Gait & Posture 50 (2016) 42–46

Contents lists available at ScienceDirect

Gait & Posture

journal homepage: www.elsevier.com/locate/gaitpost

Full length article

Gait event detection in laboratory and real life settings: Accuracy of ankle and waist sensor based methods

Fabio A. Storm[a,b,*], Christopher J. Buckley[a,b,c], Claudia Mazzà[a,b]

[a] Department of Mechanical Engineering, The University of Sheffield, Sheffield, UK
[b] INSIGNEO Institute for in silico Medicine, The University of Sheffield, Sheffield, UK
[c] MRC-Arthritis Research UK Centre for Integrated Research into Musculoskeletal Ageing (CIMA), The University of Sheffield, Sheffield, UK

ARTICLE INFO

Article history:
Received 11 February 2016
Received in revised form 28 July 2016
Accepted 11 August 2016

Keywords:
Inertial sensor
Algorithm
Gait events
Free walking
Temporal parameters

ABSTRACT

Wearable sensors technology based on inertial measurement units (IMUs) is leading the transition from laboratory-based gait analysis, to daily life gait monitoring. However, the validity of IMU-based methods for the detection of gait events has only been tested in laboratory settings, which may not reproduce real life walking patterns. The aim of this study was to evaluate the accuracy of two algorithms for the detection of gait events and temporal parameters during free-living walking, one based on two shank-worn inertial sensors, and the other based on one waist-worn sensor. The algorithms were applied to gait data of ten healthy subjects walking both indoor and outdoor, and completing protocols that entailed both straight supervised and free walking in an urban environment. The values obtained from the inertial sensors were compared to pressure insoles data. The shank-based method showed very accurate initial contact, stride time and step time estimation (<14 ms error). Accuracy of final contact timings and stance time was lower (28–51 ms error range). The error of temporal parameter variability estimates was in the range 0.09–0.89%. The waist method failed to detect about 1% of the total steps and performed worse than the shank method, but the temporal parameter estimation was still satisfactory. Both methods showed negligible differences in their accuracy when the different experimental conditions were compared, which suggests their applicability in the analysis of free-living gait.

1. Introduction

The interest in objective daily monitoring of physical activity in habitual environments is growing for both clinical and research purposes. Among activities of daily living, gait is a major marker of disease progression [1], and the step-by-step determination of gait parameters is required for the analysis and characterization of quasi-periodic motions [2], both in terms of absolute values and of their variability [3].

To avoid altering a subject's natural movement, a necessary requirement during daily physical activity monitoring is that the smallest number of sensors should be positioned in minimally cumbersome locations. Thanks to recent technological advances, wearable sensors based on inertial measurement units (IMUs) have become an ideal choice to capture continuous gait data, playing a crucial role in the transition of gait analysis from traditional assessment carried out in specialised gait laboratories to daily life monitoring [4].

To determine temporal gait parameters, the accurate detection of gait events, such as initial foot contact (IC) and final foot contact (FC) is required. Methods to obtain IC and FC timings from a single IMU positioned on the lower trunk have been proposed in both normal and pathologic gait [5,6]. Several authors have also proposed the use of two synchronized IMUs on the lower limbs, with the shanks being the most popular location [7,8]. The validity of these methods has generally been tested in laboratory settings, during straight walking, and against references such as instrumented mats [9], force platforms [5], and motion capture systems [8], often relying on a limited number of consecutive strides. However, controlled steady-state straight walking conditions that are obtained in a laboratory may not reproduce real life behaviour. Currently it is not known whether the acceleration and angular velocity patterns generated during real life behaviour can affect the accuracy of algorithms tested in the controlled laboratory conditions. Indeed, the variability of stride velocity and gait cycle time during scripted straight walking has been shown to be higher over longer distances (>20 m) in comparison to short distances

* Corresponding author at: Department of Mechanical Engineering, The Pam Liversidge Building, Sir Frederick Mappin Building, Mappin Street, Sheffield, S1 3JD, UK.
E-mail address: fastorm1@sheffield.ac.uk (F.A. Storm).

http://dx.doi.org/10.1016/j.gaitpost.2016.08.012
0966-6362/

(<10 m) [10], and repeated single walking protocols also generated lower variability in gait parameters with respect to continuous overground walking [11]. A recent study using a wearable accelerometry-based pendant showed that variability of step duration during activities of daily living performed in a semi-controlled environment was higher and did not correlate with laboratory gait [12]. These findings suggest that walking strategies may be affected by different experimental conditions, and that this might reflect into different patterns of the signals used to estimate IC and FC event. However, to the best of the authors' knowledge, the accuracy of the estimates of both IC and FC events in free living gait, i.e. carried out in a urban environment has not been yet assessed.

The aim of this study was to test the performance of two different IMU-based methods for gait temporal parameters estimation during gait in free living conditions. One method is based on the use of two shank-worn IMUs [8], and the other on a single waist-worn IMU [9]. These algorithms were selected for their previously reported robustness to changes in IMU attachments and to an individual's gait speed, and for their reported high accuracy [6]. The algorithms were applied to gait data of ten healthy subjects walking in different daily life environments, both indoor and outdoor, and completing protocols that entailed both straight and free walking, and their outputs were compared to data obtained from pressure insoles.

2. Materials and methods

Ten healthy volunteers (3 females, 7 males, age 28 ± 3 y.o.) were recruited for the study. Ethical approval from the University of Sheffield's Research Ethics Committee was obtained, and the research was conducted according to the declaration of Helsinki. All participants provided informed written consent.

