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3D Foot Scan to Custom Shoe Last

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***Abstract*—Today's customers not only look at aesthetic beauty but also quality, comfort and fit. New technologies such as digitization and virtual 3D tailoring are providing more options to consumers and designers in designing different styles with the least possible time. Next to the shoe fashion and style, good fit and comfort are the second important determinant in the purchase of footwear. Although there is a need for better fitting, there are no techniques for fit quantification. In traditional shoemaking, the shoe is categorized by the length and width (or girth), hence there is always a mismatch between the complex foot shape and shoe shape. For the industry in order to meet the demand for better footwear, new techniques for fit quantification is required in order to have a direct mapping form foot to shoe-last (a mold for making shoes). In recent years, with the rapid development of computer technology and advanced design and manufacturing technologies such as computer-aided design (CAD) and computer-aided manufacturing (CAM), the manufacturing of customized shoe lasts is becoming possible. Still research is needed to find the best shoe-last. This paper discusses the basic concepts and current methods being followed to convert foot to shoe-last, retrieve the best fitting shoe last based on the 3D foot scan of the customer, and to obtain customized shoe last.**

Keywords-custom shoe last; foot scan; computer-aided design

I. INTRODUCTION

The foot is regarded as a very important part of the human being. It is not only essential for support and locomotion, but traditionally it can easily influence lifestyle. Ill-fitting footwear have been reported to be the major causes for discomfort, pain, and even foot problems such as calluses, corns, hallux valgus, ulcers, and pressure sores [1, 2]. Foot injuries and illnesses cause reduction in mobility, hence aggravating other ailment. The human feet are complex 3D objects [3] having a wide diversity in their shapes depending upon locality, age, sex etc. (Fig. 1). It is well recognized that one's foot size changes with age, weight changes, and other factors. In fact, children and teenagers typically grow one to three foot sizes each year. There has been a growing trend among shoe manufacturers to introduce customized shoes to satisfy varying customer style, fit, and healthy comfort needs.

Figure 1. Wide diversity in foot shape and size

However, in traditional shoemaking, the shoe is categorized by the length and width (or girth). It is obvious that peoples can have the same foot length [4, 5], but with different foot shapes like wide or narrow, slim or fat, high-arched or low-arched. Traditional sizing to fit the population has not been successful since we see lot of foot problems. A customized shoe is absolutely needed for the person. The most important component of the shoemaking is a shoe last, a solid 3D mold around which a shoe is made. A shoe last is closely related to the foot and its design is based on many factors such as the foot shape/size, comfort parameters, shoe fashion/style, and type of construction [6]. It has been regarded as the "heart" of shoemaking since it mainly determines the shoe shape, fashion, fit, and comfort qualities [7, 8]. The foot can further be separated into two parts: back part and front part. The back part, including the heel, instep and waist region of the foot, is mainly for fit and comfort, while the front or toe part, covering the toe region, is mainly for fashion and style [8, 9]. The toe region can have pointed toe, rounded toe, squared toe, and complex toe design. The back part is also influence by fashion by having different heel heights. Once the shoe last has been made, other shoe components (shoe upper, outsole, insole, midsole, the heel, etc.) can be made afterwards. Custom shoe-last can still be made using traditional methods, however it is expensive, time-consuming, and complicated to manufacture due to constraints imposed by the manual measuring of several foot dimensions and manual crafting of a shoe last to fit the specific foot dimensions through a trial-and-error approach [4, 5].

In recent years, with the rapid development of computer technology and advanced design and manufacturing technologies such as computer-aided design (CAD) and computer-aided manufacturing (CAM) [4, 5, 10-17], automation of manufacturing processes is possible. Techniques are being developed to retrieve the best fitting shoe last from the available shoe last library or database based on the 3D foot scan of the customer through geometric similarity comparison [10-12]. Other techniques involve deformation of existing shoe last into the customized one that matches with the scanned foot data through free-form deformation [13]. However, very few of the proposed methods have the ability to allow the customer to freely select shoe fashion/style and then design the shoe lasts with both the customer's chosen style and unique foot size and shape.

This paper discusses the basic concepts and current methods being followed to get the best fitting shoe last based on the 3D foot scan of the customer to obtain customized shoe last and then evaluate the fit.

II. PRINCIPLES

The process commonly followed in preparation of custom shoe last has been outlined in Fig. 2.

A. Scanning and Measurement

The purpose of the foot scanning is to accurately capture the foot's shape and size measures to retrieve the important parameters of the foot, those need to be incorporated to make a perfect shoe last**.** The 3D scanners are becoming gradually cheaper and hence the adoption of new technology in the retail shop is imminent. Many different technologies can be used to build these 3D scanning devices; each technology comes with its own limitations, advantages and costs. It should be remembered that many limitations in the kind of objects that can be digitized are still present: for example optical technologies encounter many difficulties with shiny, mirroring or transparent objects.

