CUSTOMIZED FOOT ORTHOSIS MANUFACTURED WITH 3D PRINTERS

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Abstract: A study was undertaken in order to manufacture an orthotic foot insole using 3D scanning and 3D printer. The shape of the customized foot insole was determined using structured light 3D scanning technology, 3D reconstruction of foot and then very specific 3D image processing in order to achieve the prescribed data for foot insole and to control the abnormal motion of foot during gait. These customized foot orthotics manufactured with 3D printers are expected to improve gait comfort and effort, improve foot-loading characteristics and reduce fabrication time and cost compared to conventional customized foot insole fabrication techniques. The paper shows all 3D model acquisition phases, model processing phases and manufacturing phases of a customized foot insole. The correct design and fit of customized foot insole determine patient acceptance, comfort and restoration of normal foot function.

Keywords: Foot orthosis, manufacture, 3D scanning, 3D reconstruction, 3D printer

1. INTRODUCTION

Foot orthotics are functional devices designed to correct and optimise foot functions. Orthotics can help the following specific foot conditions: Overpronation, Underpronation, Achilles Tendonitis, Corns, Metatarsalgia, Sesamoiditis, Ankle Sprains, Flat Feet, Neuroma, Plantar Fascitis, Arch Pain, Heel Pain, Dorsum of the Foot Pain, Bunions, and Toe Pain etc.

Overpronation or excessive pronation (offen caused by subtalar eversion, also called calcaneal valgus) is a complex movement which exhibits: calcaneal eversion, fore leg abduction and dorsiflexion. As a result, one has a tendency to walk on the inner border of the foot (Kirby, 2002). The opposite of pronation is underpronation or supination. Underpronation exhibits inversion, adduction and plantar flexion so that one has a tendency to walk on the outer border of the foot. Figure 1 shows the foot imprints, foot pronation and overpronation and right shoe-sole wear. Foot orthotics realigns the feet and ankles supporting the arches and restores faulty foot function.modified.

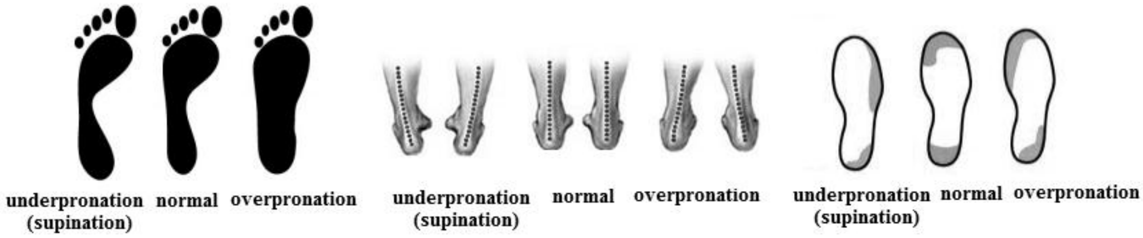

Figure 1. Foot imprints (left), feet pronation (center) and shoe-sole wear (right, view from inside)

There are 3 different types of orthotics.

- Custom made Orthotics: These orthotics are handmade or made with CAD/CAM or Rapid prototyping technologies.
- Customizable Orthotics: These orthotics are flexible insoles that can be heated to modify their shapes.
- Prefabricated Orthotics: Prefabricated Orthotics are insoles available from websites and pharmacies (Fig.2). After a period of wear, these insoles will partially customize as a result of body weight and heat.

Ergonomic orthotics have better designed arch support in order to reduce the pressure of the heel by distributing the tension over the rest of the foot.

Figure 2. Different types of prefabricated foot orthosis

The objective of this study is to fabricate an orthotic foot insole directly from digital foot shape using 3D structured light scanner, 3D printer and image processing techniques. All working steps from 3D scanning to computer aided fabrication of the foot insole through rapid prototyping are described and discussed.

2. MATERIALS AND METHODS

The most important aspects of a foot insole are insole design and qualities of insole material. The foot insole is the interface between the human and the shoe. The design and fit of insole determine patient acceptance, comfort and energy expenditure.

