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Measuring the shape and volume of an above-knee stump

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Abstract

A set of design criteria for sensing the shape of an above-knee (AK) stump is presented and used as the basis for evaluating various shape sensing technologies. A mechanical probe type shape sensing system is described and its use in quantifying the external shape of the AK stump is discussed as it relates to generating a grid for finite element analysis in CAD/CAM studies and comparing the segmental volumes of the loaded and unloaded stump. This study also discusses a method that uses circumferential measurements to compute total and incremental volumes of the stump.

Introduction

Quantifying the surface topology of an object is the first step in numerous processes ranging from making topographical maps to making coins and artificial parts for the body. Each application has its own requirements for accuracy, precision, and surface smoothness. To satisfy such diverse requirements, a number of techniques have been developed (Foort and Pentland, 1975; Zuniga et al, 1978; Karara, 1979; Duncan et al, 1980; Rongo and Gallios, 1981; Saunders, 1982; Diels and Fontaine, 1983; Saunders and Vickers, 1984). New applications for these techniques have met with varying degrees of acceptance. Before the most effective technology can be selected, the investigator must carefully delineate the required results. Sensing the shape of an amputee's stump requires a measuring system that can collect the necessary data before the amputee tries on a prosthesis. Furthermore, this system must provide data that are at least as precise as the data currently collected by a prosthetist.

Technologies that have been applied to quantifying the shape of an amputee's stump can be classified into two basic groups: contacting and non-contacting sensors. In the first category are the laser-based measuring systems and stereophotogrammetry (Zuniga et al, 1978; Karara, 1979; Rongo & Gallios, 1981; Beiser, 1983; Yamashita et al, 1983; Fernie et al, 1985), while the second includes mechanical probes (Zuniga et al, 1978) and ultrasonic systems that require the leg to be immersed in water. The devices in the first category generally provide very fast data collection (2–5 seconds), but require a mainframe computer to transform the data into useful information and a room large enough to accommodate the often bulky equipment that is needed to do the measuring. Moreover, when stereophotography is used, the space available in many prosthetics shops may be inadequate. The other performance characteristics of the measuring systems that fall into the first category are well-documented (Karara, 1979; Beiser, 1983; Yamashita, 1983; Saunders and Vickers, 1984). The devices in the second category generally require less space for operation and less computing power to create useful information, but they require substantially more time to capture the data (4–7 minutes). This data capture time requires that the subject be stabilized so that the limb segment does not move; taking simultaneous diametrically opposed readings can help reduce the effects of slight motion of the limb. Large motion artifacts can be detected during the data collection and used to signal the operator that the data must be recaptured. If efficient data transformation algorithms are used, the information generated using instruments from this category can be available for clinical use as quickly as that generated using instruments from the first category. A second issue that limits the utility of contacting shape sensors is

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the deformation produced when the probe touches the tissue; however, by using capacitance sensitive switches to contact the tissue, the deformations can be kept to less than 0.01cm.

The objectives of this study are to develop a sensing system for measuring the shape and volume of the loaded and unloaded stump of AK amputees and to analyse the relationship between the form of an AK socket and the volume distribution of the socket and stump.

Criteria for designing a shape sensing system

In designing a contact-type shape-sensing apparatus, it is imperative to consider a number of traditional electronic design parameters. The linearity of the potentiometers or Linear Voltage Dispacment Transformers (LVDT) used has to be examined and assessed in the design. When the voltage output from these devices is to be buffered and/or amplified, the offset error, maximum nonlinearity, and gain error must be considered in a worse-case-analysis to ensure that the final design remains within the constraints of the original specifications. When the system logs the data digitally, the analog to digital (A to D) converter needs to be selected by considering: 1) the least significant bit uncertainty error (assuming the utilization of the full dynamic range of the converter), 2) offset error, and 3) the speed of conversion to assure that the required data acquisition rate can be achieved. Position encoders may be used instead of LVDTs or potentiometers provided that the maximum resolution of the encoder is considered and the maximum rate of change in position does not cause counts to be missed; this is particularly important if these counts are logged by the microprocessor. Stepper motors can also be implemented in the design, assuming that the system can accurately remember the actual position of the probe. Mechanical linkages need to be minimized to reduce inaccuracies in the system, which could lead to significant uncorrectable errors.

