

Surface Laser Scanning of the Cleft Palate Deformity -Validation of the Method

K W C Foong, **BDS, MDS, MOrthRCSEd*, A Sandham, ***FAMS, FDS, PhD*, S H Ong, ****BEng (Hons), PhD, MIEEE*, C W Wong, ****
Y Wang, †*BEng (Beijing)*, A Kassim, ****BEng (Hons), MEng, PhD*

Abstract

Innovations in laser technology have led to the development of three-dimensional surface laser digitisation techniques capable of registering surface topology accurately. The clinical application of this technology in cleft palate documentation requires validation of the technique. This study determined the reliability of the surface laser scanning technique and assessed the reliability of interactive three-dimensional landmark localisation. Original and duplicate plaster models of an infant with a complete unilateral cleft lip and palate were digitised with the Cyberware 3030R-HIREZ surface laser scanner. Seven anatomic landmarks were marked permanently on the palatal surface of the duplicate model only, which acted as visual cues for landmark localisation. Each model was scanned ten times serially, and ten composite three-dimensional images were obtained for each. On-line interactive computer landmark localisation permitted the assessment of variance for the x, y and z coordinates of each landmark. The precision of the laser scanning technique was found to be less than 0.06 mm in all three axes. Anatomic landmarks with the clearest visual cue were the least variable after ten rounds of scanning. Significant differences existed between visually aided and non-aided landmark localisation ($P < 0.05$). While landmarks could be localised repeatedly without the aid of a visual marker, landmarks well defined by a clearly visible visual cue on the three-dimensional image were more reliable.

Ann Acad Med Singapore 1999; 28:642-9

Key words: Cartesian coordinate, Landmark localisation, Reliability, Surface characterisation, Three-dimensional measurement

Introduction

Cleft palate morphology and palatal dimensional changes due to growth and treatment have been analysed by numerous quantitative techniques. Many of these methods, however, produce two-dimensional measurements¹⁻⁵ of the three-dimensional cleft palate deformity. Advances in computer digital technology have facilitated the development of methods and equipment capable of quantifying the cleft palate in three-dimensions. Plaster models of the cleft palate deformity have been analysed in three-dimensions with digital-type probes such as the Reflex Microscope,^{6,7} the Perceptor⁸ and the Optocom.⁹⁻¹¹ These methods are limited in defining the scope of the cleft palate deformity as they can only digitise as many points as the number of times one cares to touch the probe to the object. Recent

applications of three-dimensional surface measurement methods of the human palate involved the use of a mathematical equation¹² and an optical surface measurement method illuminated with moiré light.^{13,14}

Innovations in laser technology have led to the development of advanced image acquisition systems such as the surface laser scanner which is capable of rapid data capture. Surface laser scanning has been employed in the analyses of a variety of clinical situations such as in the quantification of wound healing,^{15,16} the fabrication of burn masks,¹⁵ analysis of optic nerve and eye models,¹⁷ evaluation of dimensional accuracy of dental impressions,¹⁸ shape sensing for leg amputees,¹⁹ and in the anthropometric quantification of the craniofacial region.^{20,21} This technology utilises an optical range finder for precise recording of three-dimensional data in a

* Assistant Professor

** Professor

Orthodontic Section, Department of Preventive Dentistry

*** Associate Professor

**** Final Year Engineering Student

† Research Assistant

Vision and Image Processing Laboratory, Department of Electrical Engineering

National University of Singapore

Address for Reprints: Dr Kelvin Foong, Department of Preventive Dentistry, Faculty of Dentistry, National University of Singapore, 5 Lower Kent Ridge Road, Singapore 119074.

E-mail: kelvinfoong@nus.edu.sg

digitised format easily interpreted by computer systems. Image capture is entirely non-invasive, requires no contact with or distortion of the surface tissues, and poses virtually no risks to the patient. The resulting image is a high-resolution, three-dimensional model of the scanned object that can be viewed interactively. The accompanying image editing software allows for analysis, easy manipulation and rapid extraction of measurements. Surface laser scanning has been shown to be an accurate method in facial anthropometry,^{22,23} and it therefore holds considerable promise in evaluating cleft palate deformity. As such, the clinical application of this technology requires a comprehensive validation of the technique and identification of potential sources of error.

