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SURFACE RECONSTRUCTION USING REFERENCE MODEL FOR FUTURE PROSTHETIC DESIGN

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Abstract. Existing methods that use a fringe projection technique for prosthetic designs produce good results for the trunk and lower limbs; however, the devices used are expensive. This study proposes the use of an inexpensive passive method involving 3D surface reconstruction from digital images taken at multiple views. The design and evaluation methodology comprise of a number of techniques suitable for prosthetic design. A method that fits a 3D reference model of an object (e.g., a limb) to the target (actual) 3D data to reconstruct the surface of the target is presented. The reference model is generated using a computer algorithm while the target is reconstructed using a shape-from-silhouette (SfS) technique in an approximate circular motion. The fitting process involves deforming the object vertices of the reference model to better match the actual object. The experimental results demonstrate the potential of using the proposed method in prosthetic devices.

Keywords: Prosthetic; 3D reconstruction; surface fitting; shape-from-silhouette (SfS); circular motion

Abstrak. Kaedah sedia ada menggunakan teknik pengunjuran pinggir bagi reka bentuk prostetik menghasilkan keputusan yang baik pada bahagian tubuh dan anggota bahagian bawah badan. Walau bagaimanapun, peranti yang digunakan adalah mahal. Kajian ini mencadangkan penggunaan kaedah pasif melibatkan pembinaan semula permukaan tiga dimensi (3D) daripada imej yang diambil beberapa sudut/pandangan menggunakan kamera digital. Reka bentuk dan metodologi terdiri daripada beberapa teknik yang sesuai untuk reka bentuk prostetik. Kaedah pemadanan yang membolehkan model rujukan sesuatu objek dipadankan dengan data sebenar dibincangkan. Model rujukan dihasil menggunakan algoritma komputer manakala data sebenar dihasilkan dari imej yang dibina semula menggunakan teknik *shape-from-silhouette* (SfS) dan *approximate circular motion.* Proses pemadanan melibatkan pergerakan vertis objek rujukan ke arah vertis objek sebenar. Keputusan kajian berpotensi untuk menggunakan kaedah yang dicadangkan dalam reka bentuk peranti prostetik.

Kata kunci: Prostetik; pembinaan semula 3D; pemadanan permukaan; *Shape from silhouette (SfS) ;circular motion*

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1.0 INTRODUCTION

A prosthetic device (also called a prosthesis) is an artificial substitute for a missing body part such as an arm, leg, hand or foot, and is used for functional or cosmetic reasons, or both [7]. Three-dimensional (3D) digitalisation systems applied to the orthopedics domain dispenses with the necessity of making manual impressions of a socket which best fits the portion of the remaining arm or leg after an amputation, i.e., the residual limb or stump, during orthotic and prosthetic design [4].

Most of the previous works on prosthetic design are based on manual design or use Computer-Aided Design/Computer-Aided Manufacturing (CAD/CAM) systems. With a manual design, the most common means of defining the shape of a residual limb is to make a mould of the residual limb itself. A trained practitioner can then manipulate the mould in order to spread out the pressure that it exerts on the patient for maximum patient comfort. A milling or carving machine is then used to transform the physical model (i.e., the mould) into a foam or plaster shape, which is finally used on the patient as a medical support device [9]. This method is prone to deviations caused by human error. One of the advantages of using CAD is the reduced need for cast modifications and is, thus, a time saver. However, computer-aided systems increase the initial system cost and training that is needed to operate the system. The initial cost and training are decreased if the shape of the residual limb can be obtained with the minimum human effort in order to determine its dimension. This can be achieved by reconstructing a 3D computer model of the limb automatically using an imaging system. Using such an approach would alleviate further injury that might be caused by manual fabrication method.

