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# Computer-aided socket design for trans-femoral amputees

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**Abstract**
Computer-aided socket design (CASD) is a technique for the design of prosthetic sockets using the advantageous features of computer graphics and calculation. This paper describes a computer-aided technique used to design sockets for patients with trans-tibial lower limb amputations.

## Introduction

The application of CAD CAM techniques to the production of prosthetic sockets was first suggested by Novicov and Foort (1982). The system which Foort and his co-workers developed was initially for the design of trans-tibial patellar tendon bearing sockets and had two components — a software programme to design the socket and a computer-controlled milling machine to carve the finished design as a solid model, over which the socket itself was then formed. The socket design programme was based on the principle of having a "reference" shape of a socket held in the computer. This was then scaled and modified by the programme to fit the patient on the basis of a relatively small number of measurements of the patient's stump, made using calipers and tape measure. Subsequently the initial database was extended by including further reference shapes to cope with different types of stump shape.

A different approach was followed in the system developed at University College London (Dewar *et al.*, 1985). In this, the starting point for the design software, rather than being the shape of a finished socket, is the unmodified shape of the patient's stump. Obtaining this shape involves measuring the stump at a large number of points on its surface and transferring the data to the computer. The system therefore comprises three components: a software programme and carver as in a Foort's system, and in addition a stump measuring device. The latter works by measuring the inside surface of a plaster wrap cast which had been taken of the stump. The cast is rotated about a longitudinal axis as a measuring arm whose tip rests on the inside of the cast moves along this axis (Fig. 1). The tip of the probe therefore traces a helical path round the inside of the cast and its displacement

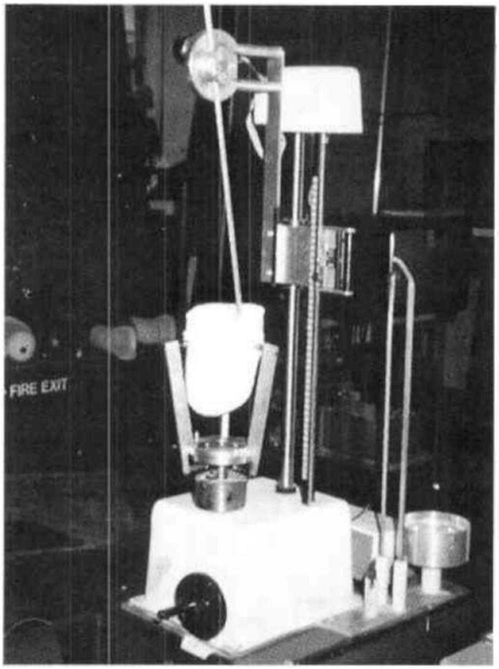


Fig. 1. The digitiser measuring the inside surface of a plaster wrap cast of the stump.

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from the axis is measured. The resulting data file then represents the shape of the stump with each data point being the polar co-ordinate of a point on the surface, relative to an arbitrary axis through the stump. Because the prosthetist using the programme will be familiar with working with a plaster model the shape is displayed on the screen as a white positive model, rather than as a negative socket. This shape is then modified by a procedure analogous to that carried out conventionally: the radial measurement values at particular points are increased or decreased. Increasing a measurement value is equivalent to adding material at that point to a plaster model of the stump in conventional practice, while decreasing it is the equivalent of removing material. The changes are described in terms of a number of discrete regions where the shape was modified. Each of these regions is known as a "patch". They correspond to the areas normally marked on the positive model by the prosthetist when he is modifying a cast. A complete set of these patches is designated as a "rectification pattern". In order to apply the pattern to a region it needs to be (a) located in the correct position and (b) adjusted to fit the size of the stump. The location is achieved by means of a reference point — an anatomical landmark which is identified on the stump prior to digitising it and transferred to the measurement file on the computer. The pattern is scaled by means of an algorithm which moves the distal-most patches in relation to the distal end of the stump, keeps some in the same place relative to the reference point and adjusts the proximal to distal dimension of the remainder to match the length of the stump.

