

Test of a vertical scan mode in 3-D imaging of residual limbs using ultrasound

Ping He, PhD, PE; Kefu Xue, PhD; Yu Fan, PhD; Yiwei Wang

Department of Biomedical and Human Factors Engineering, Department of Electrical Engineering, Wright State University, Dayton, OH 45435

Abstract--We have developed a new ultrasound system for imaging residual limbs that employs two scan modes: a vertical scan mode (VSM) primarily used for capturing the skin surface, and a horizontal compound scan mode (HCSM) primarily used for imaging the internal tissue structures. Since the HCSM was described previously (*J Rehabil Res Dev* 1997;34(3):269-78), the main purpose of this article is to elucidate the principle of reconstructing the skin surface using the new VSM and to report the accuracy of volumetric measurement based on this reconstruction method. For a residual limb with a length of up to 26 cm, the vertical scan takes about 80 s. The acquired skin surface has a resolution of 144 points per circumference in the transverse direction and a resolution of 28 points per cm in the longitudinal direction. The measurement accuracy of the system is tested using a cylindrical phantom and a custom-made limb model. The diameter of the phantom measured by the ultrasound method is 113.8 ± 0.23 mm, compared with a value of 113 mm measured by a caliper. For the limb model, cumulative segment volumes measured by the ultrasound method are compared with those measured by the hydrostatic weighing method. The relative errors are $<1\%$. This study demonstrates the feasibility of using ultrasound to perform limb measurement for prosthetic CAD/CAM applications.

Key words: *CAD/CAM, limb prostheses, ultrasound image, volumetric measurement.*

INTRODUCTION

During the last decade, several computer-aided design and manufacture (CAD/CAM) systems have been developed to assist prosthetists in socket design and fabrication (1,2). The most noticeable advantages of this new technique are the facilitation of the management of information (patient data, limb shape data, and socket design data), the ease of fabrication, and the attainment of more consistent results (3). Although the socket design software of each system often has some unique features, the major difference among different CAD/CAM systems lies in the specific method used to acquire the limb shape data: plaster casting followed by mechanical digitizing; plaster casting followed by noncontact, optical measurement; and direct optical measurement without casting. Since data acquisition is the necessary first step of any CAD/CAM process, with the consequent socket design depending upon the data acquired, the accuracy and precision of the data acquisition device is crucial to the final product.

The performance of the Swedish CAPOD system in volumetric measurements was evaluated in 1995 by a group of researchers in Sweden (4). More recently, the performance of that system was measured again and compared with that of a Seattle ShapeMaker[™] system, using either an electromechanical or an optical sensor (5). In both evaluations, the absolute error in diameter measurement was found to be less than 1 mm and the relative error in the volume measurement less than 3 percent.

We have tested an ultrasonic method to acquire limb data (6,7). The main advantage of ultrasound is its ability to display internal structures: additional information about the bony structure can help prosthetists to better locate the weight-bearing and pressure-relief areas in prosthetic socket design, which in turn can lead to improved socket fit. The ultrasonic method can also be used in establishing a finite element model for the study of the limb-prosthesis interaction (8). Preliminary results demonstrate the feasibility of developing a relatively low-cost (as compared with CT and MRI) ultrasound system to image the internal structures of a residual limb. The technique of compound scan is found effective in reducing the ultrasound speckles and in imaging both soft tissues and bony structures. On the other hand, the initial design of the system is not optimal for capturing the external geometry (skin surface) of the limb. First of all, the system requires 12-15 min to scan a typical residual limb. Since involuntary movement during the scanning is inevitable, a sophisticated algorithm for the detection of, and compensation for, limb movement is needed, and the accuracy of the final result may still not be guaranteed. Secondly, since the skin surface is reconstructed from the boundaries of each transverse slice obtained with a vertical space of 0.5 cm, the sample resolution in the longitudinal direction is not high enough in some cases to reconstruct an accurate 3-D skin surface. Finally, although the compound process greatly reduces the lateral size of the point spread function, the final resolution of the compound image is slightly worse than the axial resolution of the original B-scan image (9). In other words, the method of extracting skin boundary from the compound image does not utilize the highest resolution (the axial resolution) that the ultrasound imaging system can provide.

We have recently modified our system to address the above three problems by employing two scan modes: a new, fast vertical scan mode (VSM), designed to obtain a high-resolution skin surface in about 1 min, and the original horizontal compound scan mode (HCSM) that obtains high-quality cross-sectional images, showing internal structures. The methods of combining the data obtained in the two scan modes for prosthetic CAD/CAM applications will be described

elsewhere. The main purpose of this article is to describe the principle of reconstructing the skin surface using the VSM and to report the accuracy of volumetric measurement based on the new reconstruction method.

