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HUMAN FOOT PLANTAR SURFACE SHAPE CHANGE DURING GAIT

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Accurate shapes of the human foot plantar surface for various phases of gait (heel-strike, midstance and toe-off) are necessary to determine the physical features of the foot in motion. This type of information may be important in the understanding of the movement of the foot in the confined spaces inside shoes. Currently, there is no accurate method available to study the shape of the plantar aspect of the foot inside shoes during gait. Therefore it is necessary to develop a technique to determine plantar foot shape change of bare-footed gaits. The results show that the method developed can be used to obtain accurate measurement of the foot plantar surface change during gait. These measurements can be used to analyse the plantar surface characteristics which may be useful for the design of shoes.

KEY WORDS: 3D surface, plantar dimension, plantar shape, point cloud, video imaging

INTRODUCTION: Photogrammetric techniques and video imaging have been used in the capture of three dimensional surface (3D) of the human foot plantar region successfully (Chong et al., 2013; Amstutz et al., 2008). Research was carried out to determine the suitability of 3D surfaces for the studying of the shape change of the plantar aspect of the foot during gaits. The 3D surfaces consisted of sets of accurate 3D point cloud of the stance phase from heel-strike to toe-off of the gait. Point clouds consisted of points having x, y and z coordinates. These 3D surfaces were further processed to obtain various important transverse shapes of the plantar surface. This paper reports the methods and results of the processing of these captured surfaces. Also the paper provides a brief highlight of the suitability of the shape data for the study of the characteristic of the plantar aspect based on real data.

Blenkinsopp et al. (2012) remarked that the morphology of the human foot is an important factor in the design of sports shoes. They further argued that for a shoe to fit comfortably, it must match the shape of the foot. They investigated the shape change of the dorsal of the foot using photogrammetric techniques. It is also recognized that the plantar aspect is continuously changing shape during the gait cycle (Tsung et al., 2003). Kimura et al. (2011) reported the use of photogrammetric techniques to capture the dorsal and the plantar aspect of the human gait using twelve video cameras. The researchers gave a brief discussion on the measurement quality of various cross-sections of the dorsal and argued that the findings showed that the circumference of the ball of the foot could vary significantly during walking. They compared the largest variation of the ball circumference to that of a two sizes difference in shoe-size. Schmeltzpfenning et al. (2011) reported that the use of fringe projection and photogrammetric techniques to study the 3D dynamic behaviour of foot structure might provide additional information for shoe-last design. However, they provided very little detail of the shape change of the plantar during the heel-strike, midstance and toe-off of the gait. Telfer and Woodburn (2010) provided a list of plantar surface capture techniques in a comprehensive review of the research in this area. Again there was very little discussion on the processing of the scanned 3D surface to show shape change of the plantar during gait.

METHODS: The photogrammetric techniques developed for the creation of a set of 3D surfaces for heel-strike, midstance and toe-off by the authors of this paper were reported in Chong et al. (2013). A twelve-video camera system and a custom-built walking platform were utilised in the investigation. The accuracy of the captured 3D surfaces was maintained at the highest level by the development of a new glass refraction correction technique. Currently, the accuracy of the 3D surface is 0.3 mm using high-definition video cameras. In this paper, discussion on the methods is focused on the processing of the captured 3D surfaces to yield high quality data which can be used to determine the characteristic of the shape change of the plantar surface.

Participants: Two healthy adult male subjects (ages 26 and 24 years, heights 164 and 158 cm, body masses 78 and 67 kg) with no known foot pain or pathology were recruited for the study. The subjects were prepared for the imaging capture by painting the plantar surface with non-toxic "face and body" paint. Profile lines were drawn on the plantar region(Figure 1). Retro-reflective targets were attached to the sole and the side of the foot (Figure 2). The subjects were instructed to practise normal gait on the gait platform. When the subjects were confident, their gaits were recorded (Figure 2).

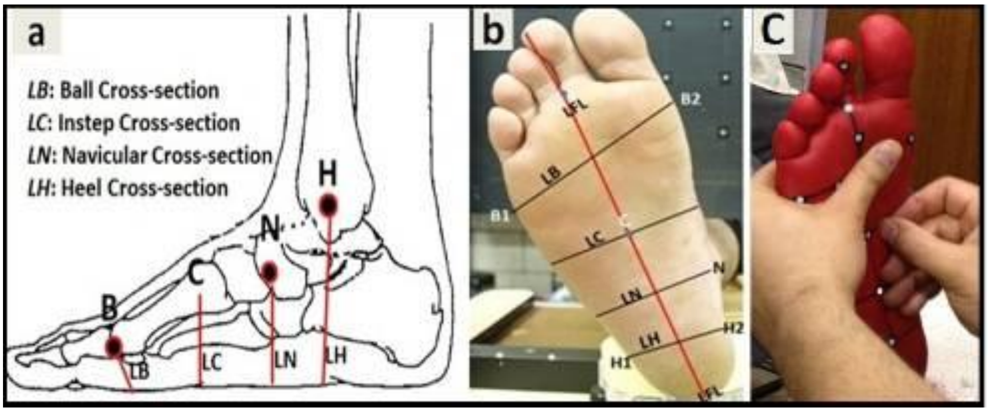

Figure 1. Subject preparation. (a) Locating anthropometric mark. (b) Drawing profile on the plantar region. (c) Attaching retro-reflective mark.

