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3D foot prediction method for low cost scanning

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ABSTRACT

With the rapid development of CAD/CAM technology and information technology, it is becoming possible to satisfy the quality, fit and comfort requirements of footwear design and manufacturing. In the footwear industry, although there are availability of design and manufacture technologies to fulfill the desired requirements, the current methods are very expensive. Cheap and accurate scanners are needed at the retail shop to acquire 3D foot shape information. This paper proposes a prediction method to model foot shapes through scaling a standard foot by using limited parameters. The accuracy of different number of parameters have been evaluated. Given that commercial expensive scanner accuracy range from 0.5 to 1 mm, in order to predict 3D foot shape to an accuracy of around 0.75 mm, foot outline, foot profile, two foot sections and standard foot model were required. The mean modeling errors were 0.76 mm and 0.75 mm of the right foot and left foot respectively. Results indicate that if more sections are used the modeling error decreases but this will increase the cost of the scanner and the computational complexity. This method provides a cost effective method to substitute expensive 3D foot scanners that usually use laser-based technology.

Relevance to industry: : This method provides the core algorithm for the development of low cost 3D foot scanners for footwear mass-customization. CCD cameras can be used to capture foot profile and outline, while fixed line laser can be used to obtain two key sections. This method reduces the need for expensive linear gears and optical systems.

1. Introduction

The high quality computer graphics and commercial computer-aided design (CAD) software have enabled the extensive use of 3D digital human models (DHMs) nowadays. Although product design is not all simulated in the virtual and CAD environment, DHMs help researchers and practitioners in multiple applications in the design fields (Duffy, 2007; Lin et al., 2002). In human simulation design, both DHM and virtual reality (VR) provide an interactive environment to the designer and users (Chaffin, 2001). In addition to virtual models, anthropometric data are incorporated in DHMs to create realistic physical prototypes. The CAESAR project collected 3D surface measurements of approximately 6000 subjects from the USA, Netherland and Italy for the design and development of better fitting clothes, protective equipment and other ergonomic designs (Robinette et al., 1999). Furthermore, these accurate digital models were used for product customization. In order to achieve the design automation of customized free-form products, Wang et al. (2007) studied the spatial relationship between two human models to virtually transform wearable products between the human models to simulate customized fit. Different DHMs have been developed in decades. Some of them tried to simulate the general human body, while others were specific to a body part (Akimoto et al., 1993; Ip and Yin, 1996; Lee and Thalmann, 1998). The head shapes and faces were modeled and used in product design (Luximon et al., 2012). Liu et al. (2008) introduced a toolkit for the helmet shell design based on three-dimensional anthropometric head scans. 3D breast models were also used in studies on developing bra size and design (Zheng et al., 2007; Zhou et al., 2012).

As far as foot modeling is concerned, different methods have been explored by various researchers. Foot dimensions were defined and were extracted based on the 3D digital foot shape (Witana et al., 2006; Yu-Chi et al., 2012; Zhao et al., 2008). The landmarks on the foot surface were located either manually (Witana et al., 2006) or automatically (Bin et al., 2008; Luximon et al., 2012). Based on foot shape model, proper shoe-last, a 3D

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model for making shoes can be manufactured. Several researches have been carried out to generate custom shoe last (Leng and Du, 2006; Shi et al., 2009). Xiong et al. (2010) developed a CAD system to generate customized shoe last by deforming the selected shoe last based on scanned 3D foot model. Tu (2014) has provided a formula for foot volume. In medical field, 3D foot model is used to design customized foot orthoses (CFOs) effectively that can greatly reduce plantar pressures (Kirby et al., 2012; Mientjes and Shorten, 2011).

An essential prerequisite to create accurate shoe last is to acquire the 3D foot shape accurately. Even though, the laser scanner has been commercialized and claimed as very low error results generally ranging from 0.5 to 1 mm, it has some drawbacks. They are expensive and bulky. Therefore, an effort is necessary in order to develop a low cost system to obtain a 3D foot shape with high accuracy. Luximon and Goonetilleke (2004) has proposed a foot prediction model based on a standard foot and 4 anthropometric parameters (length, lateral width, medial width and height). Luximon et al. (2005) improved the method to create foot prediction model with 1 mm accuracy by using foot profile and foot outline and a standard foot.

These two methods are on average relatively accurate, however since only outline, profile or anthropometric measures have been considered, there were large errors in the shapes of the cross sections. There is a need to include at least few sections from original foot to predict the real foot shape including cross sectional shape. The objective of this paper is to extend the Luximon et al. (2005) method to account for shape variation and also to improve the 3D foot shape prediction accuracy to near advanced scanning technologies.

2. Material and methods

2.1. Participants

A total of 80 Hong Kong Chinese male participants were selected for this study. Participants' demographic data including age, height, weight and foot dimensions were recorded. Both the right and left foot from $N_f = 80$ participants were scanned and sampled. Participants were instructed to fill the consent form before the start of the experiment. Table 1 shows the descriptive

Table 1
Descriptive statistics of participants.

