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RESEARCH

Reconstruction of facial morphology from laser scanned data. Part I: reliability of the technique

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Objectives: The aim of this study was to evaluate the effects of scanning parameters on the precision of the data acquired using a facial laser scanner and to assess the reliability of automatic model recording in humans.
Methods: Data were acquired using a laser scanner (Cyberware 3030RGB); analysis and measurements were performed with Rapid Form 2004 software. A mannequin and six volunteers were scanned to investigate the effects of environmental conditions, positioning, head orientation, and software procedures. Precision and accuracy of the data were evaluated comparing six linear measures calculated on scanned data with those obtained directly. Two sessions with different head inclination were performed. The reliability of repeated scans was also assessed measuring the distance between the surfaces reconstructed from two separate scans of the same subject, at 12 anatomical points, in 5 subjects, during two sessions using a different head inclination. Differences were analysed using paired *t*-tests or analysis of variance (ANOVA).
Results: The accuracy of scanning was ± 0.65 mm. The development of a specific protocol resulted in a mean scanning error of 1–1.2 mm and a recording error of 0.3–0.4 mm on repeated scans of human subjects.
Conclusions: This study indicates that scanning of the human face may be hampered by errors and artefacts, mainly due to movements. While the effect of trembling and involuntary movements during the exam may be minimized using faster scanning devices, comparative observation over time may be affected by unreal differences due to the uncertainty of facial expression. The overall error is, however, in the range useful for most clinical studies.
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Keywords: three-dimensional imaging, anthropometry, face, validation studies

Introduction

Different congenital or acquired maxillofacial diseases affect facial morphology and require that normalization of appearance be included in treatment. In most cases, the clinician relies on visual evaluation to examine the patient or to assess the treatment outcome. This method is highly subjective and non-reproducible, and thus is not suitable for comparison over time. Thus, both diagnosis of facial malformations and evaluation of surgical results would benefit from the development of objective techniques for analysis of facial morphology that are suitable for statistical evaluation and that would also ideally be non-invasive, quick, repeatable, and, therefore, automatated.[1–3]

Photographs and two-dimensional radiographic films are the methods most commonly used to document facial morphology. However, these methods are affected by a high incidence of artefacts and errors, and by the intrinsic lack of the third dimension in the representation. On the other hand, the currently available *in vivo* 3D imaging systems, such as magnetic resonance and computerized tomography (CT), have well known limitations related to cost, availability, and radiation exposure. Optical devices offer a different approach to acquisition of 3D representations of external surfaces; these systems permit high resolution, low-cost, fast, and repeatable surface scanning.[4–6] Several authors have already applied optical 3D technologies to the study of maxillofacial pathologies.[6–10] The automatic capture of anatomic data *in vivo* is, however, often affected by artefacts and errors caused by difficulties in defining protocols compatible with

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individual anatomic variability. Thus, specific knowledge of the many practical problems concerning the modalities of execution and of the possible sources of error is required in order to implement this methodology for clinical use.

To date, validation studies have mainly addressed the precision and reliability of linear measurements of scanned 3D models.[11] However, linear anthropometric measurements provide a very limited representation of the 3D facial surface. In order to investigate the entire 3D geometry, the precision and repeatability of surface reconstruction from scanned data must be specifically addressed. Moreover, most validation studies have assessed errors in scanning inanimate phantom models in an artificial setting.[5,12] The living human subject presents specific surface physical features, intrinsic motility, and orientation problems that might affect the scanning procedure. 3D scanners are at present the most used technology for optical facial surface acquisition.[4–6,12] Further specific information on the reliability and precision of surface reconstruction from 3D laser scanning of the human face is thus required in order to optimize data acquisition and measurements for clinical studies. Thus, the objectives of this study were (1) to evaluate parameters that may affect facial surface data acquisition using the Cyberware colour laser scanner, and (2) to assess the precision and repeatability of 3D surface reconstruction of the human face.

