Accuracy assessment of human trunk surface 3D reconstructions from an optical digitising system

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Abstract—*The lack of reliable techniques to follow up scoliotic deformity from the external asymmetry of the trunk leads to a general use of X-rays and indices of spinal deformity. Young adolescents with idiopathic scoliosis need intensive follow-ups for many years and, consequently, they are repeatedly exposed to ionising radiation, which is hazardous to their long-term health. Furthermore, treatments attempt to improve both spinal and surface deformities, but internal indices do not describe the external asymmetry. The purpose of this study was to assess a commercial, optical 3D digitising system for the 3D reconstruction of the entire trunk for clinical assessment of external asymmetry. The resulting surface is a textured, high-density polygonal mesh. The accuracy assessment was based on repeated reconstructions of a manikin with markers fixed on it. The average normal distance between the reconstructed surfaces and the reference data (markers measured with CMM) was 1.1 ± 0.9 mm.*

Keywords—*3D surface measurement, Optical digitiser, Non-invasive measurement, Scoliotic deformity, Trunk asymmetry*

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1 Introduction

FOR MORE than two decades, many researchers have sought an alternative to X-rays for the follow-up of scoliotic deformity, with mixed results. Adolescents with idiopathic scoliosis have to be monitored regularly so that the treatment can be adapted to the potential progression of the deformity. Currently, the frequency of the visits is limited to one every six months to limit the cumulative exposure to X-rays (DOODY *et al.*, 2000; LEVY *et al.*, 1996) but this may be too long a period with respect to the evolution of scoliosis.

One of the first non-invasive tools to assess the external asymmetry associated with scoliotic deformity, the scoliometer, is still used to evaluate scoliosis by measuring the rib hump, even if this simple manual instrument has proved to be inaccurate (BUNNEL, 1984). Several research teams have developed surface topographic analysis systems based on Moiré fringes (STOKES and MORELAND, 1989; SUZUKI *et al.*, 1981), rasterstereography (HIERHOLZER and FROBIN, 1981; STOKES and MORELAND, 1989) or scanning, such as the integrated shape imaging system (ISIS) (TURNER-SMITH *et al.*, 1988; WEISZ *et al.*, 1988), in order to quantify better the characteristics of the back surface asymmetry. Unfortunately, correlation studies to establish a relationship between surface asymmetry and the underlying spinal deformity have been disappointing, partly because of the limitations of the available technologies.

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In the past few years, a considerable evolution of technologies for surface measurement (speed, resolution, capacity) has occurred, with a renewed interest in the field of surface measurement for the follow-up of scoliotic patients. A few research teams extended the topographic analysis to the entire trunk (DAWSON *et al.*, 1993; PONCET *et al.*, 1999), and the results showed a significant improvement of the correlation with internal indices relative to back surface analysis (JAREMKO *et al.*, 2002). Furthermore, clinicians are aware of the worries that their patients have about their asymmetric appearance (THEOLOGIS, 1995) and of the importance of considering it in the treatment planning. A reliable 3D model of the entire trunk surface will allow the development of predictive tools to help clinicians and their patients with decisions, not only based on spinal correction, but also on aesthetic improvement.

2 Materials and methods

When a living subject's shape is being captured the acquisition time has a significant influence on the reliability and accuracy of the 3D reconstruction, because of postural sway and breathing movements. For a comparable high sampling density, scanning systems (PONCET *et al.*, 1999; TURNER-SMITH *et al.*, 1988; WEISZ *et al.*, 1988) that involve sequential acquisition methods take more time to capture the 3D data than digitising systems (HIERHOLZER and FROBIN, 1981). For example, PONCET *et al.* (1999) had to balance scanning speed and density of points, giving a vertical row separation of 6.7 mm and horizontal point separation of about 1.5 mm. The accuracy of the resulting 3D reconstruction was estimated at

3.37 $\pm$ 1.74 mm for distances. For the ISIS scanner, capturing only the back surface in 2 s, with a resolution of about $\pm$1.5 mm, the accuracy was found to be about $\pm$3 mm in X, Y and Z over a volume of $400 \times 500 \times 300$ mm (DOODY *et al.*, 2000; TURNER-SMITH *et al.*, 1988). With systems projecting structured light (GOLBERG *et al.*, 2001; HIERHOLZER, and FROBIN, 1981; KOZLOWSKI *et al.*, 2002), the number of points generated in less than 1 s is higher. The non-invasive system for the 3D reconstruction of the external surface of the entire trunk presented here is one of the latest models of this category of 3D sensor, widely used in the animation world. Several digitisers can be used to capture the entire surface required at one time.