METHODS

Scanning System

Figure 1 shows a part of the new scanning/data acquisition system. On the right, a limb model is shown immersed in a water tank, supported by a limb stabilizer. The tank is divided into two connected compartments: a cylindrical compartment where the residual limb is placed, and a rectangular compartment where the ultrasound transducer is housed. The limb compartment has an internal diameter of 26.7 cm and a height of 54 cm. The transducer compartment is 16.5 cm wide, 15.3 cm deep, and 52 cm high. Both compartments are filled with water for ultrasound coupling. For scanning, the entire tank rotates 360° around the limb. The transducer is then translated to another level, and the tank rotates in the reverse direction, and so on. Rotation of the water tank is provided by a stepping motor (MO91FF206, Superior Electric, Bristol, CT) located underneath the tank and vertical translation of the transducer is provided by another stepping motor (MO61FF206) installed on the side wall of the transducer compartment. Each motor is powered by its own driver (ZETA4, Compumotor, Rohnert Park, CA), and the drivers are controlled, in turn, by a single control board (AT6200, Compumotor) inside a personal computer.

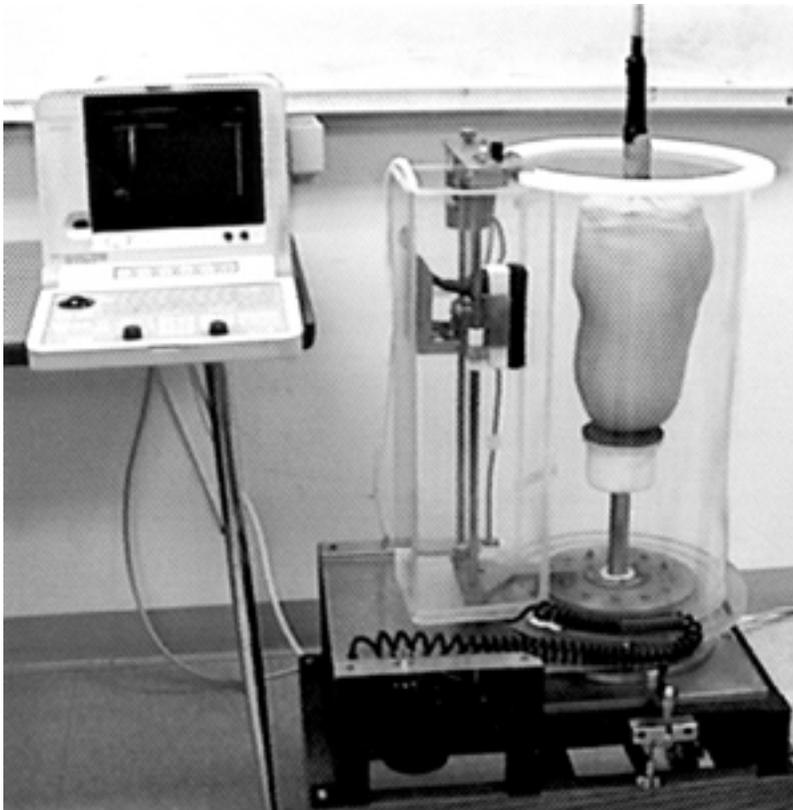


Figure 1.

The ultrasound scanning apparatus (right) and the portable Hitachi scanner (top left) equipped with a linear array transducer. In the figure, the transducer is held vertically.

A portable ultrasound scanner (Model 405, Hitachi Medical Corp., Tokyo, Japan) is used in this application and is shown on the left side of **Figure 1**. The scanner is equipped with a linear array transducer (EUP-L31, 3.5 MHz) that has 192 channels and produces a rectangular B-scan image 9.8 cm wide and 14 cm deep. The video signal exported from the scanner is transmitted to a high-speed frame grabber (DT3155, Data Translation, Marlboro, MA) that digitizes and stores the image at 8-bit resolution for later processing in the PC.

The ultrasound transducer is mounted, through a rotatable coupling, on a holder that slides up and down on two rods fixed vertically to the frame of the transducer compartment. The coupling permits the transducer to be held either in vertical direction (as shown in **Figure 1**) in VSM or in horizontal direction in HCSM. Scanning normally begins at the distal end of the limb. In the VSM, at each level, the transducer rotates (as the water tank rotates) 360° around the limb in 22 s, and an image is acquired every 2.5° . A total of 144 essentially nonoverlapping images are obtained for a limb segment 9.8 cm long. The transducer is then translated proximally 8.5 cm in 7 s, and scanning is repeated at the new level. For a residual limb with a length of up to 18 cm, the entire vertical scan requires 51 s (two levels). For a residual limb with a length of up to 26 cm, the scan time is 80 s (three levels). Although the images acquired in the VSM also show some internal tissue structures, they are primarily used for reconstructing the skin surface of the limb. After the vertical scan, the transducer is rotated 90° , and the system performs the horizontal, compound scan (7). The information obtained in the HCSM is mainly used for reconstructing the internal tissue structures of the limb.

