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Comparative assessment of different methods for the estimation of gait temporal parameters using a single inertial sensor: application to elderly, post-stroke, Parkinson's disease and Huntington's disease subjects

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ABSTRACT

The estimation of gait temporal parameters with inertial measurement units (IMU) is a research topic of interest in clinical gait analysis. Several methods, based on the use of a single IMU mounted at waist level, have been proposed for the estimate of these parameters showing satisfactory performance when applied to the gait of healthy subjects. However, the above mentioned methods were developed and validated on healthy subjects and their applicability in pathological gait conditions was not systematically explored. We tested the three best performing methods found in a previous comparative study on data acquired from 10 older adults, 10 hemiparetic, 10 Parkinson's disease and 10 Huntington's disease subjects. An instrumented gait mat was used as gold standard. When pathological populations were analyzed, missed or extra events were found for all methods and a global decrease of their performance was observed to different extents depending on the specific group analyzed. The results revealed that none of the tested methods outperformed the others in terms of accuracy of the gait parameters determination for all the populations except the Parkinson's disease subjects group for which one of the methods performed better than others. The hemiparetic subjects group was the most critical group to analyze (stride duration errors between 4-5 % and step duration errors between 8-13 % of the actual values across methods). Only one method provides estimates of the stance and swing durations which however should be interpreted with caution in pathological populations (stance duration errors between 6-14 %, swing duration errors between 10-32 % of the actual values across populations).

1. Introduction

The assessment of the temporal and spatial parameters of gait is commonly considered of importance in clinical gait analysis since it contributes to the quantitative characterization of many common gait abnormalities. The determination of these parameters requires the detection of the initial and final foot contacts (IC and FC), usually referred to as gait events (GEs). Inertial measurement units (IMUs) have been increasingly employed for this purpose thanks to their high wearability, reduced cost and low power consumption. The use of accelerometers is particular promising for the evaluation of gait parameters while monitoring daily life activities [1–3]. In this context, the instrumented setup should be even less invasive and cumbersome than in the laboratory setting, directing researchers and developers towards the use of a single IMU. To minimally alter the subject's gait, a single IMU is often attached at the waist level so that the impact of both feet could be detected [4]. A downside of this solution is the difficulty to implement a robust and accurate method for identifying GEs, since in general, the closer the IMU is to the point of impact, the higher are the chances of correctly detecting the GEs [5].

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In normal gait, some features of the lower trunk acceleration patterns (e.g., peaks, zero crossings) were consistently associated with the occurrences of ICs and FCs [4,6–9]. These observations have led several authors to propose methods for the detection of GEs and/or the estimate of temporal gait parameters from the acceleration signals of a single IMU mounted at the waist level [10–16]. In a previous study [17], we evaluated the performance of five selected methods employing a single IMU [10–14] for detecting GEs and estimating gait temporal parameters in a group of healthy young subjects. The comparison was carried out in terms of sensitivity and positive predicted values in detecting GEs, accuracy in estimating gait temporal parameters, and robustness with respect to the IMU positioning. The results reported in [17] showed an acceptable accuracy, sensitivity and robustness of all the evaluated methods in determining those gait temporal parameters based on the identification of ICs (e.g., stride duration), while a lower accuracy in determining the temporal parameters which also require the FCs identification (e.g., stance duration) was found.

The above mentioned methods were developed and validated on healthy young or elderly subjects and their applicability in pathological gait conditions was not systematically explored. The only exception is the method proposed by [10] which was later applied to pathological groups, such as amputees [18], various neurological patients [19], and patients with Parkinson's disease [20]. In most cases, only average gait parameters were evaluated (as opposed to step-by-step assessment) and caution in interpreting gait parameters was often recommended [18,19]. In some gait pathologies, deviations of the acceleration patterns, often due to impairments and consequent compensatory strategies, from those typically observed in normal gait are often present [21,22].

For example, hemiparetic gait is often characterized by an increased lateral displacement of the foot during swing in the paretic limb, consistent with limb vaulting to further assist limb clearance [23]. Other gait abnormalities, such as choreiform gait, also known as "drunken gait", are characterized by staggering from side to side, with lateral swaying, and stride-by-stride lateral deviations from forward direction during walking [24], while parkinsonian gait is generally characterized by small shuffling steps and a stooped posture [25].

The gait abnormalities described above result in changes of the trunk acceleration waveforms which may limit the applicability of the single IMU based methods in the clinical setting. The aim of the present work was to propose a comparative analysis of selected single IMU based methods for estimating gait temporal parameters in different pathological gait conditions. For this purpose, based on the findings reported in [17], the three best performing previously tested methods [10,12,13] were applied to the gait data of 10 patients with hemiparesis, 10 patients with Parkinson's disease, 10 patients with Huntington's disease, and 10 healthy elderly adults.

For each method, we evaluated the number of missed and extra GEs, along with the total number of GEs as detected by an instrumented gait mat, used here as a gold standard. The accuracy, associated with the GEs and temporal gait parameters determination, was evaluated against reference data provided by the instrumented mat. Comparative evaluations across methods within-populations (i.e., which method is the best algorithm for a given population?) and within-method for the different populations (i.e., is the performance of an algorithm dependent on the specific population being analyzed?) were also performed.

2. Materials and methods

2.1. Tested methods

A schematic description of the methods is reported in Table 1; additional details can be found in the literature [10,12,13].

2.2. Data collection protocol

2.2.1. Instrumentation

A single IMU (Opal^{TM}, APDM) featuring a 3-axis accelerometer and 3-axis gyroscope (unit weight 22 g, unit size $48.5 \times 36.5 \times 13.5$ mm, resolution: 14 bits) was positioned over the subject's lumbar spine, between L4 and S2, using a semi-elastic waist belt. For the selected methods, the robustness to the IMU positioning along the lower trunk was found not to be a critical factor for the gait temporal parameters estimation [17,27]. Sampling frequency

Table 1
Description of the tested gait event detection methods.

	Sensor type	Sampling rate [Hz]	Sensor position	Estimated GEs	Evaluated signals	Algorithm features	GEs identification steps	Estimated parameters
Z-method* [10]	3-axis acc	100	S2	IC	Antero-posterior acceleration	Zero crossing, peak detection	All accelerometer data are filtered (low-pass 4th order zero-lag Butterworth filter, cut-off frequency: 20 Hz). The IC is identified as the instant of the peak preceding the zero crossing (positive-to-negative) of the low-pass filtered (4th order zero-lag Butterworth filter, cut off frequency: 2 Hz) antero-posterior acceleration	GEs detection; mean step length estimate
S-method [12]	3-axis acc	50	Waist	IC	Acceleration norm	Sliding window summation, zero crossing	The values of the acceleration norm falling within a sliding window of fixed length (N) are summed (sliding window summation – SWS). The difference of the resulting SWS values and those obtained N samples earlier is then computed to remove gravity. The resulting pattern is a smooth curve crossing periodically the zero. The instants of negative-to-positive zero crossings are then used as markers for determining the step duration	Step length estimate
M-method [13]	IMU	100	L5	IC; FC	Vertical acceleration	Gaussian CWT, minima and maxima	IC timings are identified as the times of the minima of the signal obtained after applying a Gaussian continuous wavelet transformation to the vertical acceleration. The resulting signal is then differentiated and FC timings are identified as the instants of its maxima	GEs detection

* The acceleration signals were filtered before processed (high pass filter, cut-off frequency 1 Hz [30]).