A method to obtain 3D foot shape deformation during the gait cycle

Térence COUDERT [1], Pierre VACHER [2], Cathy Smits [3], Marc Van der Zande [3]
[1] CTC Technical center for leather, footwear and leather goods, Lyon, France
[2] LMécA, Mechanicals applied laboratory, Annecy, France
[3] TNO Science and Industry, Eindhoven, The Netherlands
tcoudert@ctcgroupe.com, pierre.vacher@univ-savoie.fr, cathy.smits@tno.nl, M.vanderZande@ind.tno.nl

***Abstract* — Developed anthropometric measurement systems for the foot are static. However, important changes occur in the 3D shape of the foot during walking. This study deals with computer vision techniques to obtain the 3D foot shape at different step moments during the gait cycle. The foot shape evolution is estimated by comparing the 3D reconstruction of the foot surface at different gait steps. This method will provide suitable information to develop footwear which is able to adapt its inner volume during foot shape changes.**

Keywords – 3D foot shape; motion analysis; measurement; footwear; 3D displacement; 3D deformation; gait cycle.

I. Introduction

This work is a part of the European CEC Made Shoe project. This project aims at moving the footwear sector from a "product – centred" (shoe) approach to a "human – centred" approach that is represented by three axis of the human being: Comfort focusing on the foot, in all the aspects of walking, running, standing; Environment focusing on 100% nature friendly materials and process sustainability; Custom focusing on Style & Fashion.

Developed anthropometric measurement systems for the foot are realised when the foot is in a static position. However, important changes occur in the 3D shape of the foot during walking. This study will provide suitable information to develop footwear able to adapt its inner volume to foot shape changes. There are many 3D foot scanners systems [1, 2]. Most of them use laser scanning, and require a long time for measurements (several seconds). These scanners are fast to digitize a foot in one or two static positions (seating or standing position for example). However, there is no system that can measure 3D foot shape in motion. Most of the existing motion capture systems are fast and accurate for a few points in the space (a few landmarks are pasted on the body and are reconstructed in 3D). Recently, a study showed a method to measure feature cross-sections of the foot during walking [3]. They show the shape changes in ball, instep and heel cross-sections of the foot.

In our approach, we propose to digitize the whole surface of the foot (like foot scanners) at different step moments during the gait cycle (like motion capture). To compute 3D shape and 3D surface comparison of the foot, a non-contact typed 3D displacement and strain measuring system is used. Other authors propose a similar method applied for surface measurement and tracking of human body parts [4].

II. Principle

A person walks on the ground and some cameras record the scene. The method consists of taking a set of images of a foot at different step moments. For each instant, this set is analysed to obtain a 3D surface of the foot. The foot shape evolution is estimated by comparing the different surfaces in time : surface S_1 at time $t_1$with surface S_2 at time t_2. To allow the correlation between two 3D surfaces, matching points are necessary, a point of surface S1 must be found on the surface S2. For matching points, a random pattern has to be fixed on the foot surface. For this purpose, it is possible to project paint drops or use a contrasted sock.

With this computer vision technique, the 3D shape of the target object is reconstructed from multiple images using triangulation between multiple cameras [5]. This method allows digitizing an object as accurate as the laser scanning.

III. Proposed System

A. Description

Our system uses six sets of IEEE1394 cameras and a PC. In fact, there are 3 stereoscopic sensors. The system used is shown on figure 1. All cameras see a common 3D area.

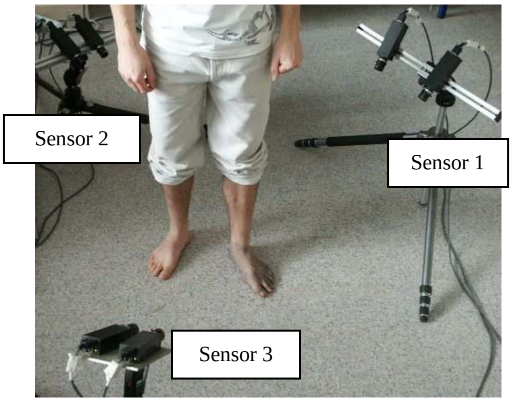


Figure 1. Cameras configuration around the foot

Image resolution is 1280×960 pixels. Camera focal lens is: 16 mm for sensors 1 and 2 and 35 mm for sensor 3. For the moment, the time synchronisation of all cameras is done by two operators. So the capture of all images is not taken exactly at the same time. So, quasi static positions of the foot are needed. In spite of these technical problems, the exploitation results are possible and we are working to synchronize all cameras.

