Available online at www.sciencedirect.com

SciVerse ScienceDirect

Procedia Engineering 34 (2012) 266 – 271

Procedia Engineering

www.elsevier.com/locate/procedia

9th Conference of the International Sports Engineering Association (ISEA)

A Method to Measure Dynamic Dorsal Foot Surface Shape and Deformation During Linear Running Using Digital Image Correlation

Robert Blenkinsopp[a]*, Andy Harland[a], Dan Price[b], Tim Lucas[b], Jonathan Roberts[a]

[a]*Sports Technology Institute, Loughborough University, Loughborough, LE11 3TU, United Kingdom*
[b]*adidas AG, adidas innovation team – ait, World of Sports, Herzogenaurach, Germany*

Accepted 02 March 2012

Abstract

This paper reports a methodology that employs a three dimensional (3D) digital image correlation (DIC) system to measure dynamic foot shape during running. DIC is a non-contact optical measurement system, capable of high resolution surface deformation measurements derived from digital images captured of a surface undergoing a deformation. The methodology presented in this paper uses a plurality of synchronised high speed cameras to capture images of the stance phase of the gait cycle, from which surface shape and deformation measurements can be made. Results related to foot morphology are presented which show the merit of the method and potential for future use.

Keywords: Footwear; dynamic foot shape; running; 3D digital image correlation; GOM ARAMIS

1. Introduction

The morphology of human feet is an important factor to be considered in the design of sports shoes. It is widely accepted that in order for a shoe to fit correctly it must match the shape of the foot. Existing studies in literature concerned with human foot shape have generally conducted measurements and comparisons in a static scenario [1], measuring specific foot dimensions derived from marker points at landmarks on the foot surface. However, the static shape of the foot is likely to change considerably in a

* Corresponding author. Tel.:+44 (0)1509 564822; fax: +44 (0)1509 564820.
E-mail address: r.blenkinsopp@lboro.ac.uk.

1877-7058 © 2012 Published by Elsevier Ltd.
doi:10.1016/j.proeng.2012.04.046

dynamic situation during the footstrike when loads transferred through the foot are much greater. Therefore the dynamic foot shape should also be considered in shoe design in addition to the static shape. Only a handful of studies have attempted to measure dynamic foot shape. A review of current literature shows there have been two approaches to this challenge, a stereo matching method and a structured light method. The former is based on the triangulation of multiple synchronised cameras [2]. It was employed to study walking movements by Kouchi *et al.* [3] to measure predefined anatomical cross sections marked on the foot and by Coudert *et al.* [4] to measure the dorsal foot surface. The structured light method employs a projector-camera system as an active device with defined patterns projected onto the moving object [2], this method has been used by Kimura *et al.* [5] for partial foot surface measurement and Schmeltzfenning *et al* [2], who was able to synchronise five sensor units and use an ultra fast pattern switching technique to capture the full dynamic foot surface, but only during walking due to restricted capture frame rates. Although there has been progress in recent years with dynamic foot shape measurements, it is apparent that current methodologies are limited in the surface coverage and measurement resolution as well the movement speeds that can be measured. The aim of this work was to develop a methodology that can be used to measure the dynamic shape and deformation of the dorsal surface of the human foot at running speeds during the stance phase of gait as measurements so far employed have only presented shape measurements for walking speeds. This has been achieved using a commercially available digital image correlation system employing three pairs of high speed video cameras to view the foot during deformation from which related morphology measurements can be made.

2. Digital Image Correlation

Digital image correlation (DIC) is a non-contact optical method where digital images of an object are captured and analysed to extract full field shape, deformation and/or motion measurements [6]. The method compares images of the object in a non deformed and deformed state in order to obtain relative measurements.

Measurements are made by creating and then tracking a number of surface points in a sequence of digital images, typically of a surface undergoing some form of deformation. Surface points are reconstructed from the digital image data either in two dimensions (2D) using images from a single sensor, or in three dimensions (3D) using a synchronised images from a stereo camera system. A data point is created from a neighborhood of pixels (subset) within the digital image at the reference stage; this subset and associated data point is then tracked at sub pixel accuracy using correlation methods to match the same area of pixels based on the intensity values, in subsequent stages of deformation. A displacement field for a surface, from which deformation vector fields can be derived, is obtained by measuring the 3D displacement of data points at a discrete number of locations across the surface of interest. The resolution of a measurement is dependent upon the number and separation of data points created, this can be controlled by defining the distance, in pixels, that a subset is translated within the image before another data point is created, usually referred to as the step parameter.

In order to create a suitable intensity field for the sensors to measure and to aid in the unique correspondence of subsets between images; a non periodic contrasting stochastic pattern that adheres and deforms with the surface is generally applied to the surface of interest to enable measurements to be made.