Using a plaster model to represent the cleft deformity, the study evaluates the clinician's ability to localise designated landmarks on digitised three-dimensional images of the cleft palate model by on-line interactive computer assessment. The reliability of the technique is determined, and variances in landmark identification evaluated to provide an insight into the advantages and disadvantages of the technique. The validation of the surface laser scanning technique hopes to lay the foundation for the development of standardised protocols for manual and automated interactive analysis of three-dimensional images of cleft palate models. Therefore, the aims of the study were two-fold: (1) to determine the reliability and precision of the surface laser scanning technique, and (2) to assess the reliability of interactive three-dimensional landmark localisation.

Materials and Method

Materials

As this study is part of a larger project to analyse the morphology and dimensional changes in the cleft palate following primary lip surgery in the complete unilateral cleft lip and palate (UCLP) infant, white-coloured plaster models of the maxillary arch of one UCLP child were used for technique validation. The plaster model was derived from a dental alginate impression taken of the cleft palate child at 3 months of age prior to lip repair. A duplicate plaster model was made from an alginate impression of the original model. Original and duplicate models are shown in Figure 1. Prior to scanning, each plaster model was placed with its flat caudal surface in full contact on a blackened wooden block and stabilised with plasticine. This is in turn positioned in the centre on the motion platform of the laser scanner.

Laser Scanning System and Method

The laser surface scanner used in the study (Fig. 2) is the commercially available Cyberware 3030R-HIREZ high-resolution, monochromatic digitizer (Cyberware Laboratories, Inc., Monterey, California, USA). The de-

vice features a laser projector that shines a low-intensity laser (<0.08 mW) on the cleft palate model to create a lighted profile. A high quality video sensor captures the profile from two viewpoints. As the video-sensor is fixed within the scanner head at an offset distance and angle from the laser projector, range data may be calculated for the array of digitised points on each profile, with each point represented by x , y , and z values.

The uneven surface topology of the unilateral cleft lip and palate model was not conducive to achieving a diagnostic quality digitised image of the entire cleft palate. In the area of the cleft, regions of the model within the undercuts were not completely digitised in one scan. To overcome this limitation, a preview scan was made initially to capture the image of the plaster model. Once the preview image appeared on the screen, one investigator (Wong) used a proprietary software to indicate the number of scans by selecting the orientation (different angles with reference to a constant horizontal plane) at which the plaster model was to be scanned. When this selection was completed, the circular motion platform first swivelled and orientated the plaster model to the first designated angle. The circular motion platform then translated laterally as the laser beam panned the entire width of the plaster model. This routine was repeated for the remaining pre-designated angles. A composite image of the scanned images at different angles was produced at the end of one round of scanning.

It took about 10 seconds to scan the plaster model at each pre-designated orientation. Each second of sampling digitised 14,580 points and the surface of the cleft palate was thereby digitised to 145,800 points per 10-second scan. The stated spatial resolution is typically 500 μm to 2 mm in the x (horizontal) axis, depending on motion platform speed, 313 μm in the y (vertical) axis, and 50 to 200 μm in the z (depth) axis, depending on surface quality.²⁴

The control of the entire digitising process was achieved through the use of an 02 Silicon Graphics computer workstation (Silicon Graphics Inc., Mountain View, California, USA) attached to a 21-inch colour monitor (Model GDM-20E21, Silicon Graphics Inc., USA) and Cyberware's proprietary CyDir® digitising software. The surface-editing tools within the software allowed for the rendering and manipulation as well as interactive localisation of the surface landmarks on the three-dimensional image.

Anthropometric Landmark Identification

Landmarks for interactive identification were selected on the basis that they were visible and easily determined on the plan view of the digitised image. Seven landmarks were identified and had been indicated in Figure 1. The landmarks⁸ utilised in the validation study are:

