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PII:	S0966-6362(14)00670-5
DOI:	http://dx.doi.org/doi:10.1016/j.gaitpost.2014.08.006
Reference:	GAIPOS 4281
To appear in:	*Gait & Posture*
Received date:	2-9-2013
Revised date:	7-5-2014
Accepted date:	11-8-2014

Please cite this article as: Auvinet E, Multon F, Aubin C-E, Meunier J, Raison M, Detection of gait cycles in treadmill walking using a Kinect, *Gait and Posture* (2014), http://dx.doi.org/10.1016/j.gaitpost.2014.08.006

Detection of gait cycles in treadmill walking using a Kinect

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Submitted as: Short Communication

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Abstract:

Treadmill walking is commonly used to analyze several gait cycles in a limited space. Depth cameras, such as the low-cost and easy-to-use Kinect sensor, look promising for gait analysis on a treadmill for routine outpatient clinics. However, gait analysis is based on accurately detecting gait events (such as heel-strike) by tracking the feet which may be incorrectly recognized with Kinect. Indeed depth images could lead to confusion between the ground and the feet around the contact phase. To tackle this problem we assume that heel-strike events could be indirectly estimated by searching for extreme values of the distance between knee joints along the walking longitudinal axis. To evaluate this assumption, the motion of 11 healthy subjects walking on a treadmill was recorded using both an optoelectronic system and Kinect. The measures were compared to reference heel-strike events obtained with vertical foot velocity. When using the optoelectronic system to assess knee joints, heel-strike estimation errors were very small (29±18ms) leading to small cycle durations errors (0±15ms). To locate knees in depth map (Kinect), we used anthropometrical data to select the body point located at a constant height where the knee should be based on a reference posture. This Kinect approach gave heel-strike errors of 17±24ms (mean cycle duration error: 0±12ms). Using this same anthropometric methodology with optoelectronic data, the heel-strike error was 12±12ms (mean cycle duration error: 0±11ms). Compared to previous studies using Kinect, heel-strike and gait cycles were more accurately estimated, which could improve clinical gait analysis with such sensor.

Keywords: Kinect, Gait analysis, Cycles, Heel strike detection, Treadmill, Motion capture

1-Introduction

To extract relevant and reliable information in clinical gait analysis, it is necessary to accurately detect gait cycle events. Recently, methods have been proposed to detect gait cycles in walking data obtained with a Microsoft Kinect^{TM} sensor [1,2,3], as it provides clinicians with a low-cost, markerless and easy-to-use gait analysis system suitable for routine outpatient clinics. Most of these studies rely on skeletal information computed from depth images with the machine learning method proposed by Shotton [4], allowing foot tracking and then toe-off events detection [3], but leading to an underestimation error of stride duration equals to -200±66ms versus Vicon measurements. Alternatively, Gabel [1] used machine learning to estimate stride duration by analyzing the position of all body joints. Mean error on stride duration estimation was 8±62ms for the right stride and 2±46ms for the left stride compared to foot switch sensor. However a machine learning approach is strongly dependent on the learning data, which could be a problem for specific population with impaired gaits. An alternative method consists in directly detecting footfalls [2], leading to errors in stride duration estimation equal to 7.74±62ms versus Vicon measurements. But no information is given about the accuracy of the heel-strike detection which is a relevant indicator in gait analysis. With Kinect this type of event is difficult to detect because of confusion between the ground and the feet that could occur around the contact phase. To tackle this problem we assume that heel-strike events could be more accurately estimated indirectly by searching for the extreme values of the distance between the knee joints along the walking longitudinal axis.

2-Methods

In this paper, we assume that the distance between knees along the longitudinal walking axis (distance called DK) is maximal concurrently to heel-strike. In the remaining of the paper, we assume that the longitudinal walking axis corresponds to the treadmill axis. Let us consider now the protocol used to validate that DK could enhance the accuracy of heel-strike event detection and stride duration measurement with Kinect, compared to previous studies.

2.1-Experimental protocol

Eleven healthy subjects (age 24.6±3.2 years, weight 67.3±6.2kg, height 168.3±12.6cm), walked at self-selected comfortable speed on a treadmill. Kinematics data were concurrently recorded with a 120Hz Vicon system (Oxford Metrics,UK) made of 12 cameras, and Kinect placed at 2 meters in front of the subject. These two systems were synchronized with the standard method proposed by Clark [3]: maximizing the inter-correlation between measurement signals (DK here, for the two systems). Each subject provided written informed consent before participation in this study, which had been approved by the Institutional Review Board. An extended version of the Helen Hayes markerset was used to satisfy the ISB recommendations [5,6] (Fig. 1).

2.2-Estimation of heel-strike events

Heel-Strikes were estimated with DK maxima which were computed using three methods. Firstly, DK was computed with knee joint centers [5] measured with an opto-electronic system (method KJ) to validate with accurate data the main assumption of this study: heel-strike events occur at maxima of DK.

