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Computer aided design of prosthetic sockets for below-knee amputees

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Abstract

A computer-aided sculpting system for use in prosthetics is described. The prosthetist's sculpting tools now consist of a computer, a graphics terminal, a mouse and an on-screen moveable cursor. Accompanied by the system software, these tools allow systematic modification of a primitive socket using techniques analogous to those used by a prosthetist working with rasps and plaster.

Introduction

In current prosthetic practice, prosthetists design sockets and cosmetically shape prostheses on a highly customized basis for every level of amputation. For socket production, a model of the stump is made by plaster casting methods, with or without the aid of jigs. Next, material is added to the model over areas which relate to pressure intolerant areas of the stump and shaved off in areas which are to be loaded for weight bearing. Both the plaster casting and modification procedures are performed on the basis of skill and judgement and take a considerable amount of time.

After the modifications are complete, a socket is fabricated over the modified mould. To free the socket, either the plaster mould is shattered, or the socket is driven off at the risk of socket distortion. This presents a serious problem. Once the mould shatters all shape modification information is lost. Thus, future fittings of the same amputee usually require the prosthetist to start from the beginning again. Even if moulds are retained, they present a significant storage problem.

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Thus, traditional socket manufacturing methods are plagued by inherent difficulties and in quantifying and recording the modifications used to produce comfortable sockets. This has a significant impact on the field because, as a result of this inability to quantify artisan techniques, expertise is gathered slowly by novice prosthetists and the quality of shape dependent prosthetic components varies from prosthetist to prosthetist.

Through the use of computer technology many of the problems cited above can be alleviated. The objective in developing an automated shape management capability is to overcome the shortcomings in artisan methods without losing the accumulated knowledge in the field. This development has been undertaken in a collaborative effort involving the Medical Engineering Resource Unit (MERU), University of British Columbia, the West Park Research Centre, University of Toronto, and the Bioengineering Centre, University College London (Saunders and Fernie, 1984).

The prototype CASD system

A prototype computer-aided display and sculpting system for use in prosthetics developed at MERU has been designed, so far as possible, to be compatible with current practices. Thus, the MERU Computer-Aided Socket Design (CASD) system software allows systematic modification of a 'primitive socket' using techniques analogous to those used by a prosthetist working with rasps and plaster.

The prototype system consists of an interactive software package written in PASCAL, operating on an IBM PC/XT microcomputer in conjunction with a VECTRIX graphics computer and monitor.

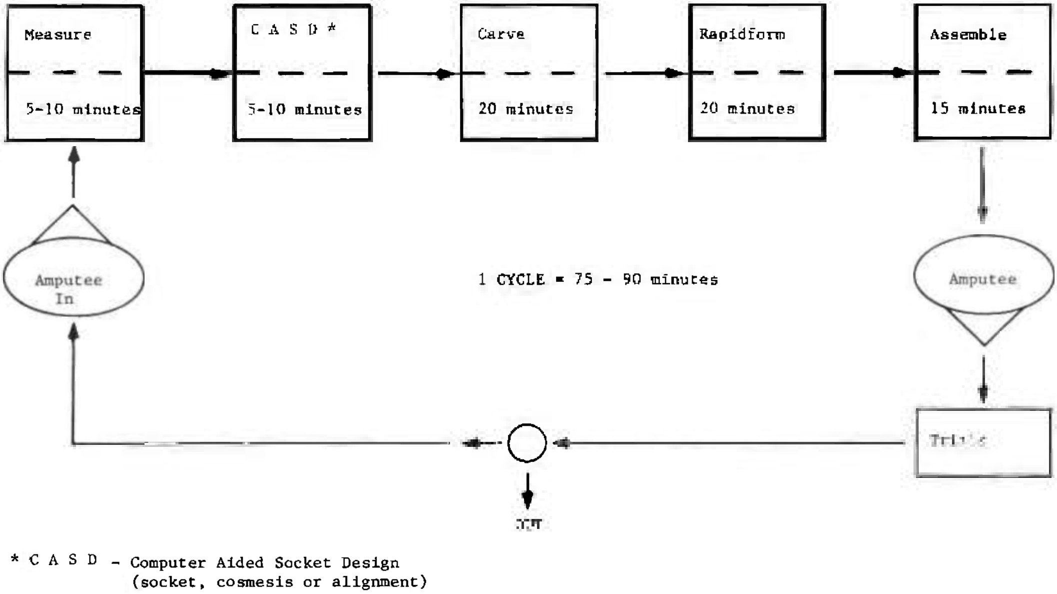

Fig. 1. Block diagram of the automated prosthetic fitting process.

While the focus at MERU has been on modifying a stylized primitive socket shape, the CASD software provides the capability to modify any desired shapes, including those obtained by shape sensing methods.

When the CASD system is combined with other automated elements, the prosthetist may have the most powerful set of tools yet devised for his field. As illustrated in Figure 1, the use of a computer-controlled milling machine and vacuum former enables a comfortable polypropylene socket to be produced in a turn-around time of less than two hours.