Materials and methods

3D laser scanner

Surface data were acquired using a Head and Face Colour 3D Scanner (3030RGB; Cyberware, Inc., Monterey, CA). The digitizer utilized a revolving scanning head that projects a vertical plane of laser light on the subject. This light profile is recorded by a digitizing camera at a defined offset distance and angle from the laser projector. The scanner shines a low-intensity laser (below 0.00008 W) on the object and poses no risk to the patient's vision. The scanning head moves 360° around the subject, digitizing 512 vertical profiles in approximately 17 s. A high quality video sensor captures these profiles from two viewpoints; simultaneously, a second video sensor acquires colour information. The scanning process captures an array of digitized points, with each point represented by x, y, and z coordinates for shape, and 24-bit R (red), G (green) and B (blue) coordinates for colour. The stated spatial resolution of the scanner is 500 μm to 2 mm in the horizontal direction, depending on the speed of the moving scanner platform, 628 μm in the vertical direction, and 100–400 μm in the depth dimension, depending on the surface quality.[13]

The digitizer transfers the acquired data via an SCSI interface to a graphics workstation for immediate viewing and modification. A Pentium III personal computer and Cyberware Echo software (Cyberware, Inc., Monterey, CA) were used for this purpose.

Shell processing

The model analysis, linear measurements, and shell recording and comparison were carried out using Rapid Form 2004 software (INUS Technologies Inc., Seoul, South Korea).

The spatial recording of different shells was done by software through alignment of manually selected anatomical regions. The procedure automatically accommodates the different shells to obtain the best fit between surfaces, *i.e.* to minimize the displacement between corresponding points in the two shells.

Evaluation of scanning parameters

Evaluations of the scanning parameters were conducted under several different experimental conditions.

Assessment of optimal scanning conditions

Phantom study A life-size phantom head was used to evaluate the effects of positioning inside the working area of the scanner. The orientation of the object with respect to the coordinates of the device and the distance from the axis of rotation of the scanning head were systematically investigated. In order to achieve a structured evaluation of these parameters, the centre of the working volume and the centre of the phantom head were located and marked. The quality of the digitized surface and the presence of artefacts were assessed for each 1 cm translation of the object along the x, y, and z axes, up to 5 cm.

Human study The effect of room lighting, head orientation (flexion/extension), involuntary movements, sound and climatic control were qualitatively assessed on volunteers through repeated scans obtained under different conditions. The effect of head restraints was also specifically evaluated, by empirical evaluation of the amount of artefacts in the acquired data.

Evaluation of scanning error

The mannequin head and six adult volunteers (four males, two females; mean age 27.5 years) were scanned by one of the authors (MCS), termed the "experimental observer". To optimize the quality of the model and to reduce artefacts, the scanning protocol was based on the preceding observations concerning object positioning and environmental conditions. The head was positioned with the axis of rotation of the scanning head at the midline, along the axis connecting the right and left *tragi*. Data were acquired from the volunteers with their eyes closed, their teeth in natural occlusion, and with their head in two fixed positions: with the Camper plane at 0° (P_1) or +25° (P_2) to the horizontal. A head-rest was used to assure minimal involuntary movement. The inclination of the head was controlled by means of an external projected light guide.

The dimensional precision of the captured data (accordance between life and scanned measures) was tested by comparing six linear measurements obtained from the scanned models (Table 1) with the corresponding *in vivo* measurements obtained using a manual anatomic calliper. To increase the accuracy of the localization of the

Table 1 Linear measurements obtained from scanned models and *in vivo*, used to assess the dimensional precision of captured data

Measure	*Description*
Tr-Tr	Left tragus to right tragus
Al-Al	Left nasal ala to right nasal ala
Ma-Ma	Left malar prominence to right malar prominence
Tr_r-Prn	Right tragus to nasal tip
Tr_l-Pg	Left tragus to cutaneous pogonion
N-Pg	Nasion to cutaneous pogonion

landmarks, reference labels were marked on the skin before scanning. Differences were assessed using paired *t*-tests, with significance defined as $P < 0.05$.

To test the accuracy of the observer on linear measurements (variance of repeated measures), the six measurements were obtained in ten repeated sessions *in vivo* and from the scanned data by the experimental observer and the control observer (LV), using a single volunteer and the same scan. The data were analysed to assess intraobserver and interobserver variability. Differences between the variances were assessed by analysis of variance (ANOVA), with significance defined as $P < 0.05$.

Evaluation of shell-shell recording accuracy

In order to assess the accuracy of the automatic process of shell-shell recording, identical non-aligned surfaces captured from three volunteers were used (*i.e.* the same data set was recorded on itself after intentional spatial displacement).

The recording was repeated three times each by the experimental and control observers, working separately. To quantify the displacement between shells, the clearance vector mapping (distance between corresponding points) of the two surfaces was obtained. Mean and maximal clearance values for shell-shell displacement were measured within the surface area representing the face at 12 fixed facial points identified at the intersections of anatomical reference lines (Figure 1). The data were analysed to assess intraobserver and interobserver variability. Differences between the variances were assessed by analysis of variance (ANOVA), with significance defined as $P < 0.05$.

