ORIGINAL ARTICLE

Reliability of measuring facial morphology with a 3-dimensional laser scanning system

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Introduction: The purpose of this prospective clinical trial was to evaluate the reliability of a 3-dimensional facial scanning technique for the measurement of facial morphology. **Methods:** A field study was conducted in 2 comprehensive schools in the South Wales region of the United Kingdom. Forty subjects, mean age 11 years 3 months, were analyzed for soft tissue changes at baseline (T1), within 3 minutes (T2), and 3 days later (T3) by using 2 commercially available Minolta Vivid 900 (Osaka, Japan) laser-scanning devices assembled as a stereo pair. Left and right images were merged to form the whole face, and these images were superimposed to assess the errors at T1 and T2, and T1 and T3. **Results:** The results showed that premerged left and right mean shell deviations were 0.38 ± 0.14 mm for scans at T1, 0.31 ± 0.09 mm at T2, and 0.34 ± 0.12 mm at T3. The mean differences of the merged composite face were 0.31 ± 0.08 mm between T1 and T2, and 0.40 ± 0.11 mm between T1 and T3. Paired *t* tests showed no significant difference between these groups ($P > .05$). Shell deviation facial maps of the merged scans showed that 90% of the created composite facial scans were within an error of 0.85 mm. **Conclusions:** Capturing the soft tissue morphology of the face with this technique is clinically reproducible within 3 minutes and 3 days of the initial records. (Am J Orthod Dentofacial Orthop 2005;128:424-430)

Our understanding of the growth of craniofacial features is improving with the development of accurate, low-cost, 3-dimensional (3D) imaging systems, which can be classified as destructive or nondestructive devices,[1] hard or soft tissue imaging devices,[2] and contact or noncontact devices.[3]

The laser scanner can be used as a soft tissue scanner and is a valuable tool for its ease of application and creation of 3D images. Images have been created to establish databases for normative populations[4] and cross sectional growth changes,[5] and also to assess clinical outcomes in surgical[6-12] and nonsurgical treatments[13-15] in the head and neck regions.

Assessing the accuracy of soft tissue simulation is complex.[16] All systems are affected by changes in muscle tone and head posture. Most reliability studies have referred to linear measurements on adults to validate their systems. No study to date has determined reliability in subjects' facial morphology over time. This is important because any changes in facial morphology could be due to inherent errors of the technique or to actual growth or treatment changes.

Previous studies have reported on the validity of the Minolta 700 and 900 scanners, and have found them to be accurate to 1.9 ± 0.8 mm[17] and 1.1 ± 0.3 mm,[11] respectively. Our independent studies showed that the Minolta 900 is accurate to 0.56 ± 0.25 mm, and the error in computerized registration of left and right scans is 0.13 ± 0.18 mm.[18] In addition, the data captured on children have been shown to be reliable.[19]

With the validity of the scanning system already evaluated, we aimed to quantify the reproducibility of obtaining 3D laser scans over time in this study.

SUBJECTS AND METHODS

A cohort of 11-year-old children from 2 large schools in South Wales was invited to participate in a longitudinal growth study. Forty randomly selected subjects (21 boys and 19 girls, mean age 11 years 3 months) were chosen to participate in the study.

Approval was obtained from the directors of education, head teachers, school committees, and the relevant ethics committee. In addition, written consent

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Submitted, February 2004; revised and accepted, June 2004.
0889-5406/$30.00

doi:10.1016/j.ajodo.2004.06.037

from parents was required for the child to be included in the growth study.

