Khalid, H.M. et al. (Editors), Proceedings of Agriculture Ergonomics Development Conference
IEA Press, Kuala Lumpur, 2007

The Use of a Foot Dorsal Height Model for the Design of Wellington Boots

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Abstract

Waterproof boots such as Wellingtons are commonly used by agricultural workers all over the world. Since this type of boot lacks laces to adjust the fit along the shoe, the design of the boot has to consider the foot height dimension besides the foot length and width dimensions. This study aims to model the height dimension of Chinese feet, so that fit and comfort of covered boots can be improved. Using 3D laser scans of the right feet of 26 Hong Kong Chinese males, an empirical model for midfoot dorsal height was developed and applied in the design of Wellington boots using a computer-aided design (CAD) system. This study shows that the midfoot dorsal height model in addition to traditional anthropometric dimensions has potential for designing and improving the fit of closed shoes such as Wellington boots.

Keywords: Foot height; boots; agricultural footwear; Wellingtons,

1 Introduction

Cultivating any crop involves getting rid of insects and pests by spraying pesticides. When handling pesticides, spills often occur and personal protective equipment is used to decrease the exposure level to such toxic substances. A pair of waterproof boots such as Wellington boots (known as wellies or gumboot) is one type of personal protective equipment that reduces the exposure to the feet and lower leg areas (Legault, 1993), and they are commonly used by agricultural workers in many parts of the world, including China.

The boots have to be comfortable if they are to be used effectively. If not, workers may avoid wearing them thereby not protecting their limbs from harmful chemicals (Maher, 1996). A good fit between the boots and the feet is essential for comfort (Miller, 1976; Xing et al. 2000). Even though boots tend to be made in different lengths and widths, they are rarely made having different heights (Cheng and Perng, 1999). Unlike other types of footwear, boots have a closed surface and lack laces to adjust the fit, so the fit in the height dimension is very critical for comfort. If the top surface or vamp of the boot is low, there will be high pressures on the top (dorsal) surface of the foot, which can result in blisters calluses or even corns (Miller, 1976); however, if the vamp is too high, the foot will tend to slide back and forth inside the boots, thereby compressing the toes and affecting foot function (Goonetilleke, Luximon and Tsui, 2000) and also worker productivity. Thus, the objective of this study was to model the foot heights for different sized Chinese feet so that the contours of boots can be improved.

2 Methodology

2.1 Participants

Twenty-six Hong Kong Chinese adult males participated in this study. None of them had any visible foot deformities and each participant was required to complete an informed consent form. This study was approved by the university research ethics committee. The mean age of participants was 21.6 years (SD=1.2), the mean stature was 170.1cm (SD=6.8) and the mean weight was 60.3kg (SD=8.8). The right foot length of the 26 participants can be classified into 4 groups of foot/shoe sizes and the basic foot dimensions are shown in table 1.

Table 1. The right feet dimensions of the 26 experimental participants grouped into 4 shoe sizes

Shoe size	Number of participants	Foot length (FL) (mm)		Foot width (FW) (mm)		Length from toe to ball of foot (L_0) (mm)		Height of ball of foot (H_0) (mm)	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
US 6	5	236.0	1.4	90.5	3.1	60.7	1.0	35.0	1.8
US 7	5	246.9	2.9	95.2	4.1	65.4	2.8	37.1	2.2
US 8	11	253.9	1.4	98.3	8.7	69.3	3.7	37.5	1.9
>US 8	5	269.9	10.4	105.4	5.3	74.3	3.7	38.4	3.2
Total	26	252.2	11.9	96.7	5.5	67.8	5.4	37.1	2.4

2.2 Experimental procedure

Nine anatomical locations were identified on the right foot of each participant and marked using black stickers. During the analysis, we found that only two of the nine marks were necessary: one on the most medial prominence of the first metatarsal-phalangeal joints (MPJ) and the one on the medial malleolus (Figure 1). The participant's right foot was aligned and laser scanned on a YETI^{TM} I laser scanner (Vorum, 2000) when each foot bore half of the body weight. The scanned data included the 3D coordinates of the points on the foot surface together with the coordinates of the nine landmarks. This data was later processed with a VC++ program to extract the maximum foot heights along the length of the foot.

