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Technical Note

Development and validation of an accelerometer-based method for quantifying gait events

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ABSTRACT

An original signal processing algorithm is presented to automatically extract, on a stride-by-stride basis, four consecutive fundamental events of walking, heel strike (HS), toe strike (TS), heel-off (HO), and toe-off (TO), from wireless accelerometers applied to the right and left foot. First, the signals recorded from heel and toe three-axis accelerometers are segmented providing heel and toe flat phases. Then, the four gait events are defined from these flat phases. The accelerometer-based event identification was validated in seven healthy volunteers and a total of 247 trials against reference data provided by a force plate, a kinematic 3D analysis system, and video camera. HS, TS, HO, and TO were detected with a temporal accuracy ± precision of 1.3 ms ± 7.2 ms, −4.2 ms ± 10.9 ms, −3.7 ms ± 14.5 ms, and −1.8 ms ± 11.8 ms, respectively, with the associated 95% confidence intervals ranging from −6.3 ms to 2.2 ms. It is concluded that the developed accelerometer-based method can accurately and precisely detect HS, TS, HO, and TO, and could thus be used for the ambulatory monitoring of gait features computed from these events when measured concurrently in both feet.

1. Introduction

Conventional gait analysis techniques, such as optoelectronic motion capture systems, are often used as gold standard methods thanks to their highly accurate three-dimensional measurements of human movements [1,2]. Nevertheless, these systems are often expensive and can only be used in a controlled laboratory environment, which hinders their widespread use.

Accelerometer-based systems have been proposed as an ambulatory monitoring solution to deal with the gait analysis, e.g., [3–7]. Accelerometers allow continuous, unobtrusive assessment of gait features outside the laboratory environment. They can also be used at home, for long-term continuous assessment, as power requirements are low.

Accurate and precise gait features are useful sources of information in, e.g., pathological studies [8,9] or remote monitoring of elders' daily activities [10,11]. In this context, accelerometer-based approaches have been proposed to extract relevant gait events and gait phases [12]. Several previous gait event detection works using only accelerometers are based on learning methods, e.g., [13–15]. However, these methods strongly depend on training data and the trained model usually resembles a "black box" that clinicians may find difficult to interpret, as pointed out by Sant'Anna and Wickström [16]. Threshold-based methods have been developed to detect temporal gait events [17,18]. However, that methods may not detect some events (e.g., in case of milder acceleration peaks pointing to relevant events while being less than the threshold) or may detect events that

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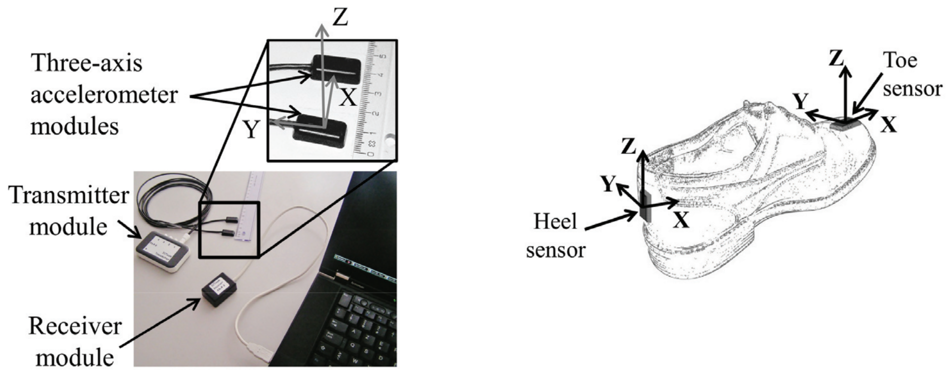

(a) (b)

Fig. 1. (a) Wireless accelerometer-based hardware system. This system is applied to the left and right foot and is used in the present work with four small three-axis accelerometer modules (2 cm × 1 cm × 0.5 cm) (two of them are not shown in the picture (a)). (b) shows a schematic illustration of the position of the sensors, i.e., the accelerometer modules and the Codamotion active markers. Two of these sensors are attached to each shoe (i.e., left and right shoe) at the level of the heel and the proximal part of the big toe, respectively.

did not occur (e.g., in case of an acceleration peak whose magnitude is larger than the threshold and is not related to a relevant event).