Interactive below-knee socket design—an overview

The first stage in the CASD software package is the recording of amputee stump measurements. The clinical measurement procedure is given in Figure 2, while the measurements themselves are shown in Figure 3. On the basis of these measurements, the primitive socket shape is scaled in size longitudinally and transversely. The operator may then view the scaled primitive socket and make interactive 'fine' modifications to it. As the prosthetist sculpts the primitive socket, the CASD software keeps track of each modification by storing the particulars of that modification on disk. Once the prosthetist has completed his modifications, the fully modified socket shape is also stored.

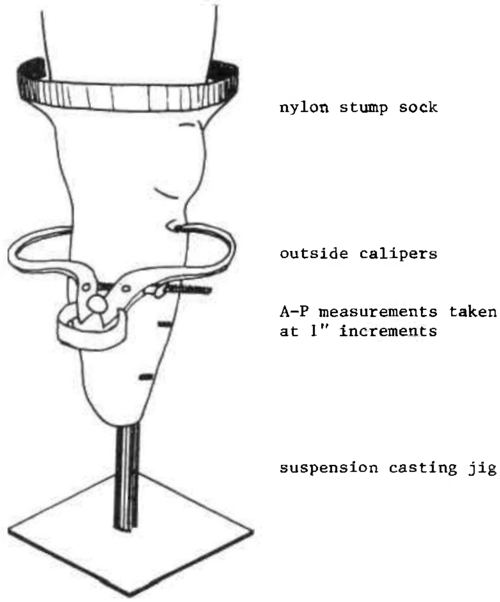

Fig. 2. Measurement of the stump.

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AMPFIT TRANS TIBIAL AMPUTEE MEASUREMENT FORM

Subject Number ______ Date amputated __________ Side _____
This date ___________________ Observer ______________________

MEASURE IN INCHES

Residual Limb Measurements in inches, seated and relaxed:

- Minimum Mediolateral Dimension 1" Above Femoral Condyles _____
- (for Condylar Suspension) distance above Tibial Plateau _____
- Mediolateral Dimension .... At Tibial Plateau _____
- Anteroposterior Dimension At Mid Patellar Tendon Level _____

Residual Limb Measurements, NU Suspension Casting System:

• Anteroposterior Dimensions		• Circumferential Dimensions	
At Mid Patellar Tendon	_____	At Mid Patellar Tendon	_____
1" below	_____	1" below	_____
2" below	_____	2" below	_____
3" below	_____	3" below	_____
4" below	_____	4" below	_____
5" below	_____	5" below	_____
6" below	_____	6" below	_____
7" below	_____	7" below	_____
8" below	_____	8" below	_____

- Length from Tibial Plateau to Tibial Tip .... _____

Sound Limb Standing:

- Mediolateral Dimensions .... Maximum Shank _____
  Minimum Shank _____
- Anteroposterior Dimensions .... Maximum Shank _____
  Minimum Shank _____
- Length from Tibial Plateau to Medial Malleolus .... _____

Residual Limb:

- Tissue Quality: Sparse( ) Soft( ) Heavy( ) Firm( )
- Maturity: Complete( ) Incomplete( )
- Shape: Tapered( ) Cylindrical( ) Bulbous( )

Suspension Plan:
Supracondylar( ) Suprapatellar( ) Cuff( )

Foot Size:
.... _____

Notes: ____
____
____

Fig. 3. Clinical measurement form.

A second program converts the socket data into a series of commands which instruct a computer-numerically-controlled (CNC) milling machine to carve a positive model of the designed socket. The Rapidform* microprocessor-controlled vacuum former is then used to produce the final polypropylene socket. Conventional procedures are used to prepare the trial prosthesis.

The CASD modificaion software

The CASD software package is made up of three major building blocks: a modelling component, a viewing facility, and an interactive modification capability. A primitive socket shape, which is actually a stylized (below-knee) socket shape, is modelled as a set of points in a cylindrical coordinate system. Viewing is accomplished by allowing the operator to select, via an on-screen menu, the cross-sections of the shape he wishes to see displayed. The interactive sculpting tools consist of an on-screen, moveable cursor and a mouse. These provide the operator with a means of altering the primitive socket shape.

Three types of modification are provided to transform the primitive socket shape into an appropriate shape for a specific amputee: scaling, tapering, and patching. Scaling involves sizing the primitive socket shape to fit a client securely in the knee area. Two caliper measurements, anteroposterior (AP) and mediolateral (ML) widths at the knee joint line on the stump, are compared to corresponding measurements from the primitive socket shape, and the primitive socket shape is scaled accordingly. Scaling does not attempt to account for differences in tissue bulk, but rather accommodates differences in underlying skeletal structure.