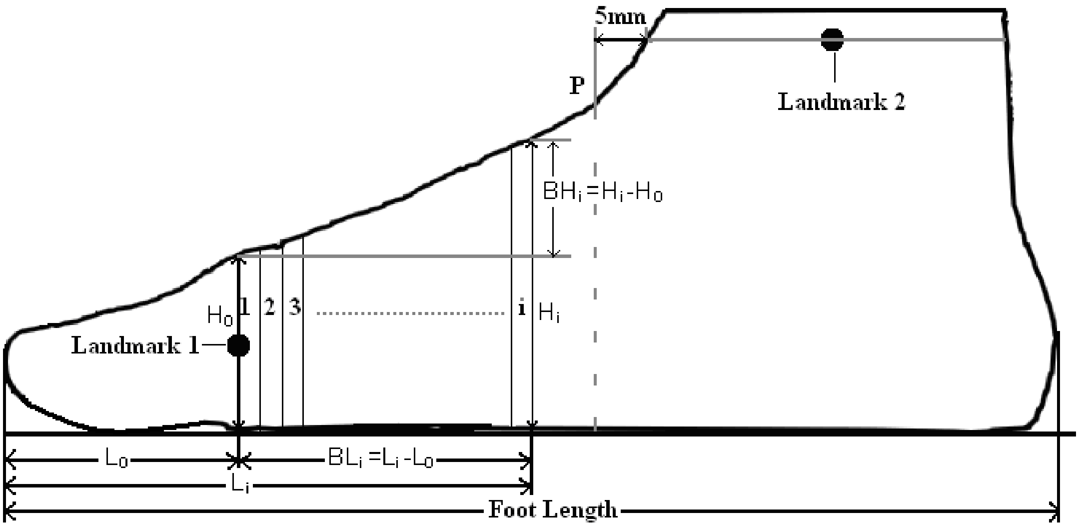

Figure 1. Sagittal plane view showing the foot height in the midfoot region. Landmarks 1 and 2 are on the most medial prominence of the first metatarsal-phalangeal joint and medial malleolus respectively

2.3 Data processing

The 3D point coordinates were aligned with the foot heel centerline as the x-axis (Luximon and Goonetilleke, 2004). The midfoot region was determined as the region from the most medial prominence of the first MPJ (landmark 1) to the foot and lower-leg junction (Point P) (Figure 1). Thereafter, the midfoot region was subdivided into strips of width 1.2mm along the length axis of the foot as shown in Figure 1. Subsequently, the height (H_i, from the floor) of each strip together with its location along the length of the foot (L_i, from the toe tip) (Figure 1) were extracted.

3 Results

Preliminary data analysis showed that there are relatively large variations in height in the toe area of the different participants (Xiong and Goonetilleke, 2006). Hence, the height (H_0) and length (L_0) of MPJ1 are of primary importance to develop a normalization procedure to minimize the height variations among participants. In addition, the participant feet are of different size as well and in order to account for both these variations, two new variables were generated. They were ball-to-strip height $BH_i = H_i - H_0$ and the normalized ball-to-strip length $NBL_i = BL_i/FL*100 = (L_i - L_0)/FL*100$.

Thereafter, BH and NBL of all midfoot strips of all participants were pooled together and modelled with a power equation. The least squares fit between BH and NBL had $R^2=0.982$ ($p < 0.0001$) and the relationship can be represented mathematically as given in equation (1) with the units of NBL being percentage. The relatively high value of R^2 indicates a strong relationship between BH and NBL. Equation (2) shows the relationship in terms of H_i and L_i.

$$\mathbf{BH\ (mm) = 1.068 * NBL^{1.038}} \qquad \mathbf{R^2=0.982} \qquad (1)$$

$$\mathbf{H_i - H_0\ (mm) = 1.068 * [(L_i - L_0)/FL*100]^{1.038}} \qquad (2)$$

Equation (2) together with the mean values of H_0, and L_0 of each "size" of foot (Table 1) allow the midfoot height to be determined along the foot length. This relationship between H_i and L_i, accounting for the different H_0, and L_0 in each of the four sizes, is plotted in Figure 2. The "shapes" for each size (Figure 2) can then be used for designing the vamp area of boots.

