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Accuracy, sensitivity and robustness of five different methods for the estimation of gait temporal parameters using a single inertial sensor mounted on the lower trunk

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ABSTRACT

In the last decade, various methods for the estimation of gait events and temporal parameters from the acceleration signals of a single inertial measurement unit (IMU) mounted at waist level have been proposed. Despite the growing interest for such methodologies, a thorough comparative analysis of methods with regards to number of extra and missed events, accuracy and robustness to IMU location is still missing in the literature. The aim of this work was to fill this gap. Five methods have been tested on single IMU data acquired from fourteen healthy subjects walking while being recorded by a stereo-photogrammetric system and two force platforms. The sensitivity in detecting initial and final contacts varied between 81% and 100% across methods, whereas the positive predictive values ranged between 94% and 100%. For all tested methods, stride and step time estimates were obtained; three of the selected methods also allowed estimation of stance, swing and double support time. Results showed that the accuracy in estimating step and stride durations was acceptable for all methods. Conversely, a statistical difference was found in the error in estimating stance, swing and double support time, due to the larger errors in the final contact determination. Except for one method, the IMU positioning on the lower trunk did not represent a critical factor for the estimation of gait temporal parameters. Results obtained in this study may not be applicable to pathologic gait.

1. Introduction

Initial and final foot contacts (IC and FC), referred to as gait events (GE), are used for the estimation of temporal gait parameters. They determine the gait phases thus allowing for the interpretation of joint kinematics and muscle activity patterns. Thanks to the miniaturized sensing technology, inertial measurement units (IMU) have been increasingly employed to detect the GEs. An advantage of using the IMUs is the possibility of evaluating spatial and temporal gait parameters while monitoring daily life activities [1–4]. In this context, the instrumental setup should be as unobtrusive and wieldy as possible, leading towards the use of a single wearable unit. The IMU location on the human body influences the robustness and accuracy of the GEs identification. As a general rule, the closer the IMU is to the point of impact, the higher are the chances of correctly detecting the GEs [5]. The most intuitive solution would be to place the IMU on the foot, but if a bilateral determination of GEs is sought, two synchronized IMUs would be needed.

A common solution proposed in the literature to minimally alter the subject's gait is to position a single IMU at waist level to detect the impact of both feet [6]. A disadvantage of this solution is the increased difficulty in implementing a robust and accurate method for determining gait temporal parameters.

Both ICs and FCs were found to be associated to specific features of the lower trunk accelerations along the antero-posterior (AP), medio-lateral (ML) and vertical (V) directions, recorded during gait [6–10]. These observations have led several authors to propose methods for GEs and/or temporal gait parameters estimation from the acceleration signals of a single IMU mounted at waist level [11–13]. In particular, some authors detected ICs to estimate the mean step length [14] or estimated step duration to determine step length without detecting ICs [15]; others focused on the estimation of temporal and spatial parameters after detecting both ICs and FCs [16].

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The method proposed by [14] was later applied to the gait of healthy adults [17,18], healthy children [19], healthy elderly [20] and pathological populations, such as amputees [21], neurological patients [22], or Parkinson patients [23]. In most cases, only mean values of gait parameters were analyzed and caution in interpreting gait parameters was often recommended [21].

Despite the clinical interest for such methodologies, there is no information in the literature on comparative analysis of: a) the number of missed GEs relative to the number of actual GEs (sensitivity) and of correctly detected GEs relative to the total amount of detected GEs (positive predictive values, PPV); b) the accuracy of the gait temporal parameters estimation, and c) their robustness to changes in the IMU positioning.

In this work, the performance of five methods for detecting GEs and determining gait temporal parameters from the signals of a single IMU attached at waist level [11,12,14–16] was evaluated in terms of: a) sensitivity and PPV and b) accuracy and robustness of the determination of temporal gait parameters. A method [14] was selected based on its popularity [17–23], while the remaining four represent the most recent published methods for the estimation of temporal parameters from a single IMU. The five methods have been applied to data acquired from an IMU attached to healthy subjects walking while recorded by a stereo-photogrammetric (SP) system and two force platforms (FP). The data from FPs and the SP system were used for reference.

2. Materials and methods

2.1. Tested methods

The methods evaluated are summarized below. A schematic description of the methods is reported in Table 1; additional details can be found in the literature [11,12,14–16].

