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TECHNICAL REPORT

A digitizer with exceptional accuracy for use in prosthetics research: A technical note

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Abstract—A mechanical digitizer was developed for use in prosthetics research where measurements of small differences in shape are of interest. Root-mean-square error was 0.075 mm in the radial direction, 0.05° in the tangential direction, and 0.1 mm in the vertical direction. The system has potential use for time-dependent assessment of changes in socket and residuum cast shape, assessment of socket fabrication systems, and development of accurate prosthetic finite element models.

Key words: amputee, prosthetic cast, residual limb, socket shape.

INTRODUCTION

Digitizers and optical scanners are devices used to measure the shapes of plaster casts or molds made during the design of prosthetic sockets for persons with amputated limbs. Essentially, there are three types of commercial products:

1. Mechanical: A mechanical arm rotates around the inside of a cast or the outside of a mold, with mechanical or electromechanical sensors to monitor tip position so that the locations of contact points can be calculated (3XL, Active Life Sciences, Flint, Michigan; d1L, Seattle Systems, Inc., Poulsbo, Washington). The cast or mold shape is reconstructed after the entire surface is scanned. The best radial resolution of commercial mechanical instruments is 0.4 mm.
2. Optical: An optical laser imager projects planes of laser light onto a mold while digital cameras record the shape of the curve of light as it hits the surface (CANFIT-PLUS Optical Cast Digitizer, VORUM, Vancouver, British Columbia; AK/BK Scanner and Orthotic Scanner, CAPOD, Kariskoga, Sweden; BIRIS Laser Profilimeters, Clynch Technologies, Calgary, Alberta, Canada; Orten, Lyon, France; 3000 Scanner, Seattle Systems, Inc.). The best radial resolution of commercial optical instruments is 1.0 mm. Alternatively, a one-dimensional (1-D) laser imaging system can be used and positioned on an arm near the mold or within the cast where a line of laser light is projected onto the surface and the position of the dot recorded (Laser Imager, BioSculptor, Hialeah, Florida; CANFIT-PLUS Optical Cast Digitizer, VORUM). Reconstruction algorithms are used to establish the mold or cast shape. The best resolution of commercial 1-D optical instruments is also 1.0 mm.

Abbreviations: LDT = linear displacement transducer, RVDT = rotational variable differential transducer.

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3. Electromagnetic: An electromagnetic handheld device contacts the surface of interest, moving within a specified electric field (Premier System, TracerCAD, Boca Raton, Florida; Virtual Casting, BioSculptor; Handheld FreeScan Scanner, CAPOD). As it is moved over the surface, the magnet serves as a sensor within the electric field. The position of the sensor in 3-D space is then calculated. The best radial resolution of commercial electromagnetic instruments is 0.76 mm. However, manufacturers of another device that operates on a similar principle (Polhemus, Colchester, Vermont) report a resolution of 0.5 mm, though use of this product in prosthetics applications has not been reported.

Though current digitizers and scanners are used with current prosthetic socket computer-aided fabrication systems, they are not of sufficient accuracy for clinical research applications where the location of shape change is of interest. It is claimed that residual limb volume changes as low as 5 percent can detrimentally affect socket fit [1]. With a 90-mm diameter residual limb and a uniform expansion, this volume change corresponds to a radial alteration of 1 mm. If different casts from different time points are to be compared, for example, or if two socket designs with very subtle shape differences are to be compared, then a resolution of less than 0.5 mm is necessary. Such a system would allow the location and magnitude of local shape changes to be determined.

This technical note describes a new digitizer with improved resolution over current commercial products. The design meets the needs of prosthetics research applications where changes in shape are of interest.