The manual method for designing insoles requires a skilled prosthetist and time consuming steps (Vicenzino, 2004) as in Fig.3. Final alignment of the prosthesis was performed using visual gait analysis and patient feedback.

Figure 3. Traditional method for forming foot insoles

Manual fabrication has a direct influence in the quality and in the operational costs. The prosthesis is geometrically irregular obligating the prosthetist to make adjustments. These adjustments increase substantially the fabrication time and costs and sometimes cause traumas to the patient.

CAD/CAM and Rapid Prototyping technologies were viewed initially as experimental even by the developers. Today, the CAD/CAM and Rapid Prototyping are considered as powerful and indispensable tools for the technological improvement in the conception and fabrication of the products (Rovick, 1992).

The methodology of the conception of prosthesis and orthosis depends on the production purpose. There are three main directions in prosthesis fabrication (Ciobanu, 2007, 2011):

- Manual manufacturing of customized prosthesis and orthosis;
- Manufacturing of customized prosthesis and orthosis using Rapid Prototyping technologies (Fig.4) ;
- Manufacturing of standardized components using CAD/CAM technologies, suitable especially for large series production of prosthesis and orthosis components and assisistive technology devices. (Fig.5).

Customized fabrication through Rapid Prototyping requires next main steps: 3D scanning of the anatomic surface, 3D surface reconstruction, building of CAD model and converting to STL format and finally machining using a special Rapid Prototyping machine (3D printer) controlled through computer (Fig. 4).

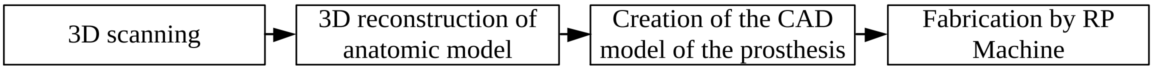

Figure 4. Phases of Rapid Prototyping fabrication

Fabrication through CAD/CAM techniques, for large series production has next main phases (Fig. 5):

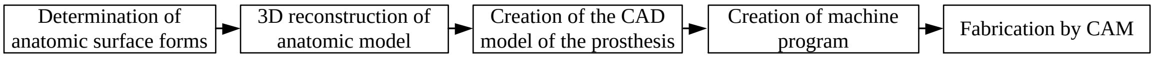

Figure 5. Main steps in the CAD/CAM technologies for customized prosthesis

Determination of anatomic forms can be done in two ways: through manually measuring and computing and through scanning with devices based on X rays, video camera, laser or other techniques (Telfer, 2010).

3D reconstruction of anatomic surfaces can be performed using different types of software, starting from CAD software (AutoCAD, Solid Works etc) or dedicated software (Mimics, 3D Doctor etc).

Creation of the CAD model can be performed in two ways:

- Generating the model starting from the 3D reconstruction model and using dedicated software in the case of customized prosthesis;
- Generating the model using CAD software and starting from standard dimensions in the case of large series production of implants or prosthesis.

CAD models of prosthesis have to be accomplished by surface adjustments. Once the model is captured and reassembled, the 3D model is modified to achieve the desired design by using a variety of software tools.

Creation of the machine-program is necessary in order to transform the geometric data of prosthesis in commands compliable to Computer Numerical Control (CNC) machine tools.

CAD/CAM fabrication is the final processing phase and is based on the use of CNC machine tools, controlled through computers or numeric equipment.

Most known materials used in Rapid prototyping manufacturing are ABS (Acrylonitrile butadiene styrene) and PLA (Polylactic Acid). ABS is a polymer commonly used to produce car bumpers due to its toughness and strength. PLA is a biodegradable thermoplastic that has been derived from renewable resources such as starch prepared from the grains of corn.

The foot orthotics made with 3D printers are expected to improve gait comfort and effort characteristics and to reduce fabrication time and cost compared to manual customized foot insole fabrication techniques

3. RESULTS

Paper describes all steps used in the data acquisition, reconstruction and fabrication of a foot insole made of acrylonitrile butadiene styrene (ABS).

