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A VIDEO-BASED SYSTEM FOR PLANTAR SURFACE ACQUISITION DURING GAIT

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Video-based systems for digital object surface feature acquisition are commonly used to provide non-contact accurate 3D mapping of objects in motion. A review of the literature shows that these systems are extensively exploited in human movement studies. The shape of the human foot plantar surface during gait can be better studied using 3D surface models and contours. Additionally, surface contact characteristics and peak pressure of the plantar surface can be determined readily using the calculated 3D models. In this article, the processing algorithms, image capture and point cloud creating methods are discussed. Further discussion includes the findings of an investigation into the stance phase of gait and the plantar-substrate contact location. Tests show that the developed video-based 3D surface capture techniques are accurate and reliable.

KEYWORDS: 3D surface, human foot, contour, point cloud, video, pathologic gait

INTRODUCTION: Video-based techniques using video clips are well-known tools in 3D motion tracking of objects. These techniques are common in tracking of objects experiencing high-speed motions (Chong 2011). Generally, the video clips captured in these applications require frame rates of 100 per second or higher (Chong 2011). The 3D measurement accuracy reported by Chong (2011) using low-cost video cameras was in the sub-millimetre values. Developing innovative data acquisition techniques for human 3D motion and human movement studies were also carried out by researchers in the various fields such as biomechanics (Chong 2012; Chong et al. 2009; Kolahi et al. 2007; Kimura et al. 2011), exercise science (Sarro, et al. 2009) and clinical applications (Chong 2011). One notable research involving human gait was Kolahi et al. (2007) who investigated the use of these techniques in the determination of the joint flexion angles during a gait cycle. The researchers exploited two high-speed mini digital video camcorders (JVC GR-DVL9800U; focal length: 3 to 60 mm, pixel size: 0·003 mm; pixel count: 1024 x 768) to capture video clips of the position of spherical fibre markers which were placed over the trunk and limb of a cohort of martial art experts and non-experts during their martial art performance. The research showed that the video-based imaging system was capable of providing 3D distance measurement accuracy of 2·39 mm. In another research, Sarro et al. (2009) utilised six low-cost mini video cameras (JVC GR-DVL 9500; focal length: 5 to 50 mm; pixel count: 760 x 520; pixel size: 0·001 mm) and retro-reflective markers to evaluate the extent of the motion of human ribs during exerted breathing. The results of the research showed that the custom-built video-based system and the processing software were capable of capturing 3D measurements at accuracy of 2·6 mm. The analysis of the acquired rib motion data confirmed the difference in the ribs' behaviour between trained swimmers and untrained healthy subjects. Chong (2011) utilised four high-definition camcorders (2xSony HDR-SR10, 1xSony HDR-XR150 and 1xCanon HFS11) to acquire the foot movement of low-speed gait to determine the suitability of the system for the monitoring the mobility of Charcot-Marie-Tooth (CMT) disease sufferers. The author reported that the developed technique provided a 3D measurement precision of 0·3 mm at an object distance of 800 mm.

In this investigation, a four high-definition camcorder imaging system was used to acquire the digital feature of the human foot plantar surface while the test subjects' feet undertake the motion of gait. The objectives of this paper are: 1) to provide a discussion of the methods used in the acquisition of the video clips of the gait; (2) to provide a discussion of the methods utilised in the calculation of 3D surface of the gait; and (3) to present the results of the investigation.

METHODS: The research involved the use of mathematical algorithms known as the collinearity equations. These equations are commonly used to process images that are acquired from a single or a multi-array of optical sensors. For tracking objects in motion, the video clips must be acquired simultaneously, thus the same instant of the object orientation is recorded by the sensors and the related image frame can be identified from the video clip accurately. These equations represent the geometry between the lens perspective centre of the video camera, the object-space coordinates of an object and the image coordinates with reference to the principal point and the sensor chip format. They give the geometry of a bundle of rays connecting the camera's perspective centre, the image points and the object points. Commonly, the perspective centre of the lens is represented by (X_0, Y_0, Z_0), with the camera rotation angles ω, ϕ, κ around the X, Y and Z axis respectively. The image coordinates of point N are represented by (x_N, y_N) in millimetres and the object coordinates of N are (X_N, Y_N, Z_N) in millimetres. The collinearity equations representing the point are given as follows:

$$x'_N = x'_0 - PD\,\frac{a_{11}(X_N - X_0) + a_{12}(Y_N - Y_0) + a_{13}(Z_N - Z_0)}{a_{31}(X_N - X_0) + a_{32}(Y_N - Y_0) + a_{33}(Z_N - Z_0)} + \Delta x'_N \tag{1}$$

$$y'_N = y'_0 - PD\,\frac{a_{21}(X_N - X_0) + a_{22}(Y_N - Y_0) + a_{23}(Z_N - Z_0)}{a_{31}(X_N - X_0) + a_{32}(Y_N - Y_0) + a_{33}(Z_N - Z_0)} + \Delta y'_N \tag{2}$$

