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Lower limb movement asymmetry measurement with a depth camera

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Abstract— **The gait movement seems simple at first glance, but in reality it is a very complex neural and biomechanical process. In particular, if a person is affected by a disease or an injury, the gait may be modified. The left-right asymmetry of this movement can be related to neurological diseases, segment length differences or joint deficiencies. This paper proposes a novel method to analyze the asymmetry of lower limb movement which aims to be usable in daily clinical practice. This is done by recording the subject walking on a treadmill with a depth camera and then assessing left-right depth differences for the lower limbs during the gait cycle using horizontal flipping and registration of the depth images half a gait cycle apart. Validation on 20 subjects for normal gait and simulated pathologies (with a 5 cm sole), showed that this system is able to distinguish the asymmetry introduced. The major interest of this method is the low cost of the material needed and its easy setup in a clinical environment.**

I. Introduction

The gait movement is a part of our daily life. We execute it without thinking of how to do it and neither knowing how complex it is. When pathologies impact on one side of the body, an asymmetry generally appears in the movement. For instance, the link between a stroke and gait asymmetry has been studied by Alexander in [1]. Another example is leg length discrepancy, where the resulting gait asymmetry is due to length differences between the lower limbs as shown by [2].

The aim of the new method proposed in this paper is to measure this asymmetry for the lower limbs using a low cost depth camera placed in front of the subject walking on a treadmill. The treadmill was used in this study (instead of a walkway) to accommodate smaller clinical rooms. Notice that our method does not need marker placement or any additional special exam preparations. In the next section, we present the state of the art for measuring gait asymmetry. Then, in section III we describe in details our methodology followed in section IV with the experimental setup for validation and the results presented in section V. We conclude the paper in section VI with possible future improvements.

II. Previous work

Different works have already been reported with sophisticated and specialized systems to investigate gait asymmetry. For example an adapted treadmill with force sensors was used to measure asymmetry gait parameters [3]. However ground reaction forces are limited to the foot and no information on other segments are provided by this system. To measure multiple segment information, Sadeghi [4] reviewed works done with electromyography measurements (EMG), joints kinematic measurement with opto-electronic systems. But all those systems still need to put numerous (wearable) sensors on the subject which is quite difficult to implement in daily clinical practice.

On the contrary, video systems do not have these drawbacks. For example, Green and Guan [5] used 2D sagittal plane images from a video camera to recognize Parkinson patients based on asymmetry information during the gait cycle. Video analysis could also take advantages of 3D reconstruction using multiple cameras system. Mundermann in [6] experimented a system where subject's volume reconstruction is done using multiple video cameras and Visual Hull computation. Unfortunately, this system needs at least 8 cameras to obtain satisfactorily results which mean a high cost and high technical knowledge to maintain it operational (e.g. camera internal and external calibration).

Depth information is typically obtained with at least two cameras and one can find stereo-cameras for this purpose. However this technology is not always robust, particularly if the scene does not offer a sufficiently textured image. Recently new types of depth camera have appeared on the marketplace. They are based mainly on three different methods to measure depth: structured light [7] and time of flight [8]. The latter is still in development with low resolution and high price which made it useless for large scale diffusion. But the first one is already in millions of home [9] and is very cheap, reliable and easy to setup. This is why we propose here a method that uses this kind of depth camera to record the depth information of a walking subject for gait analysis.

A previous work introduced by Hu in [10] uses a depth camera placed on a trolley to track the lower limbs of an elderly subject. However the fact that the subject needed to push the trolley that supported the depth camera impairs the regular gait. This is why we propose to use a treadmill to get a regular and stabilized gait during our tests (after a period of adaptation) and then to record the depth information to measure gait parameters of left/right asymmetry.

In previous works [11], we used a depth camera to measure asymmetry induced by a heel cup. The depth camera was placed behind the subject facing his back and used accumulated depth image with centroid registration to locate differences when comparing right and left side of the body.

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Another work by our team [12] used multiple (three) depth cameras to reconstruct the entire body volumes as a function of time and then summed those volumes after centroid registration to reconstruct the full occupied space during the whole gait cycle. Asymmetries were observed when a heel cup impaired the normal walk and were more important in front of the body. These two studies integrated the data over several gait cycles and it was therefore not possible to distinguish precisely when in the gait cycle that asymmetry was maximal or minimal.

That is why we propose in this paper to use a depth camera facing the subject walking on a treadmill with the aim to measure the asymmetry of the right step versus the left step during the gait cycle. This method will now be presented in the next section.