Although the technological advancements of CAD/CAM offer prosthetists an additional fabrication tool, the successful fitting of a device depends on appropriate limb data input. Hence, an alternative method of generating the data using a fringe projection technique was introduced which enables the registration of two three-dimensional surfaces of an object from two different viewpoints [11]. The capability of such a technique depends on the distance between the camera and capturing system, the object size and the shape of the object. Some objects such as those with cylindrical shape, oblong or round surfaces are suitable for this purpose. However, objects with square or rectangular surfaces and complex shapes present difficulty to the object reconstruction algorithm due to the camera projection. Furthermore, it is not easy to match each detected fringe in the image plane with the corresponding fringe on the object. The 4 head system of the active optical devices of the imaging system also results in a high operational cost. Hence, in this study we propose the use of a passive method as a means of reducing this high operational cost. The method presented in this chapter uses a multiview object reconstruction approach to determine the socket that best fits the residual limb or stump. In the approach, the shape of an object, i.e., a cylinder, a cone or a combination of these, which is similar to the limb is used as a further refinement of the reconstruction. The aim of the method is to provide a prosthetist with an easy and yet accurate means of measuring a residual limb and creating a model of the missing part of the limb.

2.0 3D RECONSTRUCTION FROM MULTIVIEWS

3D object reconstruction from multiviews is the process of estimating the shape of a 3D object from different views. Its applications include virtual reality, digital preservation of cultural heritage and medical imaging. The use of such an approach for 3D digitisation can be categorised into two groups: active and passive [5]. Active methods make use of calibrated light sources such as lasers or coded light; the most typical example of which is the shape from the structured light method. Passive methods, on the other hand, rely solely on two-dimensional (2D) images of the scene taken at different camera views to extract surface information. The common passive methods include shape from silhouette (SfS), shape from stereo and shape from shading. In this paper, the SfS method [6,12,13] is adopted because it offers the use of low cost hardware (i.e., a video camera and a turntable) and adequate accuracy in the object reconstruction.

In this study, the silhouettes of an object in motion are employed in order to improve accuracy of the reconstructed shape. In some related works, images of the object placed on a turntable are captured by rotating the turntable [10,14]. The changing relative position between the camera and the object is described by the rotation parameter of a turntable. Throughout the circular motion of the turntable, the camera's internal parameters remain identical. This facilitates the camera calibration process by enabling the camera's parameters to be estimated using the same internal parameters and 3D camera position with respect to the reference camera position. In turntable motion, the physical imperfection of the turntable as well as measurement error affects the accuracy of the object reconstruction. Hence, a modified projection matrix introduced in [10] is used. If circular motion of the turntable is assumed, then a projection matrix at a rotated position α, $P(\alpha)$, is

$$P(\alpha) = KR\left[R(\alpha) \quad -\vec{o}_{\alpha}\right] \tag{1}$$

where K is a 2D affine homography which includes the internal parameters of the camera and R is the 3D rotation matrix relating the world frame and camera frame. The 2D similarity homography $R(\alpha)$ represents a pure 2D rotation term of the circular motion. The 3D camera origin with respect to the world frame is represented as $\vec{o}_\alpha$.

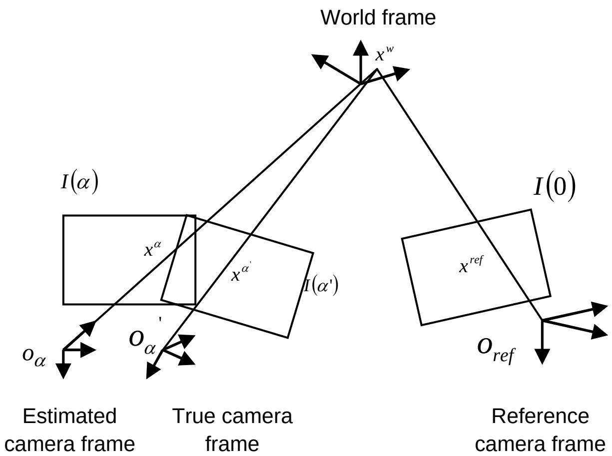


Figure 1 Geometrical illustration of circular motion

In Figure 1, $I(0)$ is the reference image plane, $I(\alpha)$ and $I(\alpha')$ respectively represent the estimated and true image planes that have been rotated by α degrees from o_{ref}. Although the true camera origin $o_{\alpha'}$ cannot be determined from images, the 2D homography between $I(\alpha)$ and $I(\alpha')$ can be estimated when there are at least four pairs of correspondences, i.e., $x^{\alpha'} \leftrightarrow x^w$, where