The experimental process to digitize 3D foot shape at different step time is the following:

- Each camera records N views of the foot in different positions during the gait cycle. Before recording images, the optical system (3 stereoscopic sensors) is calibrated.
- Images analysis is launched by specific software to get N 3D surfaces. This analysis is based on computer vision techniques like image correlation, 3D reconstruction by triangulation, multiple 3D surfaces registration. The software used is named “7D” and is developed by CTC and LMécA.

B. Image matching

Points on the images are the projection of the physical points of the scene. The aim of matching is to correctly identify the projection of the same physical point in both images. Good quality correspondence is necessary for calibration, 3D digitization or detection of deformations on surfaces. Our image matching method is an image correlation approach [6].

C. Calibrate the camera system

Camera calibration consists of determining the elements that govern the relationship between the 2D images taken by a camera and the 3D information of the imaged object. Generally this is performed by choosing a parametric model for the camera and by estimating the parameters of this model by means of a calibration object, of which the 3D coordinates are known. The operation of the calibration is developed in 2 steps:

- Calibrate each stereoscopic sensor: it consists of finding the relative positions and orientation of both cameras and corrects most of the camera’s defects.
- Set the 3 stereoscopic sensors in a same coordinate system: an experimental method was developed. The coordinate system is defined from 3 spheres on the floor. Each stereoscopic sensor determines the center of each sphere in its own coordinate system. With this information, a transition matrix is obtained. The passage of local to global coordinate system is now identified.

The global coordinate system is chosen with these rules:

- the x axis is following the length of the foot.
- the y axis is following the width of the foot.
- the z axis is following the height of the foot.

D. 3D reconstruction

A set of images is required to capture data for the entire surface of an object (in our case 3 stereoscopic images pairs). The steps of this process are:

- Triangulation: all image features matched in stereo pairs are transformed to a 3D points cloud.
- Registration: for each step moment all surfaces are transformed into a common coordinate frame. Calibration results of the cameras systems are used to register the 3 surfaces that compose the foot shape.

IV. EXPERIMENTS

Two cases are experimented:

- First the foot is with socks (figure 2) and eight moments of the gait cycle are 3D reconstructed. 3D foot shapes obtained by images analysis are represented on figure 3.
- In the second case, the foot is bare and paint drops are projected on the skin in order to obtain random gray level pattern.

For this last case, 3D displacements between three moments of the gait cycle are measured. The calculation of the 3D shape of the object is realised in four stages: the off-line calibration of cameras, the stereo matching by image correlation and the 3D reconstruction. From two 3D reconstructions of the object (before and after deformation, so in our case at time t_1 and at time t_2, which are corresponding to two different positions of the foot), the 3D displacement field and the surface deformation field using a temporal correlation image matching can be computed.

At least, two pairs of images (before and after deformation) are necessary to compute the deformation undergone by the object. In order to measure the strain fields on skew surfaces, some matching have been achieved between the left image at time t_1 (named L_1) and the right image at time t_1 (named R_1), between image L_1 and L_2 (left image at time t_2) and between image L_1 and R_2. Only the common points found on these four images are used.

This technique is used for each stereoscopic sensor. After registering surfaces, we have the 3D displacement field of the whole foot surface and the foot shape changes during walking can be evaluated. So, images of a foot painted by random gray levels (figure 4) are recorded at 3 step moments. The figure 5 shows the 3D foot shape for each moment. The figure 6 shows 3D displacement measurements on the foot surface between step 1 and step 2 and between step 1 and step 3.

At step 3, the forefoot is on the ground and the width of the foot increases with about 5 mm between step 1 and step 3. The deformation of the forepart width is about 5% for this foot when the foot is touching the ground.

On figure 6, the toes are not correctly reconstructed because this area is not viewed in each image of the different moments.

