

Fabrication of Prosthetic Sockets by Selective Laser Sintering

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Abstract

Solid freeform fabrication technologies offer exciting possibilities for improving product quality by direct manufacture of products. One example of such product improvement is the fabrication of artificial limb sockets by selective laser sintering (SLS). Currently these sockets are produced at the University of Texas Health Science Center at San Antonio by digitizing the residual limb with a 3D laser scanner, modifying this geometry appropriately using a proprietary CAD system, producing a mold with a computer-controlled milling machine, and vacuum forming the final product. This paper describes a new manufacturing technique whereby the digital socket data from the CAD system provide input to a SLS workstation to produce the final socket directly, without the intermediate step of fabricating a mold pattern. The advantages of this process include integration of the prosthesis attachment fitting and socket as one component and greater control of local socket geometry for superior stress relief characteristics.

Keywords

amputees, computer assisted design, computer assisted manufacture, prosthetics, solid freeform fabrication

Introduction

In the United States alone, there are more than 400,000 living limb amputees with approximately 60,000 new ones joining the ranks every year. (1) Ninety-seven percent of all these people are candidates for ambulation and could be fitted with prostheses (artificial limbs) if funding were available. The conventional procedure for fabricating and fitting the prostheses is more of an art than a science. It is non-repeatable and is extremely labor intensive. As pointed out by Klasson (2), there are so many amputees in the world today and many new ones joining with all the regional wars that are being fought that it would take approximately 70,000 new well trained prosthetist to take care of the present needs. It has been suggested by Foort (3)(4) that the only possible way of providing these hundreds of thousands of amputees with appropriate prostheses is to teach machines how to manufacture artificial limbs.

The most important aspect of a lower extremity prosthesis is socket design. The socket is the interface between the human and the mechanical support system. Ultimately, the design and fit of the socket is what determines patient acceptance, comfort, suspension and energy expenditure (5). All of these factors in unison determine the real utility of the final product.

The most common method for designing sockets requires a skilled prosthetist and time consuming manual steps (6)(7). First, the patient's residual limb is wrapped with plaster to acquire the shape. The plaster wrap is used to create a plaster positive. The prosthetist modifies the plaster positive of the residual limb to make a biomechanically correct pattern for a socket. The socket is molded over the pattern. It is necessary to destroy the pattern in order to remove it from the socket. Making a new socket involves repeating all the steps since the pattern is destroyed.

Computer Assisted Design (CAD) and Computer Assisted Manufacture (CAM) techniques are beginning to be used to design and manufacture sockets. Either a mechanical digitizer or a non-contact laser scanner (8) inputs the residual limb shape into the computer. The prosthetist then uses specialized software to produce a biomechanically correct socket from the limb shape. A numerically controlled milling machine carves the pattern for the socket from a plaster blank. The socket is then made using conventional molding techniques.

In all types of sockets, the remainder of the prosthetic limb must be attached to the socket. A fitting is bolted through the distal end of the socket or is attached with adhesive to the outside. (Fig 1.) This is a point of frequent structural failure. The other components of the prosthesis are attached to this fitting. The attachment point is somewhat arbitrary and cannot be exactly reproduced, even with current prosthetic CAD software. The socket design is not integrated with the design of the complete prosthetic limb.

All prosthetic CAD/CAM systems use a milling machine to produce a positive mold for a socket. The actual socket is then formed over the positive. Additional modifications need to be made to the positive mold to allow for attaching a fitting to the bottom of the socket. The fitting is used to connect the socket to the rest of the prosthetic limb. If no modifications are made for a bolt on fitting, then a fitting is attached with adhesive to the bottom of the socket.

It would be ideal to produce the socket directly and avoid producing a plaster positive. Attachment points could be molded as part of the socket. Areas of the socket could be selectively strengthened to provide additional support. The research reported here is an investigation into the use of solid freeform fabrication technologies to bypass the molding process by directly producing sockets with integrated attachments.