Test Objects

We have tested this system by scanning three objects. The first is a cylindrical, tissue-mimicking phantom (ATS Laboratories, Inc., Bridgeport, CT), having a uniform diameter of 113 mm. This phantom is used to evaluate the accuracy of the system in measuring diameters. The second object is a custom-made, residual limb model of irregular shape, shown in **Figure 1**. The hard foam body of the model is covered by a synthetic skin sleeve (Prosthetic Research, Bushnell, FL) to provide a texture and ultrasound reflectivity similar to that of natural skin. This model is used to evaluate the accuracy of the system in measuring volume. The third object is the left residual limb of a 46-year old male. A cross-sectional image of the limb in the longitudinal plane will be presented to show the actual information obtained in the VSM.

Reconstruction of Skin Surface from the Images Obtained in the Vertical Scan Mode

Figure 2 shows the orientation of the images obtained in the VSM. The line O-O;pr represents the center of rotation (COR) of the scan. The precise distance from the transducer to this line is determined through system calibration (7). Each vertical image contains 284 ultrasound scan lines (called A-lines) along the longitudinal direction, each of which represents an ultrasound echo sequence reflected back by the scatterers in front of the transducer.

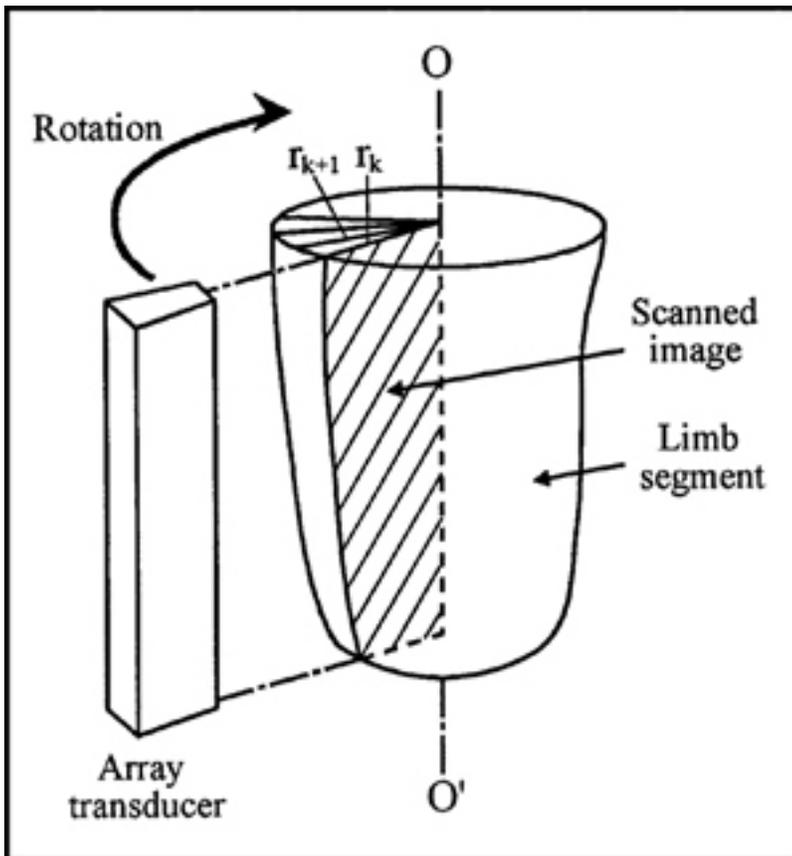


Figure 2.

In the vertical scan mode, the transducer rotates 360° around the limb, and a total of 144 images are acquired with an angular space of 2.5° . The height of each image is 9.8 cm that is covered by 284 scan lines.