The laser scanning system consisted of 2 high-resolution Minolta Vivid VI900 3D cameras (Konica Minolta, Tokyo, Japan), with a reported manufacturing accuracy of 0.1 mm, operating as a stereo pair. Each camera emits an eye-safe Class I laser, $\lambda = 690$ nm at 30 mW, with an object-to-scanner distance of 600 to 2500 mm and a fast mode scan time of 0.3 seconds. The system uses a one-half-frame transfer charged couple device and can acquire 307,000 data points. The scanner's output data is 640 x 480 pixels for 3D and red, green, and blue color data. Data were recorded on a desktop workstation with a 2 GHz Pentium 4 processor (Dell, Wicklow, Ireland). For surface registration, a Minolta medium-range lens with a focal length of 14.5 mm was used. The cameras were placed 1350 mm from the subjects (Fig 1). The scanners were controlled with multi-scan software (cebas Computer, GmBH, Eppelheim, Germany), and data coordinates were saved in a vivid file format. Information was transferred to a reverse modelling software package, Rapidform 2004-RF4 (INUS Technology, Seoul, Korea) for analysis. This software provides 9 different 3D work activities and allows high-quality polygon meshes, accurate free-form nonuniform rationale B-spline (NURBS) surfaces and geometrically perfect solid models to be created. Rapidform F4 generates data as absolute mean shell deviations, standard deviations of the errors during shell overlaps, maximum and minimum range maps, histogram plots, and color maps. All linear measurements were made in millimeters.

A custom-made portable studio facilitated standardized light conditions during data capture. The studio was sufficiently compact to fit into a corner of a classroom or medical room and house all necessary equipment. Natural head posture (NHP) was adopted for this study because it has been shown to be clinically reproducible.[20,21]

The subjects sat on an adjustable stool and looked into a mirror with standard horizontal and vertical lines simulating a cross marked on it. They were asked to level their eyes to the horizontal line and align the midline of the face to the vertical line. Seating height was adjusted to help each subject achieve NHP.[22] The subjects were also instructed to swallow hard and to keep their jaws relaxed just before the scans were taken. The scans were taken at the same time and the total scan time was approximately 7.5 seconds. If a subject moved between scans, the procedure was repeated. One raw data set, comprising 1 left and 1 right laser scan, was taken of each subject. The scans were taken at baseline (T1), within 3 minutes (T2), and 3 days later (T3).

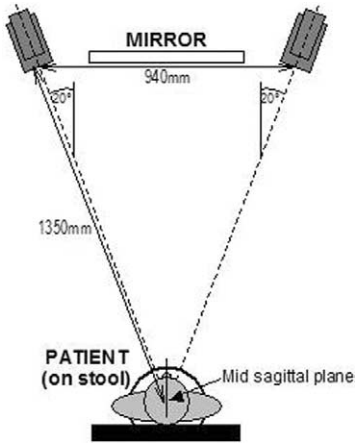

Fig 1. Camera setup and patient positioning.

Extraneous data were removed by a software subroutine developed in house[23]; it took 30 seconds to complete. This automatic and systematic process further reduced the scanned images into shells and identified small shells that represented minor scanning distortions. These images were smoothed out, preserving shape and volume, and the left and right scans were aligned based on the areas of overlap of the faces. The premerged scans were carefully 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. Finally, a composite whole face for each subject for every time frame was generated (Fig 2).

Individual whole faces of subjects were superimposed to determine changes at T1 and T2, and T1 and T3. This systematic process started by manually aligning the 5 points on the facial scans (4 points at the outer and inner canthus of the eyes and 1 point on the nasal tip) and then by fine registration where the computers determined the best fit of the 2 scans (Fig 3).

To obtain a fuller clinical picture, colored face maps were generated to determine the patterns in the face where the error was considered to be high. Tolerance levels were set for shell deviations and calculated automatically by the software. Any deviations between the faces during the 2 time intervals above a tolerance level above 0.85 mm were shown in color, and any values below the tolerance interval showed in black. Levels corresponding to 0.5, 0.85, and 1 mm were used. This helped to determine the reproducibility of the face over the time frames T1 and T2, and T1 and T3.