Where PD = calibrated focal length of the camera lens, and a_{11} *to* a_{33} are given by the following rotation matrix relationship.

$$\begin{pmatrix} a11 & a12 & a13 \\ a21 & a22 & a23 \\ a31 & a32 & a33 \end{pmatrix} = \begin{pmatrix} \cos\phi\cos\kappa + \sin\phi\sin\kappa & -\cos\phi\sin k + \sin\phi\sin\omega\cos\kappa & \sin\phi\cos\omega \\ \cos\omega\sin\kappa & \cos\omega\cos\kappa & -\sin\omega \\ -\sin\phi\cos\kappa + \cos\phi\sin\omega\sin\kappa & \sin\phi\sin\kappa + \cos\phi\sin\omega\cos\kappa & \cos\phi\cos\omega \end{pmatrix} \tag{3}$$

Each image provides a set of two equations, thus a configuration of four video cameras provides a set of eight equations for each point of interest. By using numerous image points, and four or more points with object-space coordinates, the parameters in the equations can be determined by means of a bundle adjustment which is a least squares technique. Afterward, point cloud set is calculated for all discrete image points.

A gait platform and a four video-camera mounting device were designed and built for the research. The platform has a rigid aluminium walking surface of 4 m in length and 2 m in the width with safety rails and stairs. A 45x45 cm glass stage was fabricated in the middle of the platform (Fig. 1). The platform provided an object distance of 1.2 m for video recording from under the platform walking stage. A 40x42 cm photogrammetric object-space control device was fabricated using 5x5 cm tubular composite material, thus a hole of 35x37 cm (Fig.1c) is formed in the centre of the control frame. Retro-reflective targets of 4 mm diameter were fastened onto the tubular frame on one side and the frame was attached to the underside of the glass stage with the targets facing the video cameras. A laser-guided device which was used in the video camera synchronisation was built and installed on the platform. The device activates a set of red-flash LEDs just before a person sets foot on the platform glass stage. The flash of the LED synchronizes the video cameras by tagging a recorded frame of the video clips.

The video cameras were calibrated using precision camera calibration techniques as discussed in Luhmann et al. (2006). The initial process involved capturing a set of twelve convergent video clips of a custom-built calibration test-field. First, four short video clips were acquired with the camera in vertical position (the shutter pointing forward), then four more clips with the camera rotated 90° to the left and lastly, four clips were taken with the camera rotated at 90° to the right. The image frames were extracted from the clips using image extraction Internet freeware, VirtualDub. The retro-targets on all the extracted images were digitized using proprietary software, Australis which also provided multi-image bundle adjustments of the images. A high-precision Invar scale bar was used in the calibration, thus real world scaling of the calibration parameters can be established. The calibration process was repeated three times to ensure the calibration results were reliable. After the bundle adjustment the lens distortion parameters were obtained and these parameters were used to correct the lens distortion present in the research images.

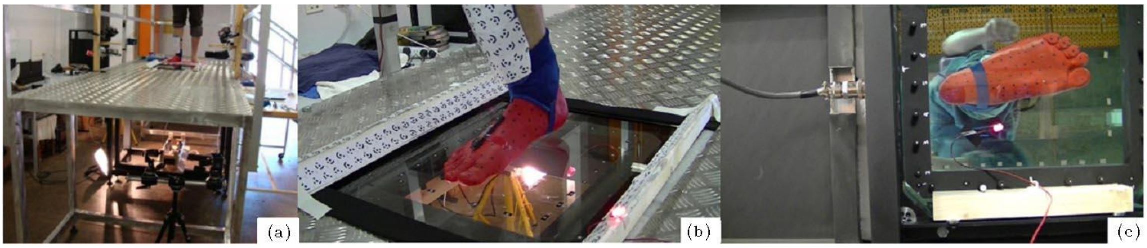

Figure 1. video clips acquisition of a test subject during gait. (a): gait platform; (b): gait phase; (c): plantar surface imaging.

Figure 2. (a): calibration test-field; (b): video camera calibration setup; (c): Image acquisition geometry.Note the camera shutter button position.

