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A reference shape library for computer aided socket design in above-knee prostheses

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Abstract
A Reference Library of socket shapes for an Above-Knee Computer Aided Socket Design (CASD) System has been created. This library forms part of a more general CASD System (Dean & Saunders, 1985; Novicov & Foort, 1982). It consists of a matrix of reference shapes representing above-knee socket characteristics and is based upon skeletal structure, residuum length and tissue mass. A set of 27 biomechanical reference shapes in the form of male plaster casts were produced by a combination of CNC milling and traditional artisan techniques. Each reference shape was digitized to obtain its cylindrical coordinates. Cross-sectional areas and tissue distributions within each shape and between the shapes were analyzed, modified and then stored numerically within the computer for further implementation of the CASD System for the above-knee amputees. The creation and the analysis of the reference shape data is described.

Introduction
Fundamental to prosthetic fitting is the process by which the socket is modified in area and shape to match particular biomechanical characteristics of the residuum, in order to provide comfort, stabilization and control of the prosthesis. The socket, which links the amputee to the prosthesis, has several design features which are a function of the residual limb's tissue properties. The forces which are generated during ambulation (radial, shear and axial forces) must be transferred from the socket to the residual limb, and distributed over areas of the residuum which can tolerate repetitive loading without tissue damage. Loading of pressure-tolerant tissue, such as muscle, is achieved through a socket volume reduction over these tissue regions, while volume increases are introduced over load-intolerant bony prominences (Barclay, 1970).

Traditional socket fabrication procedures involve plaster casting and hand sculpting to produce a modified impression of the residuum, from which a socket can be manufactured. This is done on a trial basis until the appropriate fitting is achieved. Both the plaster casting and the modification procedure are performed on the basis of individual skills and judgement according to rules, habits or concepts that might change from centre to centre.

A Computer Aided Socket Design "CASD" System for below-knee (trans-tibial) amputees was developed at the Medical Engineering Resource Unit (MERU), of the University of British Columbia (Novicov and Foort, 1982). Other systems using CAD/CAM technology in the prosthetic field have since been reported (Dewar et al, 1985; Krouskop et al, 1987; Oberg, 1985). These systems differ from the approach of MERU however, in that they require full shape sensing of the stump in order to obtain its mathematical representation on the screen, whereas the MERU System uses a reference shape held in the computer memory, which is scaled differentially to match simple anthropometric measurements taken from the amputee's residuum. These measurements are sufficient to define the shape transformations required to generate a digital customized socket model known as the "Primitive" socket shape.

The CASD system of MERU is an interactive software package written in PASCAL, operating on an IBM PC/XT microcomputer in conjunction with a Vectrix graphic system. The objective of developing an automated shape management capability is to overcome the shortcomings in artisan production methods

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without forfeiting the accumulated knowledge and experience of the prosthetists. By relating details of socket shape modification and production to the computer, and by replacing the prosthetist's rasps and plaster socket model with a cursor and a digital socket model displayed on a graphic screen, it is possible to quantify the "art" of socket design more readily. The implications of such a quantification are that socket quality can be uniform, an explicit description of the socket fit can be defined, and a digital representation of the socket shape can be readily stored and transmitted (Dean & Saunders, 1985).

Methods

With the experience and positive results from the development and implementation of the CASD system for below-knee amputees, extension of the CASD system to include above-knee amputees was initiated. The approach for below-knee and above-knee differs in that initially the former used only one reference shape, whereas the latter uses a matrix of 27 reference shapes to accommodate the larger physical variability. This different approach emerged from the fact that when the reference shape is magnified by a large scaling ratio, particular features of the socket are distorted, and the primitive socket shape then requires considerable interactive modifications to reach an appropriate fitting. The concept of the reference socket shape is based on studies which established that some surfaces of the top portion of the thigh amputee socket can be constant, and that they change proportionately from size to size. This can be standardized (Foort, 1965).

