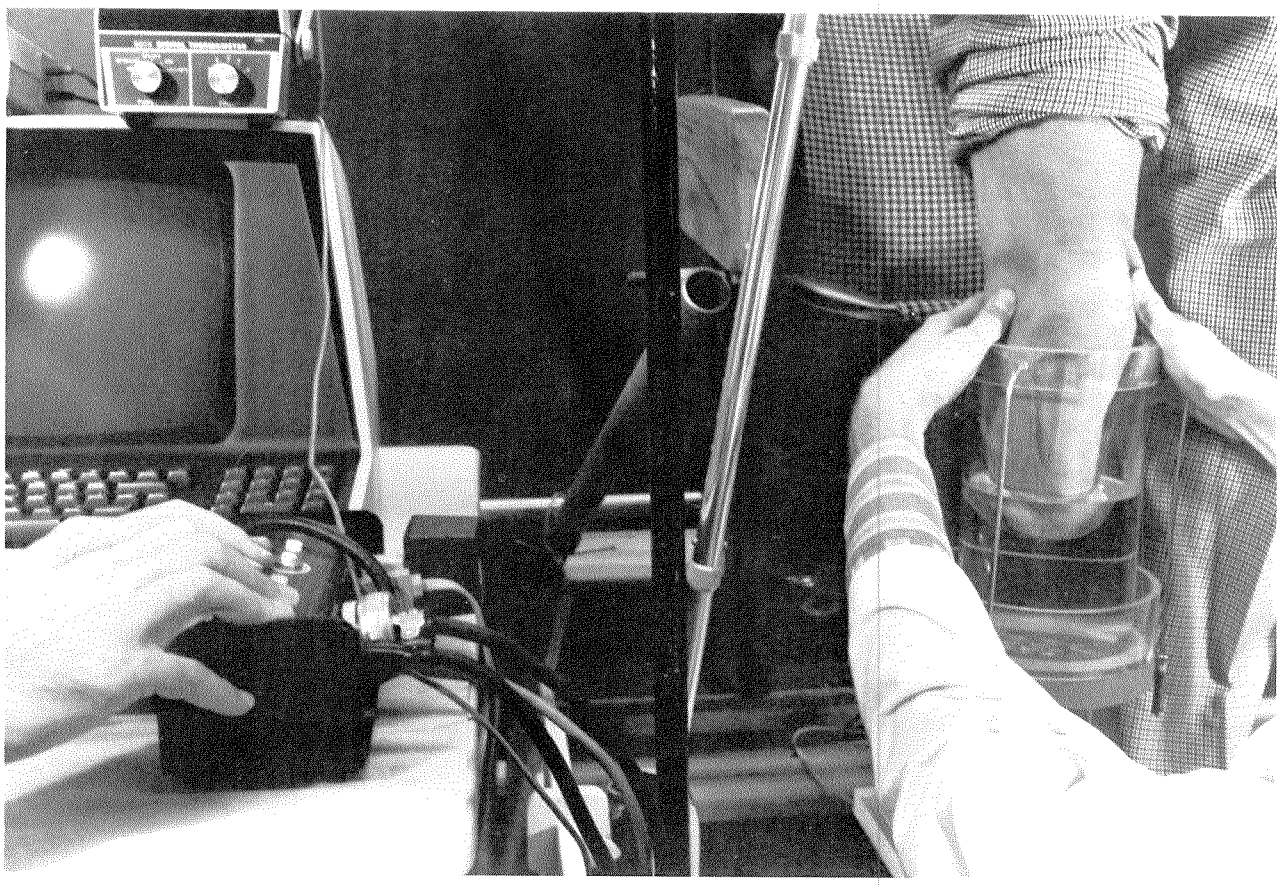

FIGURE 1.
Patient measurement process.

A Computerized Device for the Volumetric Analysis of the Residual Limbs of Amputees

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ABSTRACT

Prosthetics Research Study has developed a computerized automated system for the volumetric analysis of the residual limbs of amputees. Basically, this system utilizes the same principles as does normal, clinical fluid displacement volumetric analysis, with the addition of the following — if an object is suspended in a vertical cylinder into which water is being injected at a constant rate, then the rate of rise of the water will vary proportionally, at any point, with the cross-sectional area of the object.