$$x^{\alpha'} = H_p KR[R(\alpha) \quad -\vec{o}_\alpha]x^w \qquad (2)$$

and H_p is a projective homography with 8 degrees of freedom because the lines at infinity $\vec{l}_h$ in $I(\alpha)$ and $I(\alpha')$ are not identical. Using the Direct Linear Transform algorithm when more than 4 points are detectable to derive a linear solution of H_p, the modified projection matrix for an approximate circular motion is formulated as

$$P'(\alpha) = H'_p[R(\alpha) \quad -\vec{o}_\alpha] \qquad (3)$$

where $H'_p = H_p KR$.

The following decision function of two projection matrices

$$d\left(P(\alpha), P^{'}(\alpha)\right) = \sum_i \left\| \left(P(\alpha) - P^{'}(\alpha)\right) x_i^w \right\| \quad (4)$$

is introduced in order to achieve an accurate object reconstruction. If $d\left(P(\alpha), P^{'}(\alpha)\right)$ is greater than zero, then $P^{'}(\alpha)$ replaces $P(\alpha)$, otherwise the estimated projection matrix remains unchanged.

3.0 SURFACE DEFORMATION STRATEGY

The variations in the shape of a residual limb make it difficult to extract the features and segment of the limb, thus a reference model is used to provide prior knowledge to refine the 3D reconstruction of the limb. The surface model is obtained by deforming the reference model with constraints imposed by the SfS-based reconstruction. Two methods are used to obtain the reference model of the limb and other objects similar to a limb. The first uses the octree data generated by the SfS reconstruction technique in [10]. For simple object such as a cone or cylinder, the reference model is generated using a simple computer program.

Two data sets are involved in the reconstruction: the reference model (referred to as the model) and the target objects (referred to as the data). These need to be registered in order to merge them before a deformation process is applied to refine the reconstruction. This is achieved using the iterative corresponding point (ICP) algorithm [8], an improved version of the iterative closest point (ICP) algorithm [1]. The ICP algorithm rigidly moves (i.e., registers and positions) the points of the data to be in best alignment with the corresponding points of the model. This is done iteratively. In the first step of each iteration, the closest point on the surface of the model $Y = (y_1, y_2, \ldots)$ is computed for every data point $X = (x_1, x_2, \ldots)$, where x_i corresponds to y_i.

In the second step of each iteration, the rigid motion *m* is computed such that the moved data points $m(x_i)$ are closest to their corresponding points, y_i. This is achieved by minimizing the objective function

$$F = \sum_{i=1}^{N} \left\| m(x_i) - y_i \right\|^2 \quad (5)$$

In this minimization, the translational component of the motion *m* moves the centre mass of *X* to the centre mass of *Y*. The rotational component of *m* is obtained from the unit eigenvector that corresponds to the maximum Eigen value of the symmetric 4×4 matrix. The solution eigenvector is the unit quaternion of the rotational component of *m*. Following the second step, the positions of the data points are updated via $X_{new} = m(X_{old})$. Step 1 and step 2 are then repeated, using the updated data points, until the change in the mean-square error falls below a preset threshold. Since the value of the objective function decreases both in steps 1 and 2, the ICP algorithm always converges monotonically to a local minimum.

Following registration, a pre-processing is applied to achieve a better correspondence between the registered data sets to find the feature points on the model that correspond to the points on the data. Although the registration between two datasets produces good results, a further correspondence analysis is needed because ICP only performs a rigid registration and there is no non-rigid movement or re-sampling of the vertices. A model point corresponds to a data point if both points project to the same location on the intermediate object, where a cylinder with the unit radius is used as the intermediate object. The most prominent points on the limbs (for both lower and upper limbs) of the model and the data can be easily found, and these are used to define the cylinder's axis to ensure the relative position between the model and the cylinder is the same as the relative position between the data and the cylinder. Note that several points may be projected to the same location on the intermediate object, so that one-to-one correspondence cannot be established. To solve this problem, the distance between a point and the projection centre is used as the secondary parameter to identify the correspondence.