Two different recording procedures were then evaluated: recording based on the best accommodation of the whole facial area (R_1) and recording based only on alignment of the ears and forehead (R_2). Differences were assessed using paired *t*-tests, with significance defined as $P < 0.05$.

Evaluation of reliability of 3D surface comparisons

The reliability of comparing the reconstructed surfaces was assessed on five subjects comparing two consecutive scans (T_1 and T_2) obtained on the same day. The experiment was repeated with the Camper plane at 0° (P_1) and +25° (P_2) to the horizontal. Recording was restricted to the ears and forehead (R_2). The difference between the corresponding surfaces was evaluated by clearance vector mapping at the 12 points indicated in Figure 1. Both the shell recordings and the clearance measurements were obtained by the experimental observer and the control observer, working separately.

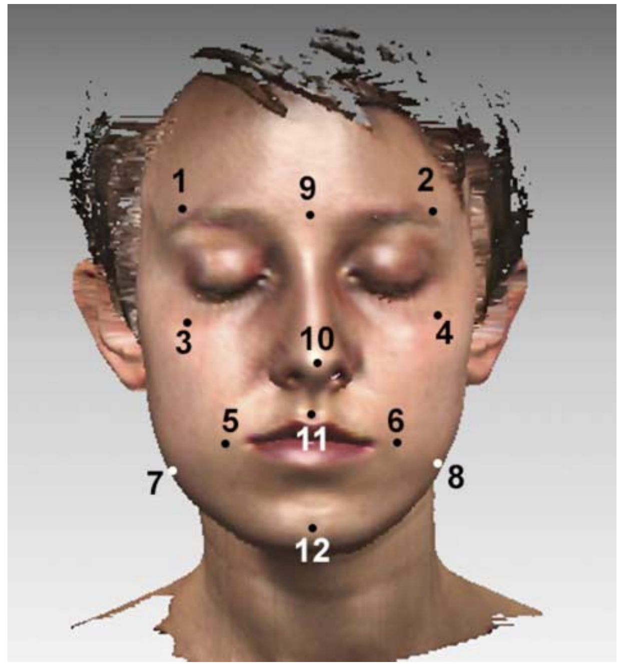

Figure 1 Mean and maximal clearance values for shell-shell displacement were measured within the surface area representing the face at 12 fixed facial points identified at the intersections of anatomical reference lines

To further analyse possible sources of error during the procedure, the correctness of the head inclination (Camper plane to the horizontal) was measured on the recorded models after completion of the scans of the five subjects. A cross-comparison of the scans with the two head inclinations, P_1 and P_2, was then performed to evaluate the effect of head positioning on recording error.

Average values, standard deviations, and maximum and minimum errors were calculated for all the collected data. Differences were assessed using paired *t*-tests, with significance defined as $P < 0.05$.

Results

Assessment of optimal scanning conditions

Positioning inside the scanner working volume Systematic displacement of the object from the rotation axis of the scanning head demonstrated that the number of artefacts increased and the number of points in the shell decreased with increasing distance from the axis, indicating that the best scanning quality was obtained when the subject was centred in the scanner working volume.

Artefacts The investigation of the factors that generated artefacts was conducted empirically and revealed that the most relevant aspects during scanning were the laboratory environment, facial surface conditions, and motion artefacts.

The precautions required to reduce artefacts were completely darkening the room and removing or masking any object in the room that had a reflective surface. The laser light used by the scanner for the recording was red and the video sensor was thus very sensitive to artefacts from direct sunlight or intense external light sources. All situations that modify the skin texture and alter refraction (*i.e.* sweat, hydration, or creams) appeared a possible cause of artefacts in the acquired data. Carefully cleaned facial skin and climate control were thus required for the exam. Voids in the acquired surface or artefacts commonly were observed in areas covered by hair, affecting mainly acquisition of the ear, and were managed by covering the patient's hair with a dark opaque drape.

The most common source of artefacts was subject motion during the time required to complete digitization (Figure 2). Motion may affect a part of the face, most commonly owing to eye movements or facial expressions, or it may affect the whole head because of trembling of the neck musculature. In all subjects, the best exams were obtained when the patient was allowed to keep the head in a natural relaxed position; forcing head flexion or extension exacerbated trembling.