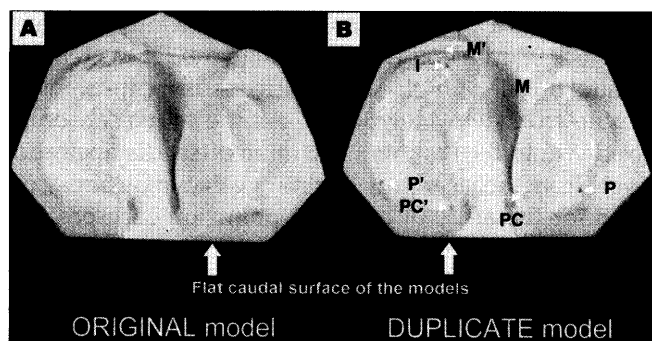


Fig. 1. Plaster models of unilateral cleft palate infant taken at 3 months of age prior to primary lip repair. (A) Original model. (B) Duplicate model with pre-marked holes, indicative of the seven anatomic landmarks. The key to the landmarks utilised in the validation study: P'-postgingival point of the major cleft segment; PC'-cleft point in the major segment; P-postgingival point of the minor cleft segment; PC-cleft point in the minor segment; I-incisal papilla; M'-anterior-most extent of the palate on the major segment; M-anterior-most extent of the palate on the minor segment.

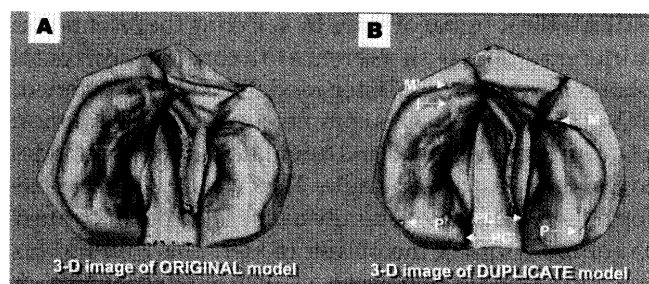


Fig. 3. Plan view of the digitised three-dimensional images of the original and duplicate cleft palate models taken at 3 months of age. The dot depressions (arrow) are indicative of the position of the anatomic landmarks. Certain landmarks, P', PC', I and M' are clearer than others on the image digitised from the duplicate model.

P'-postgingival point of the major cleft segment; PC'-cleft point on the P-P' line in the major segment; P-postgingival point of the minor cleft segment; PC-cleft point on the P-P' line in the minor segment; I-incisal papilla; M'-anterior-most extent of the palate on the major segment; M-anterior-most extent of the palate on the minor segment.

With the present monochromatic laser scanner, the use of a fluorescent label on the plaster model to indicate a landmark for recognition by the laser scanner was not practical as the scanner would not be able to differentiate the colour frequency emitted by the fluorescent label. To overcome this problem, anthropometric landmarks on the duplicated cleft palate model (Fig. 1) were identified visually by one observer (Foong) and marked permanently on the palatal surface using a round-shaped dental drill bit of 0.8 mm in diameter. These landmarks would appear on the computer monitor as dot depressions on the palatal surface and served as visual cues for interactive landmark localisation (Fig. 3). Visual cues were not present on the digitised images of the original model.

Prior to this, a simple test was carried out to determine the ideal size of the drill hole. Five round-shaped drill



Fig. 2. The Cyberware 3030R-HIREZ high-resolution, monochromatic digitizer (Cyberware Laboratories, Inc., Monterey, California, USA). A white-coloured plaster model is mounted on a blackened wooden block and placed on the circular motion platform. During the scan, the motion platform will swivel and move sideways as the laser pans the plaster model.

bits of diameters 0.8 mm, 1.0 mm, 1.3 mm, 1.7 mm and 2.0 mm were used to create holes on a flat-surfaced plaster block, with each drill bit making three holes on the plaster surface with a depth corresponding to half-diameter, full-diameter and twice the-diameter of each respective drill bit. After scanning, the clearest hole on the scanned image was unanimously chosen by two independent observers (Wong and Ong) which turned out to be that from the 0.8 mm diameter drill bit at full-diameter depth.

Experiment 1: Determination of the reliability and precision of the surface laser scanning technique

The duplicated plaster model, with pre-marked holes indicative of anatomic landmarks on the palatal surface, was used in this experiment to determine the reliability of the surface laser scanning technique in generating three-dimensional images of the cleft palate model. The position of the duplicated model was fixed in the middle of the circular motion platform for the ten rounds of serial scanning, the procedure for each round had been described above. Ten consecutive composite three-dimensional images with clearly visible landmarks of the anthropometric points were rendered on the computer monitor. Each composite image was referenced to an origin at the lower left-hand corner of the viewing area. Successive serial images, produced from scans of the same model in a fixed position, were referenced to the same origin. This enabled accurate comparison of the x, y and z coordinate measurements across the 10 digitised three-dimensional images as well as with images from an identical model scanned in the same fixed position.

