Department of Veterans Affairs

Journal of Rehabilitation Research and Development Vol. 37 No. 4, July/August 2000
Pages 383–387

A device for applying static loads to prosthetic limbs of transtibial amputees during spiral CT examination

Mark T. Madsen, PhD; John Haller, PhD; Paul K. Commean, BEE; Michael W. Vannier, MD
Department of Radiology, University of Iowa, Iowa City, IA 52242; Mallinckrodt Institute of Radiology, Washington University, St. Louis, MO 63130

Abstract—This paper describes a device that allows the imaging of prosthetic legs under load conditions using spiral computerized tomography (CT). The device consists of a chair and a vertical footplate mounted on a 17.8×1.9 cm oak board that is 197 cm long. The load device can be easily positioned onto the CT bed. A subject sits in the chair and applies force by pushing the foot portion of the prosthesis against the footplate. The magnitude of the force is monitored by a digital force gauge coupled to the footplate. Because the load is borne by the hips and lower back of the subject against the chair, substantial forces can be generated and steadily maintained for the 20–45 s duration of the CT study. This device has been used successfully with 19 transtibial amputees, allowing the acquisition of spiral CT studies with half and full body weight loads.

Key words: *loading device, prosthetic fit, spiral computerized tomography (CT), transtibial amputation.*

INTRODUCTION

This paper describes a device that allows the imaging of prosthetic legs (i.e., prosthesis socket) and leg residuum under load conditions using spiral computerized tomography (CT). Current methods of designing and evaluating prosthetic legs are more art than science. Although prosthetists have accumulated significant experience when fitting prostheses for persons with lower-leg amputation, there is still a significant failure rate. Because of the expense represented by both the prosthesis and the time lost by the subject suffering the effects of a poor fit, methods for improving prosthetic fit are important. A number of different imaging modalities have been used to evaluate prosthetic fit (1–6). Spiral or helical CT provides a high resolution, 3-D image of the residuum and prosthesis (7–10). The advantages offered by spiral CT are most useful when the prosthesis can be imaged under weight-loaded conditions. This presents a challenge because CT scanners are constrained to have subjects positioned horizontally. Several other loading devices have been described that attempt to overcome this problem. Commean et al. used a harness arrangement in which the stress of the force applied to the prosthesis was borne by the shoulders (9,11). A strain gauge viewed by the subject with a hand-held mirror was used to provide feedback so the subject could keep the force in the desired range. This device has several limitations because it requires a fair amount of setup time and a cooperative subject, physically able to exert and bear required forces without moving during the imaging procedure. Another loading device, designed for applying a load to a diabetic patient's foot, uses a stationary seat and an adjustable flat board against

This material is based on work supported by NIH 5R01 HD30169-05, Institute of Child Health and Human Development, National Institutes of Health, Bethesda, MD 20892.

Address all correspondence and requests for reprints to: Mark T. Madsen, PhD, University of Iowa, Department of Radiology, 200 Hawkins, Iowa City, IA 52242; email: mark-madsen@uiowa.edu.

which to press the foot (12,13). The seat allows the subject to sit in the spiral CT scanner, apply a known load to the foot, and read from a digital scale. The limitation of this device is that the seat is not adjustable.

In order to overcome the above-mentioned limitations, a new loading device has been developed. This device has a number of significant advantages over previously described systems. It has a comfortable, adjustable chair that allows the subject to sit during the imaging and allows the force to be borne comfortably by the hips and lower back. The chair can also be adjusted to the left or right, to center the prosthesis in the CT field of view. The subject pushes against an aluminum footplate that can also be adjusted for comfort. The footplate is directly coupled to a digital force gauge that provides accurate monitoring of the force developed during the imaging and also provides visual and auditory feedback to the subject.