A further kind of change that can be made is termed "sculpting". In this each point on the surface of the socket model can be raised or lowered individually, enabling any shape to be created.

There are therefore various ways in which the prosthetist can determine the shape of the final socket: he can modify the initial shape by moulding the plaster on the stump to "pre-shape" the cast; he can select a particular rectification pattern; for each patch in the pattern he can modify the amount of pressure or relief provided; he can "sculpt" individual points.

The system described above formed the basis of the commercial system marketed as Computer Shape in the late 1980's. Shortly afterwards another version, marketed as CASDaM, added the facility of being able to move the patches within a rectification pattern.

Although a number of other systems are now available with a varied range of facilities, these are generally used for producing trans-tibial sockets. Producing trans-femoral sockets has some particular problems. The stump is generally much less defined in its shape. The skeletal elements, the section of femur and the pelvic girdle, are buried within a large amount of mobile soft tissue. An ischial weight-bearing socket needs to fit firmly up to the ischial tuberosity. It is difficult to locate this landmark using a non-contact measuring method and even recording its position using a plaster of Paris wrap cast requires care and consistency.

The aim of the work presented here was to develop the UCL CAD CAM system so that it is applicable to trans-femoral socket design. Again it was decided that a desirable approach would be to follow a conventional philosophy such as that described by Foort (1963). This philosophy involved fitting the patient with a socket of which the proximal portion was of a standard 'brim' shape, sized correctly, and of which the distal portion conformed to a cast of the patient's stump. This involved development of a casting and measuring procedure together with a brim sizing method and computer software to fit the two shapes together, ensuring the smoothness of the generated socket shape. The final stage of design using patching and sculpting, together with the computer graphics viewing procedure, were similar to the techniques employed in the trans-tibial method, again giving wide flexibility to the system.

After an account of how the shape is stored as a computer file, the following sections of this paper describe the methods for establishing the correct brim shape, casting and digitising from the patient, the software for formulating the socket shape, modifying and sculpting the socket and producing the socket. Further information on the precise formulation of the algorithms involved in the computer modelling can be found in Travis (1991).

**Shape storage on a computer**

This section explains how the shape of a prosthetic socket is stored as a numerical file on a computer. The shape is considered as a series of "slices" at fixed intervals along a central axis. In each slice, points are recorded at regular angular intervals, and it is the radii of these points from the central axis which are actually stored in the file (Fig. 2a). The regular nature of the file also gives rise to the term "strip" in addition to "slice" (Fig. 2b). When a shape is altered or modified in any way, the effect is that some of the radii are changed, and the new shape is stored as a new set of radial values. The angular spacing between strips and the regular spacing between slices could be altered but in practice it appears that 10° and 6.35 mm (¼") are sufficient without being too dense to slow down the computer operation unnecessarily.

## Method

### *Brim shape*

In widely-used conventional procedures for the production of trans-femoral sockets the prosthetist has a number of "brims" of similar shape but different sizes available to him. One of these is chosen and fitted to the patient after certain measurements have been taken of the patient's stump to determine the correct size. Although it is likely that no brim will fit the patient's measurements exactly, the prosthetist will choose the best fit from the range of sizes. There may thereafter be some minor adjustments which he can make to the brim mechanically. This brim shape will form the proximal portion of the socket.

In the CASD approach it was recognised that if different brim sizes were essentially scalings of the same shape then the computer need only store one shape and scale it to the appropriate size using the measurements taken from the patient. One brim shape was therefore digitised and stored in the computer. In use, four key measurements are taken from the patient, three of which are used to scale the brim correctly, the fourth being used to determine the correct proximal-distal length of the final socket. The four measurements are as follows:-

1. An anteroposterior (AP) dimension is taken with the patient seated on a hard surface. The dimension is measured from the upper extent of the adductor longus tendon to the ischial tuberosity (Fig. 3a).
2. A mediolateral (ML) dimension is measured from the adductor longus tendon to the lateral extent of the head of the trochanter (Fig. 3b).
3. A circumference (Circ) dimension is measured with a tape measure tensioned so that there is just no slack, at the height of the perineum (Fig 3c).
4. The fourth measurement is a length (Len) measured from the perineum to the distal end of the stump (Fig. 3d).