The size of the viewing area is an 8-inch x 8-inch square with the rendered three-dimensional image of the model

within. Essentially, the image of the model is approximately seven to eight times that of the plaster model. One observer (Foong) interactively identified all the landmarks in the following sequence: I', PC', M', I, I', PC, M, while the computer provided the corresponding x , y , and z coordinates for each landmark.

Experiment 2: Assessment of the reliability of interactive three-dimensional landmark localisation

This experiment assessed the reliability of interactive localisation of anatomic landmarks on a digitised three-dimensional image of the original cleft palate plaster model (without pre-marked holes). In essence, it evaluated the intra-observer reproducibility in identifying the anatomic landmarks without the aid of a visual cue. Otherwise, the scanning and viewing protocol, and the position of the plaster model on the circular motion platform were identical as in Experiment 1. The same observer interactively identified the seven landmarks on ten serial composite three-dimensional images of the original model.

Statistical Analyses

The hypothesis that there was a difference in interactive localisation of landmarks between the original and duplicated models was tested. Descriptive statistical parameters comprising the mean, standard deviation and variance were derived for 10 serial x , y , z coordinate measurements of each three-dimensional anatomic landmark. Within-cast and between original and duplicate casts variances were determined for each landmark. This permitted the analysis of the reliability of landmark localisation.

For a comparison to be made between original and duplicate model data sets, deviations in the three Cartesian dimensions were reduced to a single error vector (EV) represented by the square root of the sum of ($x^2 + y^2 + z^2$) where x , y , and z were the standard deviations in landmark localisations. The variance in EV for a landmark provided estimates of measurement reproducibility. Normality of data was determined and established, and independent sample t-test was used to compare the means of the coordinates for each landmark. Paired t-test was used to test the level of significance of the EV between landmarks. The level of statistical significance was set at $P < 0.05$. All statistical analyses were carried out with the software Statistical Package for Social Sciences (SPSS) for Windows version 8.0.

Results

Reliability of the Laser Scanning Technique

High quality three-dimensional images were produced consistently for the ten serial scans. This enabled the observer to easily localise and digitise the landmarks. Standard deviation was used to assess the within-cast

variance in anatomic landmark localisation. The variance observed was less than 0.06 mm along the x , y and z axes (Fig. 4). The least variability among the x , y and z measurements were observed for landmark, I'.

Reliability of Interactive Three-dimensional Landmark Localisation

This study compared the accuracy of landmark localisation between the duplicate and original plaster models. The original plaster model was scanned in the same position as that of the duplicate model for the ten serial scans. While the scanning protocol was identical, the variance in anatomic landmark localisation for the landmarks on the original model was much larger for all three axes (Fig. 5).

The application of the independent sample t-test on the coordinate measurements showed a strongly significant difference ($P < 0.005$) in point placement for all of the x and z coordinate measurements, except landmarks PC' and M, respectively (Table I). Differences in measurements along the y axis was confined to landmark M' only ($P < 0.005$).

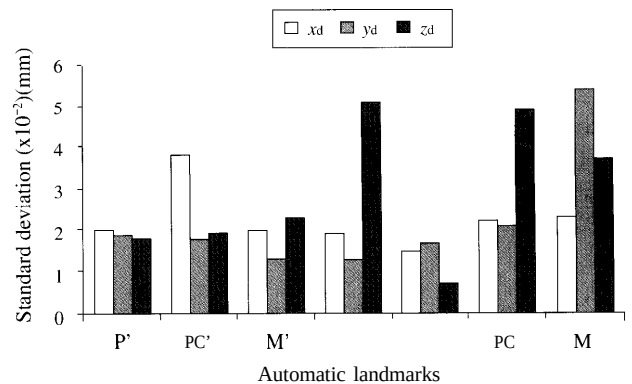


Fig. 4. Reliability of anatomic landmark localisation in three dimensions in the duplicate plaster model. Landmarks were marked in the model prior to scanning.