The benefit of DIC over other shape and deformation measurement systems is the non-contact nature of the process; additionally full field measurements are possible with the ability to obtain a high resolution of data points on a surface of interest with relative ease. DIC can be implemented on a range of materials and surface types with applications ranging from the nano scale up to large scale ($\gg m^3$).

3. Experimental Methodology

3.1. Digital Image Correlation

The DIC software used in this experimental work was the ARAMIS DIC system, developed by GOM (Braunschweig, Germany) which is owned by Loughborough University (LU) Sports Technology Institute (STI). Although GOM do supply a turnkey system for high speed deformation measurements it is also possible to use images from a range of other sensor types that are then imported into the software for processing. To make this possible, certain imaging properties of the sensors must be known and are usually obtainable from data sheets or directly from the sensor manufacturer.

In this work, Photron (Tokyo, Japan) SA 1.1 high speed video (HSV) cameras were used. Six HSV cameras were employed configured in three pairs; 2 pairs comprising monochrome cameras only and a single pair comprised of a monochrome and colour camera. The cameras operated at a resolution of 1024 pixels x 1024 pixels, recording at a frame rate of 250fps and a minimum shutter speed of 1/5000s. Images from the colour camera were saved using a 'Bayer save' function in the Photron camera software to obtain monochrome images. Adjustments were made to the setup of the paired monochrome camera shutter speed to ensure similar light intensities to the colour camera were measured.

Each camera pair was mounted to a beam to secure the cameras at a fixed angle and separation to one another; these parameters can be adjusted, to increase camera pair field of view and, therefore, the volume of measurement. All cameras were fitted with 50mm fixed focal length lenses with appropriate apertures to achieve an adequate depth of field. A sensor calibration was completed for each camera pair prior to measurements in line with the recommended protocol [7] with calibration deviations for all three camera pairs falling within the range recommended by GOM.

3.2. Creation of a Common Global Co-ordinate System

Measurements of a deforming foot were made from each individual camera pair simultaneously in synchronization; therefore each has a different individual co-ordinate system, related to the camera pair. In order to bring measurements from all three camera pairs together into a single cohesive measurement, each measurement needed to be translated into a common co-ordinate system.

The approach taken to solve this problem was to create a separate co-ordinate system to which each measurement would be translated, rather than attempting to translate to a co-ordinate system associated with a camera pair, which would require three dimensional positions of the camera pairs to one another to be known. A co-ordinate system was created using TRITOP (GOM, Braunschweig) an optical 3D co-ordinate measurement system and a sister system to ARAMIS. A point cloud was created using TRITOP by photographing, from different viewpoints, markers which had been placed on the ground within the measurement volume, arranged to define the x, y and z planes of a co-ordinate system. The 3D position of these markers was also measured in the ARAMIS software from camera images, by importing the TRITOP point cloud into the ARAMIS software; these points could be used to translate each deformation measurement from each camera pair to the common global co-ordinate system. Individual measurements in the same co-ordinate system were brought together using S-View, an extension software package of the ARAMIS software, from which further measurements using the combined data could be made.

3.3. Ground Reaction Force

Ground reaction forces during the stance phase of running were measured using a force plate (Kistler, Switzerland) with a data acquisition frequency of 2000Hz. The force plate was positioned so that the positive anteroposterior force values ran in the direction of running and the mediolateral from right to left, as shown in Fig.1. Vertical and anteroposterior force components were used to ascertain subject foot strike type and to provide a quantitative measure of intra-subject repeatability for multiple tests. GRFs were normalised to both time and subject body weight.

3.4. Running speed

A gait speed exceeding approximately $3.3ms^{-1}$ is considered to be running [8]; in this work a running speed of approximately $4ms^{-1}$ was selected to be comfortably within a speed considered running but below that which may be considered sprinting. Measurements of subject running speed were made using light gates positioned a known distance apart either side of the measurement area as shown in Fig.1 only measurements made at the correct running speed were used.

3.5. Experimental Setup

The three camera pairs were arranged around the force plate which was incorporated into a running lane made from artificial track material. Two camera pairs (1 and 3) were placed at ground level parallel to the running direction to capture the medial and lateral sides of the foot. The third camera pair was placed in front of the force plate off centre, so as not to impede the runner; this camera pair was raised on a tripod and then angled down towards the floor to view where the footstrike occurred, enabling the capture of the top foot surface. Cameras within each pair were set at an angle of 25° to one another and each pair was set at a distance of 1.1m from the centre of the force plate. A schematic of the experimental set up is shown in Fig.1.