In the first step, data acquisition is accomplished using noncontact 3D scanner (Artec MH) with structured light (Fig. 6). The scanner projects a structured light onto the foot of a patient. The Artec MH 3D Scanners use video camera technology with structured light and capture a multitude of frames.

Figure 6. Artec MH scanner

The frames are combined automatically (in the scanner software) into a single 3D mesh, in the 3D reconstruction step. The mesh represents the 3D surface model of the foot (Fig.7 left).

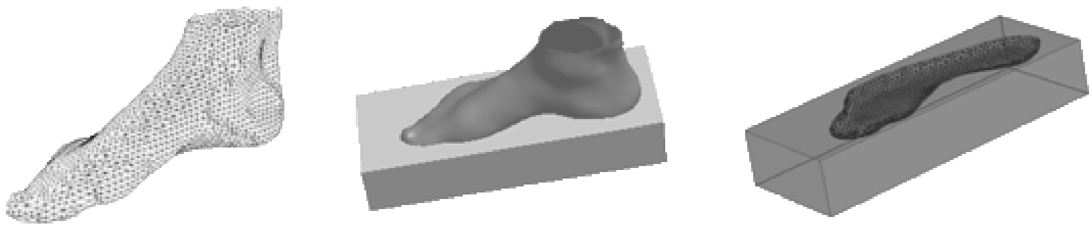

Figure 7. The 3D model of the foot (left), foot imprint process (center) and final imprint (right)

Peculiar attention has been given to the image processing steps from 3D reconstruction to the final 3D CAD model of the foot insole.

In order to obtain the foot imprint, a box was created in 3D graphic software in contact with the foot model. The 3D surface model of the foot (Fig. 7 left) was combined with the 3D model of a surface box. Figure 7 (center) shows the 3D foot model overlapped with the model of a box. The 3D foot model was then subtracted (Boolean operation) from the 3D box model. After the foot subtraction, the 3D shape of the foot was imprinted in the box model (Fig.7 right). Boolean operations with 3D surface models may be performed with 3D graphic software like Studio Max, Blender (free software), AutoCAD (special add on) etc. The surface box was then saved as 3D model of foot imprint (Fig. 7 right). In order to manufacture a foot insole which properly fits a foot of a customer, the foot angles of the customer's foot (Fig. 8) are measured.

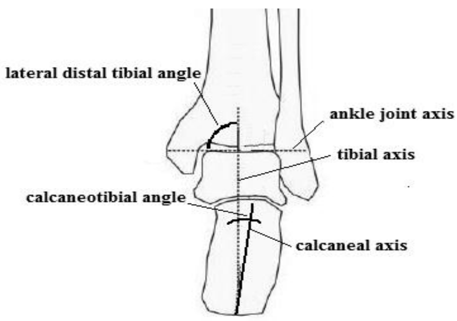

Figure 8 Foot angles (view from rear)

The foot angles are of the most critical information in custom-made manufacturing of foot insoles. Conventionally, the angles of inclination of a human foot are measured by an orthopedist, physiotherapist, artificial-limb orthotist, shoe fitter etc. while the foot is being examined by touch. Modern measurement methods include different technologies based on image recording.

The orthotic technician has to include in the foot insole model all dimensions, angles (as in Fig. 9), adjustments and details as prescribed by the podiatrist in order to restore faulty foot function.