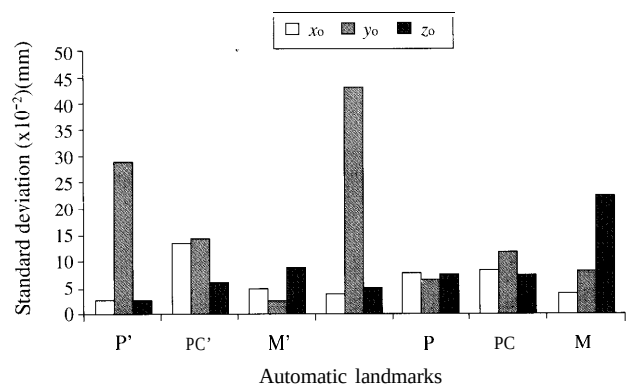


Fig. 5. Reliability of anatomic landmark localisation in three dimensions in the original plaster model. Landmarks were not marked on the palatal surface of the model prior to scanning.

TABLE I: TESTS FOR REPRODUCIBILITY AND RELIABILITY OF COORDINATE MEASUREMENTS

Landmark	Independent t-test of means			Test for equality of variance		
	x_o VS x_d	y_o VS y_d	z_o VS z_d	x_o VS x_d	y_o VS y_d	z_o VS z_d
P'	**	ns	**	ns	ns	ns
PC'	ns	ns	**	ns	ns	ns
M'	**	**	**	ns	*	ns
I	**	ns	**	ns	*	*
P	**	ns	**	ns	**	*
PC	**	ns	**	*	ns	ns
M	**	ns	ns	ns	ns	ns

x_o, y_o, z_o : x, y and z coordinates of original model, respectively.

x_d, y_d, z_d : x, y and z coordinates of duplicate model, respectively.

* $P < 0.05$; ** $P < 0.005$; ns: not significant

The difference in variance was assessed with the F test (Table I). No significant differences were observed for measurements in the x, y and z axes for landmarks P', PC' and M. Differences in variances for the y and z coordinate measurements were found to be significant for landmarks I and P ($P < 0.05$).

The variance in EV for coordinate measurements of the duplicate model was consistently below 0.1 mm (range 0.03 to 0.07 mm) (Fig. 6). However, the variance in EV_o ranged from 0.11 to 1.15 mm. A paired sample t -test was thus used to test the differences in the variance in Error Vector (EV) between coordinate measurements of the original (EV_o) and duplicate (EV_d) models. Significant differences were observed for landmarks PC', I, PC and M ($P < 0.05$).

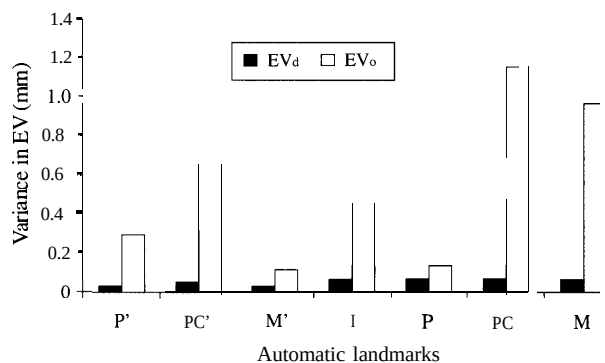


Fig. 6. Reliability of landmark localisation. Comparison of Error Vectors of anatomic landmarks of pre-marked duplicate model (EV_d) with unmarked original model (EV_o).

Discussion

Theoretically, the total error in measurement of any physical dimension comprises errors of the measuring instrument and landmark positioning.²⁵ The present study concentrates on examining the reliability of interactive landmark positioning on the plaster model taken from a complete unilateral cleft lip and palate child at 3

months of age. In essence, it examined the intra-observer reproducibility in localising landmarks on two plaster models, one with the landmarks marked out and the other without.

The use of the duplicate plaster model as a control for assessment of landmark localisation raises the question of the accuracy of the alginate impression used for the duplication. Previous studies^{26,27} showed that the dimensions of duplicate stone models derived from alginate impressions were statistically insignificant from the original models, the variance between models was less than 0.1 mm. In the present study, the alginate impression of the original cleft model was poured immediately after complete set of the alginate material. This would avert dimensional changes in the impression and produce an accurate duplicate model.