In this system, water is pumped into a Plexiglas cylinder of appropriate size so as to immerse a residual limb within a time frame of under ten seconds while a microcomputer records the water depth as a function of time.

The rate of water depth rise is recorded for 256 levels during a measurement. These results are then analyzed comparatively, on a level-for-level basis, with similar rates generated with fluid pumped into the empty cylinder, thus generating 256 discrete cross-sectional-area parameters. These are then processed (in groups of eight) into 32 actual cross sections and displayed, graphed, or stored for purposes of comparison.

Possible clinical application for this kind of device includes measurement of edema and other extremity volume changes with time, and measurement of muscle activity related to axial movements of muscle bulk.

SYSTEMS EXAMINATION

To translate water depth into an appropriate electronic signal, this system uses an unbonded strain gage driven by a 1 psig diaphragm located at the base of the measurement cylinder. (See Figure 3.) This is coupled with a specially designed high-gain differential amplifier and bridge excitation source. Features which compensate the output signal for changes in the bridge excitation,and which allow for adjustment of the zero point, are included. The signal then passes through a low-band-pass filter and into the computer's analog-to-digital converter. It is then processed, and stored in a memory buffer. Computer and visible associated hardware are shown in Figure 4.

To initiate the measurement process, water in a large Plexiglas cylinder (Fig. 2 and 3) is brought to a predetermined temperature, depth, concentration of chlorine [a] (see Ref. 9), and density. During measurement, a precision, positive-displacement, gear-type pump operating from a stabilized voltage source pumps the water through an orifice and then through unrestrictive passageways to the measurement cylinder (Fig. 3). Flow, as defined by the equation $Q = C\ A\ 2\sqrt{gh}$ (Ref. 4), varies at most with the square root of any head change. Inlet to this pump is maintained at a high positive pressure and can be turned off with a hand-operated ball valve. A centrifugal exhaust pump operating in conjunction with a solenoid valve completes the water system, returning the water to the reservoir cylinder after each measurement.

The entire system is multiply grounded through one of two hospital-grade ground fault interrupt devices (5 mA GFI's) which help to protect the patient.

Prior to measurement, patients climb by means of retractable steps to an elevated seat for examination (Fig. 1). This seat then rolls up to the measurement apparatus and locks, providing a place to sit and dry the residual limb between measurements. Patients can be seated or can stand with crutches during measurement. (Crutch height and measurement cylinder height are adjustable.) Measurement cylinder diameter can be varied (to minimize the annular space between limb and cylinder) by choosing the appropriate one of a family of Plexiglas measurement cylinders for use with each particular patient (Fig. 5).