In particular, the water-skin interface produces a strong echo used to detect the skin boundary. The space between two adjacent A-lines is measured as 0.3478 mm, and the pixel-to-pixel distance along each A-line is 0.3349 mm. Knowing these values, one can perform the geometric calculation based on pixel counting. **Figure 3** shows three representative profiles of the echo envelope obtained from the phantom, the limb model, and the human leg, respectively. Each curve has a leading segment with very low pixel values, representing the water path between the transducer and the boundary of the object, after which the curve rises abruptly, indicating the strong echo reflected back by the boundary. The exact position of the boundary is defined as the pixel location where the slope of the envelope profile reaches the maximum. Finally, each curve in **Figure 3** is terminated at pixel number 350 where the COR (line O-O;pr) is reached.

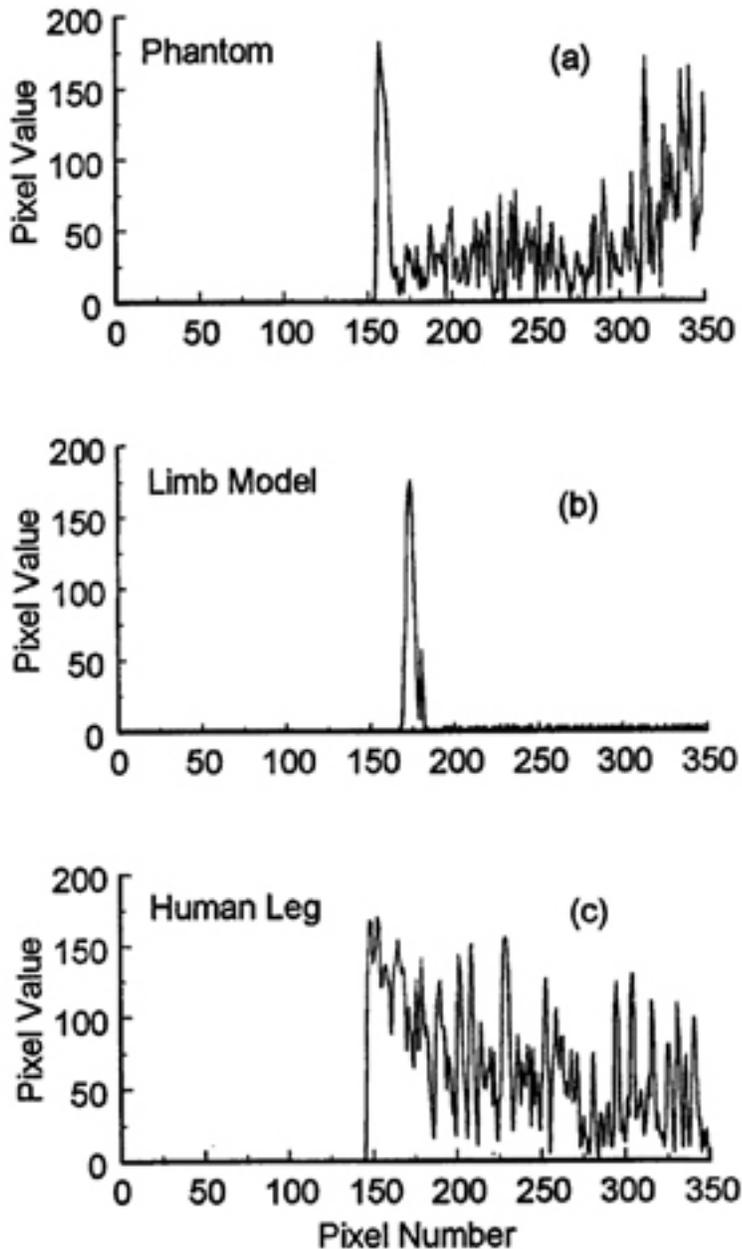


Figure 3.

Representative profiles of echo envelope obtained from the cylindrical phantom, the limb model, and the human leg. The detected boundary pixels of the three curves are located at numbers 156, 172, and 147, respectively.

From each image obtained in the VSM, 284 boundary pixels are first extracted, one from each A-line. Next, pixel locations of the skin boundaries obtained from the entire 144 images are stored in a 284×144 matrix that represents the skin surface of the scanned limb segment. If more than one limb segment is scanned, the skin surface of the entire residual limb is obtained by stacking together the skin surfaces of all the scanned segments.

