

## Shape and volume change in the transtibial residuum over the short term: Preliminary investigation of six subjects

**Santosh G. Zachariah, PhD; Rakesh Saxena, PhD; John R. Fergason, CPO; Joan E. Sanders, PhD**

*Departments of Bioengineering and Rehabilitation Medicine, University of Washington, Seattle, WA*

**Abstract**—A preliminary investigation was conducted to characterize the magnitude and distribution of volume change in transtibial residua at two time intervals: upon prosthesis removal and at 2 week intervals. Six adult male unilateral transtibial amputee subjects, between 0.75 and 40.0 years since amputation, were imaged 10 times over a 35-minute interval with a custom residual limb optical scanner. Volume changes and shape changes over time were assessed. Measurements were repeated 2 weeks later. Volume increase on socket removal for the six subjects ranged from 2.4% to 10.9% (median 6.0%  $\pm$  standard deviation 3.6%). Rate of volume increase was highest immediately upon socket removal and decreased with time (five subjects). In four subjects, 95% of the volume increase was reached within 8 minutes. No consistent proximal-to-distal differences were detected in limb cross-sectional area change over time. Limb volume differences 2 weeks apart ranged from  $-2.0\%$  to 12.6% ( $0.6\% \pm 5.5\%$ ) and were less in magnitude than those within a session over the 35-minute interval (five subjects). Multiple mechanisms of fluid movement may be responsible for short-term volume changes, with different relative magnitudes and rates in different amputees.

**Key words:** amputation, anthropometry, artificial limbs, body surface area, diurnal, limb volume, residual limb, shape change.

### INTRODUCTION

Changes in shape and volume of the transtibial (TT) residuum affect the quality of socket fit. Specifically, the residuum changes in volume over the course of a day, as attested to by the number of amputees who carry extra prosthetic socks to compensate for within-the-day volume

changes. The residuum also changes in shape over longer periods of time, as attested to by the need in most amputees for temporary or definitive socket shape modifications, if not outright socket replacement.

At present, little is known of the magnitude of short-term volume changes. Nor is it known if shape changes accompany the short-term volume changes. Board et al. measured volume change in 11 subjects following 30 minutes of treadmill walking [1]. Residuum volume decreased by an average of 6.5 percent for a “normal” suction socket, but increased by an average of 3.7 percent when a vacuum was applied between the socket and liner. Board et al. report that pilot testing indicated that the test conditions provided a volume loss equivalent to a workday.

**Abbreviations:** A/P = anterior/posterior, CSA = cross-sectional area, M/L = medial/lateral, MRI = magnetic resonance imaging, OSS = optical surface scanner, PTB = patellar tendon bearing, SD = standard deviation, SXCT = spiral x-ray computed tomography, 3-D = three-dimensional, TSB = total surface bearing, TT = transtibial.

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Address all correspondence to Joan E. Sanders, PhD, Associate Professor; Bioengineering 357962, Harris 309, University of Washington, Seattle, WA 98195; 206-221-5872; fax: 206-221-5874; email: jsanders@u.washington.edu.

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Long-term volume change in the residuum in the immediate postoperative period has been the subject of much investigation (see Lilja and Oberg for a review [2]), mainly to identify guidelines for when to switch from a temporary to a definitive prosthetic socket and also to identify treatments that minimize this time. However, only one investigation to date has characterized the shape changes in the postoperative period. Lilja et al., using magnetic resonance imaging (MRI) on three amputees at 2, 6, and 28 weeks postamputation, reported a decrease in cross-sectional area (CSA) of the overall TT residuum and of the medial muscle group [3]. Following an initial decrease, the lateral muscle group increased in CSA. Lilja et al. postulate that the initial rapid reduction in the CSA was due to a reduction in postsurgical edema and that the later slower change in the CSA was due to muscle atrophy/hypertrophy during rehabilitation. They suggest that the hypertrophy of the lateral muscle group (lateral head of the gastrocnimius and the anterior tibial muscle) was due to a new pattern of activation wherein it contributed to socket suspension. Nevertheless, structural changes in the soft tissue as discussed by Lilja et al. occur too slowly for them to be responsible for the shape and volume changes that occur during the course of a single day [3].

Short-term changes in volume in the residuum are likely entirely due to movement of fluid (blood, plasma, and lymph) in and out of specific compartments. The magnitude of the net fluid movement over the short term and its effect on day-to-day socket fit has received little attention in the literature until now, although a number of shape and volume compensation devices are commercially available or are currently being developed. Proper characterization of the shape and volume change over the short term is needed for the successful development of new socket shape control strategies that would actively compensate for short term changes and thereby provide the amputee with more convenience and comfort than existing prosthetic socks.

Of particular interest is the relative magnitude of the within-the-day changes compared with the day-to-day changes. This knowledge will be useful to clinicians while educating patients on volume changes that they can expect and the appropriate sock management to compensate for them, and to prosthetists when making socket adjustments based on patient feedback. Knowledge of the time taken for the residuum volume to stabilize following socket donning or removal is also useful in patient education and

in the casting and measuring of the residuum. Finally, it is not known if this fluid movement is distributed uniformly throughout the limb, or if there are regional variations, possibly related to the soft tissue compartments. If systematic variations were found along the length of the limb, this knowledge would have an impact on the design of prosthetic socks and other shape/volume compensation technologies.