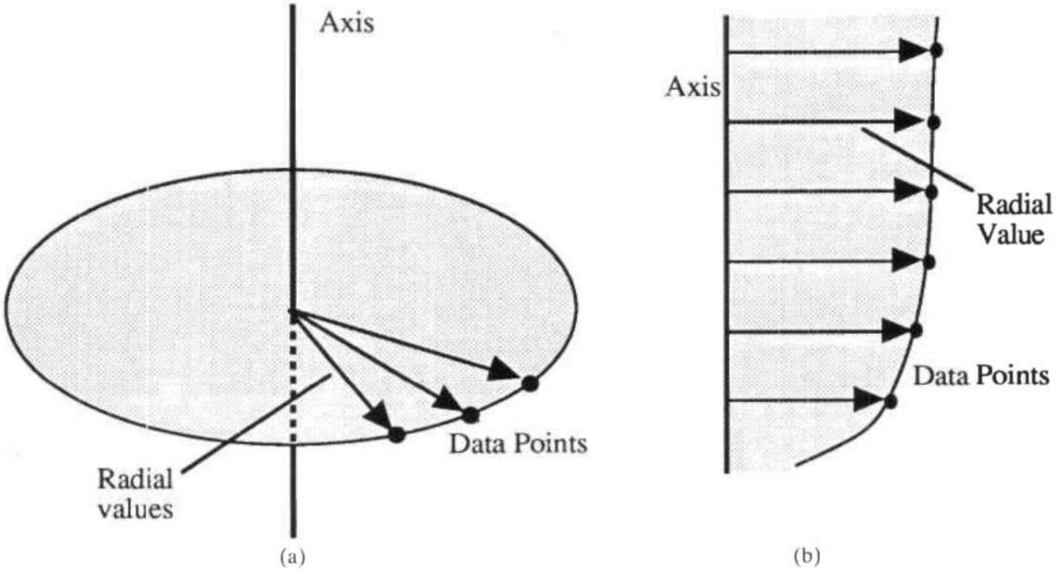


Fig. 2. (a) A slice consists of the radial values of points spaced at regular angular intervals about an axis. (b) A strip of the data consists of the points lying in a vertical plane through the axis.

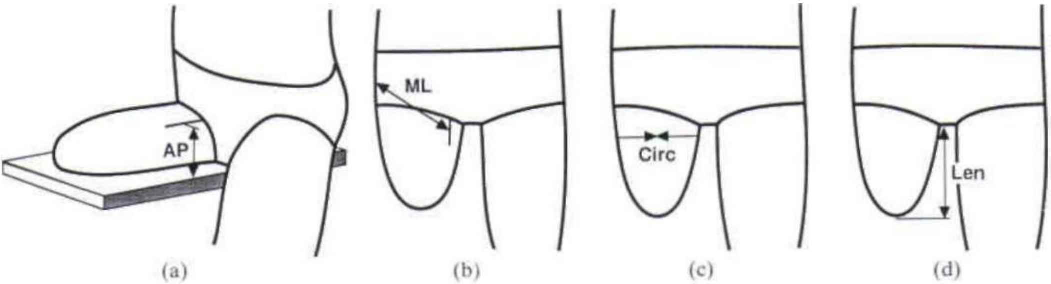


Fig. 3. Dimensions of the stump used for computer scaling. (a) The anteroposterior dimension: with the patient seated, the vertical distance between the top of the adductor longus tendon and the horizontal surface supporting the ischial tuberosity is measured.
(b) The mediolateral dimension: with the patient standing, the distance between the adductor longus tendon and the greater trochanter is measured.
(c) The circumference dimension: with the patient standing, the circumference of the stump is measured at the height of the perineum.
(d) The length dimension: with the patient standing, the distance from the perineum to the distal end of the stump is measured.