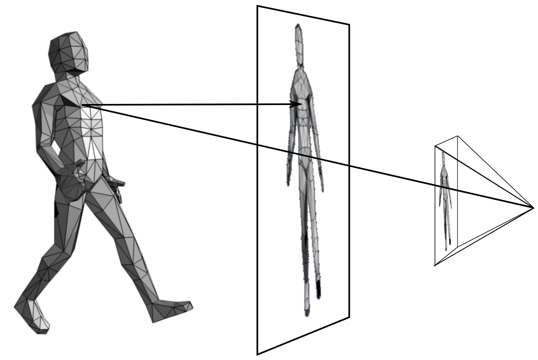

Fig. 1. Schematic representation of the orthogographic reprojection.

III. Method

The method analyses the depth map returned by the depth camera placed in front the subject in 3 distinct steps detailed in this section. The first step described in subsection III-A aims to identify parts of the depth maps belonging to the subject and transform the depth map from a projective view which is camera-dependent to an orthographic view that is more convenient. Then section III-B proposes to recover the gait cycle form the knee motion and construct mean key depth maps describing the body key positions during the gait cycle. The next subsection presents how right and left legs are segmented and compared for each instant of the gait cycle.

A. Depth map pre-treatment

1) Transformation from depth image to 3D points: The depth camera is considered as a pinhole camera model with its optical axis intersecting the center of the image plane and the focal $f = 575.82$ given by the drivers from manufacturer [13]. Then 3D points (X, Y, Z) are reconstructed from the known depth information Z returned for each pixel (x, y). The equations for calculating the coordinates (X, Y, Z) are:

$$X = \left(x - \frac{w}{2}\right)\frac{Z}{f} \quad Y = \left(y - \frac{h}{2}\right)\frac{Z}{f} \quad Z = Z$$

where w and h are respectively the width and the height of the depth map.

2) clipping: Once the scene is represented as a cloud of 3D points (X, Y, Z), the subject is localized in space within a 2.5 meters (height) x 2 meters (depth) x 1 meters (width) bounding box centered on the treadmill belt surface. Only points inside this region are kept for further processing. The result can be seen in Fig.2.

3) Orthographic projection: Once the 3D points of the subject are correctly clipped, the depth of this surface is projected orthographically on a plane perpendicular to the optical axis of the depth camera as illustrated in Fig. 1. The depth value of each pixel is computed with an inverse distance interpolation as described by Shepard in [14].

B. Key depth maps

Once each depth map is corrected, the next step is to compute the different key depth maps who describe best the gait cycle. For that purpose, each step (half gait cycle) is divided into n_{parts} equal parts in time. Then, each depth map frame is assigned (temporal registration) to the corresponding part and all frames belonging to the same part are averaged to create a key depth map. Before averaging, a registration (variance minimization) of the frames is performed in the leg region of interest to reduce variability. This leg zone is defined as the area below $0.43 * H$ (H=mean height of the subject) [15] and 10 cm above the treadmill belt. The step (half cycle) starting and ending frames are identified by double support detection with the anterior-posterior distance between knees. This distance is obtained by approximating the knee position with the anthropometric ratio $0.26 * H$ and is equal to the difference between the minimum depth of each leg. This signal is low-pass filtered at 5Hz (cut-off frequency) and the maximum and minimum are detected to get the double support (both feet touch the ground) positions and gait period. The result of these operations is represented in Fig.3.

C. Key depth maps analysis for asymmetry measurement

The left and right legs are then identified in each key depth map for a particular step (e.g. right leg is leading) to permit the comparison with the corresponding key depth map (e.g. left leg is leading) later in the gait cycle. Horizontal flipping of the left step key maps is also performed to compare left corresponding key maps to and rights ones.

1) Leg segmentation: The legs are identified on each horizontal line separately. For each line, only pixels belonging to the body for at least 80% of the frame are considered. These depth pixels are then clustered (or classified) into two groups (left and right legs) with a K-means algorithm.

2) Leg comparison: The weighted mean depth difference between the two legs is then computed line by line with the following equation :

$$\Delta_1(y) = \frac{\sum_{x \in X_1} \left(L_l(x,y) - R_r(x,y)\right)\left(l_l(x,y) + r_r(x,y)\right)}{\sum_{x \in X_1} l_l(x,y) + r_r(x,y)}$$