Reference model

In common with the geometric similarities presented by below-knee stumps (Foort, 1984), analysis of the structure of the thigh shows similarities between stumps and between sockets. Studies on one hundred fittings reported by Foort (1965), showed that the distance between the ischial tuberosity and the adductor longus tendon among adults, measures not less than 6.4 cm (2.5 inches) or more than 11.4 cm (4.5 inches), and that most adults measure from 7.6 to 8.9 cm (3 to 3.5 inches). This anterior-posterior (AP) dimension determines the distance between the anterior and posterior walls at the top medial side of the socket. With respect to the distance between the adductor longus tendon and the greater trochanter, the studies indicated that this dimension is not less than 12.1 cm (4.75 inches) nor more than 20.3 cm (8 inches), while most adults measure from 14.0 to 15.9 cm (5.5 to 6.25 inches). This measurement determines the medio-lateral (ML) dimension at the brim of the socket. The above results were obtained at the Biomechanics Laboratory, University of California Medical Centre, San Francisco, Berkeley and were used to design the Adjustable-Brim fitting equipment for the total-contact above-knee socket in 1960 (Foort, 1963).

As a result of its successful use during the past two decades in the design and production of above-knee sockets, the socket type and brim structure selected to be used in the reference shape library of the proposed CASD System was the Quadrilateral Total-Contact Socket (rigid) using the Adjustable-Brim technique. For this purpose, a set of 27 biomechanical reference shapes, in the form of male plaster casts, was produced using a combination of CNC milling and traditional techniques.

Reference shape library

A reference shape library was designed in the form of a 3 x 3 x 3 matrix of 27 socket shapes as shown in Figure 1, having as a common origin a disarticulated knee model of an average adult. The reference shapes represent three above-knee socket shape determinants: skeletal structure, residuum length and tissue mass.

The first characteristic of the reference shape matrix is the brim size and is represented by the ML dimension. Three brim sizes were selected: 13.3, 15.2 and 17.8 cm (5.25, 6 and 7 inches). Stump length, defined as the distance from the ischial tuberosity to the distal end of the residuum, constitutes the second characteristic of the matrix set. The three lengths selected were: 8.6, 18.1 and 26.4 cm (3.375, 7.125 and 10.375 inches), representing short, medium and long. The third characteristic, tissue mass is represented by three perineal circumferences included in the matrix as follows: 38.1, 43.2 and 48.3 cm (15, 17 and 19 inches) representative of sparse (skinny), moderate (average) and bulky (fat) residuum tissue. The reference matrix was