2.1 *3D reconstruction of surfaces*

The patented INSPECK system* (SONG *et al.*, 2002) consists of a colour optical 3D digitiser, a frame grabber for video signal acquisition and conversion and a computer for data processing. The computer communicates with the digitiser for operation control and timing purposes. The optical 3D digitiser consists of a standard colour CCD camera and a structured light projector (white light source and grating slide). The deformed patterns, due to the relief of a person's body, are captured by the camera for four different pattern positions obtained by shifting the fringes by displacement of the grating slide. For every recording sequence, the video images are processed to retrieve the shape and texture information with a hybrid algorithm based on interferometric techniques and active optical triangulation.

From one sequence of video images with fringe projection, the 3D data set is extracted for every pixel of the image. As the structured light was projected on the subject (Fig. 1*a*) with known position values, a set of equations can be built to represent the phase function of the digitised subject. The phase function (Fig. 1*b*) can be expressed as a function of the intensities of the pixel on each of the four video images. The intensity for each digitised level is extracted from the characteristics of the camera and the frame grabber.

Once the phase function is defined for every pixel of the image, a phase unwrapping algorithm, derived from the minimum spanning tree algorithm, is used to build a continuous surface (Fig. 1*c*) from the phase values. As the phase function is first expressed as modulo 2π, when the value of a complete discontinuity on a 3D surface is bigger than π, it is possible to obtain errors in the phase unwrapping algorithm, with an integral number of orders.

The active triangulation technique uses some characteristics of the periodic pattern, projected with a known angle with respect to the camera, giving a coarse measurement for a limited set of points. This information is used to replace the orders of interference. Then, the unwrapped phase function is ready to be processed with the conversion to a real unit algorithm.

A set of encoding points is included in the projected pattern (Fig. 1*a*), and the absolute positions of these points are determined once they are captured by the camera. A function describing the absolute positions of the encoding points and their measured position on the photosensitive area of the camera were defined experimentally after the digitiser was assembled. From this calibration table, created based on each digitiser, the measurement of every sampled point (i,j) is converted to geometric units (x, y, z), in millimetres. This process corrects any distortion in the 3D measurement.

As the same image pixel of the camera measures the 3D geometry and texture data of a point on a 3D surface, the texture mapping on 3D geometry (Fig. 1*d*) is automatically ensured by the nature of this data acquisition.

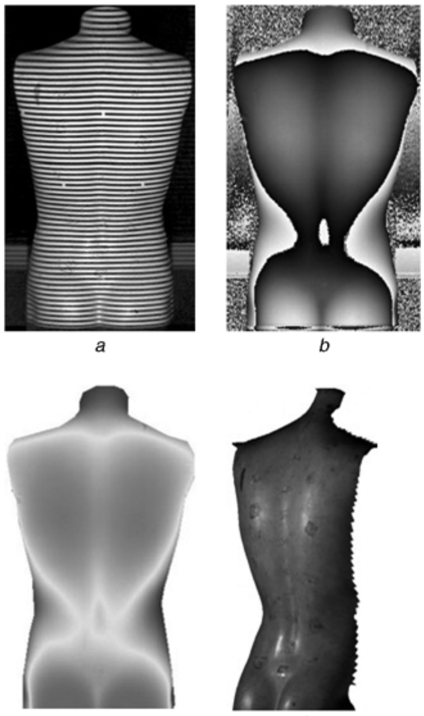

Fig. 1 *Principle. (a) Projection of fringes with encoded points on to surface. (b) Phase function. (c) Depth function. (d) 3D reconstruction with mapped texture*

The time necessary for data acquisition, 0.3 s, is much shorter than most existing techniques based on laser scanning principles, and many more data points can be measured on a subject, who does not need special training to be kept immobilised for several seconds. The system is suitable for a clinical environment and is adjustable to the application needs.

