ANALYSIS OF PLANTAR SURFACE DATA DURING THE LOADED PHASE OF GAIT ON INCLINED SURFACES

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High accuracy three-dimensional (3D) capture of the plantar surface during gait using video-based 3D image processing technique has recently been developed as part of a project to understand plantar geometry and its relationship to plantar function and shoe-design specifications. Literature review determines that the manner the plantar surface and cross-sectional changes during gait on inclined surfaces have not previously been reported. This paper outlines a 3D surface analysis method developed to examine the plantar surface geometry changes while walking on inclined walking surfaces. The plantar surface capture system has a 3D measurement accuracy of ±0.4 mm. The ICC test (using the subjects' foot) and four operators results show that the ICC (3, 4) was 0.87 with a lower bound = 0.75 and an upper bound = 0.92.

KEY WORDS: gait, inclined surface, 3D plantar surface, foot deformation.

INTRODUCTION: During the full-weight loading phase of gait the plantar surface changes its shape by as much as 3.4±1.3% in foot length, and 6±2.1% in foot width (Tsung et al. 2003). Coudert at al. (2006) investigated the change in foot shape during walking to determine the parameters needed to develop footwear that can adapt its inner volume to foot shape changes. These authors found that when the forefoot is on the ground, the width of the foot increases by about 5 mm, or about 5%. Chang et al. (2010) found significant differences between non-weight bearing and whole-weight bearing conditions, and reported arch-height and arch-index were reduced 23% and 20% respectively. Kimura et al. (2008) and Kouchi et al. (2009) provided brief discussions on the measurement quality of various cross-sections of the foot dorsum and argued that the findings showed that the circumference of the ball of the foot varied significantly during walking. They compared the largest variation of the ball circumference to that of two-size differences in shoe-size. Schemeltzpfenning et al. (2011) reported the study of the three dimensional (3D) dynamic behaviour of foot structure in regards to shoe-last design. A shoes-last is a physical model that has a shape similar to that of a human foot. However, they provided few details about the shape change of the plantar surface of the foot during the major loaded gait phases (i.e. heel-strike, midstance and toe-off). Telfer and Woodburn (2011), Al-Baghdadi et al. (2012), Thabet et al. (2014) and Mochimaru et al. (2011) provided a list of 3D plantar surface capture techniques in a comprehensive review, but there was very little discussion on the analysis of the acquired 3D surfaces to show the size and location of the shape change of the plantar surface during the loading phase (LP) of gait. By and large, detail on how the shape of the plantar surface changes during the LP of gait on inclined surfaces has not previously been reported. This investigation applies 3D surface analysis to identify the characteristic of the plantar surface while walking on a range of inclined surfaces.

METHODS: *3D gait capture system.* The custom-built system consists of eight JVC Everio GZ-HD500S high definition video cameras. The video cameras were mounted directly underneath a glass-topped AMTI force plate that was mounted flush with the walking surface. A multi-video camera synchronisation device was installed on the system which synchronised the cameras and the force plate once the laser beam is cut by the gait action of the subject (Chong et al. 2011; Al-Baghdadi et al. 2013).