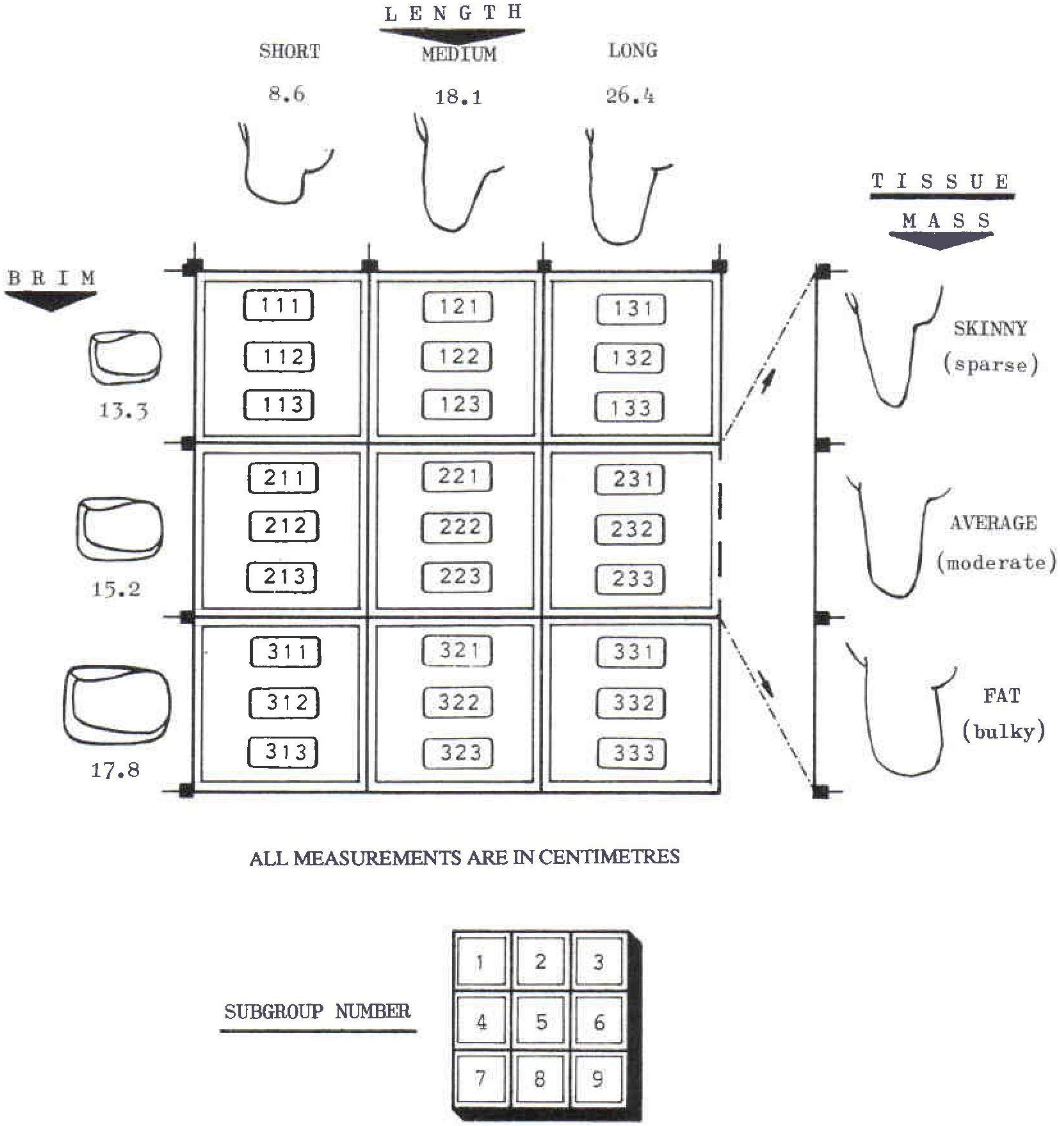

Fig. 1. Schematic representation of the reference shape library, based upon the skeletal structure, residuum length and tissue mass.

divided into 9 subgroups based on brim size and residuum length. Each subgroup consists of three shapes of different tissue mass: skinny, average and fat. In order for the CASD algorithms to distinguish between the 27 reference shapes, a code system was implemented by which each reference shape is coded with a unique three digit number (e.g. 231). The first digit indicates the distinct brim size (1=13.3 cm, 2=15.2 cm, or 3=17.8 cm); the second digit relates to the stump length (1=short, 2=medium, or 3=long); and the third digit represents the particular tissue bulk characteristic of the stump (1=skinny, 2=average, or 3=fat). The matrix set was designed to span all combinations of brim size, residual length and girth of socket for the above-knee amputee population.

In order to maintain a fixed relationship between reference shapes, the sequence of production started by digitizing the disarticulated knee positive model to obtain its cylindrical coordinates. This model was made from an average adult thigh fitted with the intermediate brim (15.2 cm), with a skeletal length of 36.5 cm from the ischial tuberosity to the tibial plateau and, an average (moderate) tissue girth (43.2 cm perineal circumference). The disarticulated knee model was then displayed on the graphic screen and "amputated" mathemetically at the length of the long residuum (26.4 cm). The cylindrical coordinates of this truncated disarticulated knee shape were first transformed into a helical path and then down-loaded to the Computer Numerically Controlled (CNC) milling machine. This data was translated by the CNC postprocessor into a series of machine instructions which control cutter tool movements, axis rotation, and axis translations. When executed by the CNC, these instructions result in a positive "cast" carved from a polyurethane foam block.

From this positive cast, the first reference shape positive cast was manually sculpted to provide a suitable distal end shape and emphasize areas of socket support. This modified shape (reference shape 232) was then digitized and carved to yield additional "casts", from which the adjacent cells (231 and 233) within subgroup 6 of the matrix (Fig. 1) were manually constructed and then digitized. Taking again the numerical data of the original disarticulated knee model, this was "amputated" to the medium length residuum (18.1 cm) and carved. From this, reference shape 222 was manually sculpted and digitized. This shape was then in turn carved and modified to yield the neighbouring cells (221 and 223) which were then digitized in turn. The procedure was repeated for the short residuum (8.6 cm) to produce shape 212 from which shapes 211 and 213 were then generated. At the end of this sequence the first set of 9 reference shape positive casts and their digital equivalents (subgroups 4, 5 and 6) were produced.

By repeating this procedure in the first and third brim size (13.3 and 17.8 cm) the remaining 18 reference shapes were produced to complete the reference shape library. By this method, the three distinctive characteristics were represented throughout the matrix set.