Knowledge of short-term volume and shape changes in the residuum therefore has obvious utility in the clinical management of the lower-limb amputee. Despite this, no published literature exists on the subject. Thus, with a view to begin building a database of characteristic TT residua volume and shape changes that will facilitate future prosthetic socket shape designs and shape control strategies, our aim with this research was, for a small population of amputee subjects, to measure the change in volume and shape of the residual limb immediately after removal of a socket, and to use that information to answer the following three questions:

1. What is the magnitude of volume increase, what is its time course, and how long does it take to stabilize?
2. Is the volume increase uniform down the length of the limb?
3. Is the volume increase on removal of the socket greater than the volume change in the limb between two points in time 2 weeks apart?

## METHODS

Unilateral TT amputees were recruited and tested following approval by the institutional review board at the University of Washington. Since this was a preliminary study, without quantitative hypotheses, we did not ensure a distribution of age, sex, race, cause of amputation, or time since amputation.

Six male subjects were studied, ranging in age from 22 to 59 years (**Table 1**). Time since amputation ranged from 0.75 to 40 years. All subjects could stand with support for 10 minutes and could walk comfortably for at least 200 meters. In five cases, trauma was the cause of amputation. Three subjects wore total surface bearing (TSB) sockets, and three wore patellar tendon bearing (PTB) sockets. We created TSB molds using a passive casting procedure over the silicone liners and then modifying globally without specific weight-bearing areas. PTB designs focused weight-bearing on the tolerant areas

**Table 1.**  
Subject characteristics.

Subject	Sex	Age (yr)	Time Since Amputation (yr)	Cause of Amputation	Amputation Side	Socket Design	Activity Level
1	Male	22	6.0	Meningitis	Left	TSB	K-4
2	Male	27	2.5	Trauma	Left	TSB	K-3
3	Male	58	25.0	Trauma	Left	PTB	K-2
4	Male	59	0.75	Trauma	Right	TSB	K-3
5	Male	57	40.0	Trauma	Left	PTB	K-4
6	Male	56	34.0	Trauma	Right	PTB	K-3

PTB = patellar tendon bearing  
TSB = total surface bearing

K-2 = limited community ambulatory  
K-3 = community ambulatory

K-4 = high-impact activities

of the patellar tendon, medial tibial flare, pretibial musculature, lateral shaft of the fibula, and the gastroc-soleus musculature. Activity levels ranged from sedentary (2 hours of prosthesis use daily) to very active (daily recreational running of a few miles).

For each subject a setup/training session was conducted on a day before the first data collection session. During that session, we obtained informed consent. The subject was instructed not to undertake any out-of-the-routine physical activity prior to arriving at the laboratory for data collection sessions. Consumption of alcohol or diuretics prior to testing was not permitted. The subject was then positioned in a custom optical scanner, an enhancement of that described previously [4]. Briefly, the scanner was a monochrome charge-coupled device camera mounted to a beam that rotated 300° around the residual limb (**Figure 1**). During the central 200°, while the camera was moving at constant angular velocity, 23 images were taken over a 1.5-second interval. All portions of the residuum surface were visible from at least two images. Special lighting, a black background, and a black stocking worn on the contralateral limb ensured good contrast of the residuum in the images. The scanner had a radial resolution of 0.23 mm, determined by scanning test objects of known shape. The scanner was calibrated and evaluated regularly during the study to ensure consistent performance.

The framework of the scanner, necessary to minimize subject movement during scanning, was adjusted and settings recorded for the individual subject so that he contacted the frame at seven points—the distal end of the residuum, the lateral thigh, the anterior thigh, each hand, the medial contralateral limb, and the anterior contralateral limb. We conducted considerable training to ensure



**Figure 1.**  
Residual limb optical scanner. Digital camera took 23 images as it rotated 300° around residual limb.

that the amputee subject could stand consistently without movement when requested to do so. With practice, a subject could move from seated wearing a prosthesis to standing in the scanning system with prosthesis off in 15 to 30 seconds. After the initial setup of the support framework, we led the amputee through the data acquisition protocol to familiarize him with it, focusing especially on the instructions of when to stand and sit and how to initiate scanning. Because delays were often long during this session while we explained procedures and techniques to the subject, we did not include the data from the setup/training session in our analysis.

Data collection session 1 was conducted in the morning between 1 and 15 days after the setup/training session. At data collection session 1, the amputee subject donned his normal prosthetic limb and remained seated for at least 20 minutes. This period of rest was a conservative estimate (i.e., 10 minutes would likely have sufficed) based on prior experience of the time needed to achieve a homeostatic condition after amputee walking [5]. The subject then removed the prosthesis and stood in the scanner system. The first scan began as soon as he gave his assent for scanning to begin. Two more scans were performed as soon as possible (approximately 1 minute apart because of the time needed to download the data).

The amputee then put on his prosthesis and walked at his self-selected walking speed for approximately 200 meters (approximately 4 to 5 minutes) on a level, noncarpeted floor. A distance of 200 meters was a conservative estimate of the distance needed for interface stresses to stabilize during walking based from previous interface stress measurements [4]. We took care to ensure the subject maintained a consistent walking speed. The subject then returned to the scanning system, and three more scans were performed as soon as possible. Subsequent scans were performed at the following intervals, measured from when the prosthesis was taken off: 5, 10, 15, 20, 25, 30, and 35 minutes. We asked the amputee to sit between scans more than 2 minutes apart. Finally, after the 35-minute scan, four more scans were performed as close together as possible. These latter scans were used to assess scanner performance, because, presumably, minimal limb swelling occurred during this time interval. Then the residuum was imaged in anterior/posterior (A/P) and/or medial/lateral (M/L) views for 1.5 seconds for each view. This test allowed subject tremor and scanner performance to be evaluated. The entire protocol excluding the setup session was repeated within 2 weeks (data collection session 2) at approximately the same time of morning.