After the AP, ML and Circ dimensions have been inputted to the computer, the brim shape is scaled accordingly, dependent upon how these dimensions match appropriate points on the stored brim shape.

*Casting*

In the trans-tibial version of CASD there is no procedure analogous to that of fitting a brim to the patient; there the entire stump which is to be in contact with the total-contact socket is cast. A digitisation of this cast then becomes the initial shape for the design of the socket.

In conventional trans-femoral procedures the prosthetist fits the patient with the desired brim shape as described, and then casts that portion of the stump which protrudes. In the CASD system for trans-femoral sockets, the brim shape is stored in the computer, and the aim was to carry out the procedure without physically fitting a brim shape to the patient. However, since the brim alters the shape of the stump to a considerable extent, taking a cast with no allowance made for this gave unpredictable results. The adopted procedure involves the use of that portion of the brim which in practice transmits much of the weight through the ischial tuberosity (Fig. 4). To allow for the alteration in stump shape, the brim segment is positioned against the patient after he has been fitted with a stump sock: a horizontal mark and a tick to indicate the central point of this posterior view are made at the stump's distal end (Fig. 5). After the brim portion is removed the stump is cast up to the horizontal mark, and the cast is digitised. The point marked by the tick is used as the reference point for orientation of the data file during the shape generation.

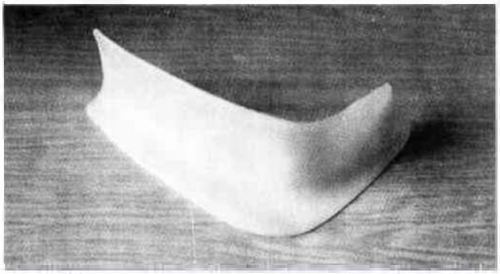

Fig. 4. The template for locating the height of the reference point is a replica of the medial posterior portion of a socket shape.

Fig. 5. The reference point is marked at the medio-lateral centre of the stump on the horizontal line under the template.

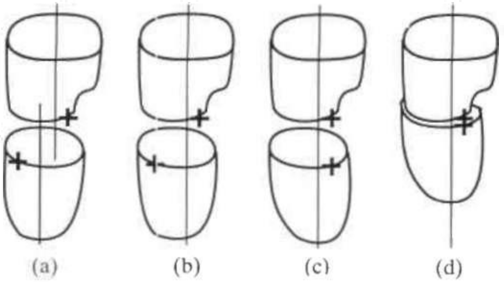


Fig. 6. The stages of creating an initial socket shape from separate brim and distal portions: (a) two separate data files on distinct vertical axes; (b) the two files with their axes aligned; (c) the distal part is oriented so that the reference point on the two parts match; (d) the files are linked together ready for smoothing.

*Socket shape generation*

After measuring, casting and digitisation are complete, the computer contains two data files, namely the brim shape scaled appropriately and the digitisation of the distal portion of the limb. Using the reference point in each file, the two files are oriented correctly and the co-ordinates recalculated to be radial values from one central axis (Fig. 6). However, at this stage, the two data files will not match smoothly, and so software has been developed which blends the two files together and, if necessary, at the same time adjusts the length of the shape to match the length dimension taken earlier. The result is a smooth socket shape shown graphically on the computer (Fig. 7).

*Modifications and sculpting*

Although at this stage an initial socket shape has been designed, adjustments may be required. The software incorporates two types, namely "modifications" and "sculpting".

Modifications are adjustments which affect large areas of the socket shape. A screen is presented to the prosthetist showing graphically six modifications which are available. These are adjustments to the ML, AP, and Circ dimensions and to the overall length of the socket and the introduction of flexion/extension and adduction/abduction to the socket. After any of these modifications, the socket is redesigned to fit the new requirements.