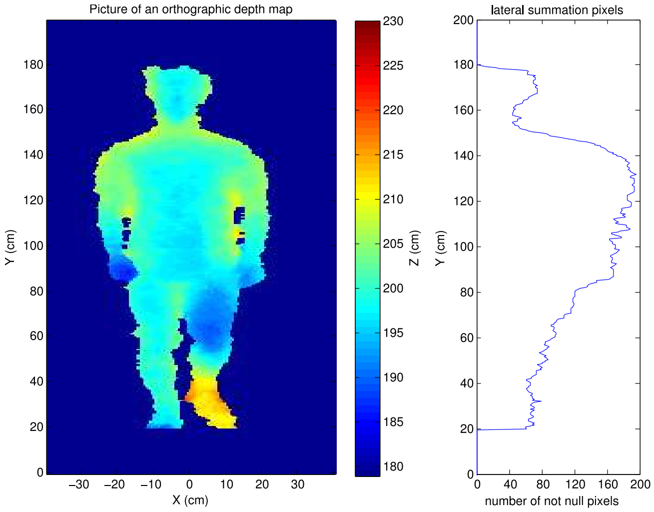

Fig. 2. Orthographic depth map and its lateral projection.

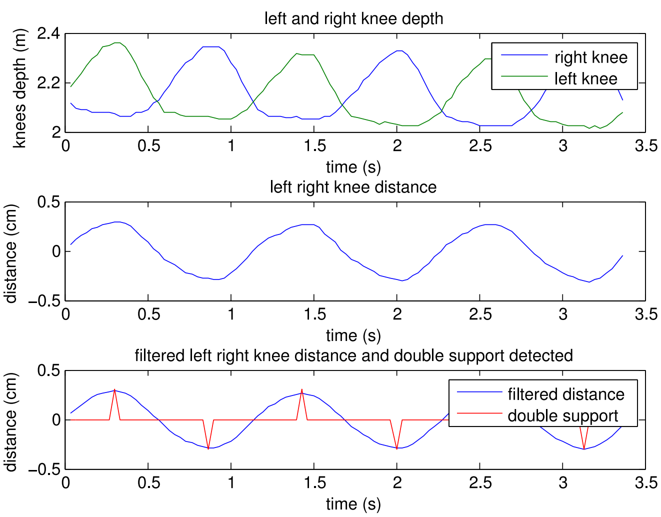

Fig. 3. Double support detection.

where L_l and l_l are respectively the depth and the number of accumulated frames per pixel for the left leg during the left step and R_r and r_r are respectively the depth and the number of accumulated frames per pixel for the right leg during the right step, and

$$X_1 = \{x \mid l_l(x,y) > 0 \text{ and } n_r(x,y) > 0\}$$

$$\Delta_2(y) = \frac{\sum_{x \in X_2} (L_r(x,y) - R_l(x,y))(r_l(x,y) + l_r(x,y))}{\sum_{x \in X_2} r_l(x,y) + l_r(x,y)}$$

where R_l and r_l are respectively the depth and the number of accumulated frames per pixel for the right leg during the left step and L_r and l_r are respectively the depth and the number of accumulated frames per pixel for the left leg during the right step, and

$$X_2 = \{x \mid r_l(x,y) > 0 \text{ and } l_r(x,y) > 0\}$$

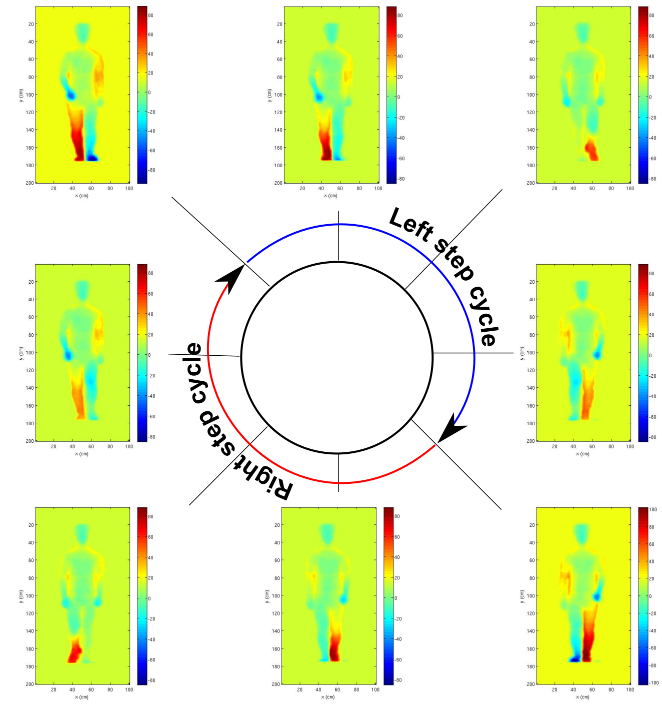

Fig. 4. Representation of the gait cycle with the key depth maps.