METHODS

A schematic of the device is shown in **Figure 1**. The device consists of a chair and a vertical footplate mounted on a 17.8×1.9×197 cm (width×thickness×length) oak board. The chair is mounted to an aluminum bar that allows the chair to be centered or positioned 10 cm to either the right or the left of center, allowing either leg to be centered in the field of view of the CT machine. The chair configuration is mounted to the oak board via a slotted uni-strut member 61-cm long that permits the positioning of the chair along the long axis of the board. The prosthetic loading device fits directly onto the CT table. Two 15×40 cm boards are mounted at right angles to the axis of the long board for stabilization and to eliminate any side-to-side tipping.

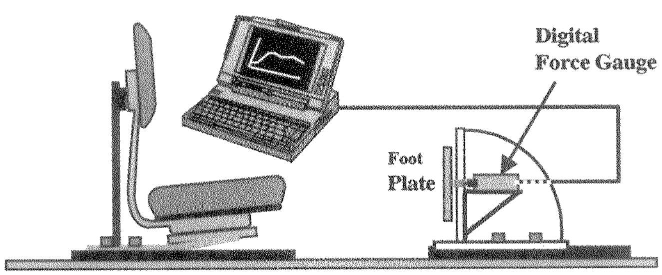

Figure 1.
Prosthetic load device. The subject sits in the chair and pushes against the footplate to apply force to the prosthesis. A digital force gauge coupled to the footplate monitors the applied force.

A vertical aluminum footplate is mounted to the opposite end of the board from the chair using a pair of 46-cm long uni-strut members that permits the positioning of the plate along the long axis of the board. The subject pushes against the aluminum footplate, which is coupled to a securely mounted digital force gauge (Imada DPS 220, Imada, Inc., Northbrook, IL) with a dynamic range of 0–1,000 N with 0.2 percent precision. The RS232 output from the digital force gauge is connected to a laptop computer programmed to sample and archive the output from the digital force gauge every 0.5 s. The program provides visual and auditory feedback to the subject so that the subject can maintain the desired force during the imaging.

The subject applies force by pushing the foot portion of the prosthesis against the footplate. Because the load is borne by the hips and lower back against the chair, substantial forces can be generated and steadily maintained for the 20–45 s duration of the CT study. For our research, the applied load is determined by the subject's weight. Spiral CT studies are acquired with no load, and with loads equivalent to one-half and the full body weight of subjects (not exceeding 1,000 N). Prior to the setup of the CT study, the desired load is entered in the computer program, which also samples the load signal from the force gauge. When the subject attains the target value and is confident that such force can be maintained, the CT study is begun. During the scan, the subject can view the computer screen that displays the current measured load. In addition, the computer emits a repeated beep while the measured force is in the acceptable range.

Nineteen subjects have been scanned to date on a high-speed spiral CT scanner (Aquilion™, Toshiba America Medical Systems, Inc., Tustin, CA). The imaging parameters were 5 mm collimation with a 15 mm/s table speed and 120 rpm for a pitch of 1.5. The axial field of view was approximately 25 cm, extending from the tip of the residuum to just above the knee. The average scan duration was 20 s. Images were reconstructed every 1 mm into 512×512 with a pixel size of 0.4 mm.

RESULTS

Figure 2 shows pictures of the completed device positioned on the CT table. As can be seen, the subject can sit comfortably while applying and maintaining the required force on the prosthesis. The chair geometry has been carefully designed so that the vicinity of the leg-