Recruiting and Preliminary Preparation. Ten adults (age: 35 ±3.4 years; height: 176 ±4.0 cm; and weight: 76 ±8.2 kg) who have differing foot arch characteristics were recruited and volunteered for this project. This recruitment was approved by the university ethics committee. The recruits had what could be considered low (AHI = 0.278 ± 0.013), normal (AHI = 0.328 ± 0.022) and high foot (AHI = 0.369 ± 0.018) arches respectively as determined by a musculoskeletal physiotherapist. Based on the standard podiatric classification four were considered to have low-arch feet, four had normal-arch feet and two had high-arch feet [18]. The recruits were prepared for the trials by placing imaging retro-reflective targets to the sole and the side of the foot along these lines and at key points on the plantar surface.
The Prototype Evaluation. A rigid adult-size plastic foot was utilised to evaluate the measurement quality of the fabricated system. In the evaluation, the plastic foot was positioned on the various inclined surfaces as explained later.
Normal Foot Dimension Measurement. The subjects were instructed to practise a three-step gait on the walking platform until they could consistently place the right foot on the glass plate without any alteration in gait. In this trial, the subjects performed two sets of activity. First, they lowered their right foot to the glass plate but not touching it and the cameras were activated to record the plantar surface. The 3D plantar model derived from this set of images is called “before contact” (BC) and no load was applied to the plantar surface at this instance. Next, each subject performed three sets of 3-step gait across a level platform. This is a level surface walking (LS).
Inclined Walking Surfaces. In this trial, the walking surface was raised in the leading edge along the transverse plan to imitate an uphill incline at a gradient of 11 degrees. Next, the surface was lowered in the leading edge to imitate a downhill incline of the same gradient. After that, the subjects carried out similar gaits over a surface which was inclined at a gradient of 11 degrees along the sagittal plane. In this trial, the foot arch was at the up-side of the incline. The final test involved walking in the reverse direction where the foot arch was at the low-side of the incline. The four sets of trials are termed: (1) uphill (UH), (2) downhill (DH), (3) medially inclined (MI) and (4) laterally inclined (LI) respectively in this paper.

RESULTS: *Colourised Plantar Surface Contour Shading.* The reconstructed 3D plantar surfaces were colourised based on the height of the plantar surface from the walking surface. The walking surface was set as the height datum and given a height of 0.0 mm. In Figure 1(Left), the (a) shows 3D plantar surface of flat and normal arch foot; (b) no load applied; (c) midstance on a level surface; (d) midstance on uphill incline, (e) midstance on downhill incline; (f) midstance on medially incline surface; and (g) midstance on laterally incline surface. The contours provide easy calculation of the area based on depth from the glass surface. The areas shows the amount of plantar surface compression and these are valuable information in the manufacture of shoe’s inner sole surface.
Cross-sections Plots on Inclined Planes. The cross-sectional plots of Figure 1(Right) were derived from the contour plots of Figure 1(Left). They show the influence of the ground condition on plantar surface deformation. In the figure, the plots of the LB (fore-foot) and LC (mid-foot) cross-sections of one subject walking on the six surface conditions using six different colours lines. Two sets of datums were utilised: (1) before contact and level surface were based on 0.0 mm while (2) the inclined surfaces (MI, LI, UH and DH) were based on 30mm datum in the graphs as the inclined surfaces did not allow the use of the glass (walking) surface as the datum.