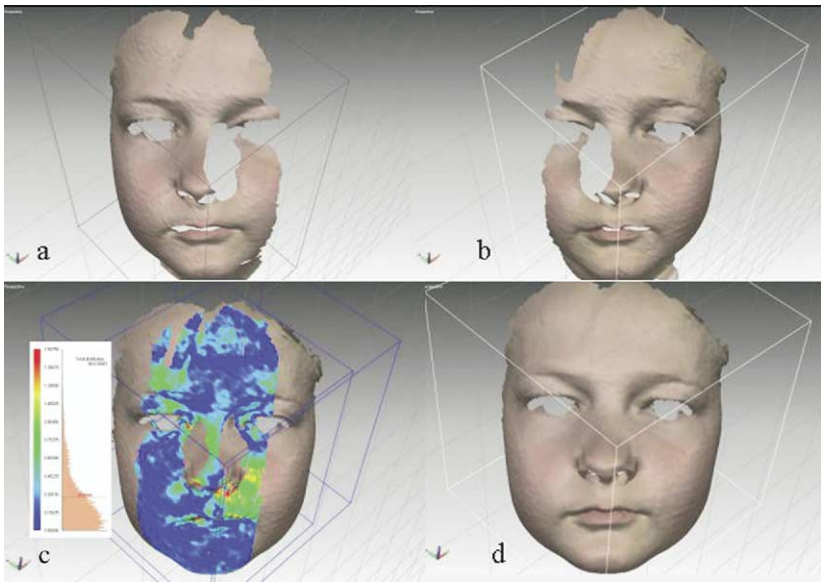

Fig 2. A, Right scan; **B,** left scan; **C,** shell deviation color map (*blue*, 0-0.5 mm; *green,* 0.5-1.0 mm; *red,* 1.0-1.5 mm); **D,** merged whole face.

A further attempt was made to quantify the errors by dividing the face into 15 segments; 9 segments in the upper and middle regions represented muscular movements during facial expressions, and 6 stringent segments represented movements of the lips and mandible. Whenever a patch corresponding to one third of the zone was recorded, the zone was marked as having 1 error score.

Statistical analyses

In Rapidform 2004, a shell-to-shell deviation map was computed and automatically produced. The results include the maximum and minimum range of shell deviations, the average distance between the 2 shells and the standard deviation. This function was used to statistically analyze the mean shell deviations and the standard deviations for the left and right premerged scans and also the differences in whole-face soft tissue morphology between the merged faces at the 3 time frames.

The mean shell deviations were tested for normality, and differences between the groups measured were analyzed with the Student *t* test (SPSS, Chicago, Ill). *P* values less than .05 were considered significant. This was done for the premerged left and right scans and the whole faces superimposed at T1, T2, and T3.

RESULTS

The mean shell deviation of the left and right scans before merging for time intervals T1 and T2, and T1 and T3, are shown in Table I. The mean shell deviations between scan times were 0.38 ± 0.14 mm for T1, 0.32 ± 0.80 mm at T2, and 0.34 ± 0.12 mm at T3. Each of these data sets was tested for normality and found to be normally distributed. Paired *t* tests were carried out on the mean shell deviations between T1 and T2 ($P = .74$) and T1 and T3 ($P = .65$). The results showed no significant differences between groups ($P > .05$).

The mean shell deviations between merged shells are shown in Table II. The results showed that the mean differences of the merged composite face were 0.31 ± 0.08 mm for T1 and T2, and 0.40 ± 0.11 mm for T1 and T3. Paired *t* tests were carried out on mean shell deviations ($P = .91$) and found to be not significant.

The results indicated that the amounts of overlap between 2 faces, expressed in percentages for the tolerance levels of 0.50, 0.85, and 1.00 mm, were 72.26%, 90.16%, and 93.53%, respectively (Table III). In general, if the clinical difference was seen in less than 90% of the face, this was deemed to be reliable and reproducible. Aligned facial maps of the merged scans (T1, T2, and T3) showed that, on average, 90% of the created composite facial scans correlated to one another with an error up to 0.85 mm, which was considered to be clinically acceptable.

