Gait & Posture 31 (2010) 322–325

Contents lists available at ScienceDirect

Gait & Posture

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

Real-time gait event detection for normal subjects from lower trunk accelerations☆

Rafael C. González, Antonio M. López *, Javier Rodriguez-Uría, Diego Álvarez, Juan C. Alvarez

University of Oviedo, Dept. Electrical Engineering. Campus de Viesques, edificio 2. 33204, Gijón, Asturias, Spain

ARTICLE INFO

Article history:
Received 13 May 2009
Received in revised form 23 October 2009
Accepted 19 November 2009

Keywords:
Ambulatory system
Real-time processing
Walking
Gait events
Accelerometry

ABSTRACT

In this paper we report on a novel algorithm for the real-time detection and timing of initial (IC) and final contact (FC) gait events. We process the vertical and antero-posterior accelerations registered at the lower trunk (L3 vertebra). The algorithm is based on a set of heuristic rules extracted from a set of 1719 steps. An independent experiment was conducted to compare the results of our algorithms with those obtained from a Digimax force platform. The results show small deviations from times of occurrence of events recorded from the platform (13 ± 35 ms for IC and 9 ± 54 ms for FC). Results for the FC timing are especially relevant in this field, as no previous work has addressed its temporal location through the processing of lower trunk accelerations. The delay in the real-time detection of the IC is 117 ± 39 ms and 34 ± 72 ms for the FC, improving previously reported results for real-time detection of events from lower trunk accelerations.

1. Introduction

Recent advances in miniaturization and the cost of sensors have resulted in the availability of different devices that have been applied to gait analysis [1], with special focus on inertial sensors. From the initial suggestion of the validity of accelerometers for gait analysis exposed more than 30 years ago [2], their current use in conjunction with gyroscopes is nowadays an accepted alternative to optical systems for the kinematic characterization of human gait [3]. As a consequence, accelerometers and gyroscopes have been greatly analyzed for offline [4] and online [5–7] gait event detection under unrestricted conditions.

Lower body segments have been mainly considered [4–6,8–13] for accelerometer/gyroscope placement when used for gait event identification. However, such approaches usually require independent sensors for each lower limb, thus increasing the cost of the solution and the interference in the everyday life of the subject. In order to keep to a minimum the number of devices to be used, we have decided to address the gait event detection from the accelerations of the lower trunk, through sensors placed close to the L3 vertebral position. This position contains information about the movement of both limbs and according to Zijlstra and Hof [14], observed lower trunk acceleration are similar for different subjects and speeds. In any case, there is a between-subject variation in the patterns and small asymmetries between left and right steps. Menz et al. [15] also reported changes in the magnitude of vertical accelerations produced by heel strike due to variations in sole hardness.

Several authors have described lower trunk acceleration patterns, including the identification of IC and FC events. Mansfield and Lyons [7] found that the minimum of the fundamental component of the antero-posterior acceleration of the lumbar region (AP7 in Fig. 1) follows the IC, and the maximum (AP8 in Fig. 1) follows the FC.

Zijlstra and Hof [14] have reported a general tendency of the antero-posterior acceleration that goes from a minimum (AP1) to a maximum value (AP5) at IC. After that, a fast decline in the acceleration is found before returning to the initial minimum (AP1). He also described the presence of a particular peak (AP3) and a corresponding indentation (AP4) for several subjects and velocities, associating them with the beginning and end of the swing phase respectively. He found that the indentation (AP4) might take negative values, especially for fast velocities.

Menz et al. [15] report