Automated Shoe Last Customization using MATLAB Algorithm

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Keywords: Shoe Last, Customization, Cycling, Automated, Algorithm, CAD.

Abstract: Footwear plays an essential role in human daily life as properly fitting and comfortable footwear will significantly improve human lives and productivity. Footwear customisation techniques aim to manufacture footwear that fits an individual's foot geometric. Footwear that exactly fits a person's foot geometric will provide more support and reduce impact when walking or when doing other activities. A customised shoe last is an important tool used by shoemakers in manufacturing customised shoes. Currently, most customised shoe lasts are made from the moulds of clients' feet and all the measurements are done manually, which is a tedious and time-consuming process. This project aims to develop a novel MATLAB (2017) algorithm that will shorten the shoe last customization process and do so with higher accuracy. This MATLAB algorithm can reconstruct the foot model to smooth the surface texture and rearrange the three-dimensional (3D) model vertices for easier dimension calculations. It can also locate makers on first and fifth metatarsophalangeal joint automatically for more accurate shoe last design. The shoe last developed using the novel algorithm was used to create its equivalent negative moulds for the manufacturing of carbon fibre cycling shoes. The negative moulds were 3D printed and used to produce a prototype of cycling shoes. Future research needs to consider developing an automated algorithm to create negative moulds to speed up the cycling shoe manufacturing process.

1 INTRODUCTION

Footwear is necessary in human daily life, as it is designed to protect the foot from external pressure and improve walking and sports performance. Well-fitting footwear is important to provide support and enhance user comfort. Ill-fitting footwear can cause injuries and foot shape deformation, which will reduce gait quality (Terrier et al., 2009). Finding the right pair of shoes with the correct fit is important for athletes, particularly with the emergence of competitive sports. Therefore, footwear must not only be designed to fit the users properly and to improve comfort, but also maximize athletic performance and minimize injury (Luximon et al., 2009, Werd et al., 2010).

Footwear customization is an essential aspect of manufacturing footwear that fits an individual's feet geometrics and dimensions to improve fit and user comfort (Davia et al., 2013). The shoe last is an important tool that determines the design, shape, size and, more importantly, the fit of the final product during the footwear manufacturing process. The production speed of shoe last is very important in shoemaking industry, in order to decrease the overall shoe production budget in terms of time and money (Zhang et al., 2012).

There are two main methods in manufacturing customised shoe lasts: (i) the traditional method; and (ii) a computer-based method (Telfer et al., 2010). In the traditional footwear manufacturing method, shoe makers use plaster to form a client's foot geometric in a mould. Then, footwear will be made according to the mould (Figure 1), normally known as shoe last. The manufacturing of a shoe last through the traditional method is done manually and through a trial-and-error approach that is a purely artisanal and based on the shoemaker's experience to fit specific feet dimensions. It is an arduous and complex process that takes a lot of time to manufacture due to constraints imposed by the manual measuring of several feet's dimensions (Leng et al., 2006).

Nowadays, with an increasing cost of labour even in developing countries, there is great interest in

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Pang, T., Soh, K., Ryan, S. and Dabnichki, P.
Automated Shoe Last Customization using MATLAB Algorithm.
DOI: 10.5220/0007949301170122
In *Proceedings of the 7th International Conference on Sport Sciences Research and Technology Support (icSPORTS 2019)*, pages 117-122
ISBN: 978-989-758-383-4

manufacturing and design automation in the footwear industry. The footwear customisation process can become a lot easier when a computer-aided design (CAD) system is introduced into this process. Shoemakers start by using a three-dimensional (3D) camera to scan the plaster last and user's feet (Figure 2) and then import the scan into CAD software for further editing and processing (Weisedel, 2007). This CAD modelling technique can speed up the prototyping process of customising shoe lasts, which saves manufacturing time and money (Jimeno-Morenilla et al., 2013). 3D scanning and CAD techniques can also recognise landmark positions on a foot scan accurately for more reliable measurement results, with less than a 2mm error (Luo, 2010). However, due to the complexity of the data, the 3D foot scan model post-processing and analysis process can be tedious and time-consuming. Significant error might occur during the analysis process because of low consistency. After the 3D data has been post-processed, shoe lasts will be produced through either the additive manufacturing processes, such as 3D printing, or the subtractive manufacturing processes such as computer numerical control machining.