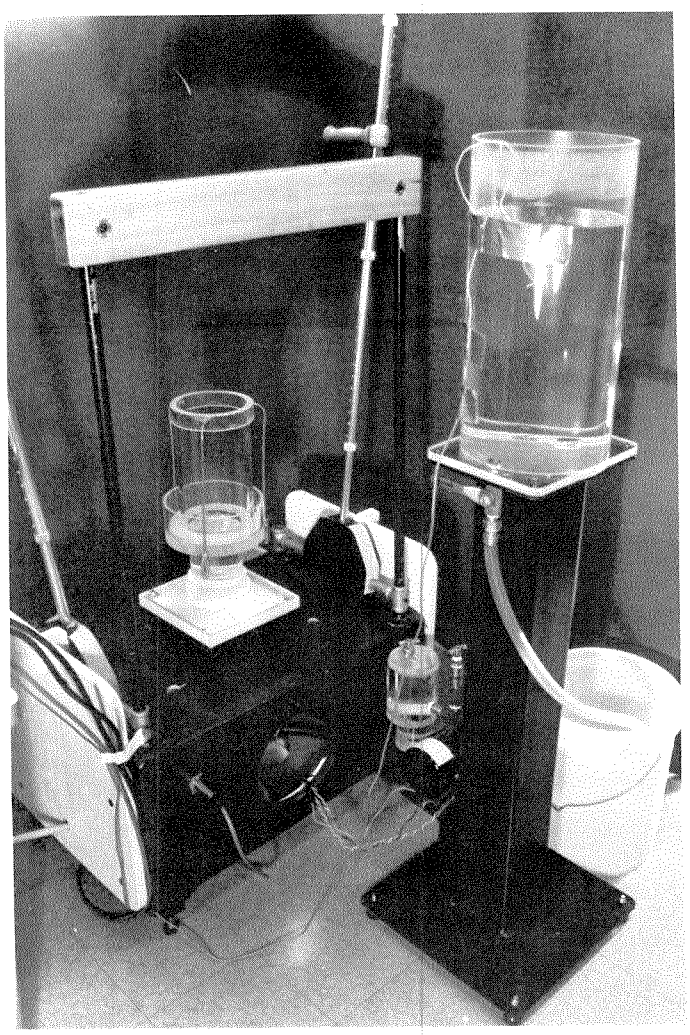

FIGURE 2.
Measurement apparatus showing reservoir, measuring cylinder, and adjustable crutches.

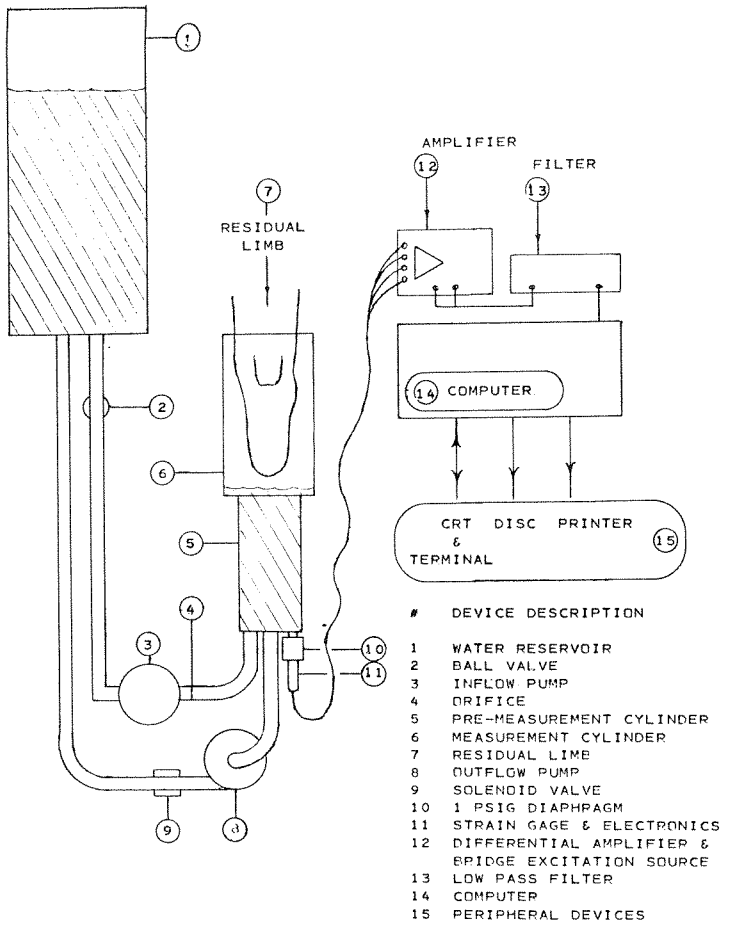

FIGURE 3.
System diagram

Different parts of this system are subject in varying degrees to minor inaccuracies stemming from non-linearity, hysteresis, thermal drift, sensitivity, and gain-stability-related parameters. To the extent that these are not eliminated by component design, they must be accounted for in the calibration and measurement procedures, as delineated in the next section.

MEASUREMENT PROCEDURE

Prior to measurement, the computer program goes through a checklist, as follows. The system (including the pump, electronics, and water) must be at operating temperature prior to measurement. Water depth and chlorine concentration must be correct. There must be a

[a] Chlorine is employed to protect subjects against transfer of infections.

minimal concentration of air suspended in the water. The upper and lower limits of the computer's range of water-level measurement must be noted, to eliminate amplifier gain-drift effects on segment thickness. A final check of residual limb dryness, water temperature, and zero-water-level output voltage is made before each run.