For each scan, silhouettes were automatically extracted from the images, with manual intervention where hair or skin color made edge detection difficult. We used the silhouettes to reconstruct a smooth three-dimensional (3-D) surface within the convex hull of the back-projected silhouette rays. A tubular Cartesian B-spline surface, as described by Zachariah et al. [6], was used to describe the surface.

We compared volume and residual limb shape between different time points for each subject tested.

Comparison of shape and volume requires that the 3-D shapes first be aligned with respect to each other. No established methodologies exist to do this, primarily because of the difficulty in reducing shape and shape-difference to a universally useful metric that can be minimized. The technique we used here, and described in the **Appendix** (available in the online version only), uses a metric and methodology appropriate to lower-limb residua. This technique has proven robust and accurate on sample shapes synthesized from socket computer-aided design/computer-aided manufacturing software.\*

By comparing residual-limb shapes over the 35-minute interval after prosthesis removal with respect to the initial scan, we calculated changes in residual-limb volume over time. We curve-fitted the volume change versus time data using the exponential equation

$$\left( \frac{V_t - V_{t=0}}{V_{t=0}} \right) = \left( \frac{V_{t=\infty} - V_{t=0}}{V_{t=0}} \right) \cdot [1 - \exp(-kt)] ,$$

where  $t$  is time in minutes,  $V_t$  is volume at time  $t$ , and  $k$  is a time constant.  $V_{t=0}$ , the volume immediately after prosthesis removal;  $V_{t=\infty}$ , the volume the limb exponentially approaches; and  $k$  were calculated for each session from the curve fit. We then used these volume changes to estimate the radial and circumferential dimension changes, under the assumption of a uniform cylinder. The basis for use of a uniform cylinder model was that it provided a consistent reference for each subject thus allowing an initial assessment of the range of the change in radius and circumference across this subject population. This model has been used previously for volume change characterization [7] and has been shown clinically useful to provide a quantitative feel for the volume change data. Future more sophisticated models should account for the change in limb diameter versus distance in the radius and circumference calculations.

We used data from the four scans taken after the 35-minute interval to assess scanner performance. Volumes from these scans were averaged, and the maximum deviation from the mean computed.

Relative increases in the CSAs along the length of the residuum were compared over the 35-minute interval to determine if the volume change had any regional

\*Zachariah SG, Sorenson EA, Sanders JE. A method for aligning trans-tibial residual limb shapes so as to identify regions of shape change. IEEE Trans Neural Syst Rehabil. Unpublished observations 2004.

(distal-to-proximal) trends. We did this by calculating the limb CSA in coronal planes and then plotting each value on a limb axial position chart. Regions of nonparallel vertical lines highlighted local swelling or shrinkage.

## RESULTS

Time between session 1 and session 2 was 14 days for five subjects, and 16 days for one subject. None of the subjects changed their preferred prosthetic sock ply during the course of the study. For Subject 4, we did not collect data after the 20-minute mark in session 1 or after the 35-minute mark in session 2 because the subject was not able to continue. Volume change for Subject 2 was less than that for other subjects; the low signal-to-noise ratio may explain the scatter in that subject's data.

For all subjects, the change over time in the fitted curves to residual-limb volume showed that volume change at more than 35 minutes after prosthesis removal was less than 0.06 percent/minute. Thus the post-35-minute scans were appropriate for assessment of the repeatability of the scanning procedure.

Maximum variability in the post-35-minute scans ranged between 0.48 and 2.55 percent volume change for five subjects (Table 2, Column 8). With the use of the uniform cylinder model [7], this maximum variability corresponded to average global radial changes of 0.15 mm to 0.81 mm. For all subjects except Subject 3, the maximum deviation from the mean volume was less than one-third of the total volume increase on socket removal (Table 2, Column 3). For Subject 3, the maximum deviation from the mean was about half the volume

increase. Notably, for this subject, the volume increase was only 2.4 percent (the smallest seen in this study).

Scans of A/P and M/L views of the limb, with the camera stationary, provided an estimate of the accuracy of the silhouette detection in combination with subject movement. In the ideal situation, the silhouettes from a set of stationary images will match exactly. In actual practice, some jitter exists in the silhouettes due to tremor in the residuum over the 1.5-second scanning interval.

For 17 out of 18 stationary A/P and M/L scans, the range of the jitter in the silhouettes in 23 successive images (averaged for each pixel row) varied from 0.85 pixels to 3.11 pixels, corresponding to maximum local radial error in a single silhouette of 0.2 mm to 0.7 mm in the horizontal direction, with corresponding standard deviations (SDs) of 0.27 pixels to 0.76 pixels (0.06 mm to 0.17 mm). For one of the A/P and M/L scans, a clear trend was detected in subject movement, with the edge translating about 30 pixels, or 6.9 mm, in 1.5 seconds. Such gross limb movement was also easily detected during 3-D shape reconstruction, although in our study, none of the almost 200 scans taken had to be rejected because of gross subject movement.