Volumetric Measurement

Volumetric measurements are performed using the cylindrical phantom and the limb model. For the cylindrical phantom, only one segment is scanned, and the locations of the phantom surface

are stored in a 284×144 matrix. With the help of **Figure 2**, one can apprehend that each row of the matrix actually stores the locations of 144 circumference pixels defining the circular boundary of a transverse cross section of the phantom scanned by a single A-line. The area of this cross section can be calculated using the following formula:

$$[1] \quad S(i) \cong \frac{\pi}{4 \times 144} \sum_{k=1}^{144} (r_k + r_{k+1})^2 \quad \text{for } i = 1, 2, \dots, 284$$

(when $k = 144, r_{k+1} = r_1$)

where $S(i)$ is the cross-sectional area (a slice) of the phantom scanned by the i^{th} A-line, and r_k is the distance between the k^{th} boundary pixel to the COR, as indicated in **Figure 2**. From the 284 measured areas, the mean and standard deviation (SD) of the area measurement can be calculated. Finally, the mean and SD of the diameter measurement can be determined (assuming the cross section is a perfect circle, i.e., $S=0.25\pi D^2$).

For the limb model, volumetric measurements are performed using the ultrasound method and a hydrostatic weighing method that serves as a "gold standard" for comparison (10). Two markers are first installed on the model: metal wires with a diameter of 0.8 mm and a total length of 4 cm are first bent into an "L"; the long arm of each L is then taped flat on the surface of the model, while the short arms (about 4 mm long) are oriented perpendicular to the model surface. In this orientation, the ends of the short arms face the incoming ultrasound beam, producing a strong reflection that makes a mark visible in the ultrasound image. The vertical distance between the two marks is 18 cm, and only the volume of the limb model between the two marks is measured. To perform the ultrasound measurement, the limb model is scanned at three levels. The two marks are then identified in two individual vertical images, indicating the lowest (i_{n1}) and the highest (i_{n2}) slice for the measurement. Starting from the lowest slice, the area $S(i)$ of every slice is calculated using Equation 1. The elemental volume between two adjacent slices is calculated as $S(i) \times h$, where $h=0.3478$ mm, the vertical resolution of the image (space between two adjacent A-lines). Finally, the cumulative segment volumes of the limb model (measured up from the lowest slice) at 1 cm, 2 cm, and 18 cm (the highest slice) are calculated. These values will be compared to the corresponding cumulative volumes measured by the hydrostatic weighing method.

The hydrostatic weighing method is based on Archimedes' Principle of Buoyancy and can be described with the help of **Figure 4**. The limb model is held by a rigid linkage connected to the moving arm of a Shape Digitizer (West Sussex, England). A plastic tape measure, placed on the surface of the model, indicates distance. The limb is immersed in the water contained in a plastic bucket on a precision scale (Toledo Scale Model 1072). The model is first lowered until the lower mark just touches the water. The reading of the scale is recorded as W_0 . The model is then lowered 1 cm and the reading of the scale is recorded as W_1 . The incremental volume of the limb

model from the first to the second water level is determined as $(W_1 - W_0)/\rho$ where ρ is the density of the water at the room temperature. This procedure is repeated at incremental water levels of 2 cm, 3 cm...18 cm, where the upper mark is reached.

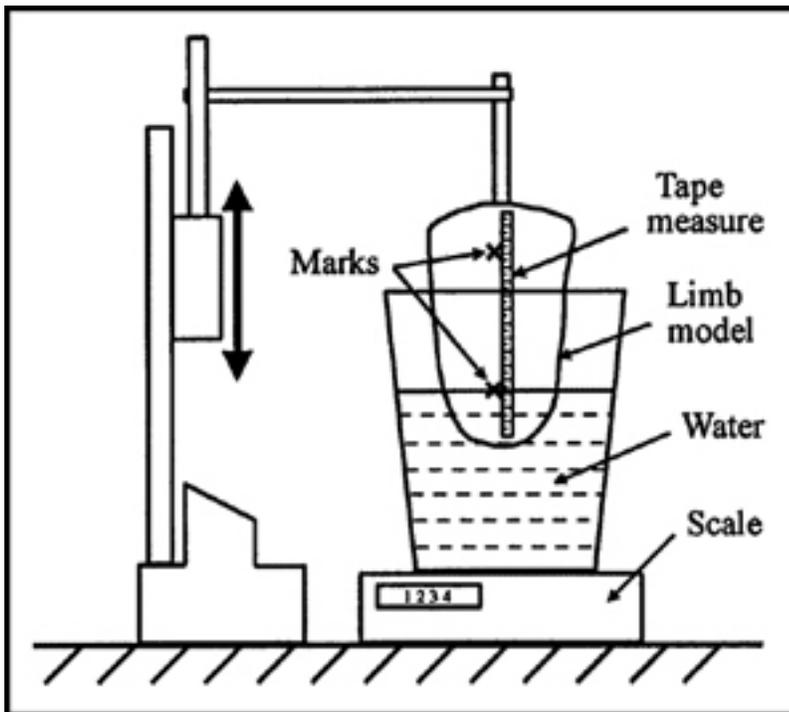


Figure 4.