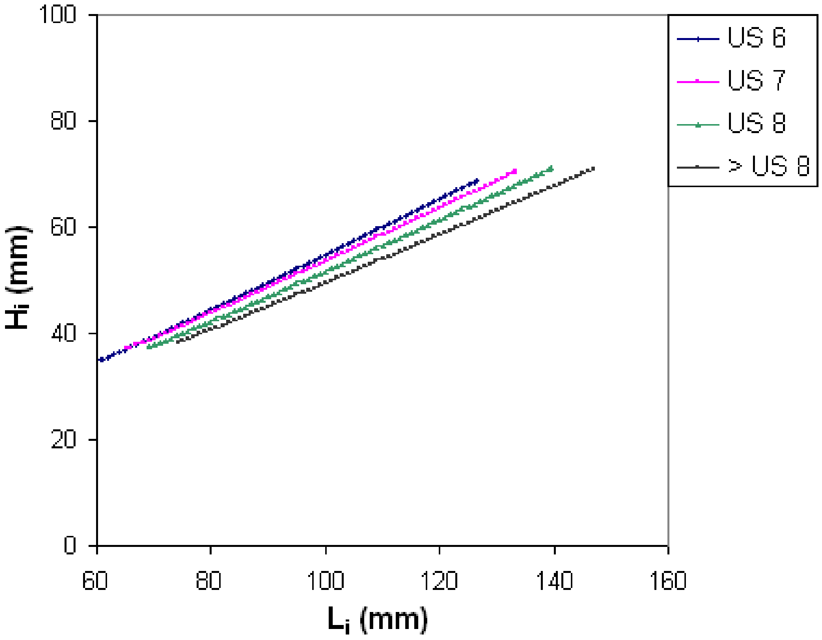

Figure 2. The modeled "shapes" of the midfoot for the 4 shoe sizes

4 Discussion and Conclusions

The study proposed an empirical model (Equation 1 or 2) to describe the midfoot dorsal height based on the foot scans of 26 participants belonging to 4 different shoe sizes as shown in Table 1. The shape of the midfoot height for each shoe size is shown in Figure 2. Knowing this shape, can help design footwear such as boots as illustrated below (Figure 3).