After the correspondence between the model and data is established, the model needs to be deformed to match the data to generate a modified model that matches all the points on the data contours. The simple constrained deformation methods operate on a 3D volume without considering the object's geometry and topology inside the volume [2]. As a result, the influence a feature point imposes on the points within its influence region is a function of the Euclidean distance between the two points.

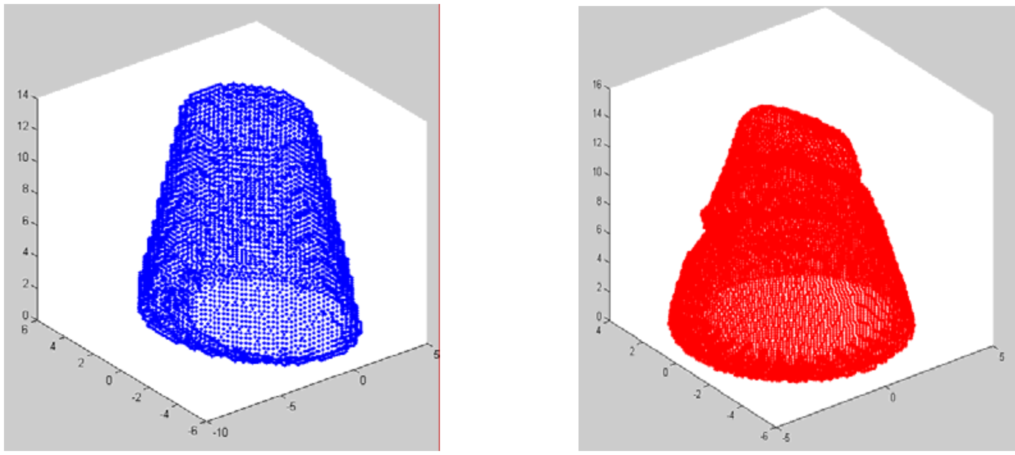
4.0 RESULTS AND DISCUSSION

The purpose of 3D model reconstruction is to generate 3D surface models from volumetric data. As a starting point, the results of two different objects using modified model-based reconstruction are presented. The objects are a candle and a fruit. Next the method is applied to a lower part of dummy limb and an upper part of dummy limb in order to realize the prosthetic design application. The data of these objects are derived from shape-from silhouette technique while their priori models are created using a computer program except for the candle. The percentage of non-matching vertices is presented and the actual measurement of a lower and an upper dummy limb is calculated in order to evaluate the deformation process performances.

4.1 Deformation Process of a Candle

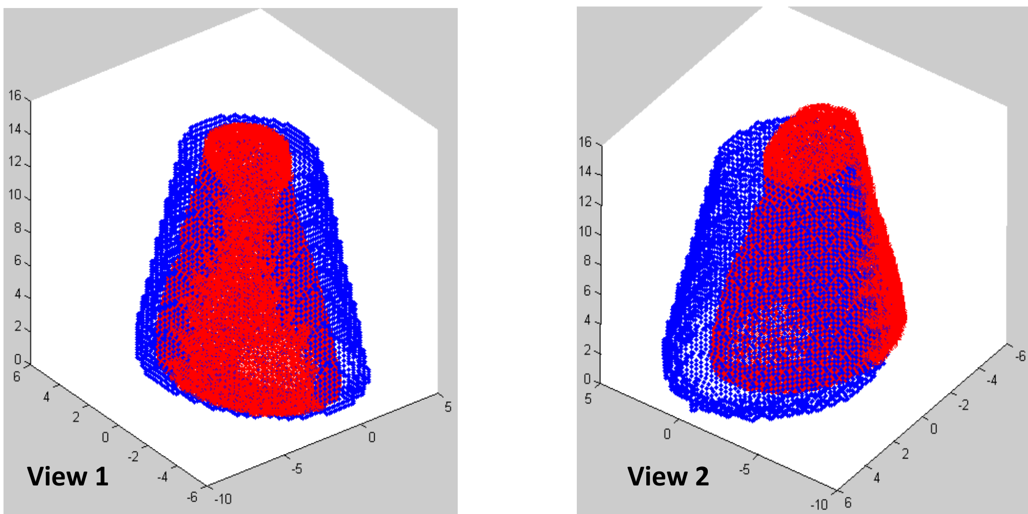
Figure 2 shows the representation of the model and the data of a candle derived by shape-from-silhouette technique. The blue vertices in Figure 2(a) are the original candle while the red vertices in Figure 2(b) correspond to the modified version. The modification of the candle is done by carving away the original shape. After the modification, the 3D data of the modified candle is obtained again by using the shape-from-silhouette technique. Figure 2(c) shows the two views of the model and the data after registration process.