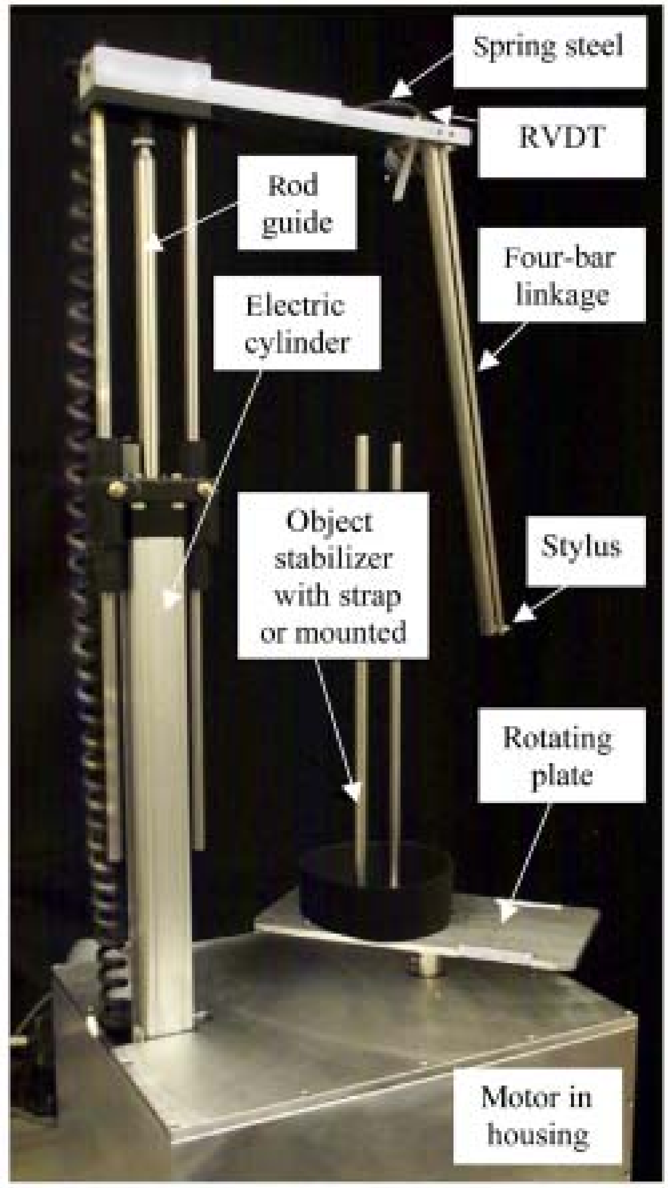

Figure 1.
Digitizer. Object to be digitized is mounted on rotating plate and strapped in place. Stylus on four-bar linkage contacts object surface (socket, cast, or mold).

DIGITIZER DESIGN

The major components of the digitizer are a servomotor (Compumotor model SM232, Rohnert Park, California), a servoelectromechanical cylinder with a linear rod guide (Parker-Daedal model ETB32, Irwin, Pennsylvania), servocontroller (AT-6250, Compumotor), a rotational variable differential transducer (RVDT) (Schaevitz model R30D, Hampton, Virginia), a linear displacement transducer (LDT) (BTL-5-A/C/E/G1-M457-R-S32, Balluff, Florence, Kentucky), a four-bar linkage, and a stylus (**Figure 1**). The digitizer uses a full contact method; that is, the stylus is always in contact with the object being digitized. The radial, angular, and vertical positions of the stylus with respect to the socket are recorded.

The socket is connected to the servomotor via a split coupling that has different mounting capabilities (e.g., straight post or mounting platform for assembled prostheses). The servomotor uses an encoder (angular precision of 0.045°) for position feedback control and angular position data (**Figure 2**). The vertical position is controlled

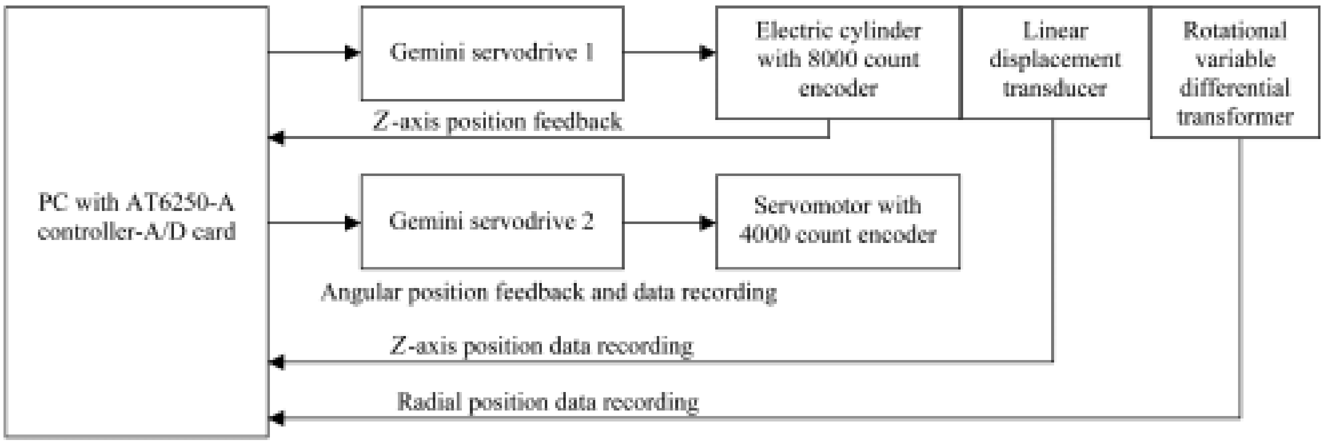

Figure 2.
Block diagram of digitizer controller. Based on data from radial, angular, and vertical position sensors, PC sends appropriate signals to servodrivers for accurate rotational and vertical positioning of stylus relative to object being digitized.

with a positional feedback servoelectromechanical cylinder. The vertical position data are recorded with the use of an LDT mounted between the base of the electromechanical cylinder and the cylinder piston.