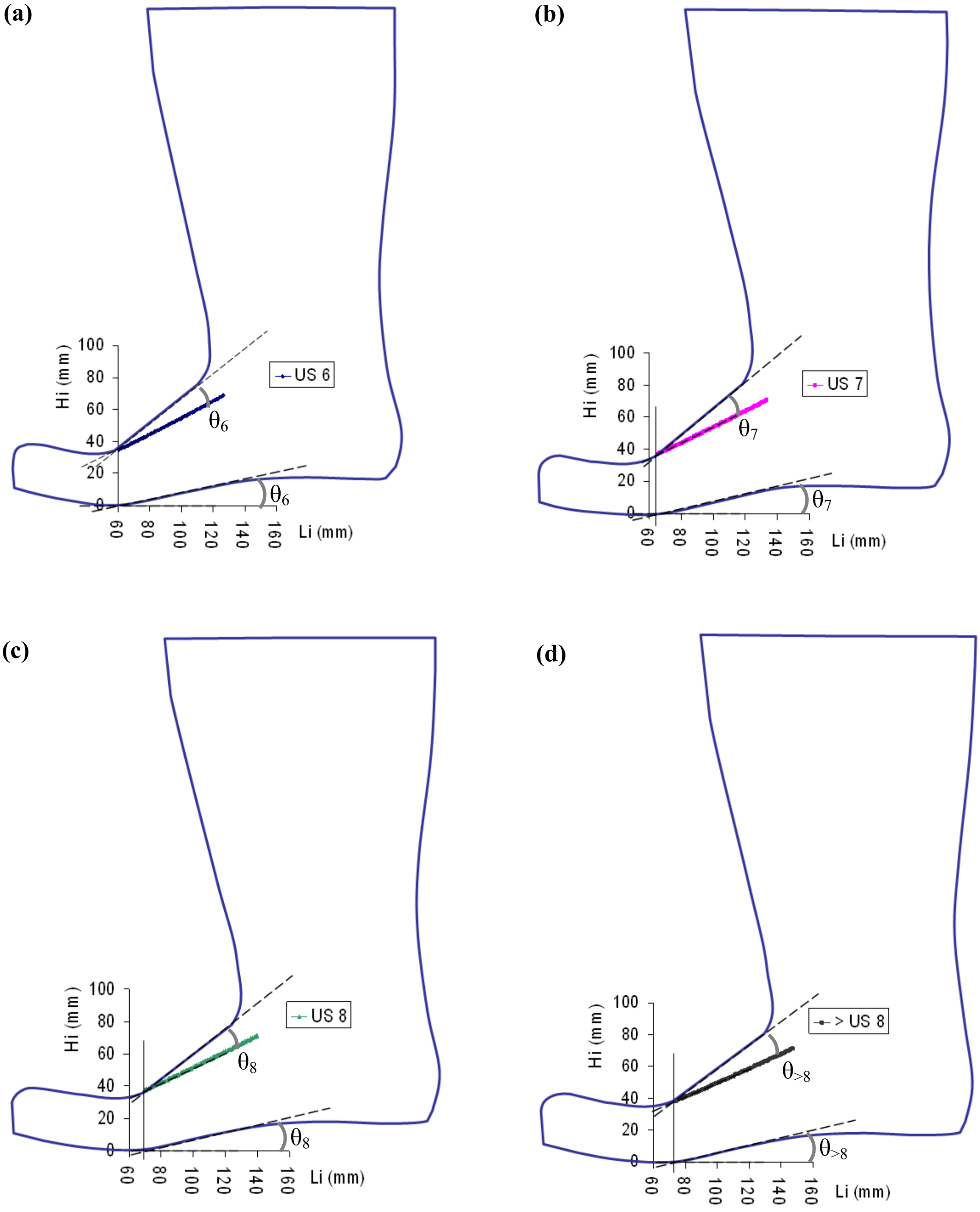

Figure 3. Lateral profile of boot-lasts designed using equation (2) for (a) US size 6 (b) US size 7 (c) US size 8 (d) larger than US size 8. The angle of rotation around MPJ-1 to account for the heel height in each shoe size is given as θ_6, θ_7, θ_8, and $\theta_{>8}$. The obtained midfoot dorsal heights were transformed by these angles θ_6, θ_7, θ_8, and $\theta_{>8}$ and the dashed line on the upper side shows the adjusted shape.

The empirical model for midfoot dorsal height was based on the foot shape when standing on a flat surface such as a floor. However, a shoe has a heel height, heel wedge angle, heel seat, shank shape and toes spring (Adrian, 1991) and therefore, the modeled midfoot dorsal height (Figure 2) has to be adjusted to account for the heel height of the shoe. If the angle of rotation around MPJ-1 between the boot-last bottom shape in the midfoot area and the floor for each shoe size is θ_6, θ_7, θ_8, and $\theta_{>8}$ as shown in Figure 3, then the modeled heights should be adjusted as shown in the figure.

Based on the adjusted profiles of the 4 different shoe sizes (Figure 3), 3D boot-last shapes were designed using Delcam PowerSHAPE CAD software (www.delcam.com). Figure 4(a) shows a sample boot-last designed using the model and the finished boot of US size 7 is shown in Figure 4(b).