In Figure 2(c), both the model and data are registered using the ICP algorithm. The result of the deformation process of the model to fit with the data is shown in Figure 3. These two views are approximately the same as the two views in Figure 2(c). This result shows that the proposed deformation process deforms the model (blue) to fit with the data (red). The fewer blue points in Figure 2 mean that the deformation process has caused more blue vertices to fit the data (red) vertices. However, the algorithm cannot handle the deformation for each vertex because of the large number of vertices between data sets (82156 vertices for the model and 77852 vertices for the data), and this affects the number of constraint points and the influence regions of are increased. This shows that the proposed algorithm cannot handle a large number of vertices which is not registered properly to produce a good result. The proportion percentage of non-matching is 58% (approx. 47650 of non-matching vertices). Another factor that contributes to this high percentage is the different number of model vertices and data vertices which is about 4304 vertices.



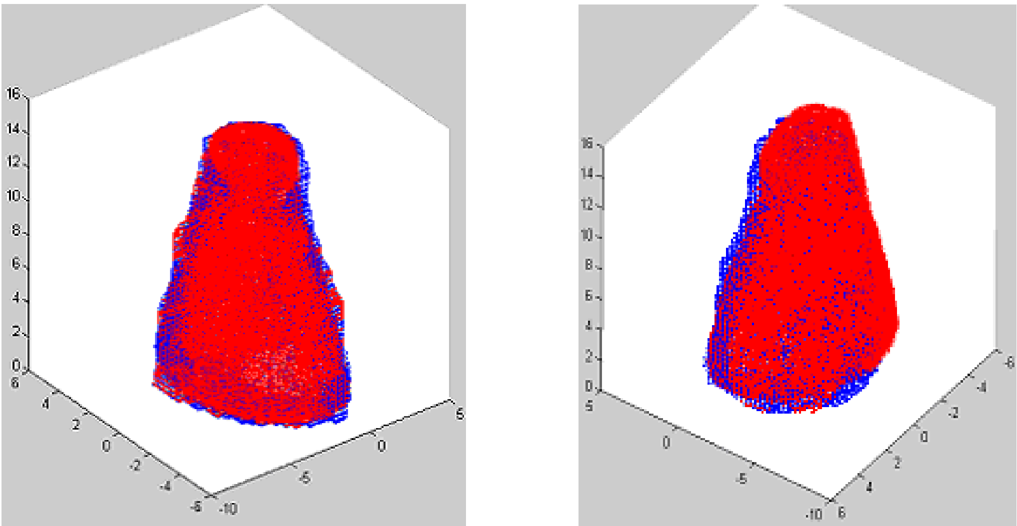
(a) Original candle (model)

(b) Modified candle after carved (data)



(c) Two views of registered candle of (a) and (b)

Figure 2 The model (blue) and data (red) of a candle



(a) (b)

Figure 3 Two views of the model and data after the deformation process

4.2 Deformation Process of a Fruit

The same procedures are applied as in Section 4.1. The model is represented by blue while the data is red. Both of the model and the data are registered using ICP and after registration, the deformation process is applied. Figure 4 shows a deformation process for a cylinder (created by a computer program) and a fruit. A cylinder is represented as a model.

In this case, the cylinder vertices are deformed to fit the fruit. However, since the fruit shape contains several parts with a sharp corner (e.g. the bottom and top part), the deformation process did not fit the cylinder to the fruit well. There are approximately 3094 non-matching vertices (denoted by blue) compared to 6584 matching vertices after the deformation process. Most problems are at the sharp corner. The percentage of the non-matching vertices (blue) compared to the red vertices is still high after the deformation process at 47%.