Volumetric measurement using the hydrostatic weighing method. The volume of the limb model between the two marks can be determined by the weight of the displaced water. The latter is equal to the difference in the readings of the scale at the two immersion levels.

RESULTS

Cylindrical Phantom

Figure 5 shows an image of the phantom obtained in the VSM. This image actually displays a half of a longitudinal cross section of the phantom, with its boundary shown as the vertical bright line near the center. The black region on the left represents the water path between the transducer and the phantom. Using the method described in the previous section, the mean and SD of the diameter calculated from the 284 measured cross-sectional areas are 113.8 ± 0.23 mm. Compared with the caliper measurement of 113 mm, the absolute error is 0.8 mm.

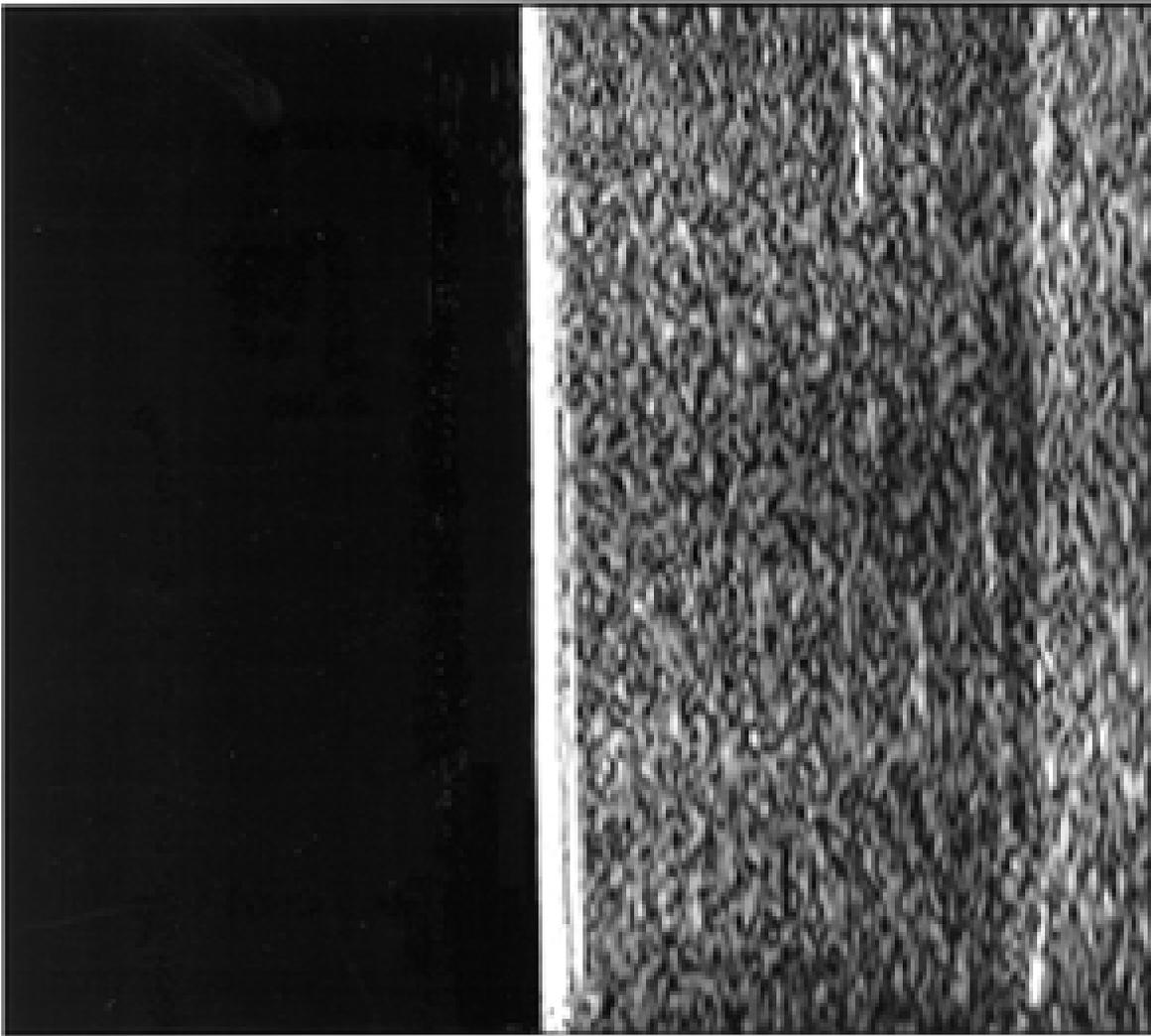


Figure 5.