### What Is the Magnitude of Volume Increase, What Is Its Time Course, and How Long Does It Take to Stabilize?

All subjects showed an increase in limb volume over time after taking off their prostheses following 200 meters of walking (Figure 2). For most subjects/sessions, the rate of volume change was highest immediately on socket removal and then decreased with time. For all subjects except one (Subject 3), the relative increase in volume

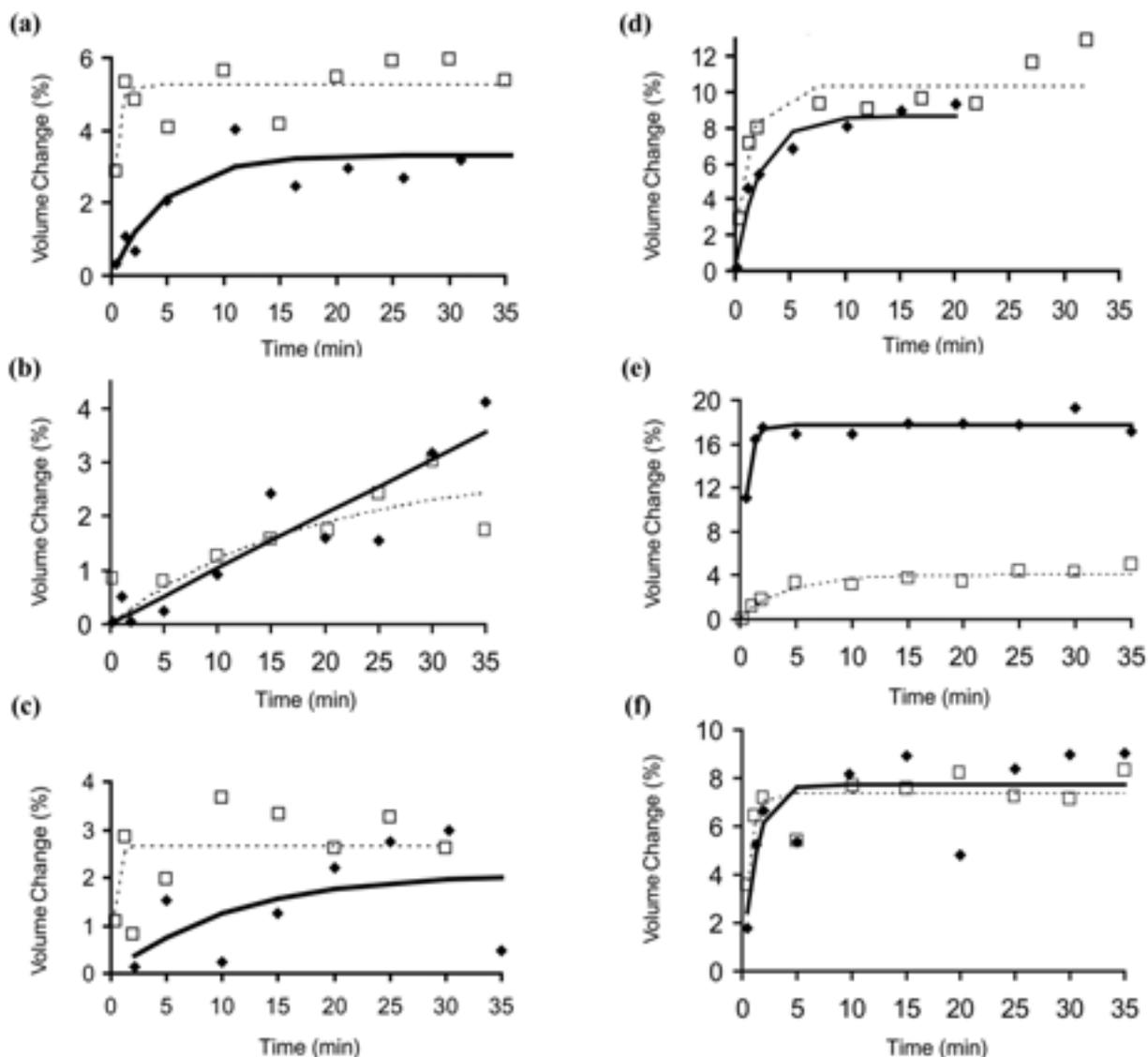
**Table 2.**

Selected volume change quantities for each subject, averaged over two sessions. Results in Columns 2, 3, and 6 derived from exponential curve fits. For  $\Delta R$  and  $\Delta C$  (Columns 4 and 5), a uniform cylinder model was used.

Subject	$V_{\text{initial}}$ (L)	$\Delta V$ (Volume increase as % of $V_{\text{initial}}$ )	$\Delta R$ (Radius increase, in mm)	$\Delta C$ (Circumference increase, in mm)	$T_{95\%}$ (Time to reach 95% of $\Delta V$ , in min)	Volume Change Between Sessions 1 & 2 (%)	Post-35-Minute Scans: Max. Deviation from Mean (As % of mean)
1	1.19	4.3	1.3	7.9	7.7	-1.1	0.71
2	1.16	3.0	0.9	5.7	1275.3	-1.3	0.76
3	0.72	2.4	0.8	4.9	17.6	-2.0	1.28
4	1.97	9.5	2.9	18.2	5.2	+2.2	NA
5	0.98	10.9	3.1	19.6	6.5	+12.6	0.48
6	1.12	7.6	2.4	14.9	2.9	+2.4	2.55