A disarticulated knee model was chosen as the best basis from which to develop a complete family of socket shapes. It was considered that

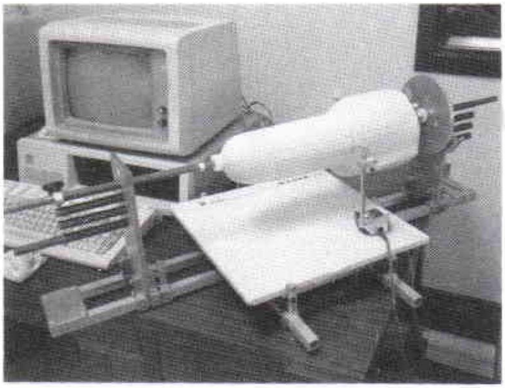

Fig. 2. Shape Copier device used in the digitization of the reference shape positive casts.

this approach would provide a more uniform distribution of shape characteristics than would be achieved if the socket shapes were to be derived from a series of unrelated amputee socket shapes. The modifications to the original disarticulated knee model to produce individual socket shapes were made by an experienced prosthetist and based on previous clinical observations and measurements (Foort 1965, 1984).

Digitization of the shapes

Digital recording of the reference shapes was performed by means of a Shape Copier (Saunders, 1986). Each positive cast was mounted on a horizontal jig similar to a lathe. The Shape Copier (Fig. 2) consisted of a cast holding device, an indexing turntable with notches at 10 degree intervals, an electronic digitizer tablet, and a cursor with an offset probe.

To digitize the male shapes, the cast was supported through its longitudinal axis by a rotatable vertical plate at its proximal end and a guide-pointer at its distal end. The cast was rotated 360 degrees in 36 steps of 10 degrees. At each step, a longitudinal trace of the cast shape was acquired by guiding the probe from the distal end to the proximal end. The software collected data corresponding to the perpendicular radii every 2.5 mm along the external wall, radii representing the distance from the longitudinal axis of the reference shape to the external wall of the cast. Once the horizontal trace was completed, the vertical plate was rotated to the next angular step and the operation was repeated until the complete cast had been digitized. At the end of one complete revolution, the numerical data consisted of a maximum of 5760 and a minimum of 3240 radial points describing each reference shape. Due to the limited dimensions of the electronic digitizer tablet being used, some shapes were too long to be digitized in a single file, therefore, those shapes were digitized in two independent data files with an overlapping range of 25.4 mm and later integrated to create the final output file. The cylindrical coordinates were then transformed into CASD system units compatible with both the CASD and the CASM software.

The final output file consisted of a two-dimensional array of raw radii; one dimension (referenced by the cross-section number "*j*") representing a certain distance from the Ischial Gluteal Shelf along the longitudinal axis; and the other ("*i*") representing the angle of rotation. Each individual cross-section within the shape was represented by 36 circumferential points, 10 degrees apart, expressed as radii from the longitudinal axis to the internal wall of the socket. This matrix represented the cylindrical coordinates (height, angle and radius) of the particular reference shape as shown in Figure 3.

Analysis

To assess the accuracy of the digitizing device, analysis of a known shape was performed. A solid cone was truncated into four sections; each section was connected to its neighbour by a solid cylindrical body to match the cone dimension, ranging from 15.2 to 5.1 cm (6 to 2 inches) in diameter. Similarly, cylinders of matching diameters were attached to either end. Using the Shape Copier device and the measurement technique employed with the reference shapes, this known volume was digitized to obtain 61 cross-sections containing 36 radii.

To quantify the deviation of the acquired cross-sections from their expected circular shape, the raw radii were plotted as a function of angle and fitted by the "least-square linear regression" method. The linear regression equation (Y=a+bX) obtained for each of the 61 cross-sections analyzed yielded b=0.00. The "standard error of estimate" had a mean value of ±0.36 mm. This represents the random error of the digitizing device. Taking the value "a" of

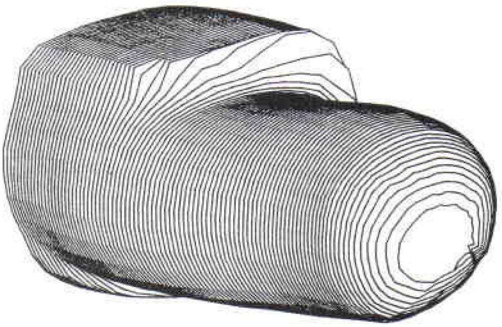

Fig. 3. Latero-posterior view of the three dimensional representation of the "left" reference shape code 222. Its "right" version can be obtained numerically by producing its mirror image.