An image obtained from the phantom using the vertical scan mode. The right edge of the image is close to the central axis of the phantom. The bright vertical line near the center of the image represents the boundary of the phantom.

Limb Model

Figure 6 shows the limb model displayed by the ShapeMaker software (M+IND, Poulsbo, WA). To obtain this image, the limb model was first scanned vertically at three levels. The skin surface is reconstructed according to the procedure described in the previous section. The surface data is then saved to a file according to the American Academy of Orthotists and Prosthetists (AAOP) Standard Data Interchange Format, which can be read in by ShapeMaker and displayed.

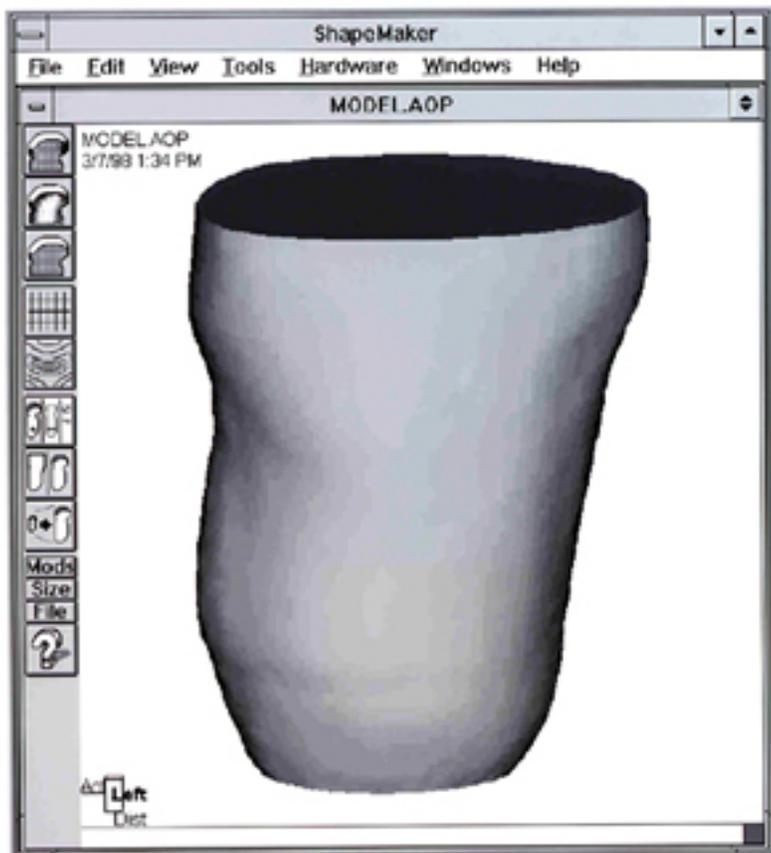


Figure 6.
3-D surface of the limb model displayed by the ShapeMaker software.

Table 1 lists the actual readings on the scale in the hydrostatic weighing experiment, the cumulative volumes determined by the weighing method, and those obtained by the ultrasound method. The relative errors of the ultrasound measurement at different cumulative volumes are all less than 1 percent.

Table 1.

Summary of the results of volumetric measurement using the hydrostatic weighing method and the ultrasound method.

Distance from lower mark (cm)	Reading of the scale (g)	Cumulative volume hydrostatic (cm ³)	Cumulative volume ultrasound (cm ³)	Percent error ultrasound (%)
0	4,874	---	---	---
2	5,124	250	249.6	-0.16
4	5,390	516	517.7	0.33
6	5,657	783	785.0	0.26
8	5,931	1057	1060.0	0.28
10	6,218	1344	1340.1	-0.29

12	6,519	1645	1643.3	-0.10
14	6,852	1978	1971.5	-0.33
16	7,217	2343	2329.7	-0.57
18	7,564	2690	2683.4	-0.25

Human Residual Limb

No volumetric measurement is performed on the residual limb. An image is presented to demonstrate the kind of information the VSM provides. Shown in **Figure 7** is a longitudinal cross section of the residual limb displayed by MATLAB software (MathWork, Inc. Natick, MA). This image is made of six vertical images acquired at three levels. The top one-third of the image is made of two images acquired on the opposite sides of the limb (180° apart) at one level. The middle one-third of the image is made of two images acquired on the opposite sides of the limb at another level, and so on. All six images are in the same longitudinal plane. Comparing with the previously reported images obtained using the HCSM (**Figure 6** in reference 7), the image in **Figure 7** shows a better continuity in the longitudinal direction. Specifically, the skin boundary is smoother. On the other hand, ultrasound speckle is more visible in **Figure 7**: that is a result of the noncompounding scan.