with respect to time for each session fitted well to the exponential equation ( $0.73 < R^2 < 0.97$ , mean = 0.88; for Subject 3,  $R^2 \approx 0.50$ ). Although only the first 20 minutes of data were available for Subject 4, session 1, given the quality of the curve fit ( $R^2 = 0.975$ ) and because the limb had reached within 0.001 percent of the maximum volume change at 20 minutes, we considered limb volume stabilized at 20 minutes and included the data in our analysis. For five subjects (excluding Subject 3), the average

maximum increase in volume ( $V_{t=\infty} - V_{t=0}$ ) ranged from 2.4 to 10.9 percent (**Table 2**, Column 3). The time to reach 95 percent of the predicted maximum volume increase ranged from 2.9 to 7.7 minutes for four subjects (**Table 2**, Column 6). For Subject 2, this time was 41.6 hours and 54.5 minutes, respectively, for the two sessions. The subject for whom the exponential curve fit was poor (Subject 3,  $R^2 \approx 0.5$ ) was also the subject with the smallest volume increase (2.4%), and this subject had a very short (100



**Figure 2.**

Percentage increase in residuum volume following socket removal plotted against time (minutes) for six unilateral transtibial amputees [(a) to (f) are subjects 1 to 6, respectively]. Data points represent measured volume data: solid diamonds for session 1 and open squares for session 2 two weeks later. Lines represent exponential curve fits to volume data: solid black line for session 1 and thin dashed line for session 2. For all subjects except Subject 3, correlation coefficients ( $R^2$ ) between the curve-fit and data are greater than 0.7.

mm) and bony residuum. This subject also had the most variability in the volume measured from the four scans at 35 minutes after socket removal.

### Is the Volume Increase Uniform Down the Length of the Limb?

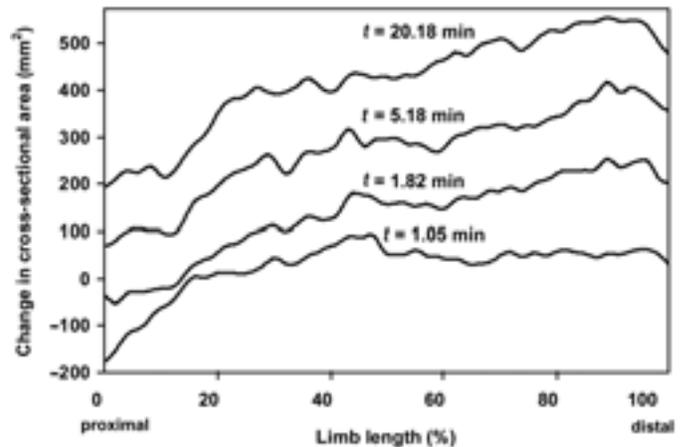
In plots of the change in the CSA along the length of the residuum, the curves were relatively parallel, suggesting no consistent differences between the proximal and distal ends of the residuum. (Figure 3 is a typical plot). For one session (Subject 5, session 2) the CSA change versus axial position plot indicated a greater increase in volume in the distal half of the residuum (Figure 4). While the residuum seemed to swell uniformly for the first minute as indicated by the relatively flat contour in Figure 4, relatively more volume increase occurred in the distal end over the next 34 minutes. This trend was not seen as clearly in the other session or for any of the other subjects. The residuum of Subject 5 had a somewhat bulbous distal end, had the maximum volume increase for any one session, and also had the maximum difference in initial volume between sessions.

### Is the Volume Increase on Removal of the Socket Greater Than the Volume Change in the Limb Between Two Points in Time 2 Weeks Apart?

The initial volume of the residuum immediately on socket removal changed  $0.6 \text{ percent} \pm 5.5 \text{ percent}$  (median  $\pm$  SD) over 2 weeks (range  $-1.1\%$  to  $+12.6\%$ ). The median absolute volume change over two weeks was 2.1 percent. For five out of six subjects, the absolute volume change between the 2 sessions 2 weeks apart was less than the mean volume increase 35 minutes after taking the socket off. For these subjects the session-to-session volume change was also less than twice the maximum variability seen in the successive scans at 35 minutes. No trend was detectable in the direction of volume change over the two sessions: three subjects decreased in volume and three increased in volume. For Subject 5, the session-to-session difference in volume was more than the mean predicted volume increase on socket removal. This subject also showed the maximum predicted volume increase.

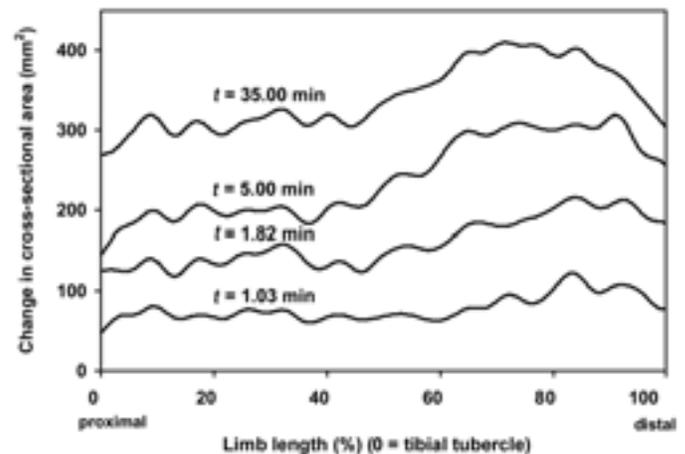
## DISCUSSION

We can quantify swelling in the residuum over a period of 35 minutes using a suitably calibrated silhouette scanner.