Secondly, to tackle the problem of localisation of knees in the depth map, we proposed to measure DK by considering the distance between legs at an estimated knee height. This estimated knee height is based on anthropometrical data [7]: 0.27H where H is the stature height of the subject. DK is then measured from raw depth data (method CEKH-KI) provided by the Kinect (see Fig. 2). Briefly stated (detailed in [8]), it corresponds to (a) isolating the body in the depth map projected in the 3D space, (b) selection of knee points at 0.27H, (c) identification of right and left knees with K-mean clustering, (d) for each knee, the closest point to the Kinect is selected to compute DK.

To evaluate the relevance of this assumption, we thirdly computed DK according to this anthropometric knee position, using accurate opto-electronic data (method CEKH-OES). To this end, each estimated knee position at 0.27H was obtained thanks to a linear interpolation of the hip, knee and ankle positions. The hip joint was estimated using Leardini's method [9] with external markers.

Finally, DK from all three methods were filtered with a fourth order zero-phase Butterworth filter with a 7Hz cut-off frequency [10]. Heel-strike events were estimated by detecting maxima of filtered DK.

2.3-Evaluation of the results

The results provided by the methods KJ, CEKH-OES, CEKH-KI were compared to heel-strike events computed with the reference O'Connor's method [10] based on vertical foot velocity analysis with opto-electronic data to obtain heel-strike detection errors.

To compare these results to previous studies using Kinect [1,2,3], we also computed the stride duration. Stride duration was computed as the elapsed time between two successive heel-strikes on the same side, with the three proposed methods and compared with reference O'Connor's method [10] to obtain stride duration errors.

3-Results

The mean number of heel-strike events per subject was 477±113 depending on self-selected comfortable gait speed for the same duration of 4 minutes.

The inter-correlation coefficient between distance signals computed with CEKH-OES and CEKH-KI was above 0.98 for all the subjects, which ensures an accurate synchronization between the two systems.

Heel-strike detection errors and stride duration differences between KJ, CEKH-OES and CEKH-KI methods are reported in Table 1. These results show that CEKH-OES was the most accurate method with an error of 12±12ms. The results obtained with the Kinect CEKH-KI were a little less accurate but show better heel-strike estimation than the method based on the knee joints using the Vicon (method KJ). Stride duration is more accurately measured (mean error: 0±12ms) with our method compared to previous studies based on Kinect data: -200±66 [3], 7.74±62ms [2] and 8±62ms or 2±46ms [1].

4-Discussion

The Results in Table I show that the first assumption of the paper seems validated: there exist a relationship between maximum DK values and heel-strike events in the gait of healthy subjects. Heel-strike detection errors for the three methods were less than the time between successive Kinect frames and were similar to those (16±15ms) reported by O'Connor [10] compared to forceplate. In the future it would be interesting to compare these results to heel-strike events detected using a forceplate.

Previous studies using Kinect did not try to detect the actual heel-strike event. However the performance of the CEKH-KI method in estimating gait cycle duration with a small mean error of 0±12ms is much better than -200±66ms reported in [3], and slightly better than 7.74±62ms reported in [2] and 8±62ms or 2±46ms reported in [1]. Moreover it is important to note that CEKH-KI does not require a learning stage compared to [1] and [3].

Thus, compared to previous studies using Kinect, heel-strike events and gait cycles seem to be more accurately estimated using CEKH-KI, which could improve global clinical gait analysis frameworks with such a sensor.

Future studies will explore how this type of method behaves for disabled people with impaired gait where the relation between the knee and the heel joint may not be so clear. Heel-strike detection is the first step of gait analysis and further research is required to accurately compute relevant gait variables, such as stride length, cadence, and duration of double support, with Kinect sensor.

5-Acknowledgement

This study was supported by FQRNT and ANRT with CIFRE-146/2009 funding.

6-Conflicts of interest

Authors declare no conflicts of interest.

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Method	HS detection error	Step duration error
KJ	29±18 ms	0±15 ms
CEKH-OES	12±12 ms	0±11 ms
CEKH-KI	17±24 ms	0±12 ms
(Stone, 2011) [6]	-	7.74±62 ms
(Gabel, 2012) [2] right stride	-	8±62 ms
(Gabel, 2012) [2] left stride	-	2±46 ms
(Clark, 2013) [8]	-	-200±66 ms

Table I – Summary of hell-strike (HS) detection error and stride duration error for different knee distance computation methods versus the reference method Vertical Foot Velocity (O'Connor, 2007) and results reported in the literature.

Research Highlight:

- Heel strikes were detected with the maximum longitudinal distance between the knees
- This distance was estimated with depth images from Kinect without using a skeleton
- The error for heel strike events estimation with Kinect information was 17±24ms
- The error for step duration estimation with Kinect information was 0±12ms

Conflict of interest statement:

None of the authors have any financial and personal relationships that could improperly influence this work.