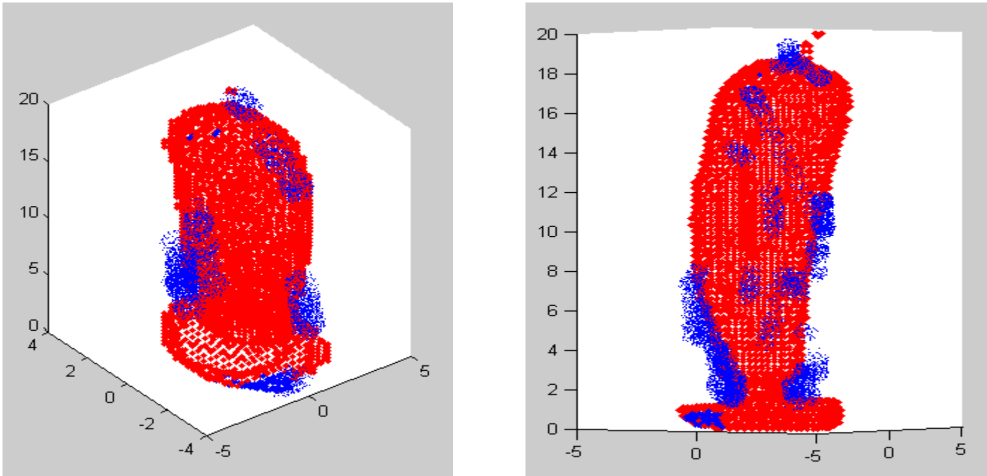
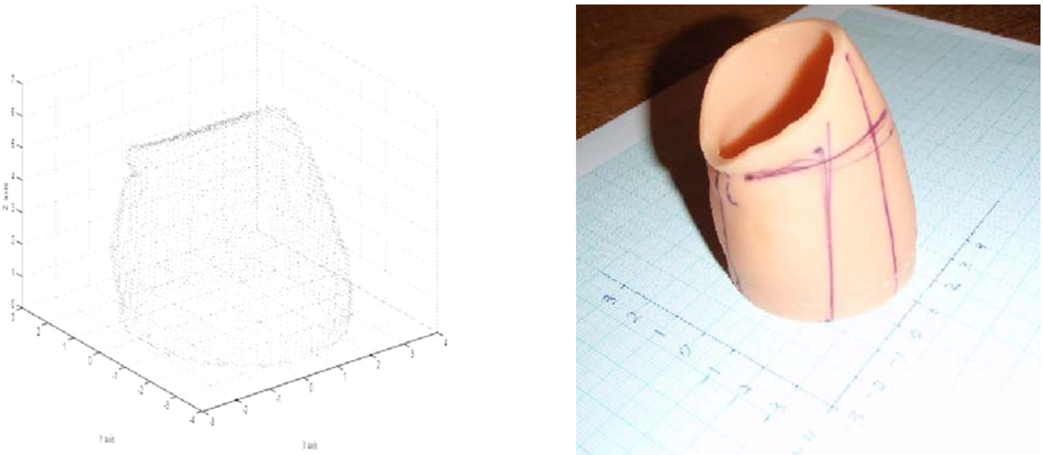


Figure 4 Two views of the registered fruit after the deformation process. The blue vertices denote the non-matching vertices

4.3 Deformation Process for Lower and Upper Limb

For lower limb, there are approximately 1720 non-matching vertices compared to 6373 matching vertices after the deformation process. Meanwhile, for upper limb, the number of non-matching vertices is 1023 and the number of matching vertices after the deformation process is 4265. The percentage of the non-matching vertices compared to the matching vertices is reduced to 26% and 24% for both lower and upper limb respectively. This is probably because that the limb has approximately similar with a cone and a cylinder combination as a reference model, thus reduce the percentage of non-matching vertices after the deformation.

