3D-Scan to Knit - Workflow and Challenges of Automated Data Processing and Knit Program Generation for Prosthetic Liners

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Abstract

This work presents the current development state of an automated algorithm for creation of knitting instructions for prosthetic liners directly from 3D scan data. This is a knitted medical textile worn by amputees, which on one hand mediates between the residual limb and the prosthesis and at the same time has to ensure appropriate protection and hygiene. Although the shape of the residual limb is very individual, liners have so far been manufactured in standard sizes. In the presented case, 3D scanning is used to obtain the geometry of the residual limb. The raw data is cleaned and adjusted manually and prepared for automated processing. The algorithms for slicing and preparing the intermediate knitting instructions are developed in Python language, using several functions inside of the open-source software Blender. The information for the loops of the knitwear is saved in intermediate bitmap (knitting chart), which is finally imported in specialized software for knitting machine design and used for the generation of the final program.

Keywords: 3d body scanning, automatic processing, prosthetics, medical textiles, knit program generation

1. Introduction

When constructing close to the body-bodywear, achieving a precise fit is always a challenge. It requires large set of individual measurement and custom pattern creation. Obtaining individual measurements is a time-consuming process and requires a lot of skill and experience. Achieving a precise fit is historically done by tailors who take care of the measuring as well as the complete design and manufacture of the clothing. However, this customization has low productivity, making the end products expensive.

3D body-scanning technologies represent an alternative to manual measuring, allowing obtaining accurate and reproducible physical measurements, with considerably less effort [1, 2]. Higher accuracy, lower cost and computer implementation of the method enables new ways of manufacturing high precision bodywear. This is particularly relevant for customization of tight-fitted garments and garments that are subject to stress.

A kind of garment with very high requirements towards fit are prosthetic liners. Those are stocking-like medical textiles which are used to cover the residual limb that remains after an amputation (see Fig.1). They serve as a transition material between the residual limb and a prosthesis [3] – thus, they are placed ad a highly vulnerable and sensitive area that at the same time is often placed under stress and worn for up to 16 hours per day. Prosthetic limb users often require multiple fittings to find an acceptable liner and still report discomfort, which may limit their rehabilitation progress [4]. Consequently, ensuring a proper fit of the prosthetic liner plays a critical role in mitigating both dermatologic problems and discomfort to ensure successful rehabilitation. However, given the shape of the residual limb varies greatly across patients, highly customized designs are needed for achieving both functionality and comfort in the liner. Studies highlight the superior efficacy of custom prosthetic liners compared to conventional options, particularly in alleviating stress concentrations within sensitive and painful areas of the residual limb [3, 5].

Achieving a more precise prosthetic fit requires individual limb measurement and pattern design. The aim of this work is to present current state of the development of an automated workflow from 3D-Scanning a residual limb to knitting a liner at the Chair of Development and Assembly of Textile Products, ITM, TU Dresden.

a) b)

Fig. 1. a) Components of a lower limb prosthesis [6]. b) Illustrative variations in prosthetic liners, diverse lengths, structures, and compositions.

2. State of the art

2.1. 3D Scanning & 3D-Based Measurement

3D Scanning is a non-contact measuring method used to obtain and digitize the physical geometry of a real-world object. This method often employs specialized software and hardware (3D scanners), normally operable by a single person. Various technologies and designs for 3D scanners exist, each based on different principles. However, the fundamental concept involves capturing information about distances, angles, or times between the scanning device and points on the object's surface to build a precise 3D model [7].
As technology advances and hardware becomes more affordable, more and more industries adapt 3D-scanning for various causes. Current notable use-cases include reverse engineering for rapid prototyping and development of industrial tools and devices, monitoring in hazardous environments like nuclear facilities, artifact, and artwork preservation within museums, identifying imperceptible dents during aircraft inspections, integration of CGI effects in movies, and precise 3D body measurements for capturing human form and dimensions [8–10].
Body measurement using 3D-scanning technologies is faster and more convenient than measurement with traditional methods. In the fashion and bodywear industries, it is used particularly for the development of size charts and virtual model fit trials as customization strategies. [1, 11, 12].

2.2. Obtaining a knitting pattern from a 3D object

The knitting technology allows production of spatial structures directly from yarn. Therefore, direct knitting of 3D models is theoretically possible. Prior works have already explored digitized fabrication of custom-fitted structures by knitting. Šurc et al. [13] developed an end-to-end knitwear pipeline using 3D body scans and automated pattern generation, though their focus was rather mass customization over individual fit. Narayanan et al. [14] enabled automated knitting pattern creation from 3D models. Their method converts digital meshes into instructions for a computer controlled knitting machine, by remeshing into quad-dominant structures and tracing knitting paths. While the feasibility of pattern creation based on 3D objects is evident, integrating these methods into established workflows is challenging. Specifically, because generating machine code for knitting requires specialized, vendor-specific software for both creation and validation, making seamless integration difficult.