Evaluation of scanning error

The reliability of the experimental observer in comparison with a control observer was tested using repeated measures of linear dimensions. ANOVA revealed that the intraobserver variance was 0.04–0.80 mm for the experimental observer and 0.04–4.65 mm for the control observer, with an interobserver variance of 0.05–2.67 mm (Table 2). The variances of the measurements made using manual callipers on the subjects appeared to be greater than those of measurements made on the scans. Four *in vivo* measurements and two scanned measurements were significantly different between the two observers; the differences in the mean measurements ranged from 0 mm to 1.3 mm. The mean variance (accuracy) of the experimental observer resulted in ± 0.65 mm.

Figure 2 Motion artefacts of the reconstructed facial surface are visible in the forehead and neck. These may cause errors during surface recording

The determination of the dimensional precision of the scanned model, in comparison with manual *in vivo* anthropometric measurements, was then evaluated on a mannequin head and on six human subjects. Comparison of the *in vivo* and scanned measurements (*t*-test for dependent samples) revealed a systematic error for one of the six dimensions (Tr-Tr). Statistical analysis revealed a mean error ($\pm$ SD) of 0.45 ($\pm$ 0.36) mm for the mannequin head and of 0.99 ($\pm$ 0.93) mm for the six human subjects with the Camper plane at 0° (session P_1). The corresponding figures were 0.23 ($\pm$ 0.15) mm for the mannequin head and 1.2 ($\pm$ 0.97) mm for the six human subjects with the Camper plane at +25° (session P_2). The absolute values of the differences were considered in order not to minimize the error by averaging positive and negative values (Table 3).

Evaluation of shell-shell recording accuracy

The accuracy of the automatic process of shell-shell recording, as evaluated on re-alignment of identical displaced surfaces, revealed an overall maximal error (displacement of the corresponding surfaces) of 0.0007 mm when recording on the whole face (session R_1). The maximal surface distance at the 12 points considered (Figure 1) was the same for both the experimental and control observers.

The recording restricted to the ears and forehead (session R_2) showed a slight increase in inaccuracy, *i.e.* an overall maximal error of 0.006 mm for the experimental observer and of 0.005 mm for the control observer. A slight misfit of the surfaces was particularly evident in areas far from the recording regions, namely the chin, the mandibular angle, and the neck. Given the very small error values recorded in both sessions, no further comparisons were conducted. The accuracy of the recording method performed by the experimental observer was thus assessed as ± 0.01 mm for the R_2 procedure.

Evaluation of reliability of 3D surface comparison

Repeated scans of five subjects disclosed a mean discrepancy (*i.e.* distance of the two surfaces) of 0.4 mm (maximum 2.4 mm) with the Camper plane at 0° (session P_1), and of 0.3 mm (maximum 2 mm) with the Camper plane at +25° (session P_2). Comparison using *t*-tests did not indicate significant differences between observers or between the P_1 and P_2 sessions (Table 4). Among the 12 anatomical points considered, the distances were larger for the cheeks, lips and chin, and smaller for the forehead, mandibular angle and nose (Figure 3). The maximal recording error was within 1.5 mm at six points, and less than 2 mm at 10 of the 12 points considered. Evaluation of head position after scanning revealed that the actual orientation of the Camper plane was −3.2° ± 4.3 in session P_1 and 24° ± 3.1 in session P_2.

Table 2 ANOVA comparison of the repeated measures obtained by the two observers

	Experimental observer			*Control observer*			*Interobserver*	
	Mean (mm)	*Standard deviation*	*Variance*	*Mean (mm)*	*Standard deviation*	*Variance*	*Variance*	*P*
Tr-Tr $_{in\ vivo}$	151.4	0.9	0.80	152.5	0.8	0.69	1.02	*
Ma-Ma $_{in\ vivo}$	106.5	0.5	0.27	105.9	0.6	0.32	0.38	*
Al-Al $_{in\ vivo}$	35.3	0.3	0.07	36.0	0.6	0.33	0.31	*
Tr_r-Prn $_{in\ vivo}$	143.9	0.4	0.15	143.7	0.8	0.68	0.40	
Tr_l-Pg $_{in\ vivo}$	143.1	0.2	0.04	144.4	2.1	4.65	2.67	
N-Pg $_{in\ vivo}$	106.8	0.2	0.06	105.7	0.5	0.29	0.48	*
Tr-Tr $_{scanned}$	152.5	0.2	0.04	152.5	0.3	0.06	0.05	
Ma-Ma $_{scanned}$	106.7	0.4	0.16	106.7	0.2	0.05	0.10	
Al-Al $_{scanned}$	35.3	0.3	0.10	36.2	0.5	0.26	0.36	*
Tr_r-Prn $_{scanned}$	144.1	0.5	0.24	144.5	1.1	1.22	0.74	
Tr_l-Pg $_{scanned}$	143.6	0.3	0.12	144.0	0.8	0.58	0.39	
N-Pg $_{scanned}$	107.1	0.3	0.08	106.8	0.2	0.04	0.10	*