Figure 1: Plaster foot mould sample.

Cycling shoes, like many other footwear, has seen a paradigm shift in its design and manufacturing processes. Some manufacturers are now offering custom-tailored and handcrafted cycling shoes to fit a specific person's feet. For instance, Simmons Racing (Simmons Racing©, 2019) offers fully customised cycling shoes made out of carbon fibre, but its process requires manual casting of a mould, which is very time consuming and costs about US $2000 a pair.

The cycling shoe is unique when compared with other athletic shoes. The sole of the cycling shoe serves as the rigid link between the foot and pedal, whereas the pedal serves as a link between shoe sole and crank arm of the bike (Werd and Knight, 2010). Hence, cycling shoes normally have a stiff or rigid sole. According to Langer (Langer, 2010), cyclists try to fit their cycling shoes as snugly as possible to minimize any motion of the foot inside the shoe in order to maximize energy transfer to the foot-shoe-crank arm interface. The foot arch, heel cup and toe box structures are the three most important parts to consider when designing a pair of customized cycling shoes. These are the parts that are required to fit the user's feet perfectly to achieve maximum support and minimum side-to-side pressure in the toe box area.

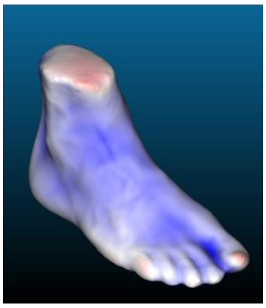

Figure 2: 3D scanned image of a user foot from plaster last.

Our project aims to develop an automated 3D design algorithm to create a customised cycling shoe last from the digital data scanned from an individual's foot shape. It is envisaged that this novel algorithm will reduce the time required for the post-processing phase and improve consistency and accuracy when reconstructing the raw scanned data. A reconstruction method is applied in this algorithm because it can repair holes in the foot model and smooth the surface texture to reduce noise. The algorithm will speed up manufacturing by casting a user's foot as a mould for a bespoke shoe last to manufacture customised cycling shoes.

2 METHODOLOGY

The detailed design process of the algorithm foundation is presented in this section. It is separated into (1) foot data collection, (2) post-processing, and (3) the raw data sectioning concept development and MATLAB code development phase.

2.1 Foot Data Collection

All 3D foot scanned data used in this project are collected using an INFOOT 3D foot scanner (Figure 3(a)). Five markers were placed on a user's feet before the scanning process, as shown in Figure 3(b). The INFOOT scanner produced the raw scanned data as a binary CADfix Geometry Database File (FBD) that includes the position of markers.

Figure 3: (a) Infoot scanner [I-Ware Laboratory Co., Ltd], (b) Landmark locations.

2.2 Post-processing and Intersection Foot Model Reconstruction

The raw scanned data were post-processed to remove noise and unwanted parts, as well as to patch holes using a CAD software. Figure 4 shows the raw scanned data and the cleaned foot model after post-processing in Standard Tessellation Language (STL) format.

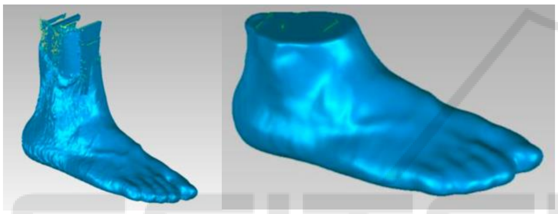

Figure 4: (a) Raw scanned data, (b) cleaned foot scan model after post-processing.

2.3 MATLAB Script Development

MATLAB was used to develop an automated algorithm that expressed matrix and array mathematics directly. The flowchart in Figure 5 describes the brief MATLAB algorithm development process.

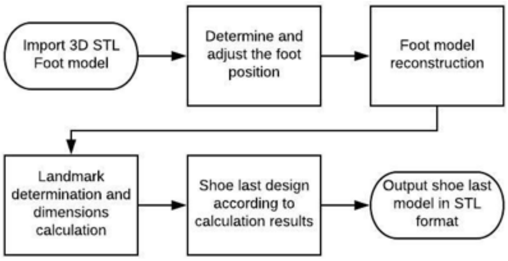

Figure 5: MATLAB algorithm development process flowchart.