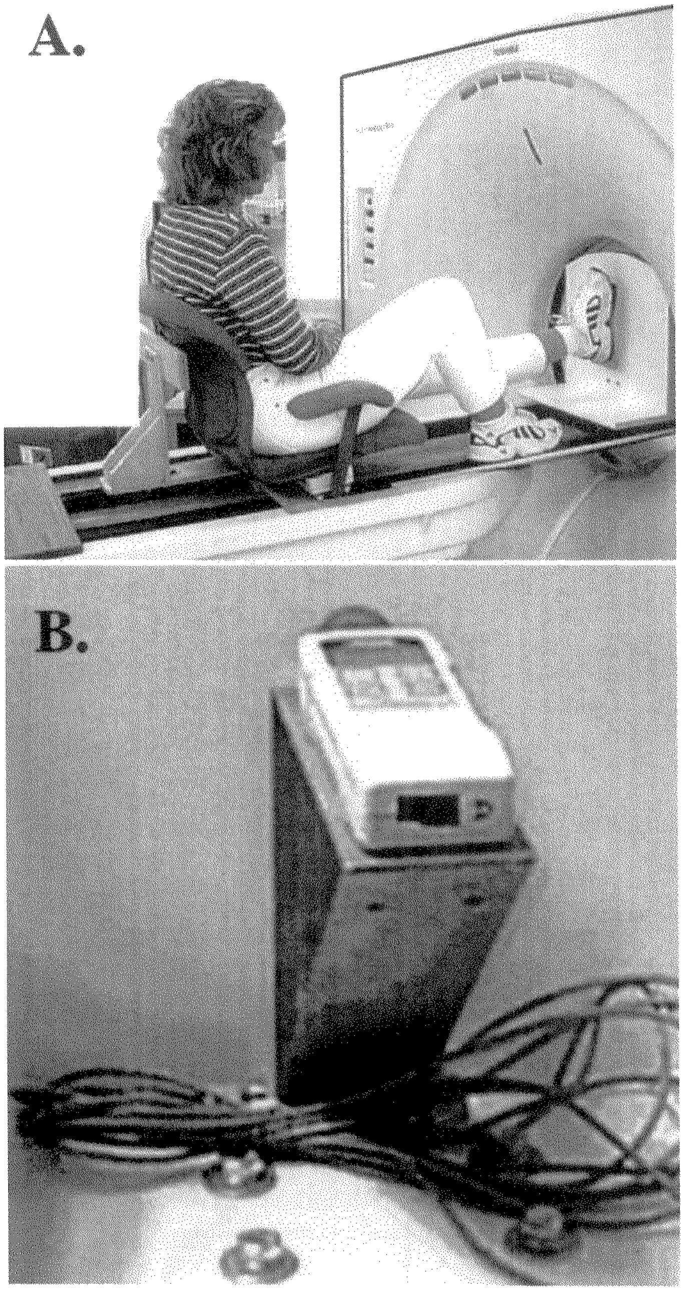

Figure 2.
Photographs of the prosthetic loading device. A. The apparatus is positioned on the CT table, allowing the residuum to be scanned under load. B. Close-up photograph of the digital force gauge.

prosthesis interface can be easily scanned without the subject impacting the gantry. To date the device has been used by 19 different subjects with transtibial amputations. In each case, the subject was able to achieve the target load comfortably and to maintain that load throughout the imaging study. **Table 1** summarizes the forces applied by subjects. **Figure 3** shows the digital force gauge output from several of the subjects. These plots verify that the subjects can maintain a constant pressure throughout the duration of the study even when the load approaches full body weight. **Figure 4** shows sagittal and coronal images along with a radial deformation plot of a residuum under no load and with an applied force of 490 N. It is expected that comparison images such as these will be useful in deriving objective measures of prosthetic fit.

DISCUSSION

Spiral CT produces high-resolution 3-D images of the body. It is a useful imaging modality for investigating prosthetic fit. The following advantages are realized with CT: it is widely available, it has high spatial resolution (better than 1 mm) and it reveals 3-D information about the prosthesis and the internal tissues of the residuum. The device described in this paper allows realization of the full potential of spiral CT imaging for evaluating prosthetic fit by providing the means to apply and maintain meaningful force loads. Most of the installed spiral CT units require approximately 30–40 s to acquire the volume that encompasses the residuum and prosthetic

Table 1.
Subject height, weight, and applied force.

Subj	Height	Weight	Force 1	Force 2
1	203	107	550	900
2	160	48	250	500
3	180	114	550	950
4	185	118	600	--
5	180	701	350	700
6	180	95	475	950
7	182	68	340	680
8	178	90	450	900
9	164	71	350	700
10	160	110	550	950
11	173	75	375	750
12	180	107	750	--
13	183	95	480	950
14	178	61	300	600
15	188	100	500	950
16	170	89	450	900
17	183	109	550	950
18	188	107	500	950
19	190	79	390	790

Subj=subject; height in cm; weight in kg; applied Force 1 and Force 2 in N.