* Significant difference, $P \leq 0.05$; $n = 10$

Table 3 Differences (in mm) between measurements obtained *in vivo* and on scanned models, using two head orientations

	P_1		P_2	
	Mannequin (n = 1)	*Human subjects (n = 6) Mean ± SD (range)*	*Mannequin (n = 1)*	*Human subjects (n = 6) Mean ± SD (range)*
Tr-Tr	0.9	1.4 ± 1.1 (0–3)	0.3	1.5 ± 0.9 (0.4–3)
Ma-Ma	0.1	0.8 ± 0.7 (0.3–1.8)	0.2	1.2 ± 0.8 (0.3–2.3)
Al-Al	0.2	0.3 ± 0.3 (0–0.8)	0.2	0.3 ± 0.2 (0–0.7)
Tr_r-Prn	0.1	0.8 ± 0.8 (0.2–2.5)	0.1	0.8 ± 0.5 (0.3–1.5)
Tr_l-Pg	0.8	1.2 ± 1.4 (0–3.9)	0.5	0.9 ± 0.5 (0.4–1.7)
N-Pg	0.6	0.9 ± 0.5 (0.5–2)	0.1	1.6 ± 1.6 (0.6–4.9)
All measures	0.45 ± 0.36	0.99 ± 0.93	0.23 ± 0.15	1.2 ± 0.97

P_1, Camper plane at 0°; P_2, Camper plane at 25° to the horizontal

Table 4 Mean (± SD) and maximal error of recording on consecutive scans, with Camper plane at 0° (P_1) or +25° (P_2) with the horizontal

	P_1 error (mm) Mean ± SD [maximal]	*P_2 error (mm) Mean ± SD [maximal]*	*P_{1-2} error (mm) Mean ± SD [maximal]*	
Point 1	0.3 ± 0.4 [0.9]	0.3 ± 0.4 [0.7]	0.3 ± 0.4 [0.8]	
Point 2	0.6 ± 0.4 [1]	0 ± 0 [0]	0.6 ± 0.5 [1.4]	
Point 3	0.6 ± 0.9 [2.1]	0.4 ± 0.5 [1.2]	0.1 ± 0.2 [0.4]	
Point 4	0.6 ± 0.9 [2]	0.3 ± 0.3 [0.7]	0.3 ± 0.5 [1]	
Point 5	0.7 ± 0.8 [2]	0.5 ± 0.9 [2]	0.7 ± 0.4 [1]	A
Point 6	0.5 ± 0.5 [1]	0.5 ± 0.5 [1.2]	0.9 ± 0.3 [1.1]	
Point 7	0 ± 0 [0]	0.4 ± 0.6 [1.5]	0.4 ± 0.4 [0.8]	
Point 8	0.2 ± 0.4 [0.8]	0.2 ± 0.4 [0.9]	0.2 ± 0.3 [0.7]	
Point 9	0.1 ± 0.2 [0.5]	0.1 ± 0.3 [0.6]	0.1 ± 0.2 [0.5]	
Point 10	0.3 ± 0.4 [0.9]	0.4 ± 0.3 [0.8]	0.2 ± 0.3 [0.6]	
Point 11	0.5 ± 0.5 [1.2]	0.7 ± 0.6 [1.6]	0.6 ± 0.4 [1.2]	
Point 12	0.6 ± 0.7 [1.4]	0.7 ± 0.4 [1]	0.4 ± 0.3 [0.7]	
Point 1	0.2 ± 0.3 [0.6]	0.4 ± 0.6 [1.1]	0.2 ± 0.3 [0.6]	
Point 2	0.3 ± 0.4 [0.9]	0 ± 0 [0]	0.6 ± 0.3 [1.2]	
Point 3	0.7 ± 0.5 [1.4]	0.2 ± 0.5 [1]	0.2 ± 0.3 [0.7]	
Point 4	0.3 ± 0.5 [1]	0.4 ± 0.5 [1.3]	0.4 ± 0.3 [0.8]	
Point 5	1.1 ± 0.4 [1.8]	0.7 ± 0.6 [1.8]	0.9 ± 0.8 [2.1]	B
Point 6	0.4 ± 0.6 [1.4]	0.5 ± 0.4 [1]	0.9 ± 0.8 [2.1]	
Point 7	0.3 ± 0.5 [1]	0.5 ± 0.7 [1.6]	0.6 ± 0.7 [1.6]	
Point 8	0.6 ± 0.4 [1.1]	0.3 ± 0.4 [0.9]	0.2 ± 0.4 [0.8]	
Point 9	0.1 ± 0.3 [0.6]	0.1 ± 0.3 [0.6]	0.3 ± 0.3 [0.7]	
Point 10	0.8 ± 0.6 [1.5]	0.6 ± 0.4 [1]	0.1 ± 0.2 [0.5]	
Point 11	0.9 ± 0.9 [2.4]	0.5 ± 0.3 [0.9]	0.7 ± 0.5 [1.2]	
Point 12	1.1 ± 0.8 [1.8]	0.5 ± 0.4 [1.1]	0.4 ± 0.4 [0.9]	