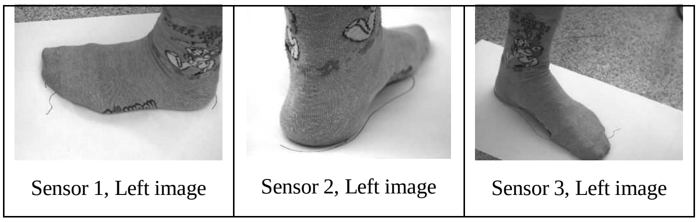
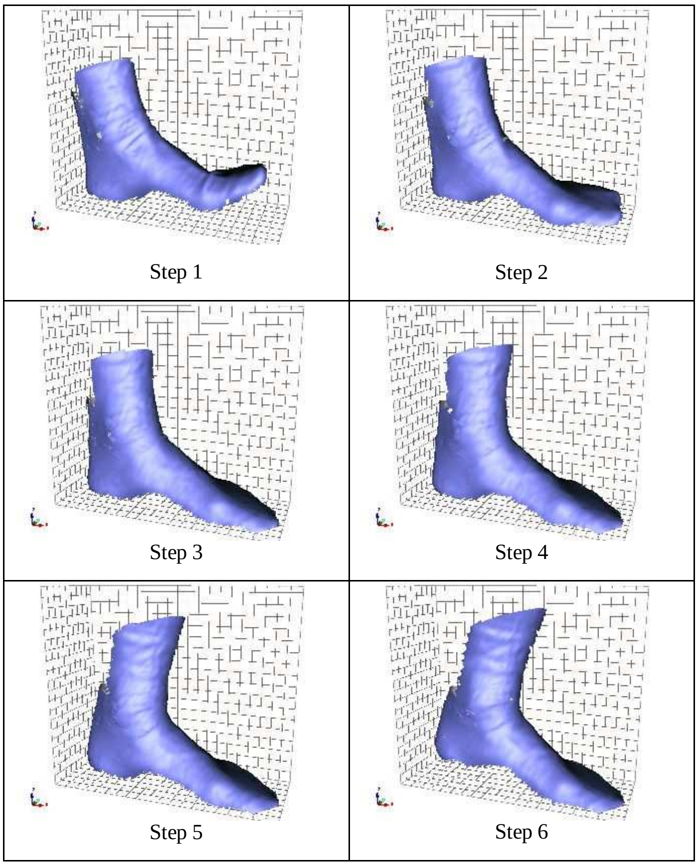


Figure 2. Images of the foot with socks taken by the 3 sensors at step 4



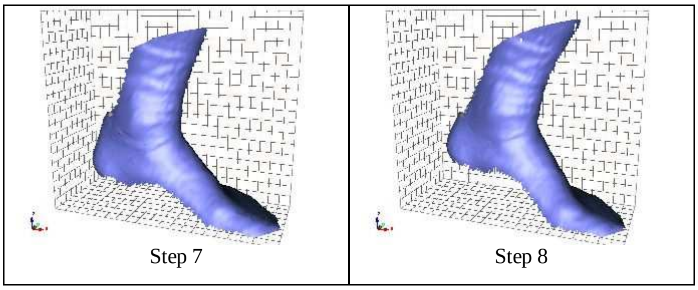


Figure 3. 3D foot shapes for each step (foot with socks)