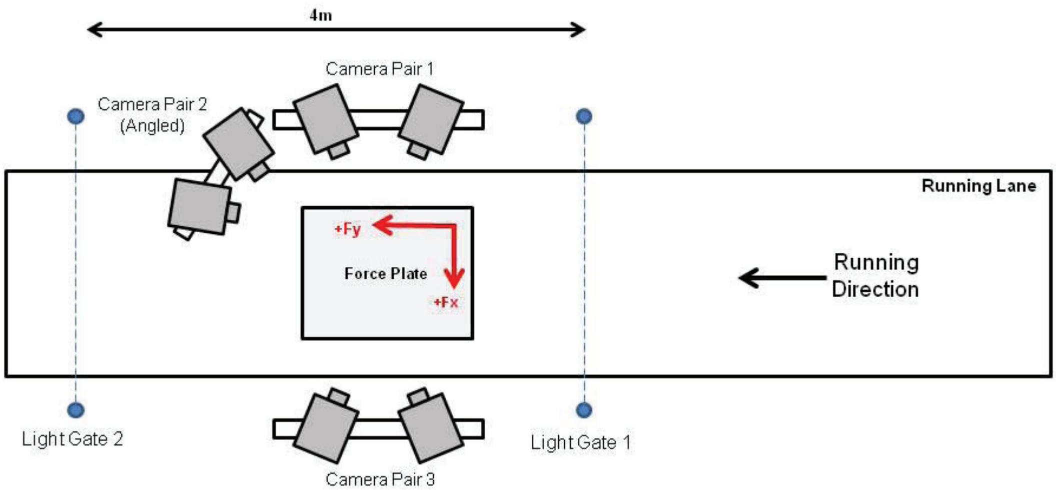

Fig.1. Plan View of the Experimental setup

3.6. Test Protocol

To create a contrasting random pattern on the surface of the foot to aid in DIC computation, water based face paint was used to create a speckled black and white pattern. A single subject was asked to run through the measurement area at an approximate speed of $4ms^{-1}$, the subject was given time to practice before measurements were made to ensure they were able achieve the correct speed and hit the correct placement on the force plate so that all cameras could see the foot surface. Measurements were made of the right foot only for each trial. A manual trigger was used to start all data acquisition devices as the runner passed through the first light gate. Data was captured for 4 seconds which was then cropped to the frames immediately before touch down until the frame immediately after toe off.

4. Results and Discussion

4.1. Shape measurements

The surface results for a stage during the stance phase of the gait cycle are shown in Fig.2a. Although a large percentage of the foot surface was captured, some areas were out of camera view and therefore were unable to be measured. With more camera pairs, it would be possible to capture these areas. Surface measurements were also limited in the toe regions as the breaks in the toes prevented data points being created across the surface. Measurements were still possible nonetheless, even with the reduced coverage.

4.2. Measurement of Foot Breadth

A simple measurement of foot breadth; the line from the metatarsal fibulare to metatarsal tibialeas as defined in previous static studies [1] and shown in Fig.2a, was made from the dynamic surface data from the single trial. Measurements were made between two discrete points on the lateral and medial sides of the foot along with the cross section across the same line. The nominal length of the foot breadth at the reference stage was shown to be approximately 96mm. Results, shown in Fig.2, show a maximum length increase of nearly 8mm in foot breadth, occurring during midstance. This increase and general shape of the graph in Fig 2c is in agreement with the known function of the foot's transverse arch, which flattens to spread the loading during the support phase of gait, causing the foot to increase in width.