2.3. Residual Limbs, Liners & Phantom Pain

Very serious injury or illness may require partial or total amputation of a limb. In case of a partial amputation, the remaining portion of the arm or leg is termed the residual limb. Loss of a limb causes permanent disability and requires extensive subsequent physical (and psychological) rehabilitation. This holistic process will vary depending on factors like medical condition and limb status, but ideally involves an interdisciplinary approach, comprising of medical treatments, pain management, emotional support, reintegration assistance and if possible, the use of a prosthesis to substitute the missing limb [15, 16]. Adapting to life after amputation is a complex, lifelong journey. Patients must adjust to prosthesis demands and potential discomfort sources [17]. Unfortunately, residual limbs are prone to various conditions including infections, swelling, phantom pain, and dermatologic problems [18, 19].

While many factors influence residual limb issues, fit is key. For instance, Ibbotson et al. [20] identified mechanical deficiencies from poorly fitting sockets as the main cause for the development of follicular keratoses, a dermatologic condition.
In addition to physical discomfort, cooling and thermal regulation are important factors for residual limb health. Heat buildup within the prosthetic socket due to ambulation or environmental factors can cause discomfort and skin issues if not dissipated [21]. Thermo-regulating liners aim to maintain optimal skin temperature during activity [22].
Many amputees suffer both residual limb pain and phantom limb pain, with phantom sensations perceived from the missing part of the limb [23]. Residual limb pain directly at the amputation site affects a significate portion of most amputees (67.7%), while up to 80% experience phantom limb pain [24]. Treatments range from limb desensitization to transcutaneous electrical nerve stimulation (TENS), which places electrodes on the skin to modulate nerve transmission [25, 26]. Although often transitory, for many patients, phantom limb pain and/or residual limb pain can be very disabling or bothersome, requiring multidisciplinary pain management integrating physical, medical, and psychological techniques [27].
A prosthesis is not directly attached to the residual limb. Instead, it is connected to the limby by a so called “liner”. The liner is an interface that is in direct contact with the residual limb on the inside and the prothesis on the outside. It can be a knitted structure coated with silicone or be made of elastomeric materials (gel or silicone) only (see figure 2). Silicon is chosen because of its biocompatibility, flexibility and high friction coefficient with skin [5, 28]. The connection between Liner and prothesis is either facilitated only trough friction, or by using a pin, which is attached to the liner and locks into the prothesis [29].

Fig. 2. Knitted liner with integrated polymer gel layer.

The liner propagates and distributes normal shear stresses between the limb and the prothesis; protecting the residual limb tissues and sensitive regions such as bony prominences that are not accustomed to bearing loads, while it also facilitates limb heat transmission and enhances comfort [3, 30, 31].
Given the sensitivity and multiple issues to which residual limbs are exposed, proper fit between the residual limb and prosthetic socket is thus critical for comfort and rehabilitation [32–34]. Consequently, more individuals with lower extremity amputations prefer custom prosthetic liners over generic mass-produced versions [3].

3. Aim & Requirements

The overall aim of the current work is to deliver a workflow for orthopedists, textile product engineers and manufacturers of medical textiles, which enables those involved to produce individually adapted liners with little additional qualification effort. The planned workflow begins with the scan of the residual limb, includes data processing, pattern making, production of the liner and ends with additional adjustments by the orthopedic surgeon if necessary.
The liner should have good thermal conductivity to allow body heat to be regulated and have electrically conductive components that allow TENS therapy without the patient having to remove the liner. The professionals involved should be spared as much additional work as possible. At the same time, the workflow must remain accessible for any additional corrections or modifications.

4. Workflow

The developed workflow essentially involves the three main steps (Fig.3).