Attached to the top of the piston is the RVDT and four-bar linkage-mounting arm. This arm provides a fixed position for the linkage and is designed so that the center of rotation of the stylus is directly over the center of the servomotor shaft. It acts as the ground arm of the four-bar linkage. Two rods of the linkage are attached via Vee-Jewel pivots, with the pivot on the front rod connecting directly to the RVDT and providing an angular measurement for the rod. The angular measurement is converted into a radial displacement of the stylus. The stylus is the fourth link of the four-bar linkage, connecting to the rods with Vee-Jewel pivots. The entire system is designed so that the stylus remains horizontal despite the angular rotation of the linkage. The contact point of the stylus is a 3.175 mm diameter sapphire ball (sphericity 0.000635 mm), the smallest size available commercially for which a stable holder could be accurately machined. The Vee-Jewel pivots and sapphire balls were used in this application for their resistance to wear and low coefficient of friction (0.05 on steel, 0.01 on sapphire). A 0.54 mm thick piece of spring steel is mounted at the top of the four-bar linkage (**Figure 1**) to ensure a consistent force is applied from the stylus to the socket.

For prosthetic casts or residual limb molds to be digitized, a different setup was used. A precision gearhead is put on the servomotor to offset its axis of rotation (**Figure 3**). The major components of the gearhead are the input and output shafts, drive gear, driven gear, and precision bearings. The gearhead-input shaft (which is pressed into the drive gear) connects directly to the servomotor shaft via the split coupling. The output shaft (which is pressed into the driven gear) has the same mounting capabilities as the system without the gearhead. The gearhead is designed with a 1:1 ratio so that no precision is lost from the angular position. The total offset of the rotational shaft is 8.89 cm. Because the gears are rotated in only one direction, backlash is not a problem.

Voltage signals from the RVDT and the LDT are input to the PC (personal computer) with a 14-bit analog-to-digital (A/D) board (OPT-AT6250-A, Compumotor) and recorded with the use of a custom algorithm (Labview, National Instruments, Austin, Texas). Angular output

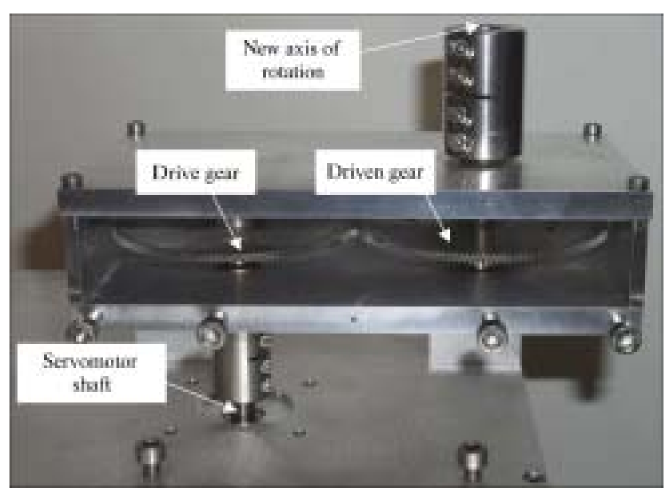

Figure 3.
Gearhead. Gearhead offsets motor axis so that residual limb molds can be accurately digitized.

signals are recorded directly with the AT6250 controller. The theoretical precision of the RVDT is 0.00968°/bit. With a four-bar arm length of 441.5 mm, the digitizer thus has a radial precision of 0.07459 mm/bit. The LDT has a theoretical precision over the entire vertical range of 0.05579 mm/bit.

CALIBRATION AND EVALUATION

We fabricated an aluminum cylinder with three different internal diameters that attached directly to the motor shaft as a calibration object. The radii of the steps were 25 mm, 75 mm, and 120 mm, with a tolerance of 0.076 mm. We developed transformation equations to convert the three digitizer outputs—servomotor, electromechanical cylinder, and RVDT positions—to spatial cylindrical coordinates using the following 14 calibration parameters: scaling coefficients and offsets on the three outputs, 3-D rotation and translation of the servomotor axis with respect to the RVDT axis, radius of the four-bar linkage, and offset of the stylus. The following four parameters do not affect the precision of the digitizer and were therefore arbitrarily set to zero: calibration offsets on the electromechanical cylinder and the servomotor, rotation of the RVDT coordinate axes about the servomotor axis, and the axial coordinate of the RVDT reference point. The factory calibrations of the servomotor and electromechanical cylinder were verified as being within tolerance and were thus used as supplied. The remaining eight parameters were determined within an optimization routine that minimized the difference between the known shape of the calibration object and the transformed digitizer outputs. The results of the optimization confirmed that the factory calibration of the RVDT and the fabrication and assembly of the digitizer were well within tolerance. No systematic trends were observed in the residual error, which had a mean of zero and standard deviation of 0.05 mm.