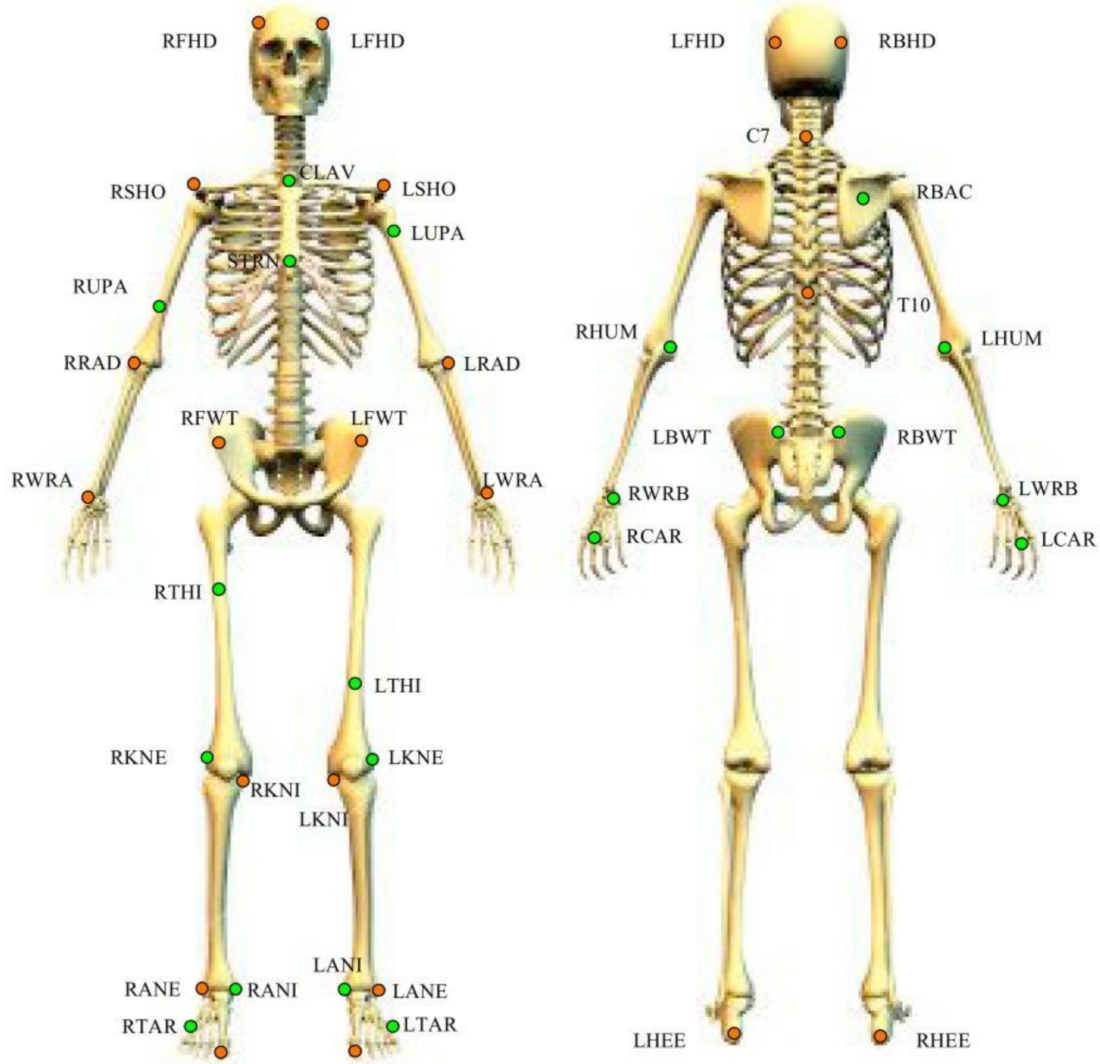

Figure 1 – Extended version of the Helen Hayes markerset with additional markers to satisfy the ISB recommendations [5,6].

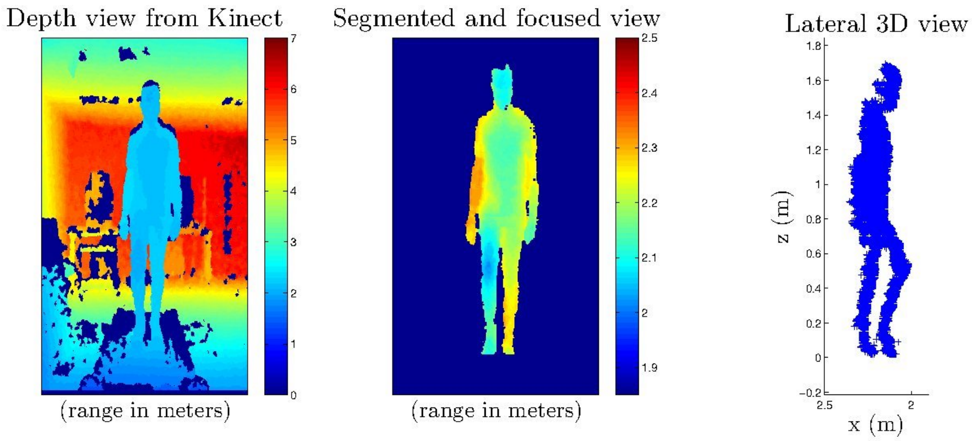

Figure 2 – Original raw depth map and segmented, focused view and the lateral 3D view of points which are used to measure gait events.