**Figure 3.**

Typical cross-sectional area change over time. Approximately parallel nature of contours indicates that volume increase is distributed uniformly along length of residuum, with all axial locations increasing in area at same rate. 0% limb length is at level of tibial tubercle;  $t$  = time.



**Figure 4.**

Cross-sectional area change over time. Nonparallel nature of contours indicates that nonuniform swelling occurred. Distal half of residuum increased in cross-sectional area more than proximal half. 0% limb length is at level of tibial tubercle;  $t$  = time.

Although this is a preliminary investigation with a limited subject population, our research is a starting point for building a database to characterize TT residua volume and shape changes. Such efforts could facilitate future prosthetic socket shape designs and shape control strategies.

The largest source of error in the shape and volume measurement originated from submillimeter tremor-like

movements of the residuum. The 0.2 mm to 0.7 mm maximum variability of the detected A/P and M/L silhouettes over 1.5 seconds with the camera held stationary compares favorably with the 0.15 mm to 0.81 mm global radial change estimated from the maximum deviation from the mean volume of the last four scans taken at 35 minutes after socket removal. The maximum variability of volume measurement for the last four scans (0.48% to 2.55%) compares well with other methodologies as reported by Commean et al., who evaluated the precision of three methods of surface measurements on 13 TT residua [8]. For pairs of repeated scans, the volume SD for a four-camera 3-D optical surface scanner (OSS), spiral x-ray computed tomography (SXCT), and calipers were, respectively, 2.67 percent, 0.71 percent, and 0.92 percent volume change. Commean et al., similarly to our study, identified subject movement as a significant source of within-session error. Any further improvements in the accuracy of residua volume measurement techniques will thus need to focus on reducing subject tremor to less than one pixel or 0.23 mm, possibly by an instantaneous measurement or by measurement of the tremor and then correction for it in postprocessing. Despite these limitations, the noncontact measurement methods are considerably better than the alternative, measurements from casts. Commean et al. determined that random deviation of cast-based measurements was greater than the gain in accuracy (repeatability) obtained over direct measurements on the residuum [8]. Random errors in cast-based volume were 4 percent to 6 percent (of mean volume) greater than those from direct measurement. Board et al. reported that the reliability of the alginate-casting and water displacement procedure they used was  $\pm <1$  percent, although details of this assessment were not provided [1].

The 2.1 percent mean absolute session-to-session changes in volume in this study are considerably less than those reported by Commean et al., who found volume SDs for sessions 1.5 to 4.0 months apart of 7.97 percent for OSS and 9.23 percent for SXCT [8]. Commean et al. identified placement of three fiducial markers affixed to the residua, used as part of the limb-alignment procedure, as a significant source of error in between-session measurements. The lower change in volume in our study might be attributable to the shorter interval between session ( $\approx 0.5$  months) and to the quality of the automated alignment method and thus reduced alignment error. In our study, we maximized shape similarity as opposed to minimizing volume difference.

### **What Is the Magnitude of Volume Increase, What Is Its Time Course, and How Long Does It Take to Stabilize?**

The median limb-swelling magnitude on socket removal of 6.0 percent measured here compares well with the 5 to 15 percent swelling reported by Commean et al. [8]. The magnitude of swelling also corresponds surprisingly well with the increase in limb CSA in nonamputees undergoing postural changes. For example, Berg et al. reported decreases in calf muscle and fat CSAs of 5.5 and 4.4 percent, respectively, in seven subjects as measured from computed tomography scans following 120 minutes of bed rest [9]. Similarly, Conley et al., using MRI on five subjects, showed that the CSA of the calf muscle decreased by 8 percent ( $\pm 2\%$ ) after 12 hours of horizontal bed rest following a day of normal activities [10]. Within 2 hours of resumption of the upright posture, the calf muscle CSA had returned to within 0.5 percent of the value at the end of a day of normal activities, with most of the change occurring within the first 30 minutes. Zhu et al., using bioelectrical impedance analysis on 11 subjects, reported an approximately 10 percent decrease in leg extracellular fluid volume after 30 minutes of standing following 30 minutes of lying supine [11]. (See the "Discussion" by Conley et al. for a more detailed review of postural change results [10].) These results suggest that removal of the prosthetic socket has a local effect on the residuum akin to a horizontal-to-upright postural change, which may not be surprising because the skeletal muscle is believed to be a major compartmental reservoir for fluid redistribution associated with postural manipulations. This similarity may enable existing knowledge of the physiology of nonamputees to be extended to understanding residuum volume change in amputees.

Based on normal limb physiology, three interrelated mechanisms may account for the net short-term increase in fluid in amputee residual limbs. Pooling of blood in the venous compartment, a first mechanism, is expected immediately upon release of the compression provided by the socket. From a clinical perspective, this mechanism can be reversed quite rapidly by autonomic reflexes and by compression when the amputee pushes the residuum back into the prosthetic socket.

A second likely mechanism is arterial vasodilatation following the release of compression. This effect may be due directly to the release of compression but could also arise due to metabolites that have accumulated in the residuum while the amputee walked approximately

200 meters before being scanned. Like venous pooling, one can reverse the effects of this mechanism at similar rates by reapplying the compression and undertaking an appropriate activity. However, amputees report that the limb becomes looser during intense activity, suggesting that changes in the other compartments (namely dehydration of the skeletal muscle) can be larger than in the arterial compartment.