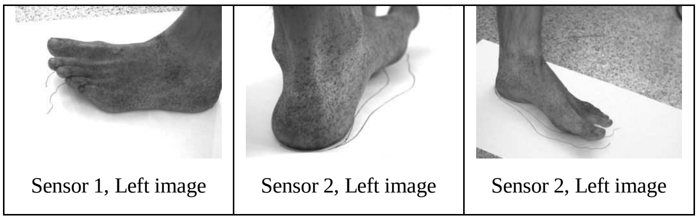


Figure 4. Images of the foot painted by random gray levels at step 1

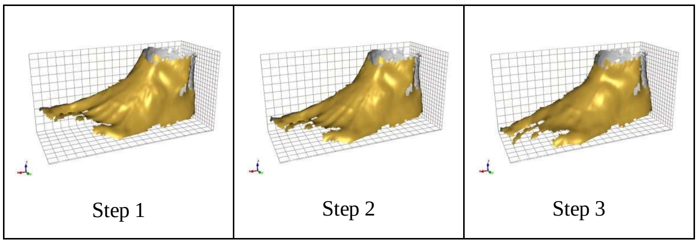
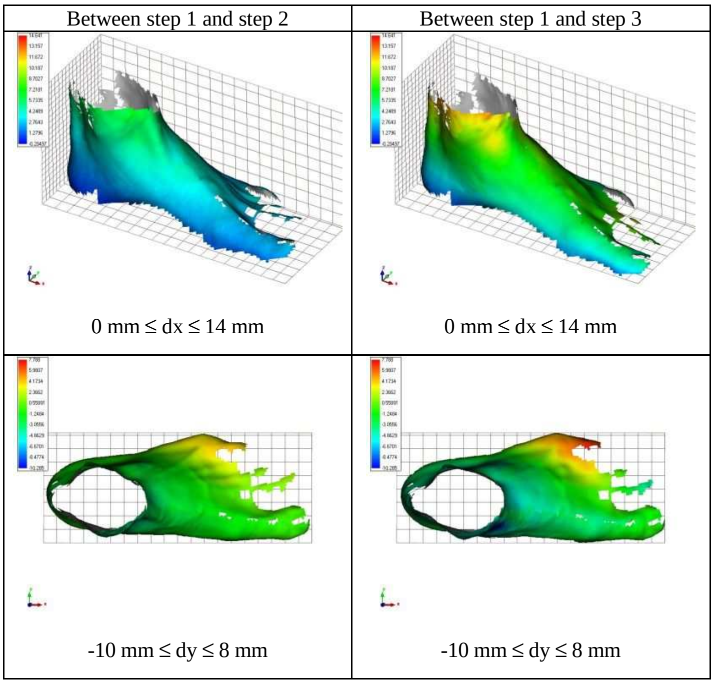
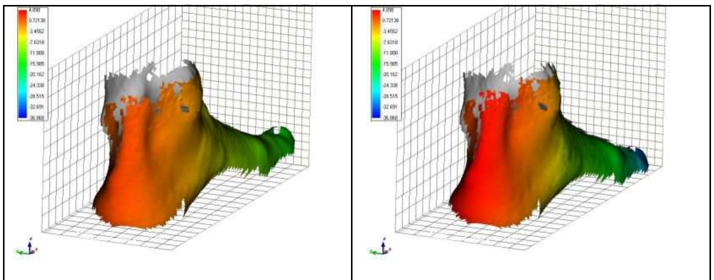


Figure 5. 3D foot shapes





-36 mm ≤ dz ≤ 5 mm	-36 mm ≤ dz ≤ 5 mm

Figure 6. 3D displacements between steps

V. CONCLUSIONS AND FUTURE WORK

A method and a system are presented to measure 3D foot deformation during gait cycle. This technique allows to derive 3D displacements of the whole foot surface between different step moments. These first results on motion capture of foot morphometrics are promising. A few defects of the quality of digitization can be noted: the 3 surfaces which compose the 3D foot shape are some times not in the best position (for example on the upper of the foot, a gap between the surface coming from sensor 1 and the surface coming from sensor 3 can be seen). This position error can be explained by:

- The time interval between each capture of a sensor: the foot can move during this time interval.
- The phase to set the 3 stereoscopic sensors in a same coordinate system: this step can introduce a global error position between surfaces.

The quality of 3D surfaces depends on the quality of images. To record good images of a foot in movement, faster cameras (25 or more frames per second) have to be used.

Our future work will follow two directions :

- further tests with faster and synchronised cameras
- with the current configuration of the cameras, it is possible to capture only the upper side of the foot. The foot plantar surface will be acquired using a glass floor.

REFERENCES

[1] M. Kouchi and M. Mochimaru. "Development of a low cost foot-scanner for a custom shoe making system", 5th ISB Footwear Biomechanics, pp.58-59., Zurich, Switzerland, 2001.

[2] D. Sutton. "Shoemaking and 3d foot scanning : stereo photogrammetry in the cad/cam chain for a custom made footwear", Proc. Scanning 2002, Paris, France, 2002.

[3] M. Kimura, M. Mochimaru, M. Kouchi, H. Saito and T. Kanade. "3D cross-sectional shape measurement of the foot while walking", Proc. of the 7th Symposium on Footwear Biomechanics, Cleveland, USA, 2005.

[4] N. D'Apuzzo. "Surface measurement and tracking of human body parts from multi station video sequences". Ph.D. Thesis, Institute of Geodesy and Photogrammetry, ETH Zurich, Switzerland, Mitteilungen No.81. ISBN 3-906467-44-9, 2003.

[5] O.D. Faugeras. "Three-Dimensional Computer Vision, a Geometric Viewpoint", MIT press Boston, 1993.

[6] P. Vacher, S. Dumoulin, F. Morestin, S. Mguil-Touchal. "Bidimensionnal strain measurement using digital images", Journal of Mechanical Engineering Science, vol. 213, pp 811-817, 1999