the linear regression as the performance radii (Rp) and the expected radii as the target (Rt), the "constant error" (CE) (Schutz, 1973) was calculated using equation 1. This yielded a constant error of CE=+0.56 mm independent of the distance being measured.

$$CE = \frac{\Sigma(\mathrm{Rp} - \mathrm{Rt})}{\mathrm{cases}} \qquad (1)$$

Analysis of the reference shapes

To quantify tissue distribution (cross-sectional shape) and size differences along the longitudinal axis of the reference shapes, a series of statistical analyses were performed within each shape and between adjacent shapes of the subgroups within the reference shape matrix. Taking each cross-section independently, the Equivalent Radii (ER) (equation 2) representing the radius of a circle with an area equivalent to that of the shape being analyzed, and the Cross-Sectional Areas (CSAR) of all the 27 reference shapes were calculated. The CSAR was derived by calculating the areas of a series of circular sectors (ACS) with an angle of 10 degrees (equation 3). The sum of the 36 circular sectors represented the CSAR given by equation 4.

$$ER = \sqrt{\frac{1}{36}\sum_{i=1}^{36} R_i^2} \qquad (2)$$

$$ACS = \frac{\pi(R_i^2)}{36} \qquad (3)$$

$$CSAR = \sum_{i=1}^{36} ACS_i = \pi ER^2 \qquad (4)$$

By plotting CSAR as a function of residuum length, and comparing adjacent reference shapes, a comparison of tissue distribution was obtained. By plotting superimposed cross-sections within each socket shape (10 cross-sections evenly spread along the shape) the horizontal and vertical orientation of the tissue distribution with respect to the longitudinal axis and the ischial gluteal shelf was determined. To quantify the differences in shape between adjacent cross-sections within each reference shape and between adjacent reference shapes (average -vs- fat and skinny -vs- average), the RMS of the difference in shape was obtained (equation 5). In order to eliminate the effect of size differences from this comparison of shape, the raw radii were divided by their respective ER to obtain a normalized radii. This shape analysis was performed between cross-sections of adjacent socket shapes within each subgroup at the same longitudinal location; and between cross-sections within the same socket shape, selected at intervals of one, four and eight cross-sections to provide different levels of sensitivity in the analysis.

$$RMS = \sqrt{\frac{1}{36} \sum_{i=1}^{36} \left(\frac{R_{ia}}{ER_a} - \frac{R_{ib}}{ER_b}\right)^2} \qquad (5)$$

Results

Discrepancies in CSAR were seen in shape 333 and 323 at 12.4 cm in the longitudinal axis from the ischial gluteal shelf. This was the result of inaccuracy of alignment at the digitization stage where some shapes were collected into two files due to their oversize with respect to the electronic tablet and then merged to form a single shape. The analyses also revealed some unexpected results: firstly, the unmatched position of the rear flare (with respect to the cross-section number zero at the ischial gluteal shelf) between shapes, which reflects longitudinal misalignment (Fig. 4, top), secondly, an overlapping of CSAR between some neighbouring shapes (i.e. shape 312 and 313) and, thirdly, perineal area discrepancies between shapes of similar brim size and tissue bulk; this being a product of the previous area overlapping and the longitudinal mismatch. Shapes of similar brim size and tissue bulk, were expected to have similar perineal CSAR, independent from their length.

Modification of the reference shapes

Each reference shape was displayed on the graphic screen and the midcoronal plane of the socket was visually located. The coordinate grid was then medially rotated about 30 to 40 degrees within the transverse plane to superimpose the maximum ML dimension with the angular coordinate position zero. This was necessary in order that the brim scaling procedure be representative of the real ML dimension parallel to the coronal plane. Finally, the coordinate grid was re-aligned vertically to locate the cross-section representing the midpoint between the proximal and the distal portions of the socket (cross-section zero) exactly at the ischial gluteal seat.