The foot scan data was converted into a vertices and faces matrix when imported into MATLAB by using stlTools. Figure 6 shows the imported foot model in MATLAB. All the vertices are connected by faces triangles, which are presented in red, while blue lines are the edges that form triangle faces.

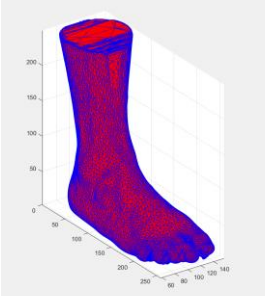

Figure 6: 3D scanned foot model imported in MATLAB.

2.3.1 Determining the Position of the 3D Foot Model

After the scanned foot data was imported into the MATLAB environment, the first step was to detect the pointing direction of the foot's scanned data. Due to the different system used to scan the user's foot, the position of foot models was not always placed on x-axis; rather, they were randomly positioned on of either positive or negative x and y axis. After ascertaining the position of the foot model, the algorithm needed to relocate the foot model to a fixed positive x direction for the calculation of landmark position.

2.3.2 Reconstructing the Foot Model

After that, the foot model needed to be reconstructed to rearrange the vertices points of the foot model. A foot sectioning needed to be considered before developing the analysis algorithm to ensure that the sectioning was clear and feasible. The sectioning process was designed to cut out the unused part of the foot scan model. Figure 7(a) shows the foot model that has been sectioned at most lateral malleolus height.

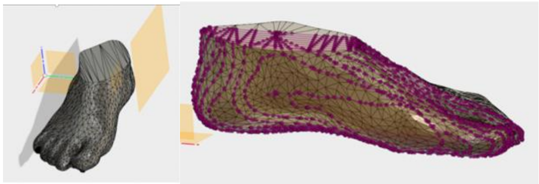

Figure 7: (a) sectioned foot model, (b) Intersection concept testing on foot model.

The MATLAB code converted the 3D foot scanned models from STL format into a 'vertices' and 'faces' matrix structure. Vertices express the 3-dimensional coordination points of the foot model and faces are the triangles connecting each vertex. The vertices from the imported foot model are usually random and messy, so an intersection method was needed to rebuild the foot model to generate uniform vertices for higher accuracy in the analysis of results (Figure 7(b)).

2.3.3 Calculating the Landmark Location

The landmark position that was calculated in this algorithm was the first Metatarsophalangeal (MTP) joint, which joins the head of first metatarsal and proximal phalanx of big toe. The reason that approximating first MTP joint position needs to be specifically calculated is for toe box development. The first MTP joint is always the most prominent part of the forefoot region for the general population. Figure 8 shows the calculated landmark position on a foot model.

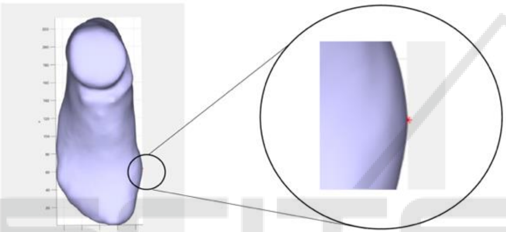

Figure 8: Calculated first MTP joint landmark position on foot model.

The red dot on the figure above shows the calculated first MTP joint position on the foot model. The landmark was used to separate the foot model into rearfoot and forefoot sections. The separation was done by calculating the instep and fibula instep length and separating the foot from the cross section of these two points. This was done because the customised shoe last required the geometric of the rearfoot (e.g. foot arch and heel) and toe box. The examples of separated forefoot and rearfoot parts are shown in Figure 9.

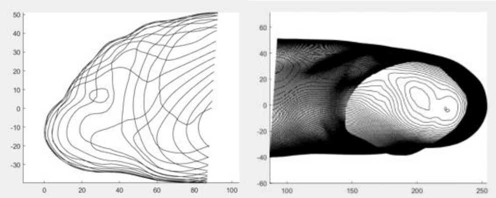

Figure 9: Forefoot and rearfoot areas.

3 RESULTS AND DISCUSSION

3.1 MATLAB Algorithm

The novel algorithm we employed processed the 3D foot scanned models in STL format by reconstructing and calculating the landmark positions on the foot model using the mathematical algorithm. The first step of the algorithm detected the normal direction of the imported foot model, then relocated it to the positive plane for easier calculation.