A final and possibly most complex mechanism to account for the net short-term increase in fluid in amputee residual limbs may be a differential between the rate at which plasma enters and leaves the local interstitial space, leading to an increase in the interstitial fluid volume. The hydraulic conductivity of skeletal muscle is generally believed to be small. For example, Aukland [12] suggests a capillary filtration coefficient (CFC)—the net filtration of 100 g of tissue resulting from a net filtration pressure of 1 mm Hg—for human limbs of 0.006 mL/min/100 g tissue/mm Hg [13]. However, Lundvall and Bjerkhoel suggest that a value of 0.01 mL/min/100 g tissue/mm Hg is more appropriate for dependent limbs [14,15]. They report decreases in whole-body plasma volume of 125 mL (3.2%), 328 mL (8.5%), and 466 mL (11.7%) during quiet standing (respectively, at 1.5 minutes, 3 minutes, and 5 minutes.) The loss of plasma volume was virtually complete at 10 minutes (671 mL, or 16.8%). In our study, total residuum volume increases were comparable, with rates of increase of up to 3 percent per minute at the end of the first minute, and four out of six subjects reached within 95 percent of maximum volume in less than 10 minutes. Surprisingly, the body possesses an almost equally rapid capacity for fluid transfer from the extravascular space to the intravascular space. Lundvall and Bjerkhoel report that within 20 minutes of recumbancy, following 15 minutes of quiet standing, plasma volume was virtually restored, with 50 percent of recovery in the first 6 minutes, and as much as 70 mL (approximately 1.7%) in the first minute [14]. Berg et al. also showed an exponential decay in leg extracellular volume during 120 minutes of bed rest, with the calf showing an initial rapid decrease [9].

Thus the minute-to-minute volume of the residuum within the prosthetic socket is likely the result of a complex interplay between possibly rapid volume control mechanisms. That an amputee's clinical history alone may not be an adequate predictor of residual limb swelling is of little surprise, then. For example, in the present study both Subject 4 and Subject 5 showed large volume increases, 9.5 and 10.9 percent, respectively. While the

increase for Subject 4 might have been anticipated since he was only 9 months postamputation, the increase for Subject 5, an amputee for 40 years using a PTB design with a single cotton sock, would not. Subject 5 did not complain of any problems related to volume change and was physically very active. Yet, based on the magnitude and rate of volume increase seen here, one would expect that his PTB socket would become loose during normal use as the swelling of the residuum was reversed. Either the subject was insensitive to volume changes or, for cultural and social reasons, he did not draw attention to them.

Similarly, no differences were seen in any of the measured quantities between users of TSB and PTB sockets. While long-term shape and volume change are likely to be affected by the pattern of stress distribution caused by differing socket styles, it is not clear if they will have similar effects on the short-term shape and volume change. In this regard, the hydrostatic stress on the gastrocnemius (the largest muscle group in the residuum) when in the socket may possibly be a determinant of the change in short-term fluid volume. This concept awaits experimental investigation.

Fernie reported that the thickness of a 5-ply sock was 1.25 mm, and that two 5-ply socks was the maximum acceptable volume change before a new socket was warranted [7]. Radius changes of 1.25 mm and 2.5 mm translate to approximately 4.1 and 8.2 percent volume changes for the subjects in the present study. Lilja and Oberg report that "one stocking," causes a volume change of 5.2 percent and "two stockings," 9.4 percent [2]. They also report that Swedish prosthetists would consider three stockings unacceptable. Volume changes of 8.2 percent (Fernie) and 9.4 percent (Lilja) are at the upper end of the range of volume increase in our study. However, amputees who adjust sock ply to control residuum volume within the course of the day are more likely to change the sock thickness by 1 to 2 ply, rather than 5 to 10 ply. Donning a one-ply sock translates to approximately 0.83 percent volume change for the subjects in the present study (assuming a thickness of 0.25 mm for a one-ply sock). Recall that of the five subjects who showed clear trends in volume increase, four reached 95 percent of the predicted volume change within the first 8 minutes. These subjects were within 0.83 percent (or one ply) of their final volume within 6.5 minutes. This would suggest that for these subjects, the faster mechanisms of fluid movement are responsible for the bulk of the volume change on socket removal. The fifth subject

(Subject 2) reached 95 percent of maximum volume at approximately 41.6 hours in session 1 and 54.5 minutes in Session 2. For session 2, the residuum was within 0.83 percent of the final volume at 22.5 minutes. Of all the subjects in the study, only this subject reported having difficulty donning the socket on waking in the morning. The subject reported putting on the prosthesis in the morning with just a nylon sheath, changing to a one-ply wool sock after about 30 to 60 minutes. Data from the subject's second session predict that he swells to within one ply of his final volume at only 25 minutes. If the reverse mechanism happens at a similar rate, then this might explain why he needs time to settle into his socket. This variation from the pattern shown by the other subjects might point to potential existence of subpopulations based on the rates of fluid movement.