2.2 *Complete model of the human trunk*

A complete model of the human trunk can thereby be created using several 3D digitisers. The global procedure to obtain a complete digital 3D model of the trunk involves acquiring several partial views of the surface, as seen from a selection of angles, to cover all the surfaces of the trunk. The configuration evaluated in this study consisted of three digitisers, placed so that they approximately formed an isosceles triangle: one pointing to the back and the other two pointing to the front surface, with an angle of about 135° with respect to the first one (Fig. 2). After tests, this set-up was chosen as the best trade-off between trunk surface coverage and robustness of the registration procedure. The digitiser used to measure the back surface covered a field of $1000 \text{ mm} \times 750$ mm for a depth field of 750 mm, with a lateral resolution of 1.8 mm and a depth resolution of 0.7 mm (dual field model). Both digitisers used to measure the front surface of the trunk covered a field of $1100 \text{ mm} \times 800$ mm for a depth field of 800 mm, with a lateral resolution of 1.8 mm and a depth resolution of 1.1 mm (capturor large field model). The three digitisers had a standard colour CCD camera allowing images of 640×480 pixels to be grabbed.

Each of these views becomes a partial 3D model, and each has its own texture. These partial models are brought into a common co-ordinate system and then registered to reproduce the overall shape of the object. As the digitisers are operated in a fixed configuration, the registration can be computed

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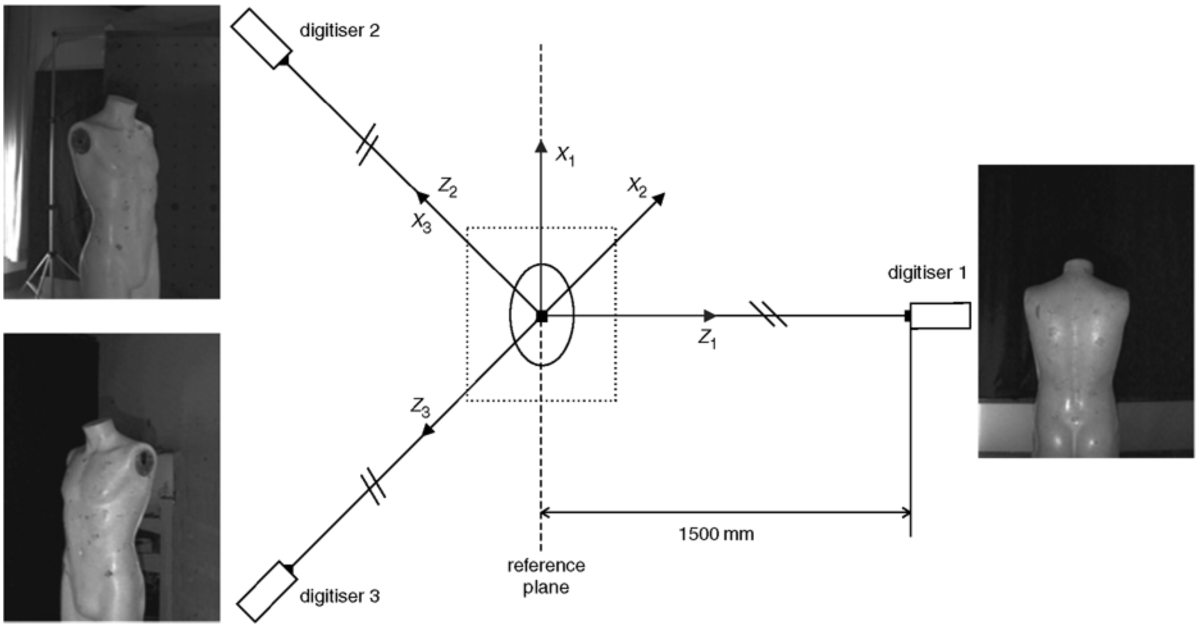

Fig. 2 *INSPECK multihead system*

before or after a data acquisition session. A planar target with a set of circles (Fig. 3) is used to register the three views in a common global co-ordinate system. The circle centres are automatically detected and matched, and their 3D co-ordinates are computed. These common points captured by different digitisers are used to compute the position and orientation of a given digitiser in the common co-ordinate system (which is the co-ordinate system of the first digitiser, in our case).