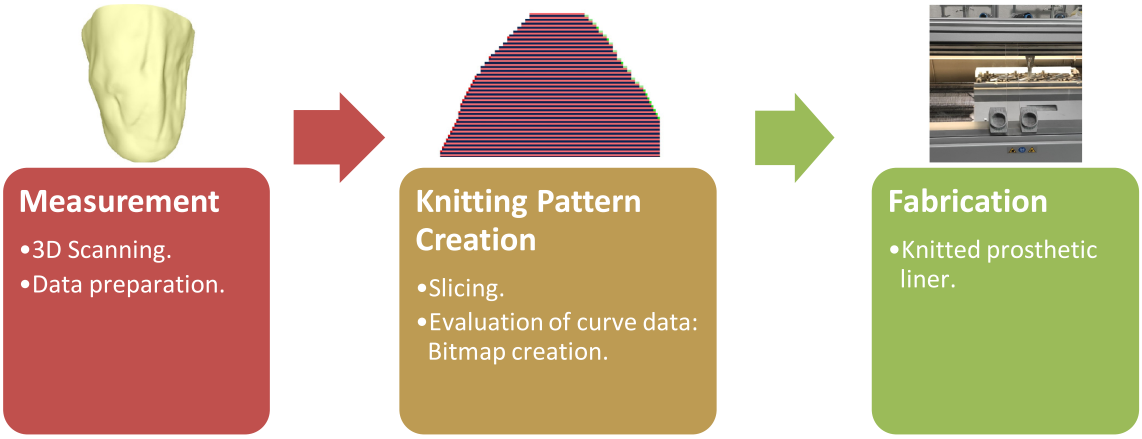


Fig. 3. Workflow from 3D scanning to individual knitted liner. (Left) 3D Model. (Middle) 2D Knitting pattern. (Right) Knitting of the prosthetic liner.

4.1. 3D-Scanning and Data Preparation

The first steps are the 3D scanning and the processing of the data. The residual limb of a patient is scanned using a handheld 3D scanner, capturing highly accurate surface geometry data (Fig. 4).

a) *b)*

Fig. 4. a) Scanning process, b) Raw 3D scan data.

3D scan data is then processed and refined into an accurate 3D model of the residual limb. The raw 3D scan data usually requires post-processing and alignment. Further refinement and smoothing of the raw aligned model are also essential, involving the elimination of fragments, noise, and protrusions from the model. Although automated alignment methods exist, generally, is necessary to initially undertake one or several manual alignments (Fig. 5) to match overlapping regions among limb scans based on geometry and texture, particularly when the raw data is visibly misaligned.

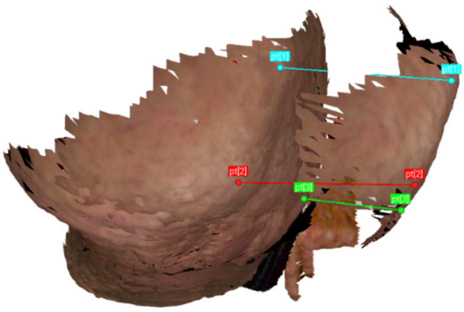


Fig. 5. Alignment process.

Multiple iterations are usually required to progressively enhance alignment while minimizing surface holes and gaps (Fig. 6.a). Once the scans are scans tightly aligned, the creation of a unified polygonal 3D model surface becomes feasible (Fig. 6b).

a) b)

Fig. 6. a) Model after multiple Global registrations, b) Polygonal model.

Subsequently, the surface requires manual smoothing, particularly in regions where holes were present and automatically filled, which effectively eliminates extrusions not originally part of the limb's shape. Finally, an automated smoothing step is performed to achieve a natural appearance. The resultant output is trimmed ensuring the preservation of the residual limb's area of interest and then exported as a high-precision 3D model, faithfully representing the limb's geometry (refer to figure 7).

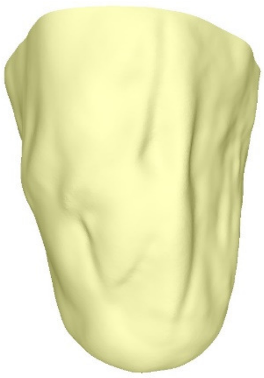
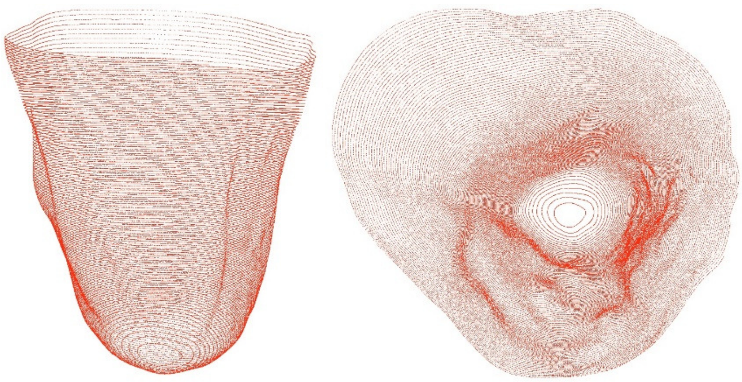


Fig. 7. Final 3D Model of the Residual Limb.

