gain a high degree of reproducibility in superimposing the scans with the chosen points being reliably located on all the scans (McCance *et al.*, 1992b, 1993, 1997b). The landmarks used were the left and right medial and lateral canthi, soft tissue nasion, chosen as the

Table 3 Kappa (κ) values for intraobserver repeatability. The standard errors (SEs) and confidence intervals (CIs) are also shown.

Surgical procedure	κ	SE for κ	95% CI for κ
Mandibular advancement	0.70	0.023	0.65–0.74
Bimaxillary Class III	0.70	0.034	0.63–0.77
Control	0.62	0.024	0.58–0.67
Overall	0.61	0.015	0.58–0.64

position of the maximum concavity in the vertical plane profile, and the maximum convexity on the transverse plane profile. Recently, there has been a move away from the use of landmarks alone in order to register facial scans (Guest *et al.*, 2001a). However, from this study, it appears that the use of the forehead area alone is inadequate and can produce errors in superimposition. For example, registration failure in three of the subjects in this study occurred when the forehead region in one scan was matched to the chin in the other, rather than to the forehead as expected. This kind of mismatch can arise when using the unmodified ICP algorithm, especially when there is a large initial misalignment between scans. In future research, manual registration should be performed first to reduce the chance of misalignment, before using the registration algorithm. Another future possibility is that a combination of the use of the forehead area and soft tissue landmarks could result in a more accurate registration process. Further investigation into this aspect of laser scan analysis is warranted.

Problems with the registration process are responsible for the low sensitivities for the identification of each subject group using each visualization method. It resulted in registration failures and rotations of scans during the process, producing incorrect identification of the subject groups. Further improvements in the registration process would eliminate these problems and so enable more accurate identification of the surgical procedure performed.

Observer feedback indicated that many of the scans were confusing and difficult to interpret, as they showed conflicting facial changes on the right and left sides of the face i.e. forward movement on one side and backward movement on the other. This can be explained by the rotation that may have occurred during the registration process. The large proportion of do not know responses in the raw data demonstrates the significant degree of observer uncertainty (Table 2). Overall, the facial scans were interpreted with good intraobserver repeatability (Cohen's κ = 0.61). Observers interpreted the same scans in the same way on two separate occasions. The intraobserver agreement for the identification of both the mandibular advancement and bimaxillary Class III patient groups had a κ value of 0.70 (Table 3). The value for the control group was 0.62 and for the three groups combined 0.61. These figures represent 'good' intraobserver repeatability/agreement for this study (Altman, 1997). However, the visualization methods investigated may not be wholly valid due to possible registration and superimposition errors mentioned earlier.

There is also a possibility that the observers may have been misled by the colour scale (Figure 2) into thinking an operation had been performed on some of the control subjects. Previous research has shown that laser scanners are capable of imaging the face with an accuracy of 0.5 mm (Moss *et al.*, 1987, 1994b; McCance *et al.*, 1992b; Kusnoto and Evans, 2002). As this study involved superimposing two scans with a possible registration error, then the total error could be in the region of 2 mm. As a result, the colour scale could be adapted so that 0–2 mm of change is displayed as 'no change' to account for this method error. This would prevent observers recording these changes and could lead to more accurate identification of orthognathic procedures and control subjects. This intrinsic registration error needs to be quantified in a separate study.

Another possible problem was observer fatigue. This study involved each observer looking at 152 facial images on two separate occasions. As the observers progressed through their task, they may have become less meticulous. This may have led to more errors with the production of incorrect results. In future studies, it may be necessary to reduce the number of images so that observers can concentrate more fully on a smaller sub-sample in order to reduce the chances of fatigue. One way to assess observer fatigue would be to repeat the analysis of the same case at the start, middle, and end of the observation session to check the consistency of the observers' conclusions.

The results of this study show that mandibular advancement was the procedure best identified by any of the visualization method, in particular with the radial method. Although the bimaxillary Class III procedure was best represented by the normals visualization method, it was not identified correctly as often as mandibular advancement patients. This finding may be expected due to the fact that bimaxillary Class III surgery is a more complex two-jaw procedure with less predictable soft tissue changes than those seen with mandibular advancement surgery. A better visualization method needs to be found in order to improve the identification of bimaxillary Class III patients. One possibility is the cylindrical method (Guest *et al.*, 2001a). This involves identifying the centroid of the pre-operative surface, then drawing a line from each point on the surface to a point that has the x and y values of the centroid and the z value of the original point. This is the equivalent of having a cylinder with a long axis through the centroid. The line from any point will be perpendicular to the long axis. The distance and direction of the displacement vector are the distance and direction from the point to the line's point of intersection with the post-operative surface.

Further investigation is required in order to establish whether this method would be more valid and accurate.

The use of visualization techniques to indicate facial changes that occur as a result of orthognathic surgery may eventually be used to communicate the expected changes to both clinicians and patients. This would allow visualization of how a particular patient may look like after undergoing surgery.

Conclusions

1. There was no significant difference between the abilities of the four different visualization methods to identify soft tissue facial changes in any or all of the subject groups. Generally, the sensitivities were low and the specificities were high, which may cause confusion.
2. There was good intraobserver repeatability with regard to interpreting the facial laser scans for all the three subject groups.
3. Further investigations into the registration process should be carried out.

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