Two healthy adult subjects were recruited for the research. Their gait qualities were evaluated to ensure they are suitable for the research. After completing the consent forms, the subjects' right foot plantar were painted with red-coloured, non-toxic body paint. Then, retro-reflective targets were stuck onto the plantar surface as shown in Figure 1. The subjects were instructed to perform a set of slow gaits on the platform until they were familiar with the procedure. The main reason for this procedure is to ensure that the subjects can perform the task comfortably while they still manage to step on to the glass stage within the marked space. Once the subjects were ready, video cameras and the laser were switched on and video clips of their gaits over the stage were acquired. The trial was repeated three times for each subject to ensure the imaging session was successful.

An image extraction Internet freeware, VirtualDub was used to search, identify and extract the synchronised image frames from all the video clips. Next, proprietary image processing software, PhotoModeller was used to generate the 3D point cloud of the plantar surface. The 3D point clouds were edited to remove incorrect points which are usually located above or below the correct plantar surface. Once the point clouds were considered accurate 3D surface model of the plantar surface and contour were produced. 3D distances or angular measurements between features could be made on the generated models.

RESULTS AND DISCUSSION: Using the acquired video clips of the gait of the test subjects, 3D surface models of the gait at various phases were generated. Figure 3 shows the 3D surface model of the stance for subjects A (3a) and B (3b). The contours in the figure show that subject A has a flat foot arch while subject B has a prominent high foot arch. Using the contours, longitudinal profiles such as the foot midline or any other lines parallel to this line can be digitally plotted and studied. Cross-sections of the plantar also can be plotted at an accuracy of 0.3 mm. Figure 4 shows the 3D surface and contour of the plantar at the last moment of the toe-off for the same subjects. The figure shows that pad of the toes and the fore foot plantar are in contact with the walking surface. However, the maximum contact surface appears on the second toes pad for subject A while the maximum contact appears on the fifth toes in subject B. A frame by frame (30 frames per second) contact surface change can reveal the change of the peak pressure location. In the figure, it is apparent that the action of the toes during toe-off is different between the individuals. This new information may assist researchers and practitioners to understand the function of the toes during toe-off in greater detail.

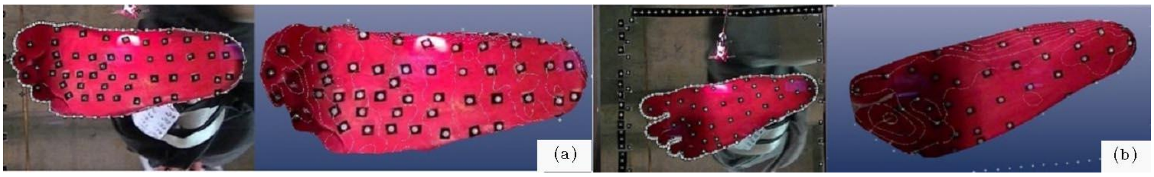

Figure 3. 3D surface model and contour over the surface model. (a): subject A; (b): subject B. Note the clarity of the contours of the foot arch of subject B.

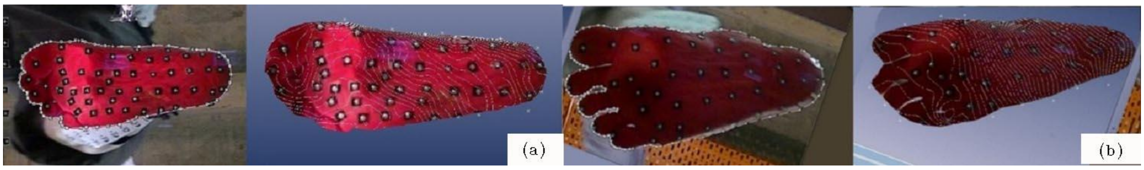

Figure 4. 3D surface model and contour of toe-off: (a): subject A; (b): subject B. Note the contours spacing at the fore-foot.

CONCLUSION: The paper introduces an innovative method in the acquisition of accurate human foot plantar 3D surface during gait. The main objective of the paper was to provide a discussion of the processing algorithms, the image acquisition and point cloud creating methods for the generation of 3D plantar surface of this technique. Tests shows that the calculated 3D surface model has a spatial accuracy of 0.3 mm and 30 models can be accurately produced in one second using off-the-shelf HD video cameras. The research shows that the 3D plantar surface features change during the gait cycle and this implies the shifting of the contact surface from the heel at strike to the pad of the toes at toe-off can be calculated at a rate of 30 samples per second. The characteristics of the shifting of the contact surface can be used to evaluate pathological gait. The evaluation may provide the information to diagnose plantar diseases, predict ulcer formation, compare surgical outcomes, evaluate orthotic device efficacy and assess the design of footwear to suit individual need.

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