Tapering is required in order to account for differences in tissue bulk between the stumps of different amputees. It affects regions below the mid-patellar tendon level and acts in such a way as to compress tissue areas and leave bony areas unchanged. Once again, measurements are the basis for the modification; AP diameters are

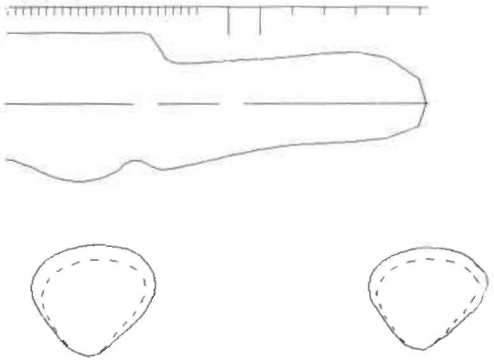

Fig. 4. Graphics display during taper modification.

taken, with the tissues compressed, at once inch increments down the stump starting from the mid-patellar tendon level. A facility is then provided whereby the operator can view the automatic tapering and decide if the contours designed by the computer are appropriate. The operator may then, in a 'manual overide' mode, refine the contours. This manual overide capability is necessitated because caliper measurements can sometimes be unreliable if they are not accompanied by objective pressure sensing. Thus, the prosthetist's judgement comes into play just as it would in a 'real' sculpting procedure.

Figure 4 shows the effect of the taper modification implemented on the CASD system. One set of cross-sections represents a socket for an amputee with significant muscle bulk and the second set of cross-sections corresponds to a socket for an amputee with sparse tissue bulk. The desired result is created by modifying the tissue areas, the bony areas remain unaffected.

The third type of modification, patching, provides the operator with the means for accommodating bony prominences and generating more load-bearing surface area. This is analogous to the removal and addition of plaster in strategic areas of a plaster cast. By modifying a single point within a specified region, the prosthetist indicates how much relief or compression is desired within that region. The software makes use of normalized Bi-beta functions (Duncan and Vickers, 1978) to automatically blend this new data point into the underlying surface. Since MERU's primitive

*Enquiries regarding the Rapidform vacuum forming machine should be directed to Prof. R. M. Davies, Bioengineering Centre, University College London, Roehampton Lane, London, SW15 5PR.

socket shape already has some relief and compressive surfaces 'built-in', patching is provided as a fine tuning tool. As a result, patch modifications rely on prosthetist judgement rather than physical measurement.

The effect of a patch modification on the head of the fibula is shown in Figure 5. Though the illustration shows relief being provided over the head of the fibula, it is important to realize that the same patch modification can be used to increase the load-bearing surface on the medial flare or to increase compression above the femoral condyles. Thus, the patch modification works equally well to add material to the primitive socket as to shave material away.

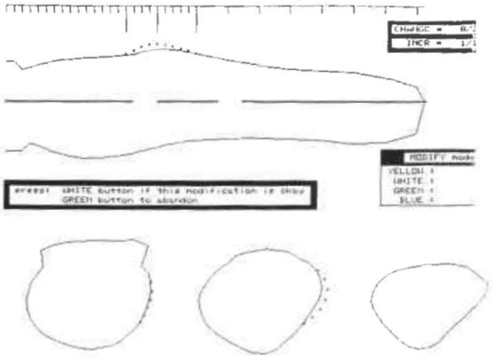

Fig. 5. Patch modification used to provide relief over the head of the fibula.

Computer-aided manufacture of prosthetic sockets

Once the socket shape has been designed on the computer, the next step is to obtain a three-dimensional replica of the shape. As a supplement to the CASD package, software has been developed which transforms the numerical definition of a socket shape into code which instructs a computer-numerically-controlled (CNC) milling machine to reproduce that shape. In this manner, a positive mould for production of the socket is obtained.

The CNC code is transferred to the milling machine from the computer via an RS–232 serial link. A polyurethane or wax blank is mounted on a rotary axis. During carving, a ball-nose cutter moves up and down as the rotary axis turns and the bed moves along. Thus, the cutter appears to move through a 'helical guide' as it traces out the suface of the shape. The small spiral ridge which appears on the carving can be removed by doing a second pass of the shape with a large diameter cutter. Corrections for possible undercutting of steep or double-curved surfaces are provided by the software (Saunders and Vickers, 1983). The resulting three-dimensional model is then used as the mould for vacuum forming or laminating the socket.

Discussion

The CASD system has the potential to be instrumental in the effective management of many shape related problems. Since the capacity to design trans-tibial or below-knee socket shapes is already available, the logical extension to the system is to include the capacity to design sockets for all levels and types of amputations. Eventually, it will also be possible to finish prostheses cosmetically based on pre-specified alignment and components.

The most important aspect of this type of automated shape management system is that shape information can be stored and retrieved very easily. With a client's original shape on file, modifications can be added to that shape at each subsequent visit. Also, shape dependent components which wear out can be easily recalled and therefore easily replaced. In this manner, the client is assured of a progressively better fitting socket and the prosthetist is assured of considerable time savings for repeat fittings.

Another important feature of the automation of the shape sculpting process is that design variations, which exist between sockets produced by different prosthetists, can also be quantified. Statistical information derived from this quantitative data can then be used to specify what the succsssful design practices are. This will then become part of the common pool of information and eventually a systematic approach to handling shape will evolve which will lead to universally high standards of interface comfort and cosmetic appeal.

In summary, automation of the shape managment process will capture the important aspects of current artisan methods and overcome their inefficiencies. Benefits of this approach include improved comfort for the amputee, reduction of costs, acceleration of prosthesis delivery, and universal quality of product.

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