After the data acquisition session, the transformation matrices are then applied to the 3D partial models. They are then merged to produce a single polygonal model that includes all the surfaces seen during the digitising process. During the merging step, involving a plane-slicing algorithm (Fig. 4*a*), the missing data are interpolated using parametric curves (SONG *et al.*, 2001). The texture of each partial model is also merged and mapped, based on a ray-tracing scheme, to provide a final, textured 3D model (Fig. 4*b*).

Fig. 3 Reference target

As some parts of the texture of the partial models overlap, a weighted average is used to obtain the final texture. The weight is representative of the reliability of each of the 2D texture points, determined by the angle between the model's normal and the camera during the capturing of the 3D points and 2D texture. The final model is a polygonal mesh. For an entire trunk of average size, the reconstructed polygonal mesh numbers around 180 000 vertices. For easier manipulations, the data can be sub-sampled.

2.3 *Assessment of the 3D reconstruction system*

The reconstruction system was evaluated from repeated acquisitions of a dummy. Thirty-nine markers were fixed on its trunk, some markers over anatomical landmarks, others distributed all over the trunk. Each marker was a wire cross with an intersection in a sphere about 1.3 mm in diameter. The 3D co-ordinates of these intersections were measured with a co-ordinate measuring machine (CMM). The accuracy of the CMM is in the order of micrometres with a normal approach. These measurement were the reference data. On the 3D

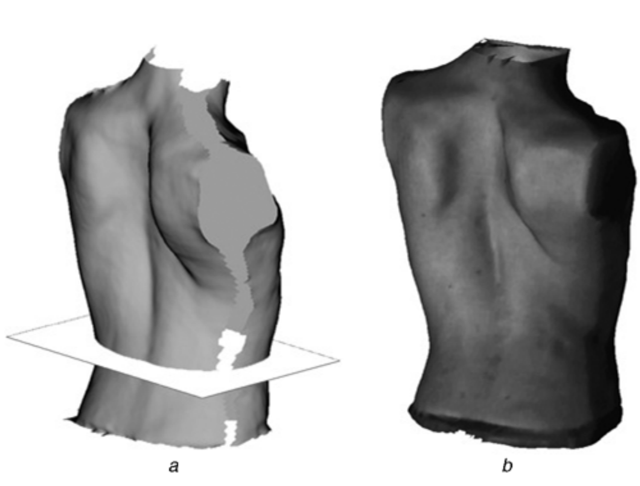

Fig. 4 *(a) Merging step. (b) 3D textured reconstruction of entire trunk*

reconstructions of the dummy, the markers were not detectable on the geometry but on the texture.

Two sets of data were compared with these reference data: 12 reconstructed polygonal surfaces of the trunk (only geometric data), and the position of the markers evaluated from texture on these reconstructions. The 12 reconstructions were built from three series of four acquisitions, and each series corresponded to a registration file. In previous trials, the acquisitions where the subject was over- or under-lighted provided qualitatively inaccurate reconstructions. The ones used for this study were made after a training period, so that lighting adjustments were better mastered.

First, the reference data were registered on the reconstructed polygonal surface with an iterative algorithm that minimised the normal distance to the closest polygon (digitised shape editor function)†. The first approximation for the iterative algorithm was to align the two axis systems. Secondly, the reference data were registered on the corresponding selected points of the textured surface with an algorithm based on the singular value decomposition method (SOEDERQVIST and WEDIN, 1993), implemented in Matlab.

A multi-way analysis of variance was conducted to evaluate the accuracy of the reconstructions and to highlight some factors with significant effect. Acquisition, registration file and digitiser were factors. The variable for the first set of data was the residual unsigned normal distance between the reference data and the 3D reconstructed surface; for the second set of data, the variables were the differences of position with respect to the system axis.