The original scanned foot model was compared with the reconstrued shoe last model constructed by the MATLAB algorithm shown in Figure 10. It was clear that the forefoot and rearfoot parts had a different number of vertices points. This occurs because a customised shoe last model keeps the detailed geometrical shape of heel and arch parts, so it needs more vertices points to provide the information. In terms of the 3D model reconstruction, it not only rearranges the vertices points but also rebuilds the faces that link all the vertices points together to form a closed 3D profile. This action was done by a boundary function in MATLAB. The boundary function can generate faces that connect all the reconstructed vertices to form a 3D object, and the details of the generated faces can also be controlled by changing the boundary function coefficient number. However, the boundary function cannot completely cover every detail of the reconstructed model. Holes will appear in some foot model data due to the complexity of the input model and some geometric information will disappear due to the boundary error.

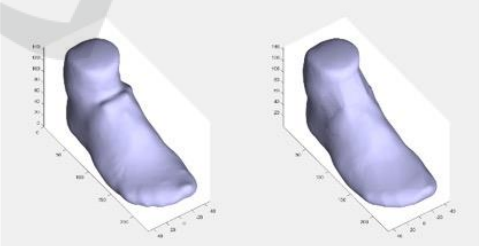

Figure 10: Reconstructed shoe last model, Original (left) and result (right) of the 3D foot model.

An overlapped comparison between the original and reconstructed model is shown in Figure 11. The red part refers to the original foot model and the blue part is the reconstructed model. The boundary error can be minimised by reducing the number of intersections produced during the reconstruction phase.

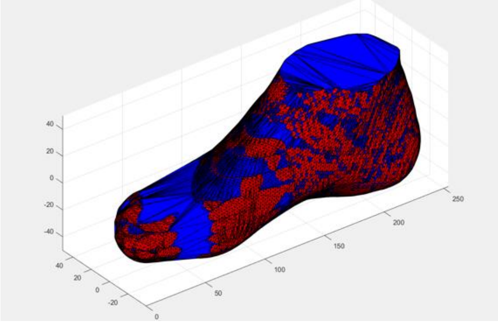

Figure 11: Overlapped comparison of original (red) and reconstructed foot model (blue).

3.2 Shoe-last Customization and Prototyping

The intention was to use the shoe last as a mould to produce a pair of cycling shoe prototypes using composites materials. The reconstructed foot model was then split into two parts: the top and the bottom parts (Figure 12).

Figure 12: The reconstructed foot model was sectioned into two parts: top and bottom parts.

The top and bottom parts was then converted into negative male and female moulds (Figure 13) for manufacturing of carbon fibre cycling shoes through composite layering.

Figure 13: Male and female mould for carbon fibre manufacturing processes.

The output products of this algorithm were 3D printed using Acrylonitrile Butadiene Styrene (ABS) 3D filament for prototype testing purposes. During the manufacturing process, a multi-layer of composite fiber materials was laid over the negative male and females shoe last moulds. The moulds and composite fibre materials were then placed into a vacuum bag to shape the materials according to the shoe last's design (Figure 14).

Figure 14: 3D printed male and female moulds, and porotype of carbon fibre cycling shoes.

4 CONCLUSIONS

The MATLAB algorithm developed in this project successfully designed a shoe last from a raw STL file automatically, regardless of the normal direction of the original input model. It cleaned up the original scan file by reconstructing the vertices of the 3D model, which allowed further calculations. In other words, the algorithm did significantly shorten the shoe last customisation process to under two seconds, as everything was done automatically by the MATLAB algorithm.

The output shoe last model had an approximate +/-2mm error difference from the original foot model, which was deemed an acceptable result for accurate shoe last design. Future development of this algorithm will focus on improving the boundary function and creating a better resolution of the enclosed surface.

The output shoe last was converted into a negative male and female moulds, 3D printed and tested by using it in the actual shoe manufacturing process. We created negative moulds based on the shoe last developed by the novel customization algorithm, and the attempt at producing a composite cycling shoe was successful. Future work in this project will focus on automating the negative mould development processes.

ACKNOWLEDGEMENTS

The authors would like to thank the technical staff from RMIT Advanced Manufacturing Precinct for their help in 3D printing the prototypes. We would also like to express our sincere thanks to Dr Floreanna Coman for her valuable advice and assistance in constructing the carbon fibre shoes.

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