In this study a 3D Foot Laser Scanner was used. The scanner uses a Class II Laser in the 670nm Visible Red Spectrum. It has a scanning volume of 350mm x 150mm x 150 mm, an optical Resolution of +/-0.25mm in the X and Y direction and a linear accuracy of linear Accuracy of +/-0.1mm. The scanning produces about 40,000 pts/sec and the data can be stored in IGES, DXF, ASCII Point, OBJ, STL, FCS format.

For the shoe-last the point cloud data was obtained from a shoe-last digitizer. The shoe-last rotates along the center axis at a fix rate while the digitizer head, having a torus shape moves along the heel to toe direction. All the time the digitizer head keeps in contact with the shoe-last body and motion of the digitizer head is encoded. Digitizer software is then use to convert the data into shoe-last surface points cloud and mesh data. On average, for a given digitized shoe-last of European size 36 there are around 60,000 points on the surface. The mean, minimum, maximum and standard deviation of the point to point distance are 0.56 mm, 0 mm, 1.6 mm and 0.3 mm respectively.

B. Principles of Extraction of Parameters and Fine Tuning From 3D Scan

A collected data from 3D scanner are now commonly employed as they can easily be used to construct digital 3D model useful for a wide variety of common application entertainment industry, industrial design, orthotics and prosthetics, reverse engineering and prototyping, quality control/inspection and documentation of cultural artifacts.

As for extraction of parameters, landmarks on the foot are used to locate location of bones and joints. Based on the position of the landmark and extreme points (maximum and minimum points) many anthropometric measures are calculated. Additional anthropometric measures can be added easily in the software. Some of the most common anthropometric measures used in foot modeling are: foot length, lateral metatarsal phalangeal joint (MPJ) length, medial MPJ length, 5th toe length, 1st toe length, 2nd toe length, foot width, diagonal foot width, toe width, heel width, instep height, lateral maleolus height, medial maleolus height, navicular height, Medial MPJ height, Lateral MPJ height, 1st toe height, 5th toe height, MPJ girth, instep girth, and waist girth.

In addition, to anthropometric measures, the 3D shape model is essential custom shoe-last design. The scanner generates point cloud, a set of vertices in a three-dimensional coordinate system. While point clouds can be directly rendered and inspected [15], usually point clouds themselves are generally not directly usable in most 3D applications, and therefore are usually converted to polygon or triangle mesh models, NURBS surface models, or CAD models through a process commonly referred to as surface reconstruction. There are many techniques for converting a point cloud to a 3D surface. Some approaches, like Delaunay triangulation, alpha shapes and ball pivoting, build a network of triangles over the existing vertices of the point cloud, while other approaches convert the point cloud into a volumetric distance field and reconstruct the implicit surface so defined through Marching cubes algorithm [16].

In this study, the foot model is represented in a structured manner such that it can be used for mesh creation or surface model creation using NURBS or spline. The foot is first aligned along the heel center line [1], then cross