The mechanisms of fluid movement just discussed would need to be investigated rigorously to understand their roles in residual-limb volume change. However, if further research showed that a range of behaviors existed based on the rate of residuum swelling, then this information would be useful to the clinician while educating patients on the magnitude and timing of volume changes to expect and appropriate sock management to compensate for them. A simple clinical test would be needed to help locate patients within the continuum of behaviors seen. Our data suggest that mid-limb circumference measurements taken recumbent, and at 1 and 10 minutes after sitting up, when combined with a comparable socket circumference, might provide enough data to characterize the magnitude and time course of volume increase. For casting, results from our study suggest the clinician should wait at least 8 minutes after socket removal for the residuum to approach its maximum volume, especially given the uncertain drying time of casting materials. The time interval, however, might be different for dysvascular patients. Consistent time points are similarly necessary when the residuum is cast under hydrostatic pressure. Only if such care is taken will the clinician be able to ascertain if the patient was prone to day-to-day fluctuations in limb volume that might affect socket fit. In our group of six amputees, only one subject (Subject 5) showed such fluctuations. The volume increases seen in this subject had not been clinically anticipated, possibly because the subject's ability to bear significant weight on the distal surface made him insensitive to socket loosening.

None of the subjects in our study had an amputation for a dysvascular reason, therefore no comparisons between traumatic and dysvascular residua are possible at this time. However, given the postulated mechanisms of volume change, most likely, dysvascular amputees would differ from traumatic amputees and the conclusions drawn from our study do not necessarily apply to dysvascular patients. Study of dysvascular amputees is needed.

### **Is the Volume Increase Uniform Down the Length of the Limb?**

From a clinical point of view, for the residua investigated in our study, the lack of a longitudinal (proximal-to-distal) trend in CSA increase over time suggests that the thickness of any wool socks that might be needed for volume control on a well-fitting socket should be proportional to the radius at that level. Thus for a residuum with very little taper between the tibial tubercle and the distal end, a uniform thickness sock may be adequate for day-to-day volume control, whereas for a very conical residuum, a sock that became progressively thicker toward the proximal end might be more appropriate. If the socket no longer fits well, possibly because of nonuniform longer-term shape changes related to structural changes in the limb soft tissue, then regional adjustment of socket volume would be needed to compensate for the long-term changes. Such a conclusion, if borne out by further research, would provide relative time scales for designers of technologies for active socket shape control.

Other volume control strategies exist, including air- or fluid-filled inserts positioned between the socket and liner (or socket and limb), as well as a vacuum socket design. Air-filled inserts, intended to replace displaced residual-limb fluid, are typically effective for only a limited range of volume change [16]. This lack of versatility might limit clinical utility. Fluid-filled inserts, because of the relative incompressibility of the fluid, overcome this limitation, and a volume control strategy based on insert pressure has been implemented (Simbex, Lebanon, NH). A suction concept has been developed to try to reduce fluid transport out of the residual limb [1]. However, it is unclear which fluid transport mechanism(s) is affected by the treatment. Appropriate investigation is needed to better understand how all of these products affect residual-limb tissues.

### **Is the Volume Increase on Taking the Socket Off Greater Than the Volume Change in the Limb Between Two Points in Time 2 Weeks Apart?**

The greater increase in limb volume over a 35-minute interval after removing the socket compared with differences 2 weeks apart (five out of six subjects) points to the relevance of short-term changes in clinical practice. When casting, a prosthetist must be aware of how long the patient's socket has been off before casting. The limb volume after a 35-minute wait could be appreciably different from that immediately after socket removal. Basing the measurement to a consistent practice is important.

This result also points to the relevance of intermittent socket removal during the day. For amputees who plan to remove the prosthesis during the day, limb swelling can be appreciable, even if for short periods. It may be difficult to redon the socket, and interface stresses could be affected. Thus, care toward the practice of socket removal during the day and attention to its impact on residual limb health is warranted.

## **CONCLUSIONS**

Optical scanning can be used to quantify residual swelling on socket removal and is comparable in accuracy with other noncontact methods of volume measurement. Further improvement in accuracy requires the elimination of residual tremors. Results from this preliminary investigation provide a starting point for characterizing TT residual volume and shape change.

### **What Is the Magnitude of Volume Increase, What Is Its Time Course, and How Long Does It Take to Stabilize?**

In our study the TT residual swelled up to approximately 11 percent in volume, or approximately 20 mm in circumference, when taken out of the prosthetic socket. The rate of swelling was largest in the first few minutes, and decreased with time, following an exponential relationship for most subjects. The median time to reach 95 percent of volume change was 7.1 minutes.

### **Is the Volume Increase Uniform Down the Length of the Limb?**

No consistent proximal-to-distal trends were seen in volume increase, suggesting that prosthetic socks with thickness proportional to radius at that level may be ade-

quate for within-the-day volume control for well-fitting sockets.

### **Is the Volume Increase on Taking the Socket Off Greater Than the Volume Change in the Limb Between Two Points in Time 2 Weeks Apart?**

For most residual, the magnitude of swelling on socket removal was greater than 2-week changes in initial volume. Different patterns of swelling of the residuum may exist in the amputee population, and clinical history may not adequately predict the pattern of swelling. Measurement of the circumference of the socket and residuum (recumbent and dependent at 1 minute and 10 minutes) may provide a simple method to characterize the pattern of swelling for amputees. Standardization of the posture/pressure and time points for clinical quantitative measurement of the residuum is warranted by the initial rapid rate of volume increase. An understanding of the dominant mechanisms of fluid movement into and out of the residuum and their corresponding rates, in conjunction with the individual amputee's ability to adjust for these, may contribute to improved patient education and socket fabrication and adjustment.

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