By working with several prosthetists, it has been possible to determine a set of criteria that the shape sensing system must satisfy if it is to match the stump characterization which is generated using a plaster wrap and tape measure. The criteria are:

1. The shape sensing process should take no more than seven minutes to collect the required data.
2. The measurements should be precise enough to match the current circumferential measurement error of ±0.64cm. This requirement means that radial distances must be accurate to ±0.1cm.
3. Vertical "z" measurements should be accurate to ±0.25cm.
4. Measurements should be reproducible within two per cent.

Methodology

Shape sensing instrumentation

The contourgraph (Fig. 1), a robotic device for sensing AK shapes, is one instrument designed to satisfy these criteria. This device is designed to take advantage of the overall cylindrical features of the body segment. The hardware is schematically illustrated in Figure 2. It utilizes a stepper motor attached to a base to drive a set of sensing heads in the theta and minus theta circumferential directions. The sensing heads read the radial distance from calibrated reference points. The "z" axis information is generated by a counter that logs the number of "next z" toggles that have

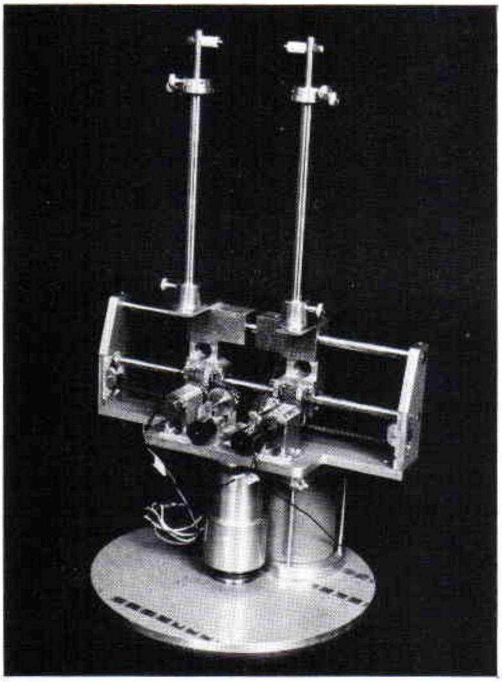

Fig. 1. The automated shape sensing instrument.

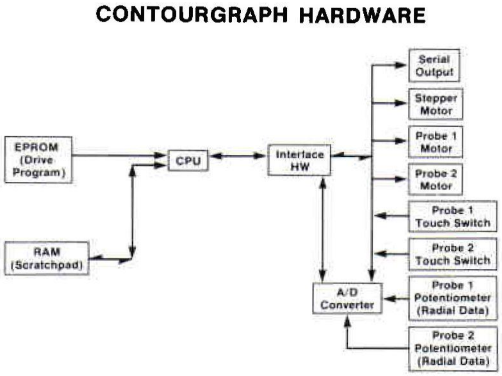

Fig. 2. Contourgraph operation schematic.

occurred; one is required for each data acquisition plane. The "z" levels are generated manually by moving the sensor head antennae to the next elevation.

The data acquisition is controlled by software that is charted in Figure 3. The radial information is generated by the sensor heads contacting the tissue. The sensor heads are driven by geared DC motors, which are pulsed by a microprocessor. The sensors are capacitance-touch switches coupled to two of the computer's interrupt lines so that when one of the sensors encounters the leg, it generates an interrupt signal. This signal causes the processsor to call a subroutine to brake both motors, log the radial position of the sensor causing the signal, restore registers as needed, and return to drive the remaining motor until the sensor driven by it contacts the limb. This motor is then braked and its radial position is logged. Braking is an important step in the process, since it affects accuracy of the data. It is achieved by using an infrared coupled triac driver and triac that is tied across the terminals of the DC motor. The processor pulses the appropriate motor output port, which activates the triac to short the terminals together. This halts the motor in less than 0.003cm of travel.