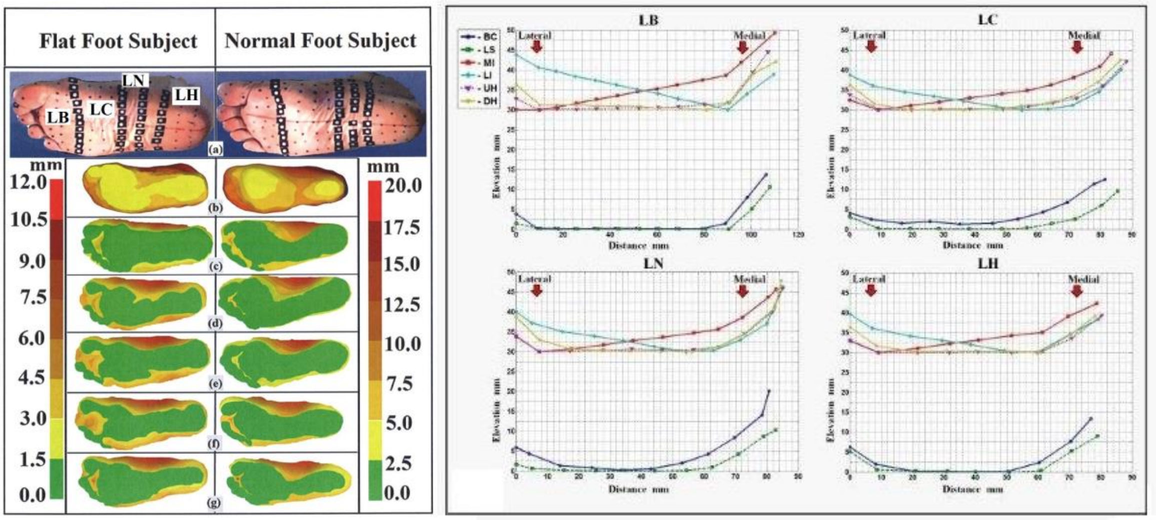

Figure 1: (Left) Colourised depth shading of the 3D plantar surface for Recruits A having flat arch foot and B having normal arch foot; (Right) cross-sectional (LB, LN, LC, LH) plots as depicted in the 3D foot (Left).

Cross-sectional Dimensions. Percentage difference in cross-sectional area (CSA) in the six trialled surface measurements (before contact (BC), level surface (LS), uphill (UH), downhill (DH), medially inclined (MI) and laterally inclined (LI) for the ten recruits were analysed. The calculated percentage change in CSA has an accuracy of ±0.2 % at 95% confidence level. It appears that during the heel-strike, the change of the CSA at LH is the largest for the Uphill incline. However, the percentage of change in CSA of LH between the walking surface LS and other incline surfaces, i.e. MI(r^2 = 0.94), LI(r^2 = 0.97), UH(r^2 = 0.94) and DH(r^2 = 0.95) has similar deforming characteristics. At midstance, the percentage change of CSA at LB during downhill gait is generally larger than all other CSAs (A= 0.4%, B=0.4%, C=0.2%, D=0.7%, E=0.5%, F=0.2, g=0.3% and H=0.2%) and this result is statistically significant because the technique developed has an accuracy of 0.2%. During toe-off, the maximum percentage change in CSA occurred at LB while the change in LH is close to zero for all walking surfaces. It appears that there is strong correlation in the percentage of change in CSA at LB between LS and all other walking surfaces (MI(r^2= 0.92), LI(r^2 = 0.85), UH(r^2 = 0.834), and DH (r^2 = 0.966)) at toe-off.

DISCUSSION: The change in the shape of the plantar surface while walking on different inclined surfaces show the need to design the shoe-inner cavity to fit the deformed-shape of the foot. Our tests show that the length of the foot change minimally while the forefoot has a substantial change in the width. The plot of the four cross sections show the shape change along the sole and the medial and lateral side of the foot. The distal and angular measures can be obtained by simple calculation. These cross-sectional dimensions can be loaded onto shoe Computer-Aided Design (CAD) easily for virtual viewing. The contact area between the foot and the shoe-inner surface can be visualised accurately. The use of the four major cross sections introduced in this paper is an appropriate recommendation as they show the change in various important locations of the foot, particularly the forefoot and heel where soft plantar tissues are compressed by the loading. The developed method is practical for the capture of useful data in shoe and orthotic design. The captured data is also useful for the study of foot biomechanics and longitudinal study of patient’s foot deformation.

CONCLUSION: This study represents an initial understanding of the 3D plantar surface of foot during various phases of gait as captured using precision 3D imaging techniques. Ten adults participated in 3-step gait on level surfaces and on inclined surfaces at a gradient of 11 degrees in the sagittal, coronal and transverse planes. The objective was to show this novel technique for the creation and analysis of distal and angular measures from dynamic 3D models of the plantar surface of the foot, thus providing new insights into the geometrical characteristics of the plantar surface, such as shape change, morphology, contact area and foot orientation during gait on various inclined surfaces. The plantar surface capture system has a 3D measurement accuracy of ±0.4 mm. The ICC test (using the subjects' foot) and four operators results show that the ICC (3, 4) was 0.87 with a lower bound = 0.75 and an upper bound = 0.92. For future work, the plan is to recruit forty recruits for testing.

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