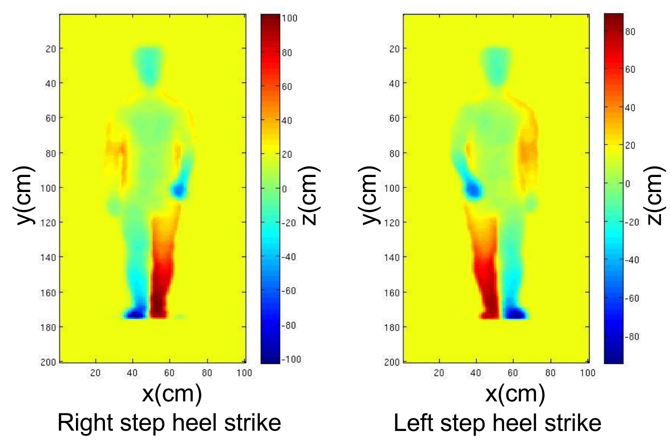

Fig. 5. Representation of right and left corresponding key depth maps from right and left step cycle. Typically the heel strike which is the begin of the step.

The final difference Δ_{depth} is obtained with the following equation :

$$\Delta_{depth} = \sum_{y \in Y} \Delta_1(y) + \Delta_2(y)$$

which corresponds to the asymmetry index.

IV. Experimentation and Validation

To validate the ability of our algorithm to detect gait asymmetry, an experiment was conducted with the approval of our university ethical committee. 20 subjects were recruited to walk on a treadmill at a comfortable speed. For each one, 3 depth map recordings were done, the first for a normal gait, the second with the sole under the left foot and then the third with the sole under the right foot. Each session began with an adaptation period before image acquisition. The recording period began once the subject felt comfortable on the treadmill. Each recording period was about 5 minutes. The analysis was done on the last 180 gait cycles.

The depth images were recorded with a depth camera Kinect at 30 frames per second with a resolution of 640 per 480 pixels. It was placed in front of the subject and rotated 90 degrees around the optical axis in order to make the width of the image correspond to the height of the subject. The optical axis of the camera was closely parallel to the translation vector of the treadmill belt.

V. Results

In this section, we present results regarding the sensitivity of the parameter n_{parts} and the difference of asymmetry measurements between a normal and an impaired walk (with the 5cm sole) during the gait cycle.

A. Parameter variability

We have investigated the variability of the asymmetry index with respect to different values of n_{parts} ranging from 5 to 20 parts per half gait cycle. Our results showed that the standard deviation was less than 10% of the measured deformation (Δ_{depth}) .

B. Intra-subject performance

To evaluate if this method was able to measure the impact of the sole on the gait pattern, for each subject the asymmetry index of normal gait test was subtracted from the deformed gait asymmetry index. The depth asymmetry index deformation induced by the sole under the left foot or under the right foot is shown in Fig.6. It is clearly visible that the left-impaired and right-impaired populations were well separated from the normal population, particularly for the first and last 20% of the step cycle (half gait cycle). The mean curves show that the asymmetry index is minimum near the middle of the step cycle. The standard deviation (plotted in dashed line arround the mean) of the asymmetry index remains relatively constant during the gait cycle.

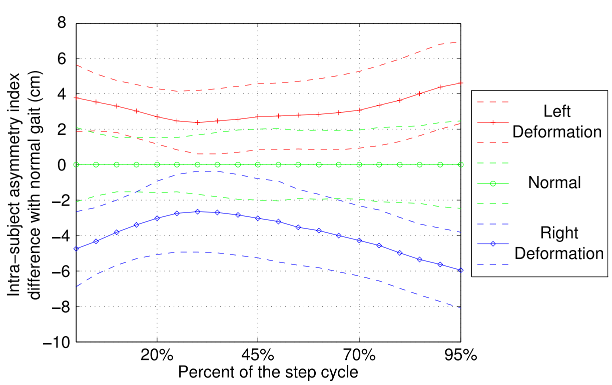

Fig. 6. Depth asymmetry index deformation vs. the step cycle.

VI. Discussion and Conclusion

The results obtained with the proposed experimentation have shown that our method is reliable to assess pathological gait. A 5 cm leg length discrepancy introduces a clearly visible depth difference that can be measured with a depth camera facing a subject walking on a treadmill. This method might be usable for other pathologies as well where asymmetry is a symptom. This method could also permit to make a follow-up of patients after a surgery (e.g. for joint replacement) and to measure the recovery after a stroke etc. Future works will consist in an inter-subject study and the separation of lateral motion asymmetry from depth asymmetry.

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