Points are illustrated in Figure 1. A cross-comparison (P_{1-2}) of scans with different head inclination was also obtained to evaluate the effect of positioning on the recording error. A = experimental observer; B = control observer. $n = 5$

Cross-recording of the T_1 scans at 0° and 25° did not show increased recording errors within the facial regions. Deformation of the skin surface related to head inclination was evident in the neck area, which prevented anatomical comparison of the scans in this region.

Discussion

The necessary prerequisite for 3D surface comparison of facial anatomy over time is a reliable process of data capture and recording. Several different steps are involved during which errors and artefacts may be generated.

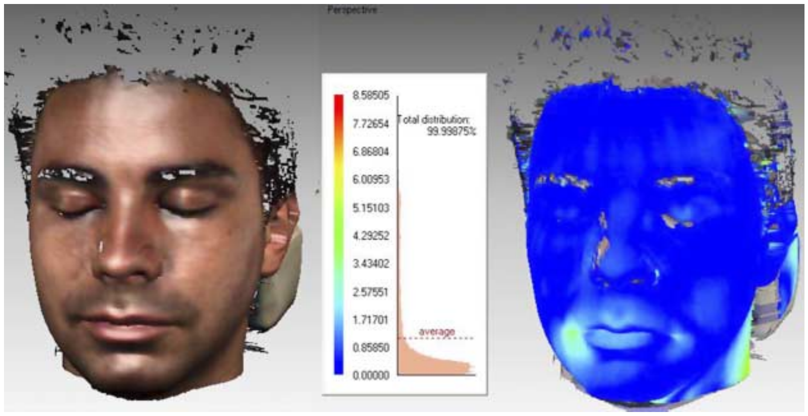

Figure 3 Clearance vector mapping of two shells obtained from consecutive scans of the same subject. Although the majority of the face reveals negligible differences, the effects of mimic movements are apparent around the lips and the neck muscles. Colour codes in mm

Although automatic instrumentation is used, a large part of the process is manual or at least appears to be influenced by the behaviour and knowledge of the observer. Thus the procedure is, on the whole, observer-dependent and requires a learning curve. Because the procedure is applied to animated human subjects, in whom sudden changes in morphology caused by trembling, eye movements, facial expressions and breathing may be reduced but not eliminated, the procedure is also patient-dependent. This implies the existence of a basal error level which must be known in order to interpret clinical data and which, at present, cannot be completely suppressed.