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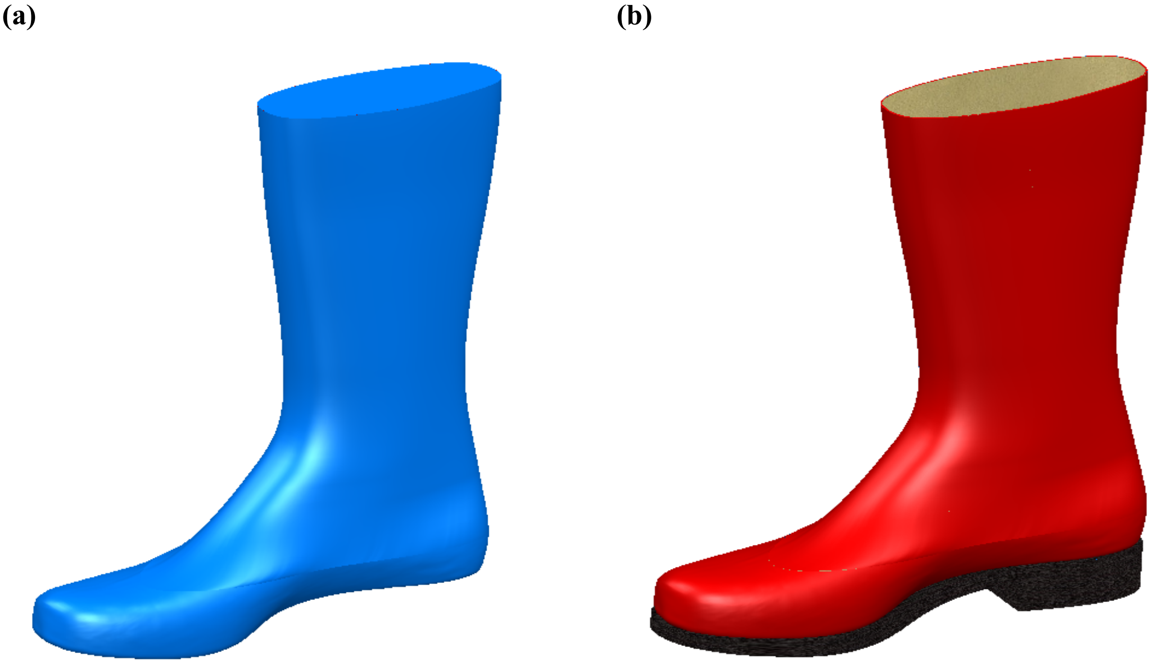

Figure 4. Rendered images of a US size 7 (a) boot-last (b) finished boot

In the generation of the boot-last, the anthropometric data of Hong Kong Chinese adult males were used. Xing et al (2000) reported several foot dimensions measured on 38216 Mainland Chinese male adult farmers as shown in Table 2. Surprisingly, the foot anthropometric data of the Hong Kong Chinese male adults who participated in this study and those of the Mainland Chinese male adult farmers appear to be quite similar in foot length, height of ball of foot, and arch length to foot length ratio (Table 2). However, the Chinese male adult farmers have a relatively larger foot width (mean difference of 6.1 mm) compared to the participants in our study. Hence, the width of the boot-lasts may have to be adjusted to accommodate the wider feet of Chinese farmers.

Table 2. Comparison of our experimental data with those of Chinese male farmers

Population	Sample size	Foot length (FL) (mm)	Arch length (AL) (mm)	Foot width (mm)	Height of ball of foot (H_0) (mm)	AL/FL ratio
Chinese male adult farmers (Xing et al.,2000)	38216	252.1	183.2	102.8	37.1	0.727
HK Chinese male adults	26	252.2	184.0	96.7	37.1	0.729

A weakness of the study is the relatively small sample size (N=26) of participants, which may limit the validity of the empirical model. Thus, the external validity may need further investigation.

5 Acknowledgements

We would like to thank the Research Grants Council of Hong Kong for funding this study under grant HKUST 613205.

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