The anthropometric landmarks used in this study of the complete unilateral cleft lip and palate deformity have been employed and reported in previous serial studies⁸ of palatal growth. Points P' and P represent the posterior limit of the palatal surface, as well as the posterior extent of the alveolar crest; they correspond to the patient's pterygomaxillary fissures. Unlike points P and I', points M' and M are not specific landmarks. Since they represent the most anterior extent of the palatal segments, the location of these points can vary among individuals as the points are identified according to the degree of deformity of the anterior region of the cleft palate. There is, however, an advantage in selecting these points. Together with points P' and P, the antero-posterior dimensions of the major and minor palatal segments are easily determined when measurements are made from points M' to P', and from M to P, respectively. The incisive papilla, denoted by point I, is easily identified in the major palatal segment. This landmark may be used to determine the degree of asymmetry of the palatal segments through simple geometric methods involving the landmarks P' and P.

The posterior extent of the cleft space is bounded by a line joining points PC' and PC. These points are easily observed on the posterior-most aspect of the palatal segments as the palatal slope merges into the cleft space. Two other landmarks that define the anterior limit of the cleft space are not reported in this study, as they are not easily observed on the plan view image. The medial sides of the anterior-most part of the major and minor palatal segments drop steeply from the alveolar crest, and it is on these medial surfaces that the anterior landmarks are located. In order for these anterior landmarks to be viewed, the digitised image must be tilted. At the time when the present study was concluded, software algorithms were still being refined to facilitate accurate landmark localisation when the three-dimensional image is tilted. Further validation studies, incorporating landmarks located in undercuts and landmarks

digitised from different plaster models scanned in varying positions, will be reported in future when software algorithms for image manipulation have been fully developed.

Many methods have evolved to evaluate the palatal configuration of the cleft palate deformity. These methods, capable of measuring two- and three-dimensional data, have permitted a qualitative description and quantitative assessment of the morphologic and spatial relationships of the palatal segments following lip and palatal surgeries. Two-dimensional measurements of the palatal deformity and changes arising from growth and treatment have been previously investigated using computerised platform digitisers.^{4,5} The advent of the Perceptor, a mechanical digitiser for three-dimensional data acquisition, provided an added dimension to cleft palate documentation with the three-dimensional serial assessment of palatal growth in the complete unilateral cleft lip and palate patient.⁸ However, these digitisers are limited in their ability in the comprehensive documentation of cleft palate models. The deformity of the palate exists in all three-dimensions of space, and two-dimensional biometric methods are not capable of quantifying the deformity fully. Mechanical digitisers are limited in their ability to document the entire surface deformity in all three planes of space as they are largely dependent on the number of times the digitising probe contacts the object. Direct palatal anthropometry is restricted to the measurement of linear dimensions between landmarks and is inadequate for the task of three-dimensional measurement involving area and volumetric parameters.

The development of laser scanners for surface measurement has created new avenues for the application of this technology. Whole-body scanners have been used in the characterisation of body contours for garment manufacturing.²⁸ Three-dimensional anthropometric measurement with the surface laser scanner facilitated accurate quantification of wound healing and enabled the fabrication of facial burn masks.¹⁵ Facial anthropometry, routinely performed by direct facial measurements, can now be accurately carried out with surface laser scanning.^{22,23,29} All these applications were the result of an innovative three-dimensional surface digitisation technology. Based on the triangulation geometry, this technology enabled range data, i.e., measurements in the third dimension, to be captured.

An accurate and precise set of measurements of the cleft palate deformity is essential; it serves as an important outcome measure in evaluating growth and treatment responses. Palatal dimensions may be used to derive indices of complexity and need, and as a measure of deformity for diagnosis and treatment planning. Beginning with the digitisation process, accurate landmark positioning will enable clinicians and researchers

to precisely quantify cleft palate dimensions. In spite of the advantages of the larger surface laser scanners used in body and facial anthropometry, the technique has not been employed previously in the quantification of palatal form and dimensional changes. The possibility of incorporating this technology as a clinical routine into the process of cleft palate care requires a validation of the surface laser scanning technique.

The study has shown that the surface laser scanner is capable of consistently producing high-resolution three-dimensional images of the white-coloured cleft palate plaster model. If the plaster model was of any other colour, the monochromatic laser scanner would not have captured the topographic points as efficiently, and the quality of the rendered image would be poorer. Accurate landmark localisation was also dependent on the size of the viewing area; in this study, a large 8-inch by 8-inch viewing area containing the three-dimensional image represented a 7 to 8-fold enlargement of the cleft palate model. The magnified view of the model, together with the use of an arrow cursor for point placement, enhanced the accuracy of landmark localisation.