Each participant was asked to wear three IMUs (Opal™, APDM; weight 22 g, size 48.5 mm × 36.5 mm × 13.5 mm) containing a 3-axis accelerometer, a 3-axis gyroscope, and a 3-axis magnetometer. One IMU was positioned on the lower trunk on the fifth lumbar vertebra (L5) [9], with its sensing axes X, Y and Z pointing downward, to the left, and forward, respectively. The other two IMUs were positioned at each ankle, just above the malleoli [8], with X, Y and Z pointing downward, to the right, and backward, respectively. The devices measured accelerations and angular velocities at a sampling frequency of 128 Hz, and the accelerometer range was set at ±6 g. Two pressure-sensing insoles (F-Scan 3000E, Tekscan) were used to obtain IC and FC reference timings. The insoles were cut to fit tightly into each participant's shoe. They were calibrated using a step calibration technique according to manufacturer instructions. Sampling frequency was set at 128 Hz and the gait events were obtained using the ground reaction force (10 N threshold) [13]. A vertical jump was used as a synchronizing event between the IMUs and the insoles in order to realign the two signals coming from both instruments at the beginning of each trial. The equivalency of the nominal sampling frequency of the two instruments was verified on three separate 20-min recordings, where at 1 min intervals a series of impacts clearly detected by both instruments were generated, and showed a consistent mismatch between signals of one sample each two minutes recording (7.8 ms). This mismatch was corrected for in the 15-min free outdoor walking data by realigning the signals each two minutes. This procedure was not needed in the other walking conditions, which lasted less than two minutes.

Fig. 1 shows typical signals collected at the shank and pelvis, and the corresponding IC and FC instants for both methods used to compute the temporal gait parameters. In the shank-based method (SHANK), the peak in the angular velocity signals in the sagittal plane during mid-swing is used to identify windows in the signal where no gait events can occur. When coupled with the alternate shank, these intervals allow the identification of search windows for IC and FC events. The IC is identified as the instant of minimum angular velocity in the sagittal plane between the beginning of the IC search window and the instant of maximum anterior-posterior acceleration. The FC is identified as the instant of minimum anterior-posterior acceleration in the FC search window [8]. For the waist-based method (WAIST), data is collected from a single IMU positioned on the lower trunk at L5 level. A first Gaussian continuous wavelet transformation is applied to the vertical acceleration signal, and the minima are identified as the IC timings. The resulting signal is then differentiated and the FC timings are identified as the instants of its maxima [9].

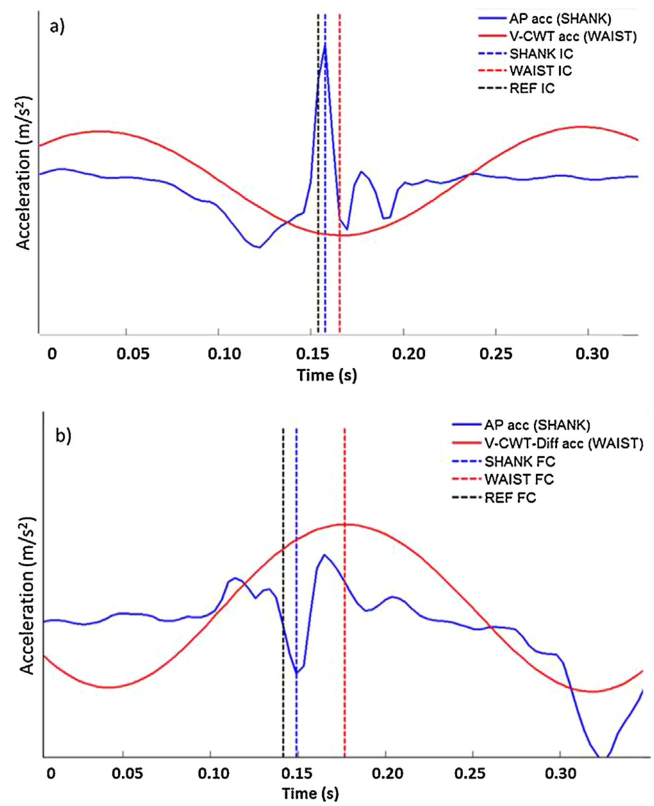

Fig. 1. Gait event detection for the tested algorithms. (a) Anterior-posterior acceleration signal of the shank (*AP acc*, solid blue line), with corresponding IC timings (*SHANK IC*, dashed blue vertical line). Wavelet-filtered pelvis acceleration signal in the vertical axis (*V-CWT acc*, solid red line), with corresponding IC timings (*WAIST IC*, red dashed vertical line). Reference IC timings are also shown (*REF IC*, black dashed vertical line). (b) Anterior-posterior acceleration signal of the shank (*AP acc*, solid blue line), with corresponding FC timings (*SHANK FC*, blue dashed vertical line). Derivative of the wavelet-filtered pelvis acceleration signal in the vertical axis (*V-CWT-Diff acc*, solid red line), with corresponding FC timings (*WAIST FC*, red vertical lines). Reference FC timings are also shown (*REF FC*, black dashed vertical line). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Subjects completed four walking tasks in the conditions detailed in Table 1, and the IMU and pressure insoles data were collected during each task. A stopwatch was used to measure walking time and compute average walking speed during the indoor and outdoor straight walking conditions.

For the outdoor free walking task, participants were instructed to walk freely in the city centre without any restrictions regarding route or walking speed, and avoiding stairs. Both the indoor free walking and outdoor free walking conditions had the potential of recording the participant's turns in addition to straight line walking, both of which were included in the analysis. On the contrary, data recorded during resting or transitory periods were