The perineal CSAR were analyzed in order to normalize the systematic proportional CSAR increments between the three different brim sizes, and the proportional increments between the three different tissue bulks. This analysis indicated that between the three brim sizes, the perineal area of the 13.3 cm (5.24 inches) ML brim size represented 79% of the perineal area of the 15.2 cm (6 inch) ML brim; and the 15.2 cm (6 inch) ML brim size represented 70% of the perineal area of the 17.8 cm (7 inch) ML brim. For any given brim size, even though the ML remains the same, the perineal area changes due to differences in tissue bulk between skinny, average and fat socket shapes. With respect to the systematic perineal area of proportion between the three tissue bulks, the perineal area of the skinny represented 91% of the area of the average socket, which respectively represented 86% of the area of the fat. To normalize the CSAR proportional increments, an homogeneous area scaling routine was implemented. The overall radial scaling factor for each reference shape was calculated by obtaining the square root of the ratio between the required perineal area and the actual perineal area of the shapes. Taking each cross-section within the shape, the original radii were then multiplied by the radial scaling

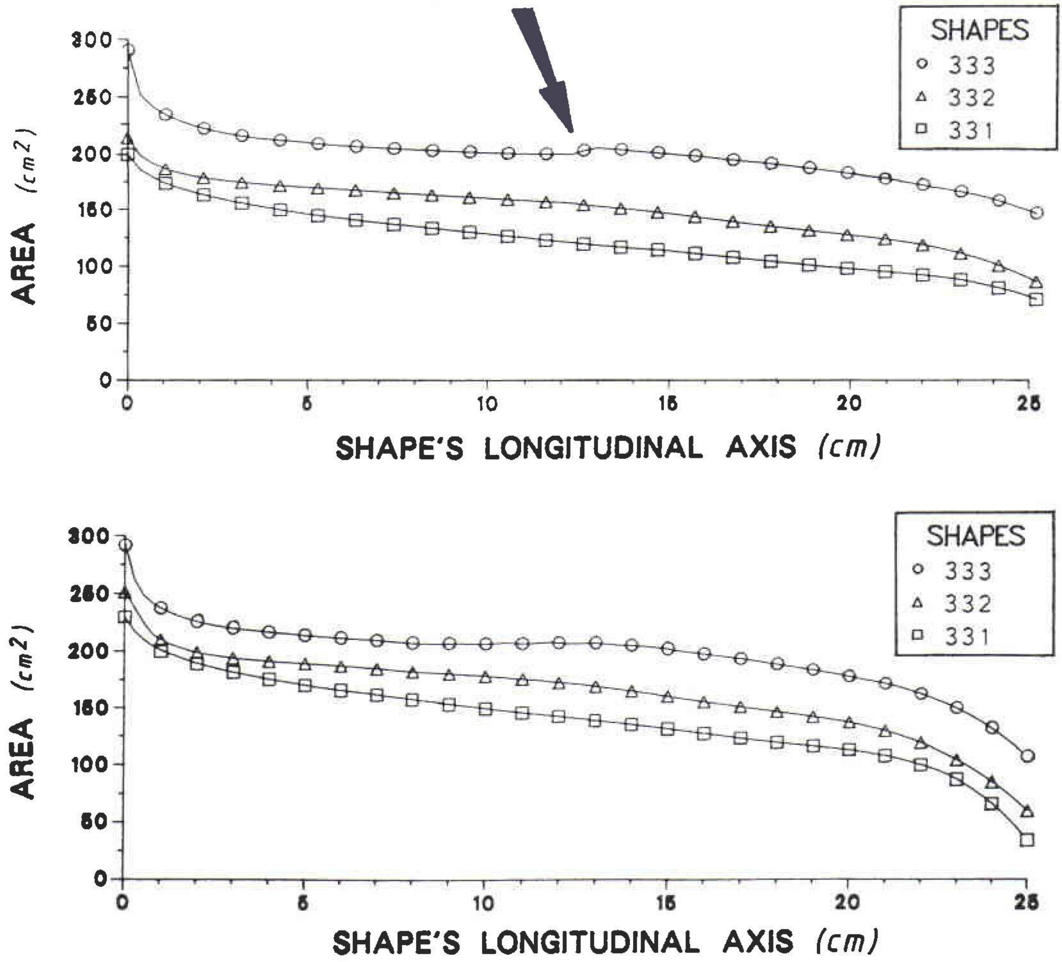

Fig. 4. Cross-sectional area plotted as a function of the residual length within subgroup 9 of the reference shape library: brim 17.8 cm, length 26.4 cm. Top, raw data, bottom, following the adjustments of the reference shapes.

factor, thus scaling the area without altering the cross-sectional shape or tissue distribution.