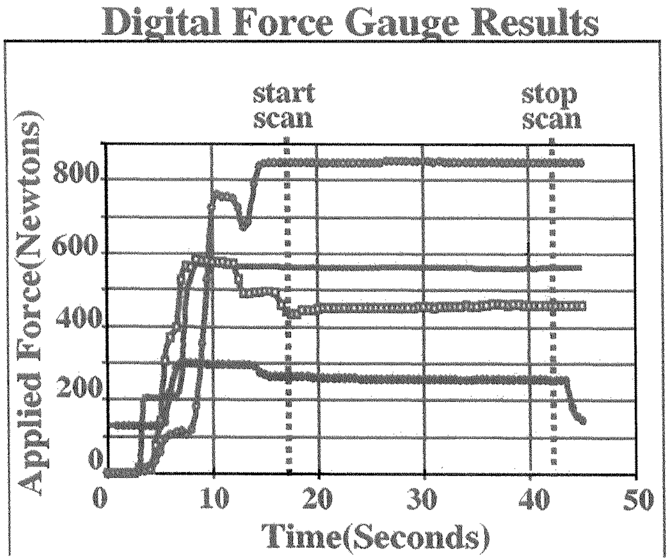

Figure 3.
Applied force data from sample studies. The plots show the stability of the applied force during the CT studies. The dashed vertical lines delineate the scanning interval.

device. Because the residuum must remain essentially motionless during the scan interval, it is necessary to have a loading device that allows the application of large loads in a stable fashion. The apparatus described in this paper is just such a device.

There is continued progress being made in CT imaging. New CT scanners already commercially available are able to reduce the scan acquisition time by a factor of 2 while increasing the axial sampling (14,15). These CT scanners will allow imaging protocols that are not currently attainable. For example, it is conceivable that fast imaging sequences will be able to image the residuum while loads several times larger than the body weight are sustained. This will more closely approach the dynamic forces encountered during ambulation than the current static force measurements. We have noted that many subjects in our study did in fact generate loads that exceeded their body weight while attempting to get within the target range.

CONCLUSIONS

The apparatus described in this paper provides a practical way to study and evaluate lower-limb prosthetic devices under realistic loading conditions. This device can be easily adapted to perform more sophisticated loading protocols as CT imaging systems evolve.