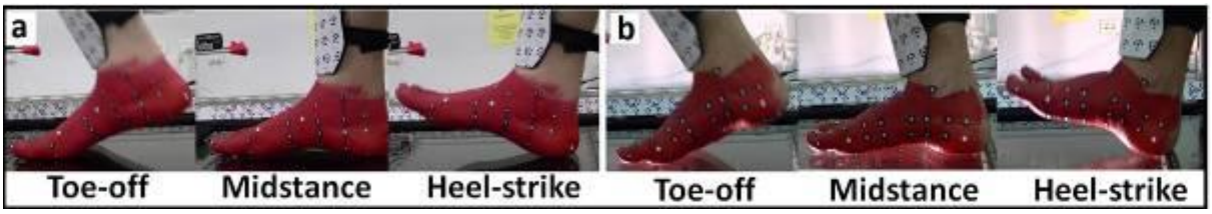

Figure 2. The retro-reflective targets and the gait phase. (a) Subject A. (b) Subject B.

3D surface generation: Additional processing of the photogrammetric captured 3D surfaces was carried out using Matlab 2011b® software with in-house add-ons. The coordinates along the plantar surface profile were extracted. Subsequently, the coordinates were used to extract the data such as areas to show the size of the shape change. Targets placed along the profile provided the characteristics of the change in the shape in terms of profile lengths, distances and angles.

Cross-sectional area computations: The profiles such as LB in Figure 1 must be a "close" polygon for area calculation, thus a line is drawn from B_1 to B_2 on the inner surface. The profile area (cross-sectional area) calculation algorithms (eq.1) are programmed as add-ons in the Matlab 2011b® software. The area of the cross-section indicates the amount of contraction and expansion of the tissue of the plantar surface.

$$A = \frac{1}{2}\left\{\begin{vmatrix} x_0 & x_1 \\ y_0 & y_1 \end{vmatrix} + \begin{vmatrix} x_1 & x_2 \\ y_1 & y_2 \end{vmatrix} + \cdots + \begin{vmatrix} x_{n-2} & x_{n-1} \\ y_{n-2} & y_{n-1} \end{vmatrix} + \begin{vmatrix} x_{n-1} & x_0 \\ y_{n-1} & y_0 \end{vmatrix}\right\} \qquad (1)$$

Where, 0…n-1 are the vertices (point of the point cloud) along the profile, listed counter clockwise around the perimeter,
X_{n-1} and y_{n-1} are the coordinates of the vertice n-1, and
A is the area of the cross-section.

RESULTS AND ANALYSIS: Figure 3 shows the cross-sections of the plantar surface during heel-strike, midstance and toe-off for subjects A and B. Using the cross-sections, the changes in the shape of the plantar region can be ascertained easily. For example, at the heel-strike position subject A's LH cross-section is a smooth curve. The cross-section changes to an undulating curve at midstance and it is back to a comparatively smooth curve during toe-off. The shape of the curve at midstance shows the skin surface along the cross-section is not in contact with the walking surface completely. In subject B, more skin surface along the cross-section is in contact with the walking surface. Thus, the results show that the characteristic of the LH cross-section is different between the two individuals. Figure 4 shows the closed cross-sections. These cross-sections are used to calculate the enclosed area identified by anthropometric marks. The calculated enclosed areas and the cross-sectional lengths are provided in Table 1. The findings show that the marked plantar areas contract during midstance as body-weight loading is applied to the plantar surfaces. Also the cross-sectional lengths increase during midstance. Thus, the cross-section shows the stretching of the plantar surface. As subject B has a high foot-arch the area of LN is smaller than Subject A who has a flat foot-arch.

