Prosthetics and Orthotics International, 1985, 9, 12–16

Shape sensing for computer aided below-knee prosthetic socket design

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Abstract

Shape sensing is useful in the computer aided prosthetic fitting process for two purposes.

1. To input characteristic prosthetic shapes that have been developed over the years through the experience of prosthetists.
2. To provide an accurate and rapid measurement of the anatomical shape of the stump.

This paper describes two instruments which have been built to meet these objectives.

Introduction

The traditional shape fitting process involves two steps: 1) a plaster cast is taken to obtain a replica of the shape to be fitted, 2) the prosthetist or orthotist modifies the replica further by adding and subtracting plaster to generate a different shape which he knows from experience will provide optimal comfort. This process has been simulated by computer aided prosthetic fitting software developed by the Medical Engineering Resource Unit of the University of British Columbia. The current version allows the prosthetist to modify a 'primitive' socket shape on the computer screen to match the individual subject's shape and size. Shape sensing offers the opportunity to enhance this system by facilitating the input of alternative 'primitives' based on studies of hand modified plaster casts. It may also improve precision and speed by replacing hand measurements of the amputation stump by automated high speed shape sensing.

The first task for shape sensing is to "capture" the standard elements of shapes that have been developed over the years for prosthetics and orthotics. For example, in trans-tibial amputee fitting it is important to provide the computer with knowledge of the characteristics of shape of a typical modified cast. Ideally, the computer aided software should be designed in such a manner that prosthetists, orthotists and other users can input their own designs of standard shapes simply and quickly so that this development takes full account of the varied experiences of these many individuals.

Secondly, a shape sensing instrument is required to provide accurate and detailed measurements of the anatomical shape to be fitted. Such shape data would be used as input to the shape modification software and would also be retained as a record of the anatomical shape in order to observe changes with time consequential to the wearing of the device.

Instrument design

A laser beam is directed through a cylindrical lens to generate a line of light that is projected onto the object to be measured. When viewed from an angle, this line of light can be seen to be curved representing the shape of the object that is illuminated. A television camera is used to view the laser light and an electronic circuit determines the intersection of this line with each horizontal scan line of the video image. A total of 240 horizontal lines is used in the video image and therefore 240 numbers are stored by this electronic circuit. The object is rotated and this measurement process is repeated at appropriate intervals in order to generate a full record of the shape. An instrument based on this simple principle has been used to measure plaster casts before and after cast modification as an educational aid for student prosthetists (Fernie et al, 1984).

When measuring the human subject directly, it is necessary to reduce the time required for the measurement to avoid problems caused by

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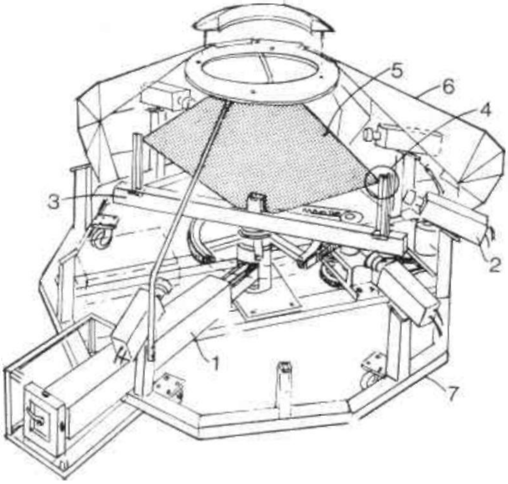

Fig. 1. A simplified sketch showing the layout of the amputee shape sensor.

involuntary movement. The version of the shape sensor for measuring amputee stumps completes the measurement in 600 ms. This is achieved by rotating the laser line around the object to be measured rather than rotating the object as in the simpler machine described above.

Figure 1 shows the configuration of the instrument. The laser projects a line towards the axis of a rotating arm in the centre of the base. This beam is deflected up the axis of rotation and is then split to cause two beams to travel to the opposite ends of the rotating arm. These beams are further reflected up columns at the ends of the rotating beam and through cylindrical lenses which cause lines of light to be projected onto opposite surfaces of the amputation stump. The arm is caused to rotate at a precisely controlled and constant speed of 1 revolution every 1.2 seconds. Each camera captures 8 sets of data. Thus the 9 cameras provide 72 sets of data at 5° intervals around the stump.

For optimum sensitivity the angle between the projected laser line and the viewing camera should be 90°. However, this angle would cause portions of the projected line to be obscured from the view of the camera where the line would be hidden in concavities. Consequently, it is necessary to reduce this angle and a range of 40–60° has been found to be appropriate for stump measurement. As the line of light rotates, the electronic control circuitry selects cameras that are appropriately positioned. In fact, each camera records 4 frames of information at 5° intervals beginning when the light reaches an angle of 60° from the camera and finishing when it reaches an angle of 40°. Other cameras capture data until the light has passed the centre of the field of view and has reached an angle of 40° on the other side where another 4 frames of information are taken. Since light is being projected simultaneously from the two ends of the rotor arm onto both sides of the stump, the measurement process is completed in one half rotation, equivalent to the time required for 36 video frames.