Three empty-cylinder runs comprise the first half of the system baseline dataset. These are followed by any number of residual limb measurement runs. Measurements corresponding to different states of the residual limb (i.e., resting state and contracted) are always interleaved, both to cancel ongoing system changes and to allow a maximum resting period between runs with contracted muscles. With a stable patient, three or four measurement runs have been found to be sufficient. An unstable or tremorous residual limb necessitates more measurements — sometimes 5 to 6 — to allow motion errors to be effectively removed from the data. When all measurements are completed, three final system baseline dataset runs are made (for a total of 6) and the range of water depth calibration is rechecked.

DATA PROCESSING PROCEDURE

As the water increases in depth, it passes consecutively through all of the analog-to-digital converter's 256 levels. A value for the length of time spent at each level is created and stored in a memory buffer by the computer. The value is accurate to approximately one ten-thousandth of a second or less than .004 cm^3. Recording commences automatically when the water leaves the lowest level and ceases when the topmost level is reached. After each measurement, the computer processes the data into the correct format for later processing and analysis in the BASIC language and stores it on floppy disc. (The measurement process itself is accomplished with assembly language programming.)

Further analysis consists of seven steps through which the dataset must be processed to arrive at its final form. The first step conglomerates the six system baseline dataset runs into average, range, and standard deviation files of 256 elements each. The average file then generates a normalization file by which all files are multiplied to remove repeatable non-linearities. Measurement files are then processed individually to locate distal contact in each. This is determined from the point of greatest slope discontinuity in each file. Post-distal-contact data are then compared on a level-for-level basis, with the system baseline dataset utilizing the following relationship:

CSA = cross-sectional area

t(1) = time spent at a particular level during limb measurement

t(2) = time spent at the same level with the cylinder empty

The relationship is:
CSA (limb) = CSA cylinder x (1-(t(1)/t(2)))

This generates a value for the limb cross-sectional area every (approximately) .8 mm. If segment volumes rather than CSA's are desired, then each CSA is multiplied by the amplifier gain calibration factor for level thickness. For all data this parameter serves to locate the individual CSA's with respect to the distal tip of the residual limb.

The format for final data display consists of (a maximum of) 32 limb segments, each comprising 8 contingent analog-to-digital converter levels. This format facilitates interpretation of the data and enhances accuracy. Consecutive measurement files are displayed concurrently and a standard deviation value is calculated for the difference between consecutive measurement files at corresponding limb levels. To create this standard deviation value, the dataset is normalized and the resulting dataset, (comprising typically about 95 entries, 95 deviations and one average) is used to generate a global S.D. in percentage form. A new corrected average file is then generated, using only those values occurring within(±) one standard deviation of the uncorrected average for each limb segment. This process is undertaken to eliminate stray values in the data caused by patient motion during measurement.

Final cross-sectional or volumetric data can then be listed

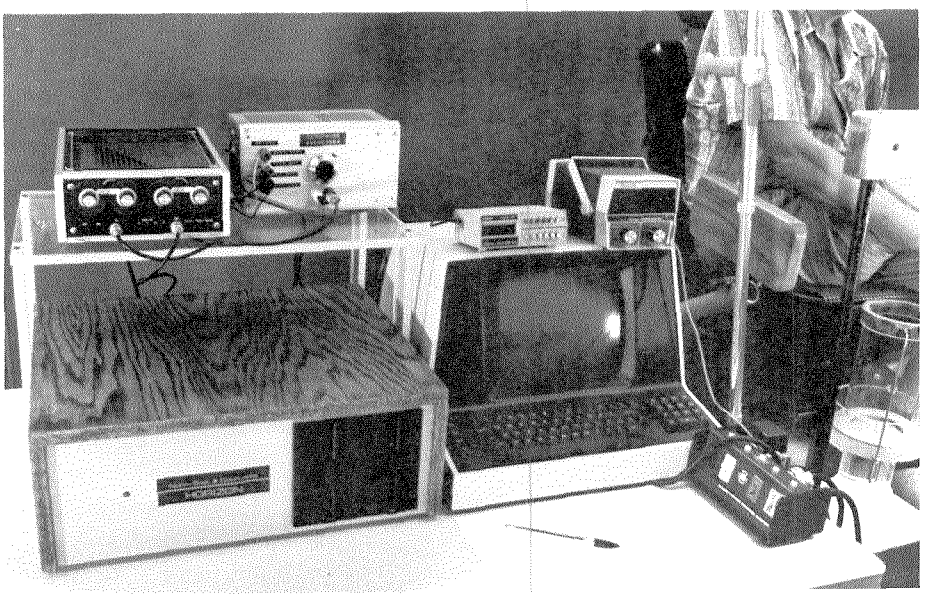

FIGURE 4.