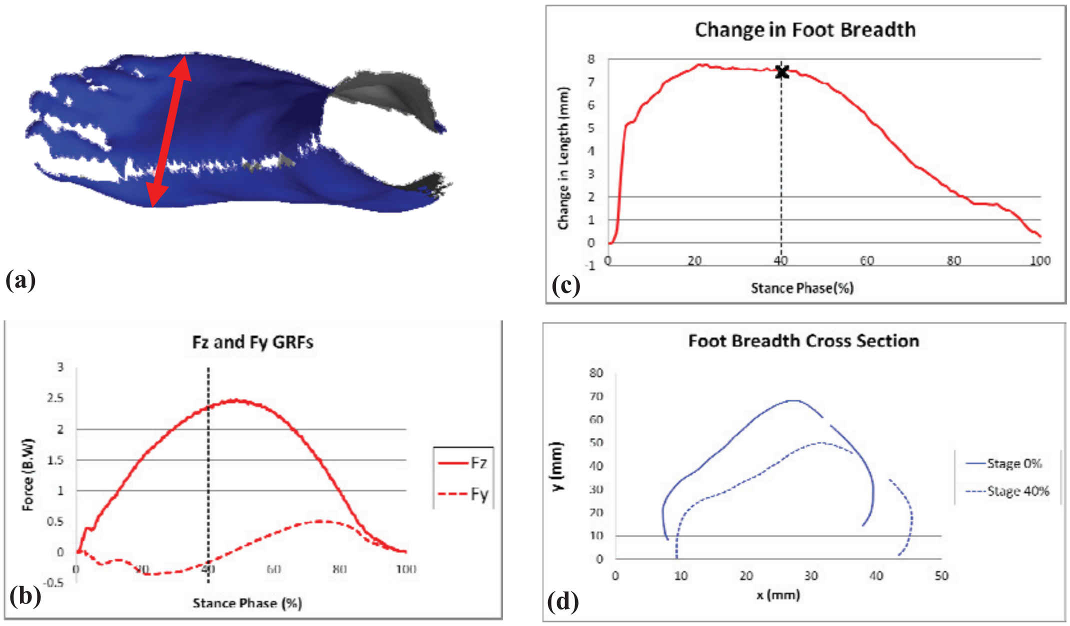

Fig. 2. (a) Foot breadth definition (b) Anterio-Posterior and Vertical GRF Data (c) Foot breadth over whole stance (d) Foot breadth cross sections

4.3. Surface Deformation

Using the ARAMIS software it was also possible to create strain maps, using the 3D data point displacement field, as shown in Fig.3, with the approximate strain-gauge size of 3mm. The visualizations show deformation of the surface relative to the unloaded reference stage, prior to touchdown. This measurement shows the dynamic deformation across the whole surface as opposed to just a cross section or between two discrete points.

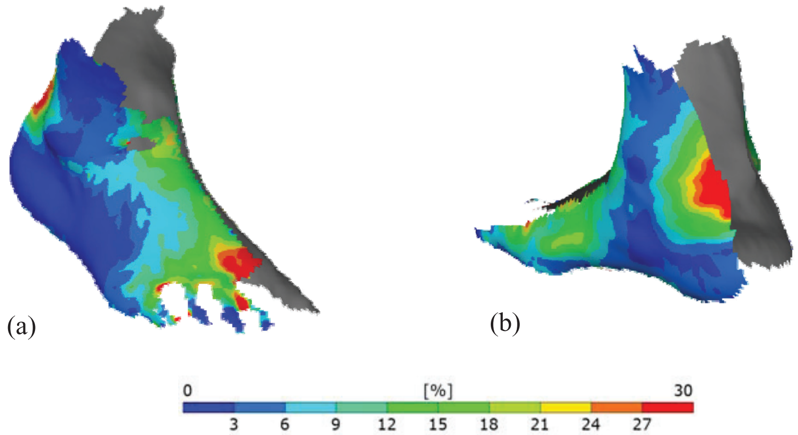

Fig.3. Major strain map at point in stance phase (a) lateral and anterior; (b) medial and posterior

Conclusion

This paper has presented a methodology for dynamic surface and deformation measurements of the dorsal foot during running. This methodology is different to existing methods as it employs a multiple camera DIC system using HSV cameras that enable deformations at running speeds to be measured. The method has enabled foot morphology measurements to be made as well as the facilitating the potential for many others, some of which would not be possible using existing methodologies. More work is needed however, to improve coverage of the foot surface measurements by increasing cameras pairs used, as well as investigating accuracy of measurements in comparison to static scanning systems.

References

[1] Wunderlich RE. and Cavanagh PR. Gender differences in adult foot shape: implications for shoe design *Medicine & Science in Sports & Exercise* 2001; 33: 605-611.

[2] Schmeltzpfenning T, Plank C, Krauss I, Fritz, B, Aswendt P, Grau S. 3D Dynamic behavior of foot structure may provide additional information for last design *Proceedings of the tenth footwear biomechanics symposium Tübingen, Germany,* 2011.

[3] Kouchi M, Kimura M, Mochimaru M. Deformation of foot cross-section shapes during walking. *Gait&Posture* 2009;**30**: 482-86.

[4] Coudert,T, Vacher P, Smits C, Van der Zande M. A Method to obtain 3D foot shape deformation during the gait cycle. *9th International Symposium of 3D Analysis of Human Movement. Valenciennes, France.* 2006

[5] Kimura M, Mochimaru M, Kanade T. Measurement of 3D foot shape deformation in motion. *Proceedings of the 5th ACM/IEEE International Workshop on Projector Camera Systems Marina del Rey, California.* 2008

[6] Sutton, M. A., Orteu, J. and Schreier, H. W. *Image correlation for shape, motion and deformation measurements: basic concepts, theory and applications*. New York: Springer Science+Business; 2009.

[7] GOM, *ARAMIS User Manual RevA – Software*; GOM, Braunschweig, Germany; 2009.

[8] Sammarco, GJ. and Hockenbury, RT. Biomechanics of the Foot and Ankle. In: Nordin M, Frankel VH editors. *Basic Biomechanics of the Muscoskeletal System*, Philadelphia, Lippincott Williams & Wilkins; 2001, p 222-255.