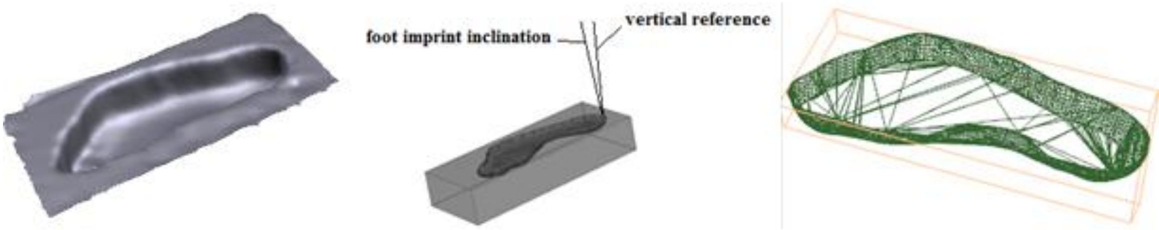

Figure 9. Adjusting imprint depth (left), inclination (center) and cutting foot insole shape (right)

Also, technician has to fit the foot insole and the shape or the last (straight, inflared or outflared) used by shoemakers in the manufacture of shoes (Fig.9 right). Final shape of foot insole has to be saved in STL format. Final modifications can be done with different editing functions in any 3D modeling software.
In the final step, the 3D model of the foot insole was transferred to the software of a 3D printer, BFB 3D type (Fig.10) in order to convert CAD model to 3D print data (www.bitsfrombytes, 2012).

The BFB 3D Touch printer has multi-material free forming capabilities, 3D printing volume of 275x275x210mm³, and 125μm layer thickness. This printer is one of the most affordable 3D printers in its category and is on the market for about euro 3,000.

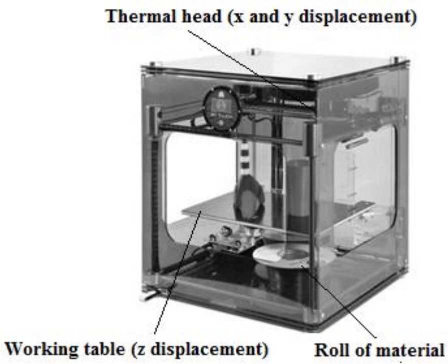

Figure 10 The BfB 3D Touch printer

The printer use melting or softening material (ABS or PLA) to produce the layers of the object. Figure 11 shows the 3D foot insole created by the 3D printer.

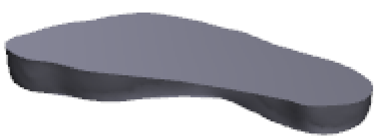

Figure 11. The 3D printed foot insole

4. DISCUSSION

Table 1 shows a comparison between manual and computer aided manufacture of prosthetic components. Equipment and software costs are presented in order to know the benefits and drawbacks of computer aided fabrication.

Table 1. Comparison between manual and computer aided manufacture of prosthetic components

Categories	**Manual manufacture**	**Computer aided manufacture**
Raw material	Classic materials	Special materials for 3D printers
Computer aided equipment	No	3D Scanner, 3D printer, PC
Software	No	Scanner and CAD software
Qualification, training	Basic training	Basic training + scanner, CAD and 3D printer training
Modification of design	Difficult	Very fast modifications
Equipment costs	Basic	Euro 12,000 for scanner and software; 3,000 3D printer;
Raw material costs	Basic	Euro 750 for 1,8 kg (liquid) or Euro 2 or 3 per rendered cubic inch (powder)
Main advantage	Low investments	High productivity, fast design and modification
Main disadvantage	Low productivity	High costs of printing materials

Although new CAD/CAM and Rapid Prototyping fabrication techniques appears, the prosthetics and orthotics industry has not yet taken full advantage of the possibilities in computer aided manufacture. The teaching of prosthetics and orthotics must also keep pace and evolve with the expanding technologies in fabrication of medical devices. Practitioners must also be taught about the benefits and drawbacks of computer aided fabrication.

5. CONCLUSIONS

The study showed the feasibility of the use of 3D scanners with structured light in the scanning of anatomic surfaces and of the 3D printers in the fabrication of foot orthosis. Proposed solutions use the most economically computer aided equipment and software in this domain. Also solutions may help the medical staff having poor engineering skills to fabricate orthosis or different pieces for orthosis and prosthesis.

Most important advantages of the use of rapid prototyping technologies (3D scanners) are: speed, repeatability, material uniformity and digital image capture.

Prices for optical scanners, CAD software, and 3D printers range widely and have gradually come down over time.

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