Reliability Of the Laser Scanning Technique

The presence of the visual cues on the duplicate plaster model greatly facilitated the accurate localisation of the anatomic landmarks. Variance in landmark localisation was much lower than that reported for three-dimensional laser scanning facial anthropometry.²⁹ Anatomic landmarks with the clearest visual cue were the least variable after ten rounds of scanning. This is clearly exemplified by the landmarks I' and P which had a variance of less than or equal to 0.02 mm for all three axes. The visual cues for these landmarks are clearly visible as a dot depression on the flat plaster surface. The next clearest cue was for landmark M'. Visual cues for landmarks PC', PC, I and M were not clear on the plan view, and this is reflected with a larger standard deviation in one of their three axes. While variance was less than 0.06 mm for all landmarks, the clarity of visual cues would greatly enhance the accuracy of landmark localisation.

Reliability Of Interactive Three-dimensional Landmark Localisation

Without the aid of a visual cue, landmark localisation on the original model was more variable. Except for landmark I', large differences in standard deviation were observed among the three axes after ten rounds of scanning.

Consistency in landmark localisation between visually aided and non-aided digitisation was evident in the y axis for six of the seven landmarks. Otherwise, the variability in correctly locating a landmark was mark-

edly different in both x and z axes, except for landmarks PC' and M, respectively. When reproducibility of landmarks over ten rounds of scanning for each model was tested between duplicate and original models, it was surprising to note that little separates the two. This observation suggests that while marked differences in landmark positioning exist between visually aided and non-aided interactive localisation, the repeatability of the coordinate measurements after ten rounds of digitisation is consistent for each model. In other words, without the aid of visual cues, the exact position of the landmarks localised in the original plaster model is different from that of the duplicate model. Within-cast measurements are however, consistent. This may indicate a learning effect that enables an individual to re-define a landmark more precisely after a few rounds of digitisation.

The reliability of interactive landmark localisation was further evaluated by combining all three coordinates of each landmark into an error vector. Interactive localisation of landmarks PC', PC and M were unreliable as the differences in the variance of error vector were more than 0.5 mm.

It is, however possible that interactive localisation be improved with the use of high quality plaster models. The use of elastomeric impression materials will add greater detail to the surface topography of the palatal deformity. Adequate registration of the entire palatal deformity will allow the clinician to identify the landmark positions without ambiguity. The use of a colour high-resolution laser scanner permits the application of fluorescent labels as markers of landmark positions on the surface of plaster models. This saves time and energy that might otherwise be expended on duplicating of models and drilling of holes. A possible modification of the surface rendering software to ensure consistency in the image platform when the image is rotated will enable a larger number of landmarks to be reliably digitised, especially those in undercut areas of the cleft palate model. The use of a cross-hair cursor that provides real-time readouts of three-dimensional coordinates will greatly enhance the user's ability to localise the landmarks.

Other than its accuracy, surface laser scanning is a simple and rapid way of digitising the cleft palate model. Once the model is digitised, the image may be viewed at any preferred position and angle. When the anatomic landmarks are localised, accurate linear, area1 and volumetric measurements may be derived from any part of the palatal deformity. Customisation of the proprietary software tools is possible for added measurements such as cross-sectional evaluation of palatal form and depth. Referencing of subsequent images of plaster models from the same cleft patient to the original image is possible for evaluation of dimensional changes arising

from growth or treatment. Conversion of plaster models into accurate three-dimensional images will save precious physical storage space. Given the increasingly cheaper cost of computer memory, about 500 high-resolution three-dimensional images of approximately 200 kilobytes each can be stored in a 100 megabyte diskette. This will be very useful for documentation of large samples of plaster models.

The surface laser scanning technique presents a new and innovative method of rapidly capturing an accurate three-dimensional image of a plaster model from an infant with unilateral cleft lip and palate deformity. This enabled accurate localisation of anatomic landmarks. The repeatability of landmark positioning within each model was consistent, and this highlighted the operator's ability to accurately select the landmarks. While landmarks could be localised repeatedly without the aid of a visual marker, landmarks well defined by a clearly visible visual cue on the three-dimensional image were more reliable.

Acknowledgements

The authors are grateful to the statistical guidance provided by Dr Dong Fang of the Biostatistical Consultancy Unit of the Department of Community and Family Medicine, Faculty of Medicine, National University of Singapore. This grant was supported in part by Academic Research Funds RP950625 and RP950372.

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