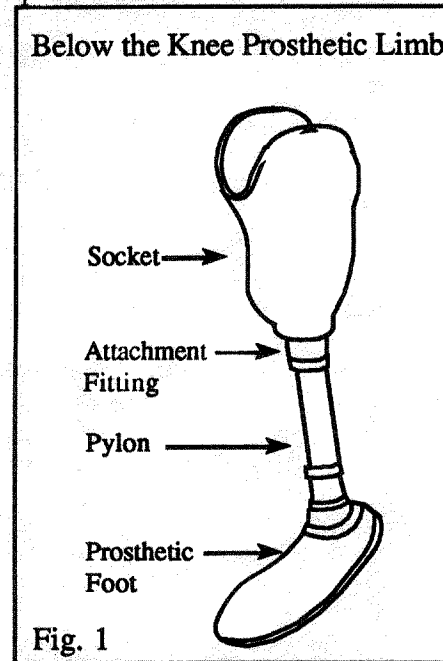


Fig. 1

Introduction to SLS

Solid Freeform Fabrication (SFF) technologies address the problem of creating three dimensional objects directly from a geometric database without specific tooling or human intervention. The research in SFF at UT Austin has concentrated on a particular process called Selective Laser Sintering (SLS). (9)(10) In SLS, components are built by material addition rather than by material removal by using a directed energy beam which causes individual particles to adhere in selected regions of space. The process begins by first depositing a thin layer of powder into a container. The powder surface is raster-scanned with a high power energy beam, such as a laser or electron beam. The intensity of the beam is modulated to sinter the powder in areas to be occupied by the part at that particular cross-section. In areas not sintered, the powder remains loose and may be removed once the part is completed. Successive layers of powder are then deposited and sintered until the entire part is complete.

Selective Laser Sintering has the potential to produce accurate, structurally sound three-dimensional solid versions of objects designed with a computer and to make such objects available in minutes or hours to the designer. The technology has been licensed commercially to DTM Corporation of Austin, TX, to produce parts composed of polymer

powders. Ongoing research at UT Austin is concerned with investigation of SLS of ceramic and metallic powders as well.

There are essentially no limitations on the shape of parts that can be fabricated by SLS. Geometric processing consists of two basic steps: slicing and rasterizing. The slicing operation is performed by intersecting the geometric description of the part with planes which represent each of the powder layers. The result is a series of contours which describe the part boundaries in each layer. Rasterization is the process of converting these layer contours into a series of laser toggle points. For this operation, each layer is divided into a number of scan lines. Each scan line is intersected with the contour boundary to produce the toggle points in a manner analogous to scan conversion algorithms used in computer graphics. (11) Where the scan line intersects the geometric description of the part the laser is alternately toggled on and off. The toggle points are then passed to the SLS process controller, along with other process parameters, and the part is produced.

Part accuracy in the SLS process is affected by the resolution of the geometry processing operations. Currently, parts are made with layer thicknesses of 5 mils. Typical scan line resolution within layers is 20 mils in both directions, although new process software is being developed which will increase the scanning resolution.

Prosthetic CAD/CAM at The Health Science Center at

The Departments of Rehabilitation Medicine and Radiology have developed a system for the computer aided design and manufacture of prosthetic sockets for below the knee amputees. The steps involved are the scanning of the shape of the residual limb of the amputee, the design of the socket from that shape, and the machining of a pattern to mold a socket over. A laser scanner and software to create sockets from limb shapes have been developed at the Health Science Center.

In this computerized system, a laser scanner is used to sense the shape of the residual limb. The scanner uses a laser to project a line on the limb and uses two video cameras to determine the location of the projected line in space. The laser and video cameras rotate on a turntable in order to see all sides of the limb. Video interface boards developed by the Department of Radiology are used to determine the position of the laser line in 3D space. These boards and specially developed software allows shape acquisition on a low cost IBM/PC.

Data from the scanner is then modified using an interactive 3D shape modification program. This program called "Sockets" has been developed by Rehabilitation Medicine. This program allows the prosthetist to modify the computer generated limb shape in much the same way it is done manually. The limb shape can be moved in 3D space as it is being worked upon. There are functions to modify the shape to that of a proper socket. In addition there are measurement functions to check circumferences, distances and volume changes. There are viewing functions to allow the user to see the before and after shapes overlaid in both cross section and 3D wireframe. The shape can be viewed in both wireframe and solid shaded modes. There are versions of "Sockets" for the Macintosh, IBM/PC, and Silicon Graphics computers.

A plaster pattern for the socket is then created using a numerically controlled milling machine. The socket is produced by molding plastic over the pattern in the conventional manner.