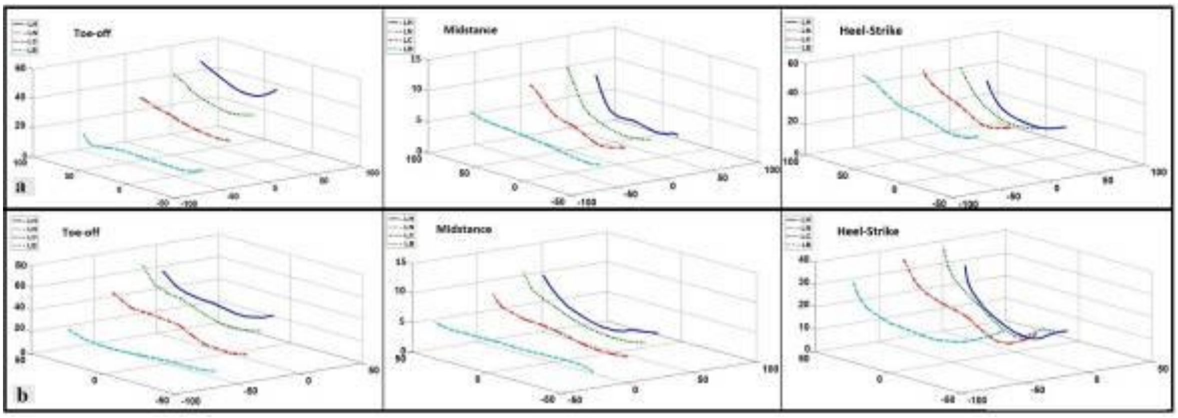

Figure 3. Cross-sections of the heel-strike, midstance and toe-off. (a) Subject A. (b) Subject B.

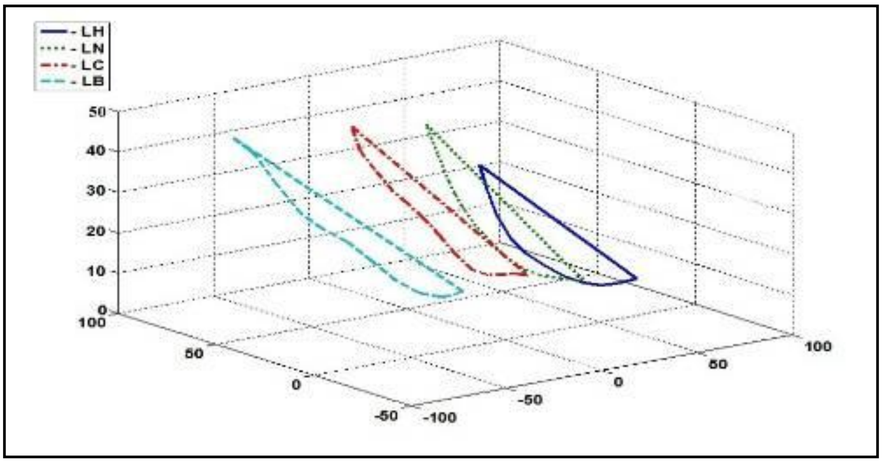

Figure 4. Cross-section for area change calculation (Heel-strike of subject A).

DISCUSSION: The techniques developed in this research are suitable for the study of the foot shape change for the following reasons:

1. The computed 3D plantar aspects are accurate to within 0.3 mm for all phases of the gait.
2. The computed plantar models can be manipulated on the computer screen to highlight various perspective views and physical dimensions can be obtained digitally.
3. The computed models are suitable for the design of shoe in-sole.
4. Additional profiles and cross-sections can be marked and physical dimension measured digitally.

CONCLUSION: This paper presents the techniques used to determine the cross-sectional changes in the shape of the plantar area during the heel-strike, midstance and toe-off of slow gaits. These cross-sections can be manipulated on the computer screen to highlight various perspective views and dimensional measurement study. 3D viewing can identify abnormality of the plantar area during the various phase of gait. Additionally, cross-sectional area and profile length can be calculated. The length of LB varies by 7% between toe-off and midstance whereas the length of LH varies by 9.8% between toe-off and midstance. The research results show that the characteristic of the impact of body weight loading on the plantar surface varies between individuals. Based on the data of the test subjects the impact of the loading is apparent between high foot-arch and low foot-arch individuals. This data can be used to determine the quality of in-sole for the arch-support. Further research will focus on the assessing the fore-foot plantar characteristics during gait.

Table 1. Area and cross-sectional length for midstance, heel-strike and toe-off.

Subject	Cross-Section	Toe-off		Midstance		Heel-Strike	
		Area mm^2	Length mm	Area mm^2	Length mm	Area mm^2	Length mm
A	LB	315.67	109.05	350.73	110.03	403.32	101.84
	LC	279.53	75.40	253.89	80.50	307.56	75.44
	LN	419.39	72.88	420.54	78.86	460.78	77.58
	LH	496.02	71.67	485.64	79.50	490.82	76.01
B	LB	291.20	82.67	314.53	83.61	396.90	81.19
	LC	271.52	74.02	185.60	76.67	300.89	74.13
	LN	228.04	64.03	239.80	67.39	332.31	64.72
	LH	392.74	59.28	311.63	61.08	373.07	59.40

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