At the tolerance level of 0.85 mm, the errors recorded in the zones did not exceed 8 readings per zone, and the number of zones with more than 5 readings was small. This accounted for only 5 of 15 zones (Fig 4). Furthermore, the shell errors were often

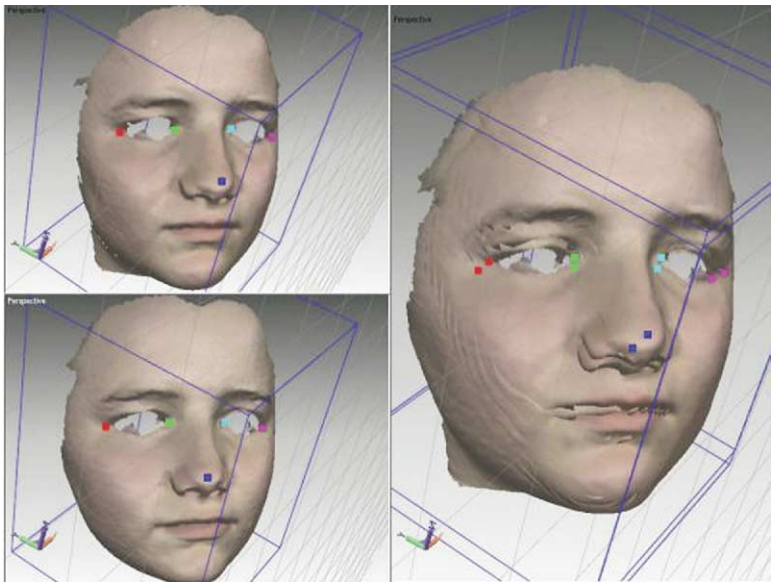

Fig 3. Initial facial alignment using 5 points on face. *Red points,* outer canthus of right eye; *green points,* inner canthus of right eye; *light blue points,* inner canthus of left eye; *purple points,* outer canthus of left eye; *dark-blue points,* nasal tip.

Table I. Mean shell differences for left and right scans at T1and T2, and T1and T3

Subjects (n = 40)	*Mean differences (mm)*	*SD (mm)*	*Maximum (mm)*	*Minimum (mm)*
T1 and T2	0.08	0.06	0.26	0.01
T1 and T3	0.14	0.11	0.48	0.01

Table II. Mean shell deviations of composite facial images at T1 and T2, and T1 and T3

Subjects (n = 40)	*Mean shell deviations (mm)*	*SD (mm)*	*Maximum (mm)*	*Miimum (mm)*
T1 and T2	0.31	0.08	0.51	0.02
T1 and T3	0.41	0.082	0.76	0.21

Table III. Tolerance level between shells at 0.5, 0.85, and 1.00 mm as percentages

Subjects (n = 40)	*1.00 mm*	*0.85 mm*	*0.5 mm*
Mean	93.53	90.16	75.26
SD	4.00	5.08	9.65
Maximum	99.67	99.30	92.96
Minimum	85.40	79.45	50.71

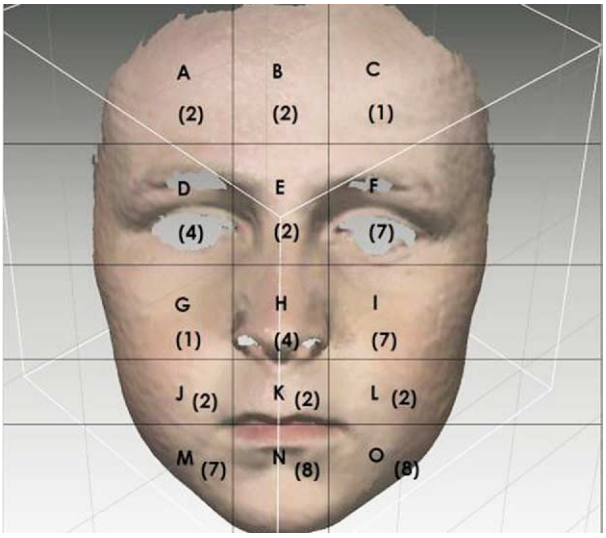

Fig 4. Facial map showing 15 zones and number of errors in each zone.

small and nonuniform. Representations of the range of facial maps corresponding to a tolerance of 0.85 mm are shown in Figure 5.