	Experiment set (1–50)				Validation set (51–80)			
	Mean	Max.	Min.	SD	Mean	Max.	Min.	SD
Age	21.68	36	19	3.06	21.50	41	19	3.88
Weight (kg)	62.42	89.80	47.20	8.16	65.88	88.30	55.05	8.19
Height (cm)	171.73	186.1	160.1	5.92	173.31	185.4	162.2	5.91
Measurements of right foot (mm)								
Foot length	245.8	273	225	1.11	249.8	273	226	1.09
Foot width	99.0	112	90	0.49	99.9	112	92	0.46
Measurements of left foot (mm)								
Foot length	241.1	273	221	1.13	249.4	268	228	1.10
Foot width	99.8	116	90	0.49	100.4	112	92	0.50

ANOVA results indicate that there were no significant difference between the experimental and validation groups (age ($F(1,78) = 0.053$, $p = 0.819$), weight ($F(1,78) = 3.362$, $p = 0.071$), height ($F(1,78) = 1.344$, $p = 0.250$), right foot length ($F(1,78) = 2.446$, $p = 0.122$), left foot length ($F(1,78) = 0.666$, $p = 0.417$), right foot width ($F(1,78) = 2.216$, $p = 0.141$) and foot width ($F(1,78) = 0.313$, $p = 0.577$)).

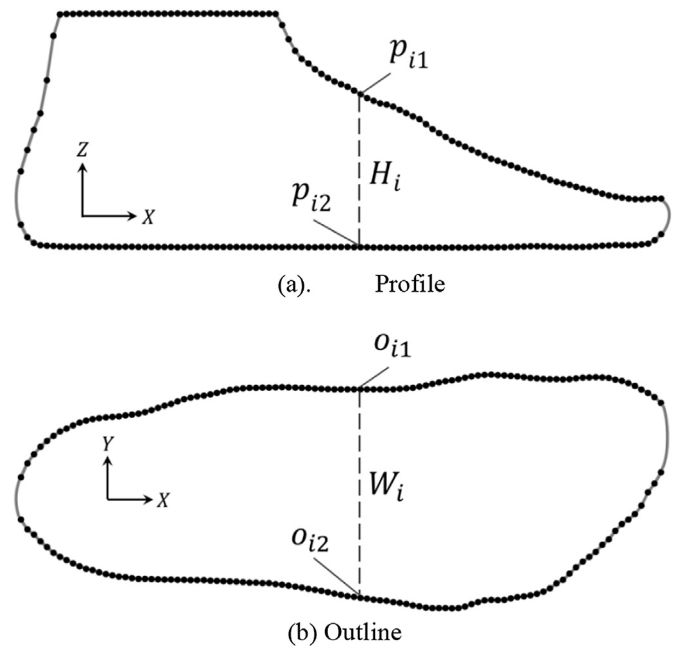

Fig. 1. Foot profile and outline.

information of the two data sets. Firstly, the digital feet data were numbered from 1 to 80 randomly. The numbers 1 to 50 (experiment data set) were used to generate the standard foot by the method proposed by Luximon and Goonetilleke (2004). The other 30 pairs of feet data numbered from 51 to 80 (validation data set) were used to validate the effectiveness and precision of the presented methods.

2.2. Data preprocessing

In order to reduce and optimize calculation, the point cloud data were simplified and sampled after alignment. Each foot was aligned along the heel point and heel center line once the axis system was established (Luximon et al., 2005). The aligned foot was then separated into N_s paralleled sections along the foot length direction (X direction), while each section was sampled into n_s points which had a fixed angular interval σ°, then $n_s = 360^\circ/\sigma^\circ$. Hence each sampled foot data was a set of $N_s \times n_s$ points, which is $F\{f_k(x_{ij},y_{ij},z_{ij}),\ k = 1,2,\ldots,N_f;\ i = 1,2,\ldots,N_s;\ j = 1,2,\ldots,n_s\}$. Numbers 1–50 feet were selected to generate the standard foot. The coordinates of its point were obtained by averaging the corresponding points of feet 1 to feet 50 (Luximon and Goonetilleke, 2004). Let h_i be the height of section i of the standard foot, and w_i be the width.

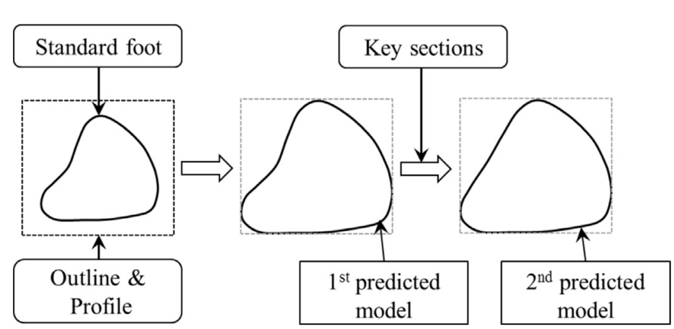

Fig. 2. Diagram of two steps prediction.