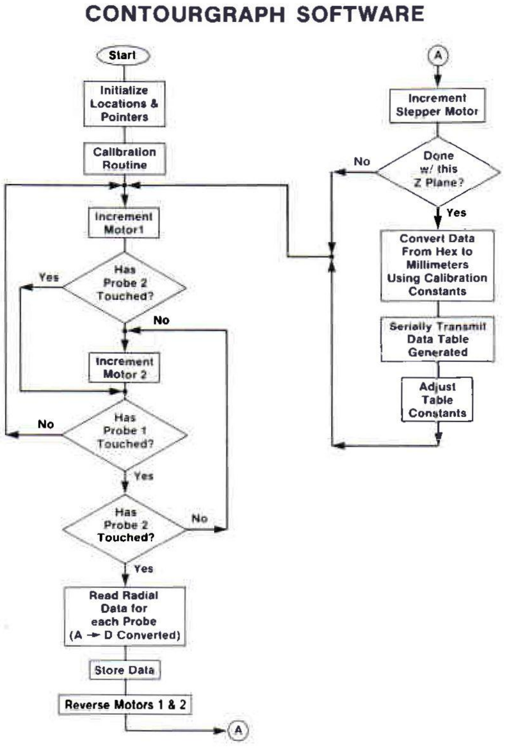

Fig. 3. Control software for shape data collection.

The radial information is provided by sensing the voltage level generated at the wiper of a potentiometer that is gear-coupled to the motor-drive mechanism. This potentiometer output (0.03% linearity) is buffered by an operational amplifier and fed to a multiplexing device to permit multiple analog inputs to the microprocessor. The processor selects which channel it desires to interrogate and initiates a 10 bit analog-to-digital converter to encode the signal. The information is then stored in memory for later calculations.

In this system, an integral calibration routine sets maximum and minimum radial measurements. Using a set of precision cylinders, the system measures their diameters and logs the radial endpoints. The differences between the endpoints are then stored in the processor as constants that are used to calculate an adjustment factor for the stump data as they are collected. This process is necessary to account for changes in the mechanical adjustments that are made as part of the premeasurement setup procedure; this calibration scheme also compensates for variations in voltage offsets and gains.

Theta direction data are logged by counting the number of pulses sent to the stepper motor that drives the carriage. Due to the gearing between the motor and the carriage, one pulse rotates the carriage 1.25 degrees. This enables the system to conveniently use theta increments of 5, 10, 15, 20, 30, 45, and 60 degrees. However, information every 20 degrees for the AK amputee seems sufficient. Since the system is a two-sensor device, it only needs to travel

180 degrees to characterize a given elevation. When it is ready to move to the next "z" elevation, the processor knows which direction the sensors should rotate, making it possible to collect the required data without developing cable difficulties.

Once a "z" level is complete, the system stops to allow the operator to increment the sensor supports to the next level. During this time, the computer is taking data it just acquired and processing it into a tabular format. This information is then stored or downloaded in serial ASCII form to a viewing device, printer, etc. When this cycle is complete, the user may inspect the data before proceeding to the next elevation. Once satisfied with the data, the user restarts the device by pressing the "next-z" button. If the data are not satisfactory, the user pushes the "redo-z" button and the data are remeasured.