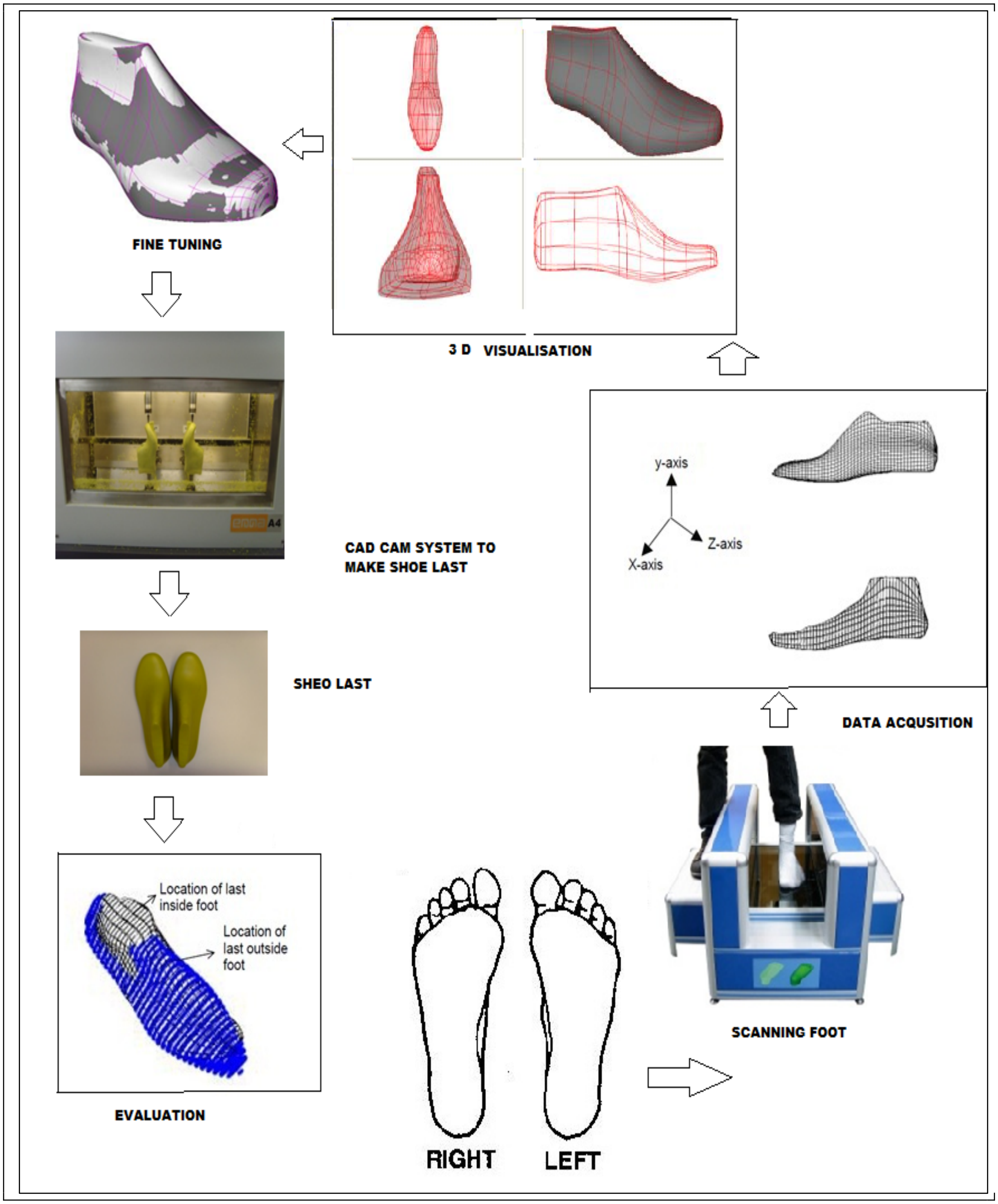

Figure 2. Flow diagram of custom shoe-last processing steps

section of the foot is created at 1% equal interval. This guarantee that irrespective of different foot length, same number of sections is generated. Also the section from one foot somewhat matches with the shape of another foot, since it is taken at same percentage of foot length. Any variation in the shape of the cross section can be used for statistical analysis. For each section, equal number of points are then generated. By locating the center of the section and converting the points into polar coordinate system, and sampling at 1° interval, 360 points are obtained for each section. Hence all feet are represented by 99 (sections) x 360 points + 2 (front and back points). It is important to have same number of points for all feet, then it will be easy to compare errors and do statistical modeling.

Since the shoe-last can have heel and is different from the foot, the foot has to be modified. First the foot is converted to have a heel height. This is done by modifying each section of the foot to align with the bottom curve of the shoe-last. The matching of the shoe-last and foot can be visualized. Professional shoe-makers and shoe-last designers have experience and thus we have provided an option for them to modify the shoe-last interactively. There is always a tolerance between the foot anthropometric measures and the shoe-last. This is determined either by experience or experimental study.

C. CAD/CAM for Manufacturing the Custom Shoe Last

Thus foot point cloud is aligned to a shoe-last CAD model (or even another point cloud), and compared to check for differences. These differences can be displayed as color maps that give a visual indicator of the deviation between the manufactured part and the CAD model. Geometric dimensions and tolerances can also be extracted directly from the point cloud.

D. Estimation of Comfort Properties

A method based on dimensional differences is more acceptable concept to quantify footwear fit. In order to compute the dimensional differences, the minimum distance from the foot to the shoe-last is calculated. The dimensional differences were then color-coded for easy interpretation. It is important to differentiate the positive and negative differences. A positive "error" exists if the last surface is outside the boundary of the foot surface, while a zero or negative "error" is present otherwise. The concept of sign difference is very important in footwear fitting as a positive error will result in a loose fit, while the presence of a negative error can be categorized as a tight fit.

III. Discussions and Conclusions

This method allows the designer or developer to understand areas that may cause fit problems for users so that design modifications may be performed even without fitting trials and should be further enhanced through perception and sensation studies [2]. Since the discomfort and pressure tolerance level on the surface of the foot may be different, there may exist a need to scale the allowable dimensional differences to account for “similar” sensations. Custom footwear is not only of interest to researchers, but also to manufacturers. Complete customization is still under research but some companies have demonstrated a clear example of how technology can be employed to achieve mass customization in the footwear industry. This can be achieved in a simple 3 step procedure: dimensional measurement, pressure measurement and design.

In dimensional measurement, the customers’ foot length and width are precisely measured for each of the right and left foot, to provide a perfect fit. For pressure measurement, a pressure foot-scan captures the plantar pressure. The consumer then engages in designing the shoe appearance by selecting different sets of colors for various shoe components, including the ability to print his/her name or phrase on the shoe.

This process enables consumers to design and manufacture better fitting shoes. In the near future, it will be possible for large companies to adopt technologies with 3D foot shape modeling and custom shoe-last design. This paper has indicated how custom shoe-last can be made. The software technology and advanced machinery used will be able to generate custom-made shoes at a rate and cost that is close to mass production. Further study is needed to generate guidelines for the clearances between feet and shoes.

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