Scaling of the primitive library shapes was followed by smoothing the numerical data representing each circumferential string or horizontal cross-section, and along the 36 longitudinal strings. The smoothing routine used was based on the technique known as Fourth Differences (Lanczos, 1964). It assumes that the data is sufficiently close together to justify the hypothesis that in a certain finite neighbourhood of points, the second derivative of $f(x)$ does not change significantly, and adjacent points can be joined by a least-squares parabola of the second order. For circumferential strings, 5 adjacent data points were taken, whereas for longitudinal strings, which displayed less curvature, 7 points were taken using the same technique.

Final shapes

Once the refinement of the complete Reference Shape Matrix was performed, the 27 reference shapes were re-analysed in shape and area as described for the original digitized shapes. The cross-sectional shape analyses within each shape showed (Fig. 5) that in the central portion of the sockets, there is no significant change in shape. Change in the proximal portion (proximal 2 cm) of the socket results from the effect of the medio-posterior flare as the socket reaches its proximal end.

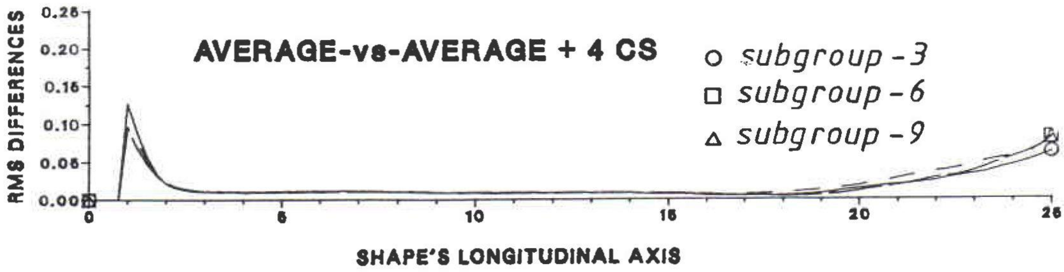

Fig. 5. Differences in shape between cross-sections at intervals of four cross-sections for the reference shapes within subgroups 3, 6 and 9: length 26.4 cm, average tissue girth.

Towards the distal end (distal 4 cm), there is a gradual change in shape but not to the extent seen at the proximal end. These changes in cross-sectional area and shape (tissue distribution) are designed to account for differences in muscle mass at the thigh and the way the residuum was designed during the amputation. The particular shape changes at both ends are emphasized when the analysis is performed between cross-sections at intervals of four cross-sections.

Three well established trends show that there is a larger degree of shape similarity between average and fat socket shapes than between skinny and average socket shapes. In the case of the skinny and average comparisons, shape similarity decreases in a linear fashion as the distance from the ischial gluteal shelf increases; whereas for the average and fat socket shapes, their similarity remains relatively constant along the socket until the distal 5 or 6 cm (Fig. 6). Three socket shapes (skinny, average and fat) of similar brim size and length, can be seen in axial view along the longitudinal axis (Fig. 7). Each of the three diagrams contains 10 superimposed cross-sections which where taken from their respective socket shapes at similar levels. As tissue mass decreases, the medial wall gradually shifts laterally towards the distal end, guided possibly by the femur's position. As the muscle mass increases (fat) the cross-sectional shape maintains its circular shape towards the proximal end, rather than tending towards an eliptic shape as in the case of less muscle bulk (skinny). This may be due to a greater change of muscle mass in the anterior