DISCUSSION

Most studies have concentrated on reliably measuring distances between chosen anthropometric points on the 3D-generated images against corresponding points

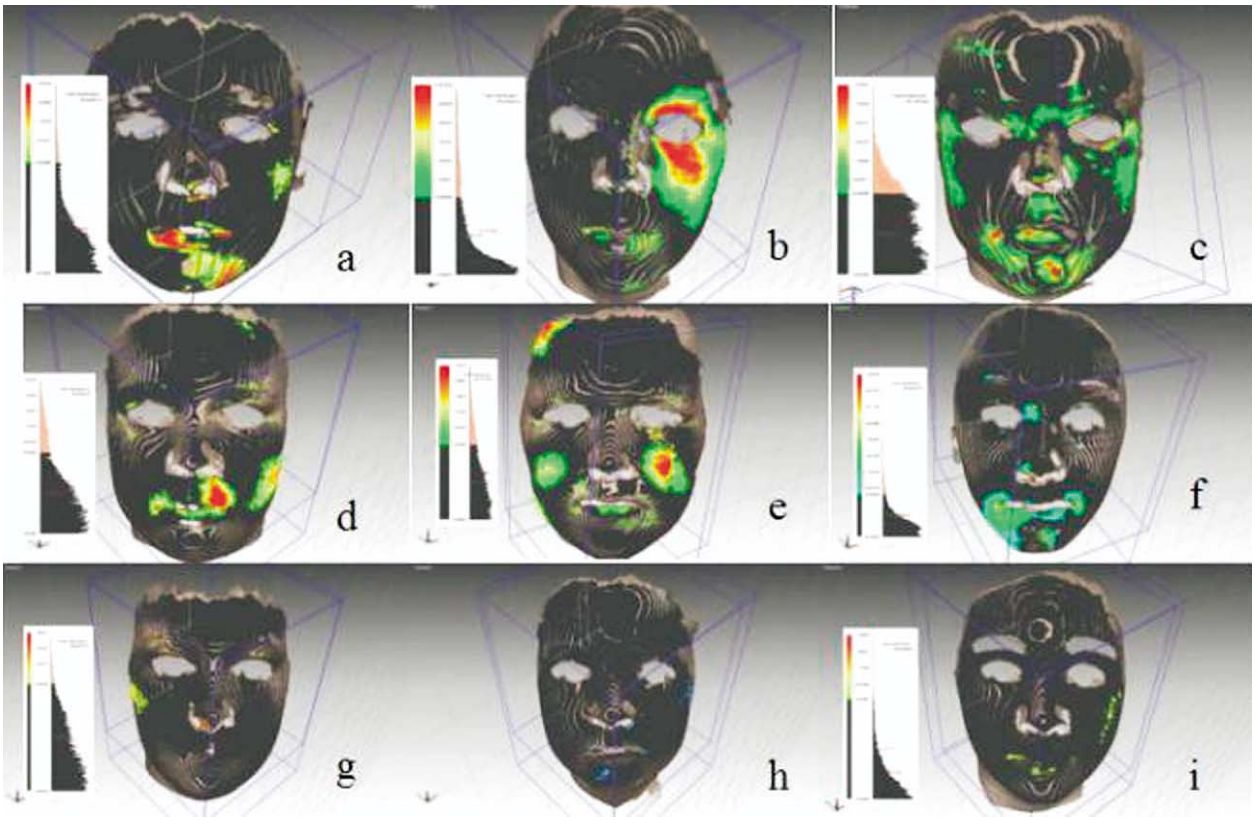

Fig 5. Shell deviation maps with merged composite faces aligned with tolerance level of 0.85 mm (*black*). Colored areas indicate errors greater than 0.85 mm. *Red,* 1.5-1.8 mm; *green,* 0.9-1.5 mm. **a,** scores (1) in zone N; **b,** scores (1) each in zones F and I; **c,** (worst facial map) scores (1) each in zones D, E, F, K, and N; **d,** scores (1) in zones K and L; **e,** scores (1) in zones G and I; **f,** scores (1) in zone M; **g, h, i,** do not accrue scores.

on live subjects[6,24-26] as a form of validation. Some studies use complex mathematics to derive and analyze shapes.[27,28] Recently, attempts have been made to analyze the dynamic face by linear measurement between points[29] and facial polygons.[30]

Error studies to measure accurate facial soft tissue reproducibility are rare. Only one study to date has attempted this, but the small sample consisted of adults, and the images were averaged before measuring between times.[5] This potentially amalgamates all errors during the averaging process (eg, cancellation of positive and negative errors) and might not give a true picture of reproducibility. No study to date has measured subjects individually and quantified the soft tissue changes with time.

This study attempted to accurately show the reproducibility of soft tissue measurements over a short time during which growth changes were unlikely. It relied on a strict protocol for capturing facial soft tissue morphology.

When comparing the mean shell deviation of the 2 groups (T1 and T2, T1 and T3), the results were similar. This implies that the subjects could adopt the same facial posture at other times.

Further analysis with color differences between facial maps showed that a high level of soft tissue reproducibility could be achieved. The greatest errors were in zones L, M, and N in the lower jaw area. This finding was expected because the lower jaw is freely movable. This error, however, does not, with the exception of 1 subject, affect more than 2 adjacent zones and never exceeds a mean error of 1.35 mm (Table IV). All other error zones are patchy and not systematic and are not detrimental to the overall reproducibility of facial morphology.