In prosthetic design, it is necessary to perform quantitative analysis and measurements. The length, angle, area of region, 3D surface area and volume of the limb need to be measured. The analysis and measurements are employed to ensure that the 3D model created will fit the actual limb. In order to evaluate the experimental results, the modified 3D model created after the deformation process and the actual limb data are compared. The evaluation is done by comparing some selected points on the actual limb with the corresponding points on the modified model. In next discussion, the lower dummy limb is considered. To facilitate the comparison, a grid is superimposed onto the modified model as shown in Figure 5(a). The actual limb is positioned to correspond to the modified model as illustrated in Figure 5(b).



(a) (b)

Figure 5 (a) Modified 3D model of the dummy limb after deformation process.
(b) Measuring the approximate position of an actual dummy limb

Fifteen measurements of cross sections of the model in the x-y plane (as shown in Figure 6), in the z-x plane (as shown in Figure 7), in the z-y plane (as shown in Figure 8) and from the top view (as shown in Figure 9) were made. The corresponding cross sections on the actual dummy limb were also made. Both sets of measurements were scaled to centimeter (cm) unit and are shown in Table 1.

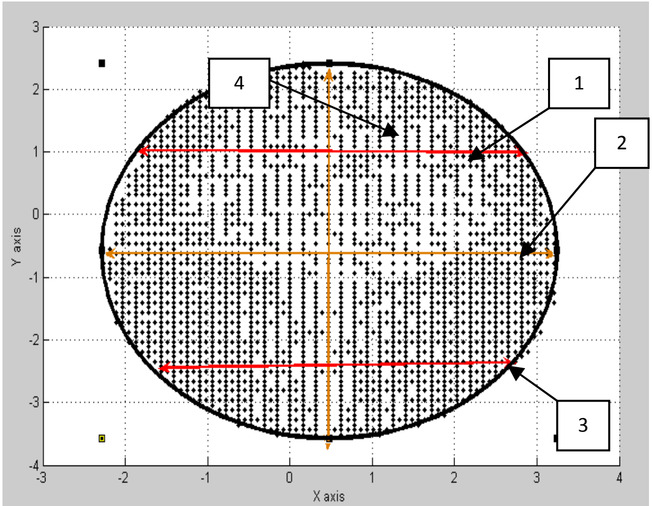


Figure 6 The cross-sections of the modified model in the x-y plane. Each labeled line represents the measurement of a length in Table 1

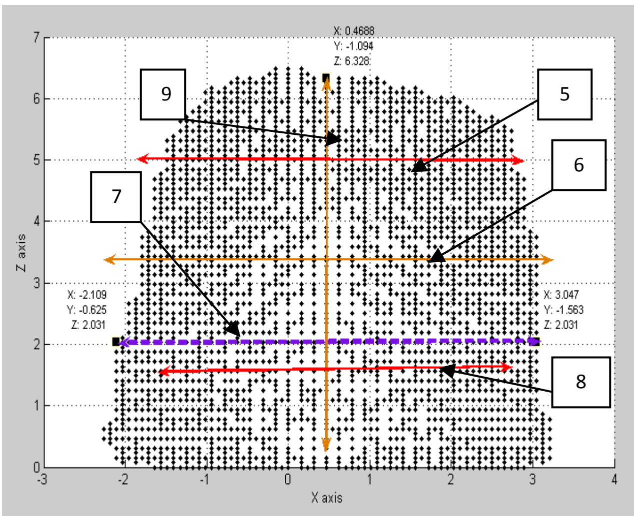


Figure 7 The cross-sections of the modified model in the z-x plane. Each labeled line represents the measurement of a length in Table 1