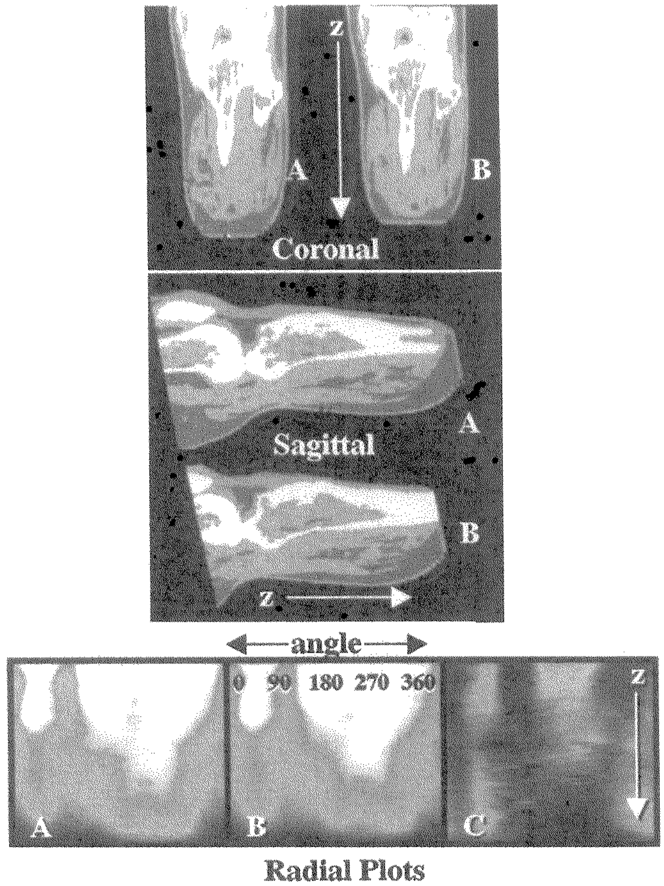

Figure 4.
Tomographic evaluation of prosthetic fit. The upper images show coronal and sagittal views of a residuum under (A) no-load and (B) full body weight loading. The lowest row of images shows radial plots from the same limbs aligned in the same orientation as the coronal slices. The radial distance from the centroid of each transaxial slice of the residuum to the surface is represented as a grayscale level under no-load (A) and full body weight (B) conditions. The radial samples are plotted at 1-° intervals. The far right panel (C) contains deformation information derived from the difference of the no-load and full body weight load conditions (C=A−B). The grayscale ranges from 0 mm to 32 mm in images A and B and the grayscale range is −15 mm to 15 mm for image C.

REFERENCES

1. Irwin GA, Friedman L, Shapiro D. Prosthetic fit in below-knee amputation: evaluation with xeroradiography. AJR Am J Roentgenol 1987;148:99–101.
2. Newton RL, Morgan D, Schreiber MH. Radiological evaluation of prosthetic fit in below-the-knee amputees. Skeletal Radiol 1988;17:276–80.
3. He P, Xue K, Chen Q, Murka P, Schall S. A PC-based ultrasonic data acquisition system for computer-aided prosthetic socket design. IEEE Trans Rehabil Eng 1996;4:114–9.

4. Bocobo CR, Castellote JM, MacKinnon D, Gabrielle-Bergman A. Videofluoroscopic evaluation of prosthetic fit and residual limbs following transtibial amputation. J Rehabil Res Dev 1998;35:6–13.
5. Douglas TS, Solomonidis SE, Lee VS, Spence WD, Sandham WA, Hadley DM. Automatic segmentation of magnetic resonance images of the trans-femoral residual limb. Med Eng Phys 1998;20:756–63.
6. Fergason J, Smith DG. Socket considerations for the patient with a transtibial amputation. Clin Orthop 1999;361:76–84.
7. Commean PK, Smith KE, Cheverud JM, Vannier MW. Precision of surface measurements for below-knee residua. Arch Phys Med Rehabil 1996;77:477–86.
8. Smith KE, Commean PK, Vannier MW. Residual-limb shape change: three-dimensional CT scan measurement and depiction *in vivo*. Radiology 1996;200:843–50.
9. Commean PK, Smith KE, Vannier MW. Lower extremity residual limb slippage within the prosthesis. Arch Phys Med Rehabil 1997;78:476–85.
10. Commean PK, Brunsden BS, Smith KE, Vannier MW. Below-knee residual limb shape change measurement and visualization. Arch Phys Med Rehabil 1998;79:772–82.
11. Commean PK, Smith KE, Vannier MW, Szabo BA, Actis RL. Finite element modeling and experimental verification of lower extremity shape change under load. J Biomech 1997;30:531–6.
12. Mueller MJ, Smith KE, Commean PK, Robertson DD, Johnson JE. Use of spiral computed tomography and plantar pressures for management of neuropathic ulcers in patients with diabetes. Phys Ther 1999;79:296–307.
13. Smith KE, Commean PK, Mueller MJ, Robertson DD, Pilgram T, Johnson J. Assessment of the diabetic foot using spiral computed tomography imaging and plantar pressure measurements: a technical report. J Rehabil Res Dev 2000;37(1)31–40.
14. Taguchi K, Aradate H. Algorithm for image reconstruction in multi-slice helical CT. Med Phys 1998;25:550–61.
15. Hu H. Multi-slice helical CT: scan and reconstruction. Med Phys 1999;26:5–18.

Submitted October 14, 1999; accepted December 23, 1999.