Computer, terminal, bandpass filter, differential amplifier, voltage display, temperature display, control switches and recording form (in front of keyboard). Subject can be seen at right behind one of the adjustable crutches: the Plexiglas measuring cylinder appears at extreme lower right.

out as hard copy, graphed on the systems printer, and/or stored on floppy disc for later comparison.

Programing which displays and graphs the data can realign the distal tips of the measurement curves. It also provides a feature whereby the total volumes of two measurements can be normalized so that the differences in their patterns can be observed alone.

TABLE OF RESULTS

Table 1 represents the measurement accuracies attainable in measuring both human beings and various types of inanimate objects — geometric cylinders, a quiescent irregular shape which is a replica of a limb, and the patient's limb with tremors and irregular vertical motion. It also shows the improvement in accuracy which the data undergoes throughout the data processing procedure.

Reaveraging of the data remaining within the final data envelope produces final data sets for each object or subject being measured. The system achieves its highest accuracy in the measurement of regular cylindrical bodies, but still produces final data in the greater than 98 percent range for the exaggerated irregularities found in the plastic residual limb replica. Accuracy can be seen to increase as the ratio of cylinder size to measured object cross section decreases. (This holds true up to the point where meniscus interference begins to occur.) There is also a component of inaccuracy related to the rate of head change which affects the pump rate. This component is being dealt with as described in the refinements section.

CONCLUSIONS

It has been found to be possible, using the described system, to measure the cross-sectional areas and/or segmental volumes of the residual limbs of below-knee amputees to an accuracy of approximately 98 percent. It has been found further that, despite precautions, the greatest part of the inaccuracies involved stem from motion on the part of the patient during measurement. (This