Z-method [14,24]. The study aimed at determining gait temporal parameters and mean step length using a 3-axis accelerometer positioned over the second sacral vertebra (S2). The ICs were identified as the timings of the peaks of the low-pass filtered AP acceleration (20 Hz) preceding the positive-to-negative transitions of the AP acceleration filtered at 2 Hz. The method was later improved by the authors [24] by aligning the IMU to the V direction during an upright posture.

G-method [11]. The study proposed a real-time GEs detection method. The IMU was fixed on the third lumbar vertebra (L3). The IC was searched in a region of interest defined by the positive values of the filtered AP acceleration. In this time interval, local maxima of the raw AP acceleration were searched. The timing of one of the maxima was identified as the IC. To select the correct local maximum, several empirical rules were applied. Once the IC was identified, the timing of the first local minimum occurring after the IC was identified as the FC timing.

S-method [15]. A 3-axis accelerometer was attached to the waist in the back (W). The values of the acceleration norm falling within a sliding window of fixed length (N) were summed (sliding window summation – SWS). The difference of the resulting SWS values and those obtained N samples earlier was then computed to remove gravity. The resulting pattern was a smooth curve crossing periodically the zero value. The instances of negative-to-positive transitions were then used as markers for determining the step duration. FC timings were not estimated.

M-method [12]. IC timings were identified as the times of the minima of the signal obtained after applying a Gaussian continuous wavelet transformation to the V acceleration recorded with a single IMU over the lower lumbar spine (L5). The resulting signal was then differentiated and FC timings were identified as the instances of its maxima.

K-method [16]. The method required the IMU to be positioned on the subject's belt on the right side of the body, since it was developed for monitoring physical activity. GEs were searched within regions of interest identified from the signal reconstructed with the first three levels of detail of a stationary wavelet decomposition of the V acceleration. Since the number of regions of interest identified in a trial could be higher than the number of gait cycles, only those featuring the highest peaks of the V acceleration (i.e. containing the instrumented side IC) were kept. First, the ipsilateral IC and contralateral FC were determined from the V acceleration in the region of interest, then the ipsilateral FC was identified from the AP acceleration; finally the contralateral IC was identified from the ML acceleration.

2.2. Data collection protocol

2.2.1. Subjects

Fourteen healthy volunteers (eight females, six males; age: 31.8 ± 5.2 y.o.; height: 1.71 ± 0.09 m; mass: 64.1 ± 15.6 kg; walking speed: 1.2 ± 0.3 m/s) were recruited.

2.2.2. Measurement protocol

A single IMU (Opal^{TM}, APDM; weight 22 g, size 48.5 mm $\times$ 36.5 mm $\times$ 13.5 mm) featuring a 3-axis accelerometer ($\pm$6 g range) and 3-axis gyroscope and sampling at 128 Hz, was used. For each method, the suggested IMU locations were identified by a physical therapist and the IMU was attached using a semi-elastic band. The IMU performance was tested according to the guidelines proposed by Picerno et al. [25].

For each IMU location, subjects were asked to first maintain an upright posture for ten seconds and then walk barefoot at their self-selected comfortable speed along a walkway featuring two FPs (AMTI, 1000 Hz) located in the calibrated volume of a SP system (six cameras, VICON T20, 128 frames/s). The trajectories of three markers placed on each foot (toe, heel and lateral malleolus) were also recorded. The GEs were obtained by thresholding at 10 N the V ground reaction force [26] (or by applying the method proposed by Alton et al. [27] for those ICs occurring outside the FPs) and used as reference for all methods.

For each subject, three trials including a full right and a full left gait cycle were recorded for each IMU location.

2.3. Data analysis

For each trial and method, IC timing, stride and step duration estimations were obtained. Since FC timing estimations were provided only by the G-, M- and K-methods, stance, swing and

Table 1
Description of the tested gait event detection methods.

	Sensor type	Sampling rate [Hz]	Sensor position	Subjects #	Shoes	Estimated GEs	Gold standard	Missed/extra GEs	Estimated parameters
Z-method [14]	3-axis acc	100	S2	15	Yes	IC	FPs	No	GEs; mean step length
G-method [11]	IMU	100	L3	6	Yes	IC; FC	FPs	No	Real time GEs
S-method [15]	3-axis acc	50	Waist	1	n.a.	IC	n.a.	n.a.	Step length
M-method [12]	IMU	100	L5	18	n.a.	IC; FC	Instrumented mat	No	GEs
K-method [16]	IMU	100	Right side waist	9	n.a.	IC; FC	SP system	n.a.	Step length