To evaluate the performance of the digitizer, we scanned a test object in different orientations. A right circular cylinder with unknown surface roughness and eccentricity was positioned in the digitizer so that it was visually well aligned with the servomotor axis. Three scans were performed. The object was then removed, flipped 180°, then rescanned three times. It was then translated approximately 1.5 cm and rescanned twice. Next, it was titled approximately 20° and rescanned twice. For each of the 10 scans, the radius of the cylinder was computed from the reconstructed object. Consistency in the shape measurement among the scans was assessed. The mean radius was 46.75 mm (standard deviation of 0.076 mm). The radius of the cylinder as measured by a digital vernier caliper was also 46.75 mm. Root-mean-square error was 0.075 mm in the radial direction, 0.05° in the tangential direction, and 0.1 mm in the vertical direction. The time for digitization was 60 s/slice for the resolution settings just described.

To illustrate performance of the digitizer on a socket, we digitized a laminated patellar-tendon-bearing socket of a transtibial amputee at a vertical spacing of 1.0 mm. Then a 47-mm diameter disc was cut from a Pelite sheet, feathered and smoothed, and then attached in the fibular head region to the inside of the socket with adhesive insulation tape. The socket was then digitized again, and the shape difference between the modified and unmodified socket was determined and superposed on the original socket shape. Results showed measurable differences in shape only at the Pelite patch location (**Figure 4**).

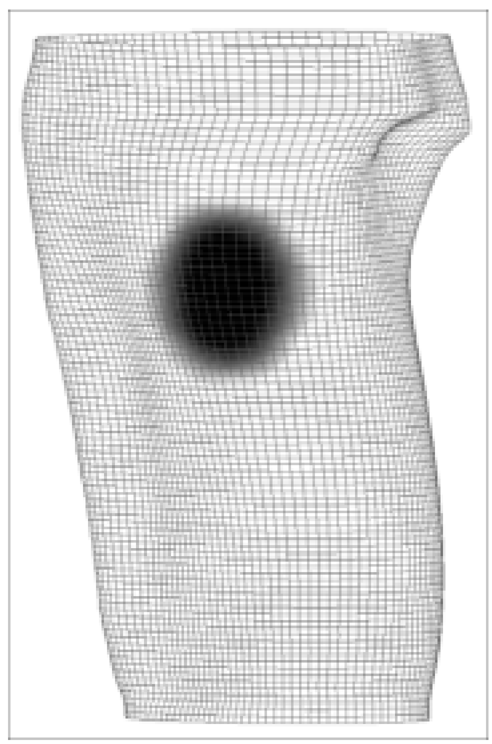

Figure 4.
Socket-shape modification. Shape difference between a socket with and without a 47 mm diameter Pelite insert over fibular head. Scale ranges from no difference (white) to 5 mm (black).

DISCUSSION

The system described here was created to provide an exceptionally accurate digitizer for prosthetic research application purposes. The improvement in resolution over existing systems was achieved through several novel design features. A four-bar linkage for the stylus arm eliminated torsional rotation and bending in the rod and kept the stylus horizontal, thus reducing positioning error. Vee-Jewel pivots reduced friction so that a consistent force was applied from the stylus to the socket. Precision controllers with closed-loop position feedback control were used to ensure that the rotational and vertical displacements of the socket were accurate.

A system with this accuracy is needed for prosthetics research where measurement of subtle changes in socket or mold shape is of interest. If one is to evaluate socket modifications to determine if they overcome a 5 percent volume change [1], for example, then a socket-shape measurement system with less than 0.5-mm resolution is needed. If prosthetics research demonstrated that these subtle socket-shape modifications significantly enhanced socket fit and performance, then use of more accurate digitizers in clinical practice would be warranted. Use of highly consistent casting procedures would also be suggested.

Computational models developed to predict interface stress distributions for different socket shapes have been substantially enhanced in recent years [2–4]. Potentially, these models can be used as tools for prosthetic socket design. However, computational model development is still in its developmental stages, and for correlations between experimental and analytical results to be improved, accurate input data (e.g., socket shape) are needed.

While a number of commercial socket fabrication systems are on the market, their performance in a quantitative sense has not been compared. The system described here would allow such a comparison and further would allow the comparison between the resolution of the software packages for socket design and the resolution of manufacturing systems. If the latter were substantially lower than the former, then concentration on enhancement in manufacturing methods would be appropriate.

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