Figure 7.

Lateral view of a longitudinal cross-sectional image of a residual limb. The posterior side is on the right. This image is made of six component images obtained at three scan levels using the vertical scan mode. Total length of the limb shown in the image is 20.3 cm.

DISCUSSION

The most important advantage of the VSM is the significant reduction in the time required to capture the skin surface of the residual limb. Although the vertical scan time of the current system is still longer than that of an optical scanner (CAPOD claims a scan time of about 10 s), it is already significantly shorter than the MRI method and the X-ray CT method, including the spiral CT (10), the two other modalities capable of imaging the internal tissue structures. It should be pointed out that the scan speed of the current system is mainly limited by the time required to store the acquired image data to the hard disk of the PC. With the rapid advancement of the PC technology, it is anticipated that the vertical scan time can be further reduced to about 30-40 s in the near future. With such a relatively short scan time and an improved mechanism for limb support, the effects of motion artifacts can be largely eliminated. This will make the ultrasound method a practical modality for limb measurement.

The second advantage of the VSM is its improved resolution and accuracy in measuring external geometry. The resultant surface data represent a resolution of 144 boundary points per circumference, and a resolution of 28 points per cm in the longitudinal direction. Such a high resolution in the longitudinal direction may not be actually needed in socket design, but it helps to extract an accurate and smooth skin boundary from the vertical image.

Based on the description of the method for reconstructing skin surface, the accuracy in measuring external geometry is first determined by the accuracy in measuring the distance between the transducer surface and the skin boundary. The basic equation for distance measurement, using the pulse-echo technique is:

$$[2] \\ D = 0.5 c \Delta t$$

where D is the distance between the transducer surface and the reflector (e.g., skin boundary); c is the sound velocity in water (1,480 m/s at 20 °C) and Δt is the time lag between transmitting and receiving the ultrasound pulse. To determine the uncertainty in the distance measurement, we first calculate the variance of D using the principle of error propagation in physical measurement (11):

$$[3] \\ \sigma_D^2 = 0.25 (c^2 \sigma_{\Delta t}^2 + \Delta t^2 \sigma_c^2)$$

where σ_D^2 , $\sigma_{\Delta t}^2$ and σ_c^2 are the variances of the distance measurement, the time measurement, and the sound velocity, respectively. To estimate σ_D^2 , we use the following typical data: $c=1,480$

m/s with an estimated $\sigma_c=5$ m/s (variation of c with temperature and water purity), $\Delta t=9.46\times 10^{-5}$ s for a reflector located 7 cm from the transducer. According to the Hitachi manual, the sampling frequency of the scanner is 12.5 MHz, which is also the sampling frequency of the frame grabber. Such a frequency results in an estimated uncertainty in the time measurement of $\sigma_{\Delta t}=8\times 10^{-8}$ s.

Based on these data, we obtain $\sigma_{D^2}=5.94\times 10^{-8}$ m², or $\sigma_D=0.24$ mm. The above calculation only considers the uncertainty in determining the location of a particular pixel. To determine which pixel is the actual boundary pixel, there is an additional uncertainty that is essentially determined by the axial resolution of the B-scan image. The axial resolution of the ultrasound scanner used in this study is carefully measured across the entire scanning area and shows a small variation at different depths, with an average value of 0.75 mm. Combining the above two uncertainties, the overall uncertainty in the geometrical measurement is estimated as 1 mm. This uncertainty is consistent with the actual accuracy obtained in the diameter measurement of the cylindrical phantom. In summary, based on the theoretical analysis and the actual measurement, the current ultrasound system can achieve an accuracy of 1 mm in diameter and an accuracy of 1 percent in volume, values comparable with those of several commercial CAD/CAM systems (4,5).

In this article, we have been mainly concerned with the VSM. The actual data acquisition employs both the VSM and HCSM. While the VSM is best suited for obtaining an accurate and smooth skin surface, the HCSM is best suited for obtaining detailed internal structures. Because the HCSM uses a compound technique, it takes much longer to scan an entire residual limb (>10 min); consequently, motion artifacts are a more serious problem. On the other hand, since there is a significant overlapping of images obtained in the compound scan, one can use the redundancy to detect and compensate for those artifacts. We have tested a cross-correlation method for motion detection, and the preliminary results are encouraging (12). We are currently testing and comparing several more advanced methods for motion detection and compensation. In addition, we are investigating effective methods for integrating the information obtained in both the vertical and horizontal scan modes and developing a convenient 3-D visualization tool to present the information.

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