The present study has attempted to separately evaluate the different sources of error. Precision (the variance of repeated measures) and accuracy (the difference from the true measure) have been considered. The first aspect considered was the error due to the procedure of surface scanning of the human face. Our findings confirm that 3D laser scanning is a rather precise and accurate method for surface acquisition. A trained observer using a repetitive scanning protocol provides consistent data within a 1.1 mm uncertainty. A mean difference of 0.45–1.2 mm was observed when the measurements on scanned data were compared with the corresponding *in vivo* measurements. This comparison does not exactly represent an assessment of the accuracy of the scanner, as it includes the inaccuracy of both scanned and *in vivo* measurements, but allows estimation of the reliability of the technique in comparison with the most widely accepted facial measuring system. With regard to errors in the laser scanner data for the face, previous investigators have reported variable results. The reported precision of the laser scanner has been assessed as 0.6–2 mm on plaster head models,[12] depending on the use of pre-labelled landmarks. Laser scanner accuracy for point localization on human subjects, in comparison with direct anthropometric measurements, was determined to be within 1.5 mm for only one third of the most commonly used measures, and unreliable (>2 mm) for the other two thirds.[11] Previous investigations of the reliability of laser scanning of the head, using an inanimate plaster model, reported observations similar to those of the present study.[12] Head positioning and head inclination were considered to be the most common sources of error. In investigations of the accuracy of 3D scanning of human subjects, motion and trembling were revealed to be the most relevant problems that must be managed. The accuracy of the scans in the present study appears rather high when compared with that of CT scans. The repeatability of landmark localization on CT scans has been shown to be 0.5 mm on dry human skulls,[14] and the dimensional accuracy of the CT technique in optimized *in vitro* settings was within 2 mm.[15] The accuracy of stereophotogrammetry is similarly reported to be within 2 mm.[16]

The second aspect of validation of the method considered in the present study was artefacts. These were shown to be the most important problem. Trembling appeared to be a common source of error; this varied according to the ability of the subject under study to remain immobile. Specially designed head-rests and reduction of the scanning time of the digitizers should greatly reduce artefacts of this type. In this respect, structured light and infrared 3D sensors, which present a much lower measuring time, might be preferable.[17] Other authors have suggested that head positioning could be a possible source of errors in scanning the human face,[7,12] which was only partially confirmed in the present work. No major errors were experienced in centring the head in the working volume of the scanner, nor in the orientation of the Camper plane during the study on human subjects. However, placing the head in an unnatural or uncomfortable position increased trembling in most subjects. These aspects should be kept in mind when defining scanning protocols for specific clinical studies of patients undergoing surgery.

With regard to the accuracy of repeated scans over time and of the automatic recording procedures, very little information is available from the literature. The rationale for applying sophisticated 3D technologies to the study of human facial surgery is mainly to allow accurate outcome and control studies to be performed. In this regard, it is the authors' personal opinion that how the recording and surface analysis is performed is as important as the accuracy of the scanning itself, if not more so. It has been reported that recording accuracy depends on the algorithm used, and that the mean displacement of the facial points in consecutive scans of volunteers may range from 0.66 mm to 1.91 mm.[18] In the present study, the recording software appeared very reliable, with an intrinsic error below 0.01 mm. When matching different scans of human subjects, however, distances between corresponding points of up to 2.4 mm were observed. Although the mean observed value for the differences was 0.4 mm, and 95% of the differences were within 1.1 mm, these results indicate a possible problem involved in comparing the same subject at different times. In fact, the present work indicates that the variability of head posture and of facial expression are the primary limits of sequential studies. This artefact is independent from the acquisition technology and no practical means of obtaining a relaxed, repeatable ("neutral") rest position of the facial musculature can be suggested at present. This observation also indicates the inadequacy of performing validation studies on inanimate phantoms. Other investigators have studied scanner and recording error through use of a portable laser scanner and software based on radial basis functions.[7] The overall error (0.0–7.6 cm^3) was assessed as the differential volume between consecutive scans; these data are thus difficult to compare with those of the present study, in which linear distance (clearance) between the two surfaces was calculated. Variability of positioning was in any case considered to be the main source of inaccuracy. Recently, recording of facial surface data sets obtained through the use of a 3D structured light sensor was used to quantify volume changes after midfacial distraction.[19] The recording error was determined to be 0.2–0.5 mm.

In the present work, regional recording restricted to the forehead and ears was used, because these areas are far from the regions modified by maxillofacial surgery and the least affected by facial expressions. Regional recording does not appear to generate a substantial error. However, it must be noted that model recording has the potential to produce errors when facial anatomy has changed. Recording must rely on stable, unchanged anatomical reference points. In some clinical situations, this may be difficult to obtain.

In conclusion, three-dimensional surface digitization through laser scanners offers excellent possibilities for objective analyses of the human face. Laser scanning of the human face may, however, be affected by errors and artefacts, depending on the hardware and software used, as well as on the acquisition protocol. For all clinical applications, accurate definition of the scanning modalities and recording techniques were shown to be essential to ensure the validity of observations.

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