3 Results

The unsigned errors on the geometry-based evaluation of the reconstruction system followed a half-normal distribution with a standard deviation of 1.4 mm ($n = 468$). For the entire set of markers, the error was estimated as 1.1 ± 0.9 mm, which is of the same order of magnitude as the digitiser resolution and as the marker thickness. The analysis of variance (Table 1) showed a significant difference between acquisitions and between markers. Using series rather than acquisitions as factors in the analysis of variance, the results showed a significant difference between series and within series.

From these results and additional qualitative information, it can be deduced that part of the errors comes from the registration of the partial surfaces and another part comes from uncontrolled changes in lighting conditions. Lighting conditions affected the results in two ways. First, the surface illumination was not uniform owing to the shape and the material of the object (local reflectance). Secondly, owing to the infiltration, small but not negligible, of daylight into the room, lighting conditions changed between acquisitions according to the sunlight intensity.

More specific differences were highlighted between the markers placed on the back of the trunk and the other ones (see Table 2). The smallest errors were obtained for markers located on the flattest areas. Registering back surface data only, the errors were estimated as 0.45 ± 0.34 mm.

On the texture-based evaluation, the errors were normally distributed, with a standard deviation of 1.8 mm in the horizontal lateral direction and 1.6 mm in the vertical direction. For the direction of the depth co-ordinate, the standard deviation was 1.6 mm. These results are comparable with the lateral resolution (1.8 mm) and with the intersection area of the markers, which is included in a sphere of about 1.3 mm in diameter. This error is small with respect to the variability of positioning markers on the anatomical landmarks of patients.

†CATIA, Dassault Systems, v5r8

Table 1 Analysis of variance

	Sum of squares	Degree of freedom	Mean squares	Fisher coefficient	Prob > F
Acquisitions	32.28	11	2.93	5.6	0*
Markers	119.65	38	3.15	6.01	0*
Error	218.89	418	0.52		
Total	370.82	467			

Table 2 Errors related to areas

Area	Errors	Range	N
Posterior	0.8 ± 0.7 mm	0–3.5 mm	264
Anterior and lateral	1.5 ± 1.0 mm	0–4.8 mm	204
All markers	1.1 ± 0.9 mm		468

4 Discussion

The system was evaluated with a dummy, the shape of which was similar to the human trunk. The accuracy of the 3D reconstruction system evaluated from this dummy was adequate for analysis of the human trunk asymmetry. A significant difference was found between the errors measured on the markers fixed on the back surface and the other ones. The difference can be explained by the orientation of the front digitisers, by their different technical specifications and by registration errors (all the partial views were registered in the co-ordinate system of the back surface model). The errors in the registration procedure came from the deformation of polygons when the projection axis of the digitisers diverged from the normal direction to the target plane.

To reduce the noise due to bad lighting conditions, it is preferable to have control of the lighting source, which means no light from outside and no ceiling-mounted luminaire. With rather dark ambient lighting, the fringes are sharper, and the surfaces are less noisy. As for all systems, the settings have to be adjusted according to the application. For our clinical application, a unique set-up which suits all patients was found.

The acquisition time is relatively fast, compared with scanning systems, but still quite long considering the natural oscillations of a subject in a standing position. Therefore trunk movements still interfere with the accuracy of the 3D reconstruction of patients, but in a more acceptable proportion for a clinical application.

5 Conclusions

In this preliminary study, a commercial acquisition system was set up and evaluated. The proposed system allows fast capture, requiring about 3 s, of the entire textured trunk surface. The experiments on the multi-head system led us to recommend modifications to the configuration. Better results should be expected from a system with two facing digitisers, reducing errors in the registration computation due to the angle between the projection of the digitiser and the target plane. To cover the surface area on the sides, two lateral digitisers would be needed. The lighting conditions must be fully controlled and standardised for the trunk surface acquisition of patients. Fortunately, the skin offers better conditions than the surface of our manikin.

The advantages of having a reliable system to assess the external asymmetry would be to document the external asymmetry and its progression; to reduce the exposure to radiation and increase visit frequency for the non-hazardous follow-up of the patient; to allow early treatment thanks to prediction models based on learning approaches (BERGERON *et al.*, 2004); to integrate the cosmetic factor in treatment planning, particularly when a thoracoplasty could be needed; and to improve brace design and adjustment (BELLEFLEUR *et al.*, 2004).

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