The system is calibrated by inserting a stepped cone of known dimensions into the measurement field and running a program that defines the video frame data equivalent to the known radii and heights of the steps in the cone for each video frame of each camera in the system. Equations are then set up relating radius, height and angle in a cylindrical polar coordinate system to video line and count for each of the 72 camera frames. The coefficients of these equations are found by a least squares fitting technique and are stored to be used in the computer program that transforms raw data to real coordinates. In our present system the stepped cone is driven through the measurement field by a stepping motor drive directly under the control of the calibration software. Thus, when it is in its upper position the upper section of the video cameras is calibrated for smaller values of radius and as it moves down through the field successively larger radii cross each line of the video frame.

The amputee is seated on a wheeled chair with a panel removed corresponding to the side of the

Fig. 2. The amputee shape sensor in use.

amputation. The chair is positioned over the centre of the shape sensor and the subject lowers his stump into the sensor (Fig. 2). A collar around the opening of the sensor supports 4 adjustable pads that are slid into place to help position the stump in the centre of the field of view. When the measurement is completed the computer requires a further 2 minutes to process the data.

Figure 3 shows the organization of the software in block diagram form. The raw data is first smoothed using a median smoothing routine and reduced from 240 points to 80 in each frame. The smoothing routine is used primarily to determine the upper and lower limits of the stump being measured and to eliminate spurious data points. It searches from the centre of the field outwards until significant discontinuities are encountered. In the next step the smoothed data is transformed to real cylindrical polar coordinates. The real shape can be displayed at this stage but a final routine is provided that will linearly interpolate between data points horizontally and vertically to obtain points lying on a regular cylindrical grid with 5° intervals in longitude and 5 mm intervals in latitude. Thus the final data set consists of one two dimensional array of radii with one dimension corresponding to fixed angles of rotation and the other to known heights. This provides for very economic data storage, transfer and faster display.

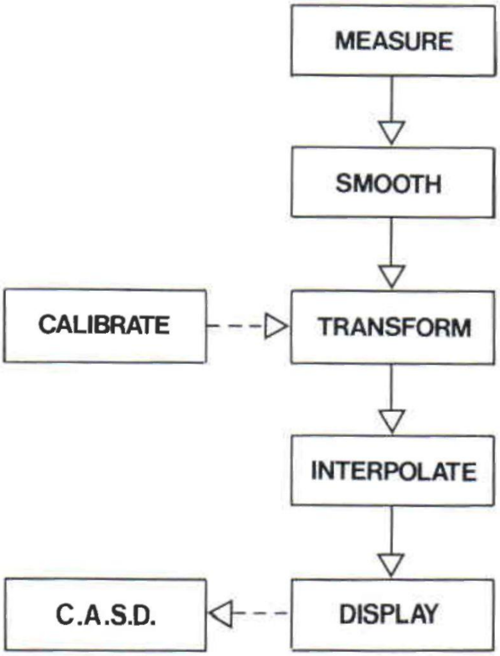

Fig. 3. Block diagram of the software design.

The data is processed presently using a VAX 11-730 with software written in Fortran. Display software has been written for a DEC VS11 colour graphic system attached to the VAX. This presents a pseudo three dimensional wire frame image of the amputation stump together with vertical and transverse cross-sections (Fig. 4).

Circumference, cross-sectional area and height are continuously dimensioned so that the shape and dimensions may be explored on the display screen. Following this visual examination, the data file can be submitted to the shape modification software package. In the present system the file is sent to an IBM PC which is the host for the MERU CASD (computer aided socket design package).

Discussion

The shape sensors that have been built so far by the research team in Toronto have been designed for the purpose of computer aided

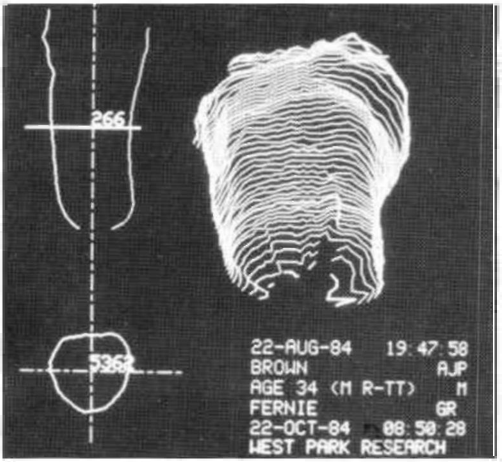

Fig. 4. An example of the computer display showing an oblique view composed of transverse sections at 5 mm intervals. A longitudinal section and a transverse section with measurements respectively of circumference and cross-sectional area are also displayed. The image may be rotated to view the residual limb from other directions and different sectional views may be selected.

socket fitting of amputees. However, instruments are currently being developed for other shape measuring applications for other parts of the body and for the whole body. A number of characteristics of this shape sensing system make it particularly amenable to these various applications.