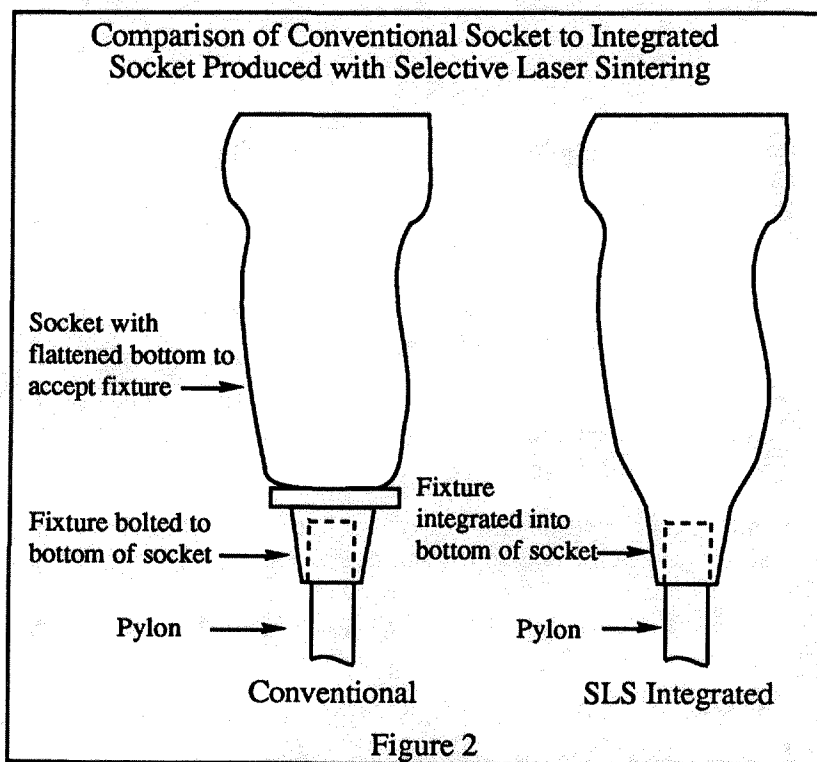
Using SLS to produce a socket

The prosthetic CAD data output from "Sockets" is not sufficient to produce a socket using selective laser sintering. Though geometric data comes from the prosthetic CAD program in the form of contours, the contours only describe the inside shape of the socket

and contain no information about attachments for fittings or the wall thickness of the socket. In addition, the typical contour thickness is much higher than that required for SLS (0.125 inch versus 0.005 inch).

A conversion program produces contours at the required resolution for the SLS system from prosthetic CAD data files. Software development was done on a Silicon Graphics 4D/25G. The conversion program allows input of wall thickness, a scaling factor, and the addition of an attachment fitting. The program outputs a data file in the contour file format used by the SLS system. This contour file describes the polygonal outline of each layer of a part to be manufactured by the selective laser sintering process. The format is keyword driven and handles contours with multiple loops. The loops are oriented both clockwise and counter clockwise with respect to the z-axis. Outer loops are oriented counter clockwise, while inner loops, representing holes, are oriented in the clockwise direction. If this convention is followed, the order of the loops within a contour definition is insignificant.

The conversion program looks at the socket as being four separate parts. There are inner and outer socket walls and inner and outer fitting walls. The outer socket wall is created by scaling the inner wall appropriately to achieve the desired wall thickness. The fitting is made of inner and outer cylinders of fixed lengths. All the parts are represented by sets of vertical splines. Spline interpolation is used to produce contour slices of any desired thickness. The fitting is geometrically intersected with the bottom of the socket, producing the integrated socket and fitting. The outer socket wall and outer fitting wall are written as counter clockwise loops while the inner walls are written as clockwise loops.



The integrated fitting is designed to accommodate a standard 30 mm pylon. A pylon location is completely reproducible as it is added during the design process rather than after socket construction. As can be seen in figure 2, the socket shape does not need to be distorted to accommodate a fitting. The integrated SLS socket preserves the anatomical shape at the distal end of the limb.

Results

The SLS contour data files are sent by Internet from the Rehabilitation Engineering Lab at the Health Science Center at San Antonio to a Silicon Graphics workstation in the Mechanical Engineering Department at UT Austin. The contour files are converted to rasterized toggle point files. Several parts have been produced from prosthetic CAD data. These parts were scaled down so that they could be produced quickly. They were made using polycarbonate powder at a 5 mil thickness. All the parts so far have been made using the prototype machine on the UT campus.

Discussion

More sophisticated mounting fixtures will be developed in order to swiftly fit patients. These will be adjustable in order to change the alignment of the prosthesis. The mounting fixture is currently added by a postprocessor. The addition of the fixture will be incorporated into the prosthetic CAD program. The initial alignment will be done in the design phase rather than after socket construction. This is a very important step toward computer design of the entire prosthetic limb rather than just the socket.

As experienced is gained new features will be tested. By varying the wall thickness, load bearing areas can be supported while retaining flexibility over sensitive areas of the residual limb. The cosmetic cover for the socket can be produced during socket fabrication. Other plastic compounds such as polypropylene will be tested as well.

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