Validation tests

To evaluate the precision and reproducibility of the shape measurements, two tests were performed using the contourgraph as shown in Figure 4. In the first test, an immersion method and the standard prosthetic shop method of tape measuring were compared with the measurements obtained with the contourgraph. A prosthetist marked and measured the circumferences of a series of casts, a procedure normally done by placing the top mark at the level of the ischium and others every 5cm down the length of the stump to the tip, then measuring the circumferences at each level using a tape measure. The total and incremental volumes were then calculated with these circumference measurements. Using the immersion method, the incremental volumes, volumes between two consecutive markings, and the total volume of the cast were determined. This was done by placing a tank inside a larger tank, then filling the smaller vessel with water until it just overflowed. The whole system was then placed on a balance and weighed. After noting the weight of the system, the cast was immersed in the water. The amount of water that overflowed from the inside tank was equal to the volume of the cast. The weight of the overflow water was recorded and its temperature noted. By knowing the density of water at this temperature, the volume of the cast could then be determined. For incremental volumes, five casts chosen at random were tested by submerging them 5cm at a time and weighing the overflow after each submergence.

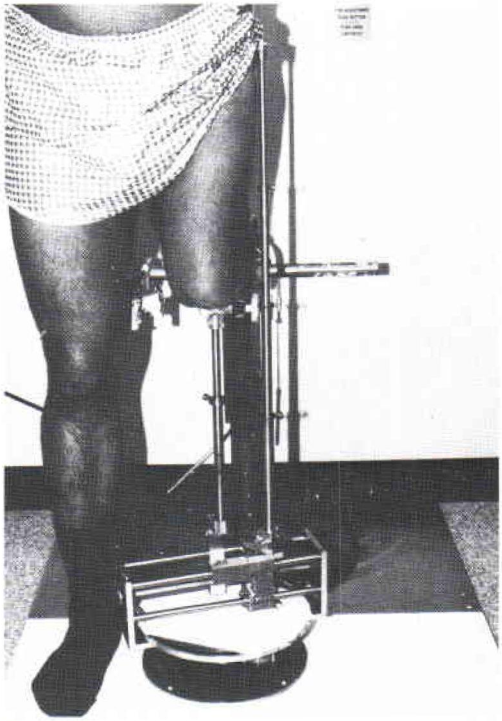

Fig. 4. Contourgraph in use to measure the shape of an above-knee stump.

The procedure for making the shape measurements with the contourgraph was to suspend the plaster cast in a vertical position over the shape sensor. Circumferential tracings were then made at 2.5cm increments, starting at the ischial level and moving down the length of the cast. The areas of the cross sections were then calculated using a planimeter. The circumferences were measured using a small wheel device often used to measure distances on road maps to trace the length around the cross-sectional shape.

In the second test, an attempt was made to evaluate the volumetric differences between the plaster cast, which represented the stump, and the plastic mould of the socket. This was accomplished by measuring the circumferences at marked levels of the casts of five amputees and calculating the total volume by the mensuration formula, as in the first test. Then, plastic moulds of these stumps were made, and after all the holes were covered with tape so that no water could leak out, they were filled with water until they just overflowed. The volume of the water in the mould of the socket was measured with a 5000ml (50ml divisions) graduated cylinder. The volumes of the sockets were then compared with the cast volumes.

These tests demonstrated that the contourgraph produced repeatable shape and volume characterizations of an AK stump that compared well with the measurements made by a prosthetist using a tape measure.

Clinical tests

A series of 100 AK amputees was evaluated to study the shape and volume relations in sockets that were considered to fit well. A good-fitting socket was defined as one that did not produce pain when worn daily for at least eight hours. The subjects used in the clinical tests were AK amputees selected from the amputee clinics in the Baylor College of Medicine Affiliated Hospital Programme and the large reservoir of amputees who have been fitted by Muilenburg Prosthetics, Inc., Houston, Texas. Since the majority of amputees are male, an equal balance between the sexes was not possible. Males made up 90% of the total sample. All subjects were between 18 and 80 years of age. Fifty-four per cent were left-leg amputees, 45% right leg, and one per cent bilateral. Follow-up measurements were made on 80 of the subjects.