1. The system is modular. Each camera is supported by a circuit board with built in memory for several frames. An instrument can be conceived using any number of cameras to provide the appropriate coverage of the shape from all angles and to cope with major irregularities. Thus instruments can be configured in a variety of different ways. Some designs utilize rotary scanning motions and others use linear scans. If the speed of scanning is no issue then sometimes it is less expensive to move the object past fewer cameras, whereas, if speed is more important then it is possible to either scan light beams over the object with stationary cameras or move the cameras and light beams together.
2. The calibration procedure and mathematics are generalized and allow for a reconfiguration or adjustment without measurements or geometric calculations.
3. The speed of the measurement can be increased by increasing the number of light beams projected simultaneously. In the system described in this paper the light beam was split in two and the measurement time was halved. One advantage of this physical arrangement is that there is no possibility of a laser beam entering the lens of a camera directly since the opposite projection source is always obscuring that path.

The resolution of shape measurement instruments based on this principle is dependent primarily upon five factors.

1. Video camera selection. The least expensive systems use standard video cameras with 525 lines, of which 242 are useable from half of an interlaced scan. The circuits used by the authors have 240 lines and hence have a resolution of one 240th of the height of the field of view. The resolution across the scan is typically 800 lines or more and is chiefly a function of camera cost.
2. Object size and shape. Larger objects will require a larger field of view for the cameras and there will be a proportional decrease in absolute resolution. The shape of the object is important in this regard in that ideally it should fill the field of view of camera as much as possible. Evidently a long thin object being viewed by one camera would require the field of view to be very large in order to accommodate the whole shape and consequently the resolution would decrease.
3. The number of cameras. The field of view of each camera in the measurement system can be decreased either by moving the object or the camera with respect to one another and obtaining multiple images or by using multiple cameras to divide the field of view into smaller segments, thus increasing resolution.
4. Number of video frames analysed. The resolution of the instrument described in this paper is 5° about the long axis since 72 video frames are taken at 5° intervals around the stump. Evidently that resolution can be increased by increasing the number of video frames measured.
5. Software design. The resolution along the vertical axis was decreased by a factor of 3 through a smoothing process that reduced the number of data points on each video frame from 240 to 80. This was done to economize on data storage and computer time since it was realized that the resolution would still be more than adequate for the task of measuring stumps and would provide a longitudinal resolution that would correspond to the circumferential spacing between the scans at 5 degree intervals.

The resolution referred to above is the resolution of the number of measured points. Since most anatomical shapes involve smooth curvature it is possible to produce an image with effectively higher resolutions by curve fitting to the measured data points.

The accuracy of the stump shape sensor was assessed by comparing the calculated circumference of regular cylindrical objects with the measured circumference. Agreement was within 1% for cylinders with diameters greater than 5 cm. For smaller diameters the percentage error increased but the dimensional error did not exceed 2 mm in circumference.

The repeatability of the measurement of inanimate objects is very high but it would be more relevant to determine the repeatability of measurements of human subjects. We are now engaged in this task. Amputation stumps will often swell very rapidly when removed from a prosthetic socket or from elastic bandages. It is also clear that soft tissue will change in shape depending on the alignment of the limb with respect to gravity and depending on muscle tension. Presently, the measurement is made with the subject wearing an elastic stocking suspended by elastic webbing straps from the seat. Current research efforts are directed at determining the optimum conditions for measuring amputation stumps.

The importance of shape sensing as a component of computer aided prosthetic/orthotic design should not be underestimated. The appliance must have the right *shape* for load transfer or cosmetic appearance and must be the right *size* to fit the patient. We have observed prosthetics students sometimes striving for sockets that have the right features of shape but failing to achieve dimensions corresponding to reference measurements of the amputee taken with measurement tape and calipers. Consequently, the socket is too loose or too tight. An important aspect of shape sensing is the ability of computer software to use these data to maintian a dynamic check of critical linear or volumetric dimensions during the shape modification process.

Certain differences have also been observed in some characteristics of modified shape from one prosthetist to another. Shape sensing will allow the individual user to build his own library of 'primitives' by sensing shapes that he has produced by hand.

Conclusion

A comparatively inexpensive and modular system for measuring anatomical shape has been developed. Two instruments have been built incorporating this principle for the measurement of plaster casts and for the measurement of amputation stumps. Other designs for the measurement of different body segments may now be produced by configuring this system in a variety of different ways to optimize its performance/cost ratio for different tasks.

Acknowledgement

This project was supported by a grant from Health and Welfare Canada, Project #6606–2404–51 and Dr. Fernie is funded as a National Health Research Scholar.

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