Sculpting is a procedure which affects only one point of the socket at any one time. The prosthetist can alter the radial value at any point of the shape. With a continual visual feedback of how the socket is affected this feature means that the prosthetist is able to introduce either very localised alterations to the shape or to combine sculpting of many points to affect broader regions or "patches".

The result of these alteration features is that the prosthetist is able to determine the socket shape he desires. The fact that all these modifications and sculptings are stored on the computer means that any subsequent sockets can use the current socket shape as a starting point, therefore increasing their predictability and repeatability.

*Socket production*

After a socket shape has been designed, the production of the socket is very much as for the trans-tibial CASD system. The same equipment is used, but larger plaster blanks are required for the milling process because the sockets are of greater volume. In summary, the procedure is as follows:

The file containing the shape data for the socket is sent to a numerically controlled three-axis milling machine which carves the shape out of a plaster blank. The carved shape is removed and placed in a Rapidform oven where a pre-heated polypropylene sheet is lowered over the plaster and conformed to the shape by use of a vacuum pump. When cooled, the plaster is broken out and the plastic trimmed so that the desired socket shape remains. This is then fitted to the patient with the necessary fittings and attachments.

**Results**

A key part of the procedure is the design of the brim portion of the socket. The

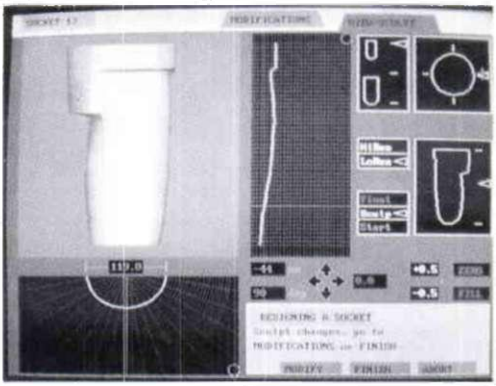

Fig. 7. The socket shape is displayed graphically on the computer. The final image shown is the resulting socket shape.

conventional philosophy followed suggests that the socket should fit with the patient's ischium resting approximately 10 mm posteriorly on the posterior shelf with the tendon of the adductor longus muscle fitting in the anterior medial corner and the head of the trochanter contained within the lateral wall. If this is achieved then the ramus is positioned above the medial shelf. The relationship between brim shape and the measured dimensions is demonstrated in Figure 8. An approximate guide for the relative sizes of these dimensions is as follows, and indeed the computer programme allows for entering of the Circ value only, the other values being estimated by these formulae:-

$$AP = (^1/_5)\ Circ$$
$$ML = (^1/_3)\ Circ$$

In initial patient trials, a comparison was carried out and a good degree of correlation observed between the AP, ML and Circ dimensions measured on the patient for subsequent input into the computer, and the dimensions as they occur on a brim adjusted by a prosthetist to fit the patient under conventional practice. It was found that the dimensions of the brim were correct to within the accuracy of measurements taken with calipers and tape-measure, and that the Circ dimension is particularly difficult to measure accurately. It was found that for the first socket produced for each patient, the Circ value required adjustment. However, because of the ability of the computer programme to build on previous socket designs, in each case the second socket fitted satisfactorily. This shows that even though a prosthetist may need experience with the system, for example to know how tight to pull the tape measure to produce a predictable

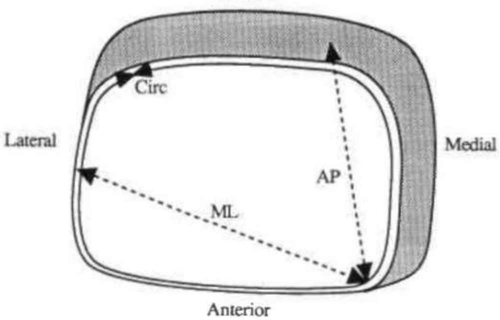


Fig. 8. The relationship between the anteroposterior, mediolateral and circumference dimensions and the brim shape.