Contourgraph characterizations of the unloaded stump and prosthetic socket were obtained when the amputee's prosthesis was initially issued. At sequential intervals, contourgraph measurements were made of the stump to determine the changes in shape and size that had occurred at given cross-sectional levels. This was done by determining the variances of the contourgraph readings.

The procedure for making the measurements was as follows. With the amputee seated or standing comfortably, circumferential measurements of the amputation stump were made at designated and marked levels. To perform the contour tracing of the prosthetic socket, the prosthesis was mounted upside down on an adjustable support. Contour tracings of the inverted socket were made, distal to proximal, at one inch levels corresponding to the stump contour tracings levels. The topographic relationships (anterior, posterior, medial and lateral) and cross-section levels of each stump and socket tracing were identified. The circumference and cross-section levels of each stump and socket were then calculated as in the calibration test. A good approximation of both the stump or socket volume was obtained by using three cross-sectional areas and the linear distance between the consecutive cross-sectional areas.

The data were then represented graphically to show: (a) respective stump and socket volume distribution curves, (b) socket-stump volume differences, and (c) variations of stump or socket volumes at sequential intervals.

Results and discussion

The results of the tape mensuration technique and the immersion technique are given in Figure 5.

When the direct mensuration technique was employed, the total volume of the cast was obtained by adding each incremental volume approximated by equation 1:

$$V_i = \frac{h}{12\pi}\left(C_k^2 + C_j^2 + C_kC_j\right) \qquad (1)$$

where h is the thickness of the increment, C_j is the circumference of the top cross section and C_k is the circumference of the bottom cross section.

In this case, an additional volume had to be added to the sum of the incremental volumes to account for the tip of the stump. To calculate the volume of the tip portion, the tip was assumed to be a section of a sphere, and the following formula was used to approximate it:

$$V_t = \frac{\pi h^3}{6} + \frac{hC^2}{8\pi} \qquad (2)$$

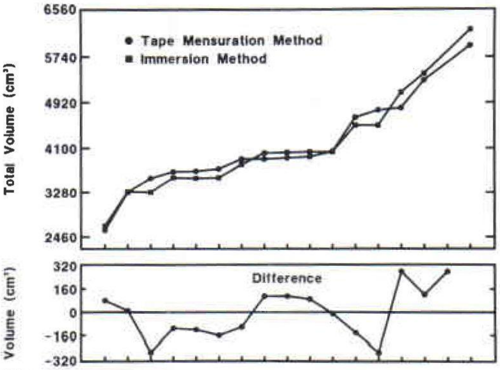

Fig. 5. Results of tape mensuration and immersion techniques.

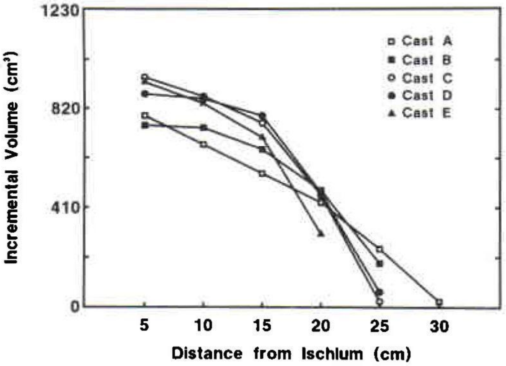

Fig. 6. Comparison of incremental volumes of casts.

where h is the thickness of the tip increment and C is the circumference of the top cross section of the tip increment.

Figure 6 depicts the volume distribution for the casts as a function of the distance from the ischium. The trend in this figure shows an elevated level at 15cm from the ischium. This is attributed to the residual build-up of water in the outside tank for casts B through E, since the outside tank was dried only half-way through each measurement. The drying of the outside tank in the case of cast A was done after the 20cm mark. The mean of the differences in the volumes measured by the immersion method and the tape mensuration technique was 10 cubic centimetres, with a standard deviation of 185. The incremental volumes were also analysed and the results are shown in Figure 6.