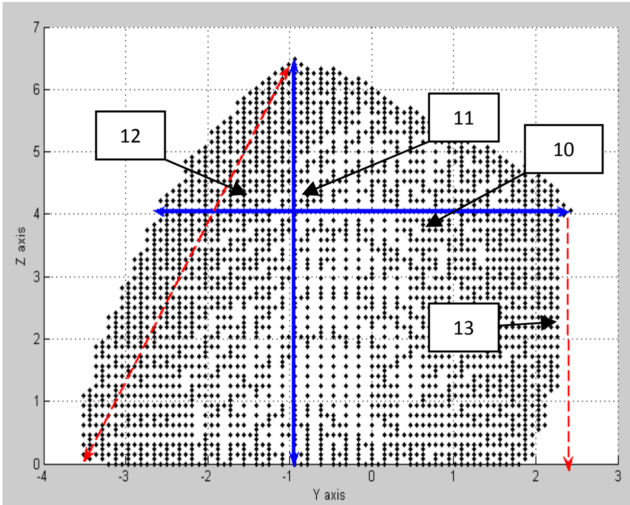


Figure 8 The cross-sections of the modified model in the z-y plane. Each labeled line represents the measurement of a length in Table 1

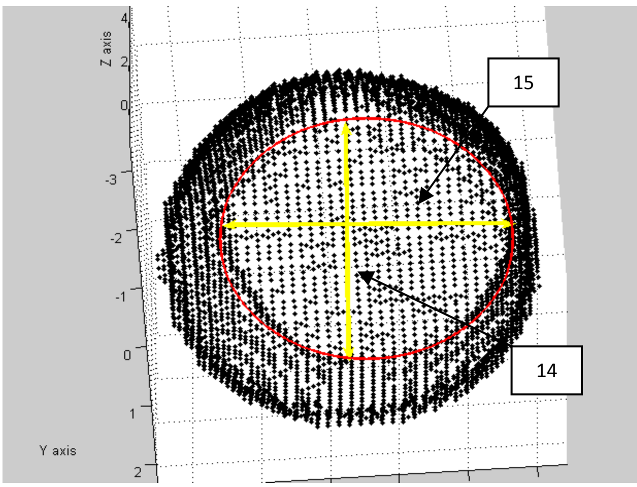


Figure 9 Top view of the modified model. The labeled lines represent the measurement of a length in Table 1

Table 1 shows that the difference between the two sets of measurements are small. The small error between the model and actual limb is dependent on several factors such as resolution and processing of the actual 3D image data, thickness and distance between vertices, the method of reconstruction (i.e., control parameters of the decimation algorithm or triangulation), and factors associated with marking the measurement points by a human.

Table 1 Differences between the modified model and the lower limb data

Length	Modified 3D model (cm)	Actual limb (cm) ± errors	Difference (cm) ± errors
1	4.8	4.8 ± 0.2	0.0 ± 0.2
2	5.5	5.4 ± 0.1	0.1 ± 0.1
3	4.1	4.1 ± 0.1	0.0 ± 0.1
4	5.8	5.9 ± 0.1	0.1 ± 0.1
5	4.4	4.4 ± 0.1	0.0 ± 0.1
6	4.8	4.7 ± 0.2	0.1 ± 0.2
7	5.3	5.3 ± 0.1	0.0 ± 0.1
8	4.0	4.0 ± 0.1	0.0 ± 0.1
9	6.3	6.2 ± 0.0	0.1 ± 0.0
10	5.1	5.0 ± 0.1	0.1 ± 0.1
11	6.5	6.4 ± 0.1	0.1 ± 0.1
12	7.2	7.3 ± 0.2	0.1 ± 0.2
13	4.0	4.0 ± 0.1	0.0 ± 0.1
14	4.1	4.0 ± 0.2	0.1 ± 0.2
15	4.0	4.0 ± 0.2	0.0 ± 0.2

5.0 CONCLUSION

As a conclusion, a method of generating a 3D model of a limb which involves fitting and modifying a reference model generated by either a SfS based reconstruction technique or a simple program, and a deformation process is presented. The experimental results show that the use of the deformation process to reshape the 3D model of a limb produces good fit with the actual limb data, especially for a limb that has a small number of vertices. For real applications on limb data, if the model of the residual limb of a patient is available, prosthesis can use the proposed method to fit model to the current patient's limb data. If the available model is similar to the limb data, then the deformation process will achieve a better performance. The reconstruction from multiviews in this study uses a turntable system, which in practice is difficult for obtaining 3D data of real human limbs. Rotating the camera instead of the object is a possible approach to overcome this problem.

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