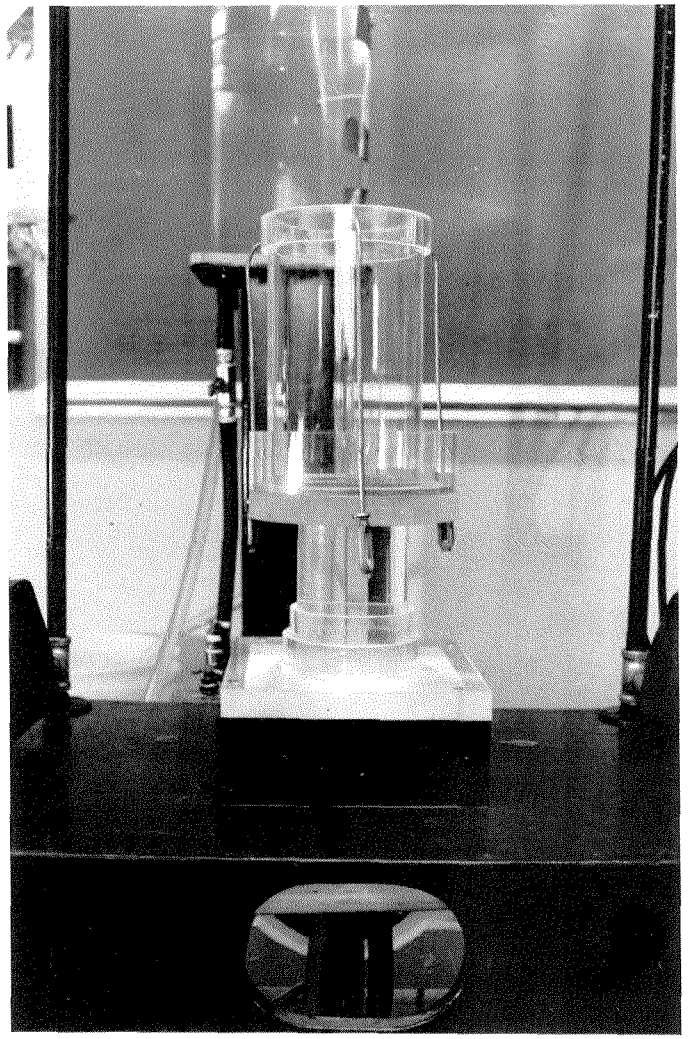

FIGURE 5.
Height-adjustable portion of measurement apparatus shown with five-inch ID Measurement cylinder in place. Pressure measurement cell can be seen below (through access hole).

TABLE 1. — Results

Object or Subject	Measure. Cylinder Size (cm^2)	Average Object or Subject Size over Measure. Range (cm^2)	Average Cross Sectional Area of Water Remaining (cm^2)	Average Range Within Which Consecutive Measurements Occur (Percent)	Final Data Envelope Size (Percent)
Cylinder	114	81	33	0.240	0.232
Cylinder	103	81	22	0.491	0.402
Cylinder	103	46	57	0.767	0.611
Replica [a]	103	66	37	1.505	1.305
Patient 3	81	61	20	4.5	2.3
Patient 1	114	76	38	6.0	2.4
Patient 2	114	75	39	9.5	3.7
Patient 4	103	58	45	4.8	2.1

[a] Indicates a plastic residual limb model

system was found to be able to measure some inanimate objects to an accuracy of greater than 99 percent.)

These patient motion-induced inaccuracies have been limited by the use of consecutive measurement runs which are then processed together for the removal of stray data. Inaccuracies stemming from other sources were limited through the use of a bracketing baseline dataset and through the use of other procedures as described in this paper.

Further refinements to the system, as described in the refinements section, will serve to exert further control on motion, repeatability, and linearity-based inaccuracies.

REFINEMENTS

The following refinements to this device are underway. Despite our efforts, patients did exhibit an unacceptable degree of motion during measurement. In order to thoroughly remove this artifact from the data, an underwater LVDT (Linear Variable Displacement Transformer) is being incorporated into a float-type distal-tip-motion sensor. Data from this device will be processed as is water depth data, and stored, for use in correcting final data. The use of relays will enable total software control of pump and valve operation. Longer measurement cylinders will be used to enable measurement of longer residual limbs. A faster pump motor (20 percent) is being fitted to decrease the measurement time; this motor is of the synchronous type and will operate from a line conditioner which stabilizes the voltage, removes transients, and provides maximal isolation from power line deviations. This will enhance the repeatability with which pumping takes place — and will also increase the safety factor by increasing the degree of isolation between the system and power line transients.

Finally, it has been found that the capacitors at the input to the A to D converter are too small, the unit being set to be able to operate at 16 Hz, which introduces avoidable fluctuations into the data. Also, a weighted regression type analysis will replace simply dividing the data into 32 segments arbitrarily to further increase accuracy.

ACKNOWLEDGEMENT

I would like to express appreciation to the following persons who have been of invaluable assistance in the pursuance of this project. First is Ted Levake, a professional engineer who, in appreciation for prosthetic services (due to him as a WWII veteran) built our amplifier, which was the first major step in allowing this device to become a reality. Second, Richard Harrington, Research Engineer, Seattle Veterans Administration Medical Center; third, the knowledgeable salespeople and engineering representatives from several companies who provided not only equipment but a wealth of information; and finally, the staff of Prosthetics Research Study for their support.

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NOTE:
The following materials have been provided by Mr. Starr and will be sent upon request to interested readers—

1. A schematic drawing of the differential amplifier and bridge excitation source.
2. A measurement graph of a stepped Plexiglas cylinder and of a typical below-knee residual limb, in relaxed and contracted states. The format of the data presentation is shown.
3. A detailed equipment list of the apparatus described in the preceding pages.

Readers wishing to receive these materials should write to the Editor, Bulletin of Prosthetics Research, Office of Technology Transfer (153-D), Veterans Administration, 252 Seventh Avenue, New York, N.Y., 10001. There is no charge.