Despite the growing popularity of accelerometer-based systems for the quantification of human gait, the validation of the extracted accelerometer-based features against gold standard methods is scarcely reported [19], i.e., in terms of identification of fundamental temporally ordered stride events of walking: heel strike (HS), toe strike (TS), heel-off (HO), and toe-off (TO). The detection of these gait events allows a precise and accurate subdivision of each stride into stance and swing phases, and subsequently to split the stance phase into sub-phases [20,21]. The validation of the extraction of HS and the TO events identified using accelerometers has been performed previously against reference methods, e.g., [5,22,23]. However, there is limited information about the validation of measurement of TS and HO events using only accelerometers. In the study carried out by Ghoussayni et al. [24], TS and HO were detected using two adjacent force-plates. However, the contact position of the foot regarding the junction between the platforms could have a critical effect on the accuracy of the results. More recently, HO has been identified as the first frame where the derivative of the 3D gyroscopic signal norm rises above an empirical threshold [25]. This requires the numerical differentiation of this norm which may amplify the signal noise. To the best of our knowledge, no purely accelerometer-based approach has been previously presented to extract TS and HO without the need of a critical filtering step.

In this paper, we present an original signal processing algorithm that automatically extracts, on a stride-by-stride basis, four consecutive fundamental events of human walking, denoted HS_{accel}, TS_{accel}, HO_{accel}, and TO_{accel}, from the recordings of a three-axis accelerometer-based wireless hardware system [17]. This system/algorithm is applied to the left and right foot and is used here with four three-axis accelerometers. Two accelerometers are attached to each shoe at the level of the heel and the proximal part of the big toe, respectively. We validate this accelerometer-based method by comparing these gait events with reference data (denoted HS_{ref}, HO_{ref}, TS_{ref}, and TO_{ref}) provided by a force-plate, a kinematic 3D analysis system, and video camera used in various combinations. Throughout, the subscripts *accel* and *ref* refer to our method and to the reference methods, respectively.

2. Accelerometer-based hardware and algorithm

2.1. Accelerometer-based hardware system

The hardware system includes several three-axis accelerometers, a transmitter, and a receiver (Fig. 1(a)). Two accelerometers were tightly attached to the shoes, one at the level of the heel and one at the level of the forefoot of each foot, i.e., right foot and left foot (Fig. 1(b)). The wires connecting accelerometers and transmitter module (positioned at the level of the waist) were tightly strapped around the legs so as to avoid disturbing subject's movements. Acceleration data were recorded at 200 Hz and analyzed using Matlab 7.6.0.

2.2. Developed signal processing algorithm

The main steps of the developed algorithm are described hereafter. Times of occurrence of HS_{accel}, TS_{accel}, HO_{accel}, and TO_{accel} are identified mainly from the *z* axis (Fig. 1(b)).

The gravitational component is first removed from vertical acceleration signals by subtracting, from them, their respective averages over the whole signal. The algorithm then detects time intervals during which feet are on the ground. In this paper, these time intervals refer to "heel flat phases" and "toe flat phases" associated with heel and toe accelerations, respectively. It is assumed that these heel and toe flat phases correspond to

$$a_{ns} \leq th_s, \quad (1)$$

where s is either h (for heel) or t (for toe); $a_{ns} = \sqrt{\ddot{x}_s^2 + \ddot{y}_s^2 + \ddot{z}_s^2}$; $\ddot{x}_s$, $\ddot{y}_s$ and $\ddot{z}_s$ are the accelerometer outputs; $th_h = 0.5 \times \text{std}(a_{nh}) / \text{mean}(a_{nh})$ and $th_t = 0.5 \times \text{std}(a_{nt})/\text{mean}(a_{nt})$ are threshold accelerations. This threshold-based detection is just a rough preliminary step toward the final segmentation. Unlike in [17,18], this method is not used directly to detect specific events, but only to isolate time intervals in which the accelerometer is at rest, i.e., the three acceleration signals are close to zero, from time intervals in which the accelerometer is moving. It is thus anticipated that the selection of these thresholds do not affect the quality of the final results. This leads to heel and toe binary functions, i.e., functions equal to 0 in flat phases, and to 1 in non-flat phases (Fig. 2(a) and (b)). To precisely extract the four gait events of interest, the algorithm exploits local information related to flat phase boundaries as follows:

1. HS_{accel} is identified using the magnitude of $\ddot{z}_h$ filtered with a fourth-order zero-lag Butterworth high-pass filter (cutoff frequency = 10 Hz). HS_{accel} is detected as the time of occurrence of the maximum value of the magnitude of this filtered $\ddot{z}_h$ in the second half of the heel non-flat phase (Fig. 2(c)). This filtering step was not critical to determine HS_{accel} in a robust way, since HS_{accel} occurs rapidly with a frequency larger than 10 Hz.
2. TS_{accel} is detected as the time of occurrence of the maximum peak of the raw $\ddot{z}_t$ in the interval whose extremities are the previously determined HS_{accel} and the lower boundary of the toe flat phase (Fig. 2(d)).