Fig. 9. A patient wearing a transparent test socket produced by the CAD CAM system.

socket size, the consistency of the system built in by the memory of previous designs can enable him to produce predictable designs. An example of a socket made from clear perspex can be seen in Figure 9.

**Discussion**

Two alternative approaches are apparent for the design of a trans-femoral total contact socket. The first is to mimic the method commonly used for trans-tibial sockets and employ a "patch" approach based upon a cast of the entire stump as described in Dewar *et al.* (1985). However, this would not have followed conventional trans-femoral procedure and, as mentioned above, would have led to difficulties because of the flexible nature of the body tissue in the proximal portion of the leg. After initial consideration and tests, using this approach alone was rejected because of these difficulties.

A second approach is that used by Torres-Moreno *et al.* (1992) and consists fundamentally of the judicious scaling of one of several "reference shapes" previously stored in the computer, the scalings and adjustments being decided by certain measurements taken from the patient's stump. This approach has particular advantages in the proximal portion of the socket where in conventional practice the overall shape of a total contact socket is largely independent of the individual patient – only the scale of the proximal portion is adjusted to ensure a good fit.

The method adopted is a combination of the two: it has the advantage of the second approach in the proximal portion of the socket, since a predetermined brim shape is adjusted according to certain anatomical dimensions taken from the patient's stump, but also uses the shape of the distal portion of the stump as the starting point for the distal portion of the socket, with the advantage of accurate fit which this involves.

The advantages of a computer graphics approach were demonstrated with the trans-tibial CASD system. They include the ability to view the socket on the computer before production, which enables any large defects to be detected and removed. The ability to base a design on a previous socket and to use a modification or sculpting technique is a considerable advantage over conventional methods where the initial plaster shape is destroyed in the manufacture of the socket. This means that if a socket is a good fit except in localised areas, for example, a new socket can easily be designed and a predictable fit produced. Moreover, if a first socket design is not correct, then a second one has a greater chance of being satisfactory.

The measured dimensions chosen were selected because they are measurements which prosthetists commonly take already, allowing quicker adaptation to the new system. However, it may be that other prosthetists decide that different measurements would result in a better prediction of the desired brim shape. These could readily be included within the computer software.

Only one brim style was used in fitting of most of the patients. It would be straightforward to introduce further styles by producing a plaster cast of the desired brim shape and digitising it. One advantage of the CASD approach is that it does not limit the prosthetist to a standard range of sizes of his chosen brim style. Rather, because the computer can scale up to any degree, a complete range of sizes is available. Moreover, the approach allows individual prosthetists the freedom to develop their own brim styles, or particular styles to suit particular types of patient.

A further stage in this research is currently being investigated, and that is the possibility of introducing surface modelling of the type discussed by Travis (1991) into the socket design and to determine the extent to which such surface modelling is an advantage and to what extent it is an unnecessary feature whose effect is to slow down the graphical representation by the requirement of further calculations.

## Conclusions

The major advantages of computer-aided design over conventional design are that because the entire shape is kept on the computer in a digital form, an accurate record of the shape and modifications made to it can be maintained. This has the benefit of increasing the predictability of the fit of a socket, especially where the design of a new socket for a patient is based upon the design of a previous socket for that patient but with minor alterations. Furthermore, the CASD system for trans-tibial amputees has introduced the powerful concept of computer graphics in the visualisation of the socket before its manufacture. This, together with the techniques of "patching" and "sculpting" the shape whereby regions ("patches") or individual points on the surface have their shape modified in a predictable and consistent manner, introduces a wide flexibility into the system.

An extension of the CASD approach for trans-tibial prosthetic sockets to trans-femoral prosthetic sockets has been developed, and a good degree of success is indicated by initial trials. The system offers to trans-femoral prosthetic socket design the considerable advantages of repeatability, consistency, ease of use and computer graphics visualisation before production, as offered by the trans-tibial CASD.

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