Three-dimensional imaging with laser-scanning techniques has great potential in assessing changes in facial morphology as a result of orthodontic treatment, surgery, and facial growth. The scanning system used in this study is quick and easy to use. By

Table IV. Number of errors in each zone and mean errors in different zones

Zone	*Number of errors*	*Mean errors*
A	2	1.18
B	2	1.18
C	1	1.20
D	4	1.24
E	2	1.26
F	7	1.32
G	1	1.20
H	2	1.27
I	7	1.21
J	2	1.23
K	2	1.31
L	2	1.23
M	8	1.32
N	8	1.35
O	7	1.24
Average error over all zones		1.25

using NHP with the subjects looking into the mirror, repeatable images are ensured within 3 minutes and 3 days. This system will enable accurate and reliable assessment of growth as a result of facial change and treatment.

CONCLUSIONS

This study has confirmed that the laser scanning system used to capture facial morphology is reliable over 3 minutes and 3 days. It also provides the foundation for laser scanning to be used as a measurement tool for craniofacial imaging. The following conclusions can be made:

1. 3D imaging can be reliably undertaken in a school setting.
2. The error of the system in aligning left and right facial scans is 0.13 ± 0.18 mm.
3. The mean shell deviations in superimposition of whole faces were 0.31 ± 0.08 mm for scans taken 3 minutes later and 0.40 ± 0.11mm for scans 3 days later.
4. The reproduction of facial morphology is accurate to within 0.85 mm.
5. The 3D imaging system is a reliable tool in the study of changes in facial morphology from treatment and growth.

We thank the staff, students, and parents of Cardinal Newman Comprehensive and Coedylan Comprehensive Schools for their enthusiastic participation in the study; Louise Theaker and Connie Newton for their supportive roles; and Susan Boumann and Reuben Scheer from the University of Amsterdam for their invaluable participation during their Erasmus elective period.

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