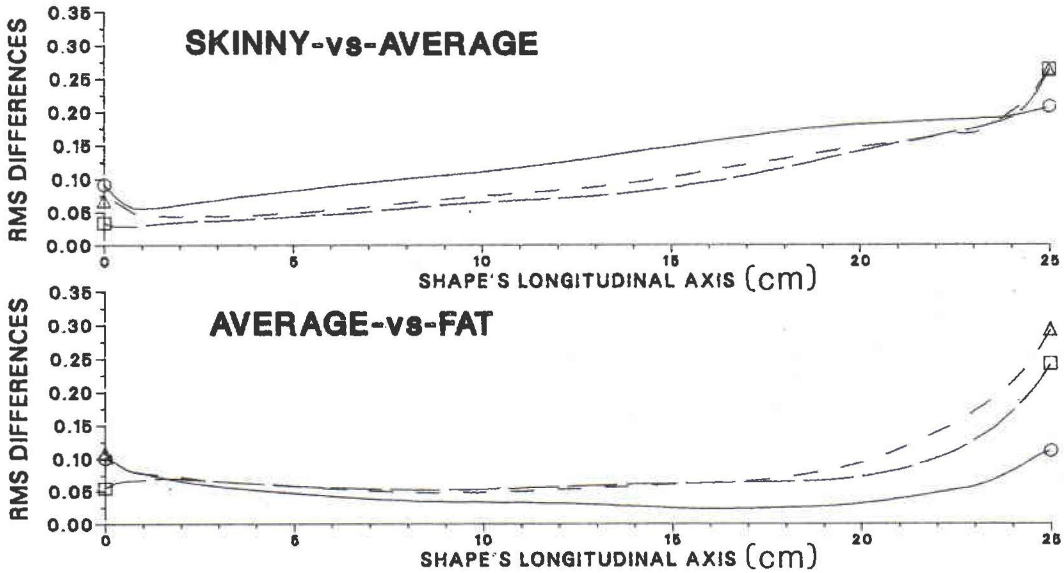

Fig. 6. Differences in shape of corresponding cross-sections between the reference shapes within subgroups 3, 6 and 9: Three brim sizes, length 26.4 cm.

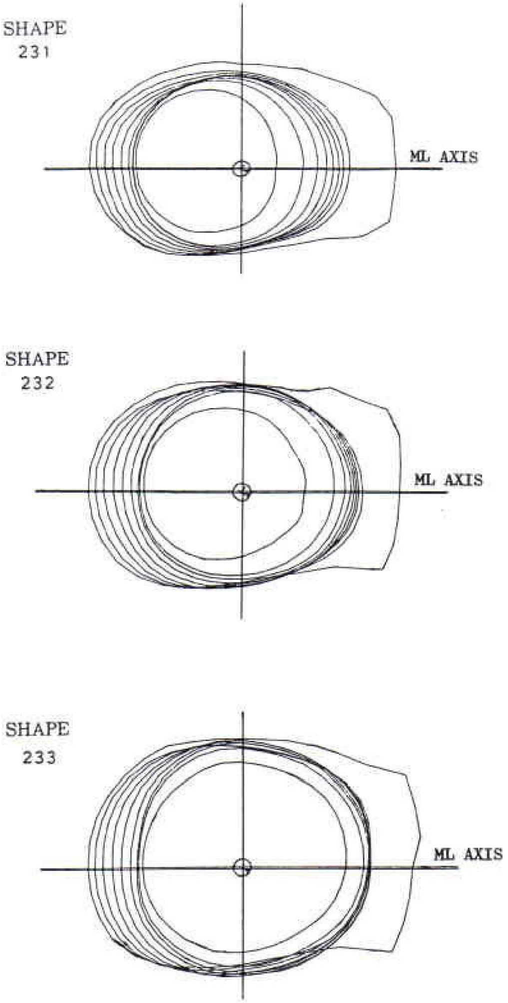

Fig. 7. Difference in tissue distribution along the longitudinal axis between the three tissue girths (skinny, average and fat): brim 15.2 cm, length 26.4 cm.

and posterior muscle groups than in the lateral and medial muscles.

Implementation

The above-knee Reference Shape Library has been integrated with the MERU shape modification procedures in order to produce socket shapes customized to the individual amputee. Using these procedures, a primitive socket shape was produced to fit an above-knee amputee. The primitive shape was then modified interactively using the CASD System to obtain a final socket shape. This shape was manufactured and worn by the amputee during a 2 month trial period with satisfactory results. As a further outcome of this process, a Reference Shape Library is now under development to enhance existing below-knee CASD procedures.

Conclusion

The basis of a computer aided socket design procedure (CASD) has been developed, whereby the unique configuration of an above-knee amputee's socket can be systematically created based on measurements of skeletal structure, residuum length and girths taken from an amputee. The complete library of above-knee reference shape data files, comprising a Matrix of 27 Reference Socket Shapes for the CASD System, have been stored on magnetic tape in the Research Data Library at Simon Fraser University. The data files may be accessed through the MTS operating system on University's main frame computer.

Nomenclature

ACS : area circular sector
CASD : Computer-Aided Socket Design
CASM : Computer-Aided Socket Manufacture
CNC : Computer Numerically Controlled
CSAR : cross-sectional area
ER : equivalent radii
i : angular location within the slice
IGS : ischeal gluteal shelf
Ri : raw radius
R'i : new radius
Rp : performed radius
Rt : target radius
RMS : root mean square

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