4.2. Knitting Pattern Creation

Focusing on establishing the full workflow and avoid long development cycles, we chose to develop own, less sophisticated method of pattern creation. In a first step, the 3D-model of the stump is sliced along the z-axis, which runs roughly along the bone in the limb. The slicing takes place incrementally with the height of the rows of stitches, which results from the machine configuration and the material used. The slicing produces anatomically contoured cross-sectional curves representing the shape of the limb at each row (Fig. 8).



a) b)

Fig. 8. Sliced 3D object: a) Front view, b) Top view.

The length of the curves can then be calculated by summing up the Euclidean distances of all the curve's points. Figure 9 shows the progression of the curve length along the z-axis.

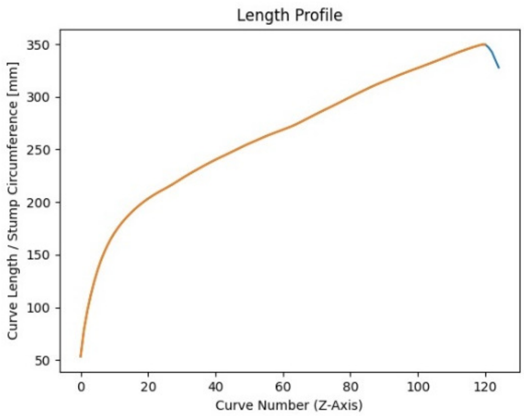


Fig. 9. Circumference of the profile as function of the z-axis.

Based on the calculated curve lengths, a knitting chart is derived. A knitting chart is usually presented as a grid, with each square representing a type of stitch to be worked. For example, a filled square might represent a knit stitch, an empty square might represent a purl stitch, and various other symbols can represent different types of increases, decreases, transfers, or special stitches. A simple knitting chart can be drawn as a raster graphics image, where the pixel (smallest unit) of the grid corresponds to a knitting stitch. To illustrate a knitting pattern structure, grids' squares are filled with different colors [35].

Based on the gauge of the machine, the number of needles that is necessary to knit a row (or corresponding front- and back row) can be calculated. This then allows the representation of each curve on a bitmap. As these bitmap lines also define the knitting machine's fabrication path, certain constraints have to be met when constructing the knitting chart. Specifically, the knitting machine cannot (easily) perform diagonal loop transfers between needle beds. Therefore, a new row should start at the same needle index as the previous one. The whole workflow was implemented with Blender 3.6 [36] and a Python 3 [37] script.

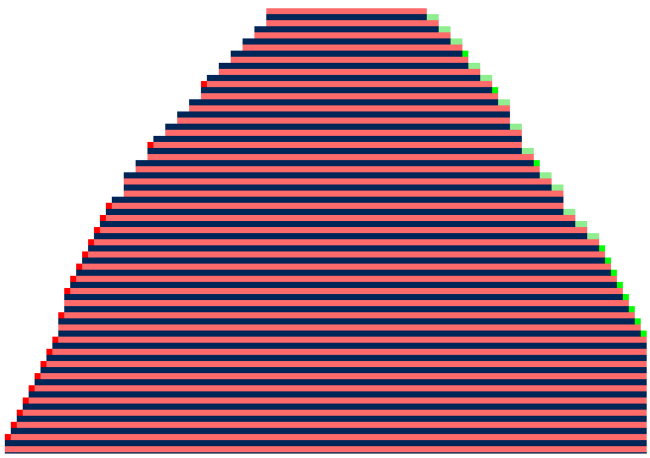


Fig. 12. Generated knitting program as resulting Bitmap

4.3. Fabrication

Based on generated bitmap with the knitting pattern, the knitting program for the knitting machine can be created. Usually, knitting machines use vendor-specific programming languages for the knitting program. A special dedicated software platform can be used to interpret the knitting pattern and generate a valid knitting program for the knitting machine.

In the current work CREATE PLUS [38] of Karl Mayer Stoll was used to create the knitting program and a Stoll ADF 830-24 KI computerized flat knitting machine for knitting the prosthetic liner.

Conclusions

We presented a workflow for automatic creation of program for knitting prosthetic liners based on 3D scanned data. Although the scanning hardware produces good results, manual data refinement is still necessary before the model can be processed any further. An intermediate bitmap for import in specialized knitting software allowed independence of the 3D processing algorithm from the machine type and instructions. This gives the knitters the freedom to adjust and validate the settings for the machine in their vendor specific software.

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