The results of measuring the casts of the unloaded stumps and corresponding sockets are shown in Figure 7. This figure shows the volume distribution in increasing orders of volume. The differences between the socket and cast volumes, approximated by two different methods, indicate that the overall difference is less than 0.1%. This implies that the immersion method and the tape measurement method predict the volume with the same accuracy. The results of comparing the contourgraph measurements to the other two measuring techniques are shown in Figure 8. As can be observed in this figure the three methods of measuring the stump volume are within 3–6% of each other. In one stump (number 4), all three measurements gave a large difference. In this case, the AK amputee was at his second fitting and his stump was swollen and very soft. When the amputee was being measured with the contourgraph, he was unable to hold his stump steady. The great variation possible in the measurement implies that the amputee must be very steady during the measurements.

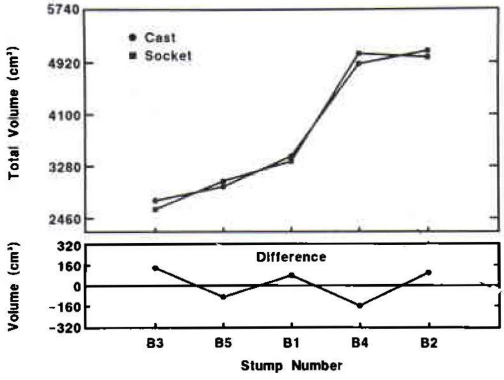

Fig. 7. Comparison of cast and socket volumes.

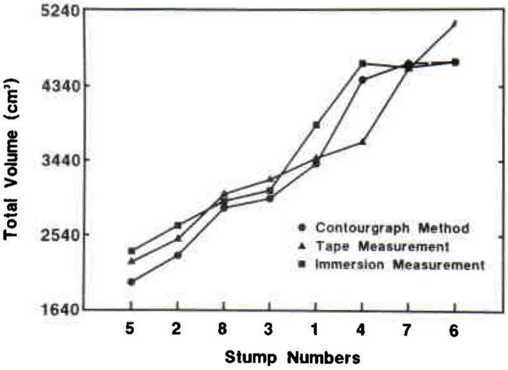

Fig. 8. Contourgraph results compared with tape mensuration and immersion measurement techniques.

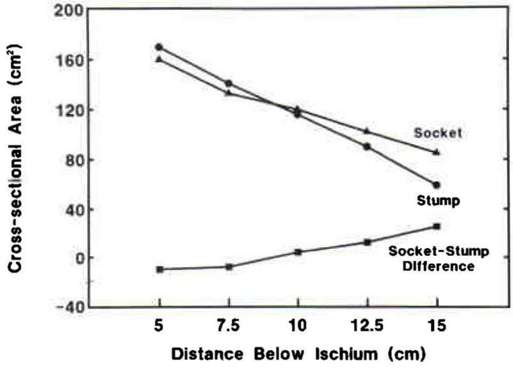

Fig. 9. Typical results with well fitting socket.

The clinical data were analysed. Typical results for the stump-socket volume relationship found with sockets that fit well are given in Figure 9. Reproducibility of the measurements within 1% was obtained using the contourgraph. A 0.25% – 1.0% variation of socket volume difference was also obtained. Variation of stump volume difference was found to be 1.5% with an amputee seated and leaning forward compared to an amputee seated upright.

Conclusions

Based on the results of this study, the following conclusions have been drawn:

1. When used by a trained operator, the contourgraph is capable of producing stump measurements that are as precise as those made by a trained, experienced prosthetist.
2. The contourgraph is able to produce reliable, reproducible data.
3. There is a relationship between the volume distribution of the AK socket and the stump and socket fit. The proximal 30% of the socket must have a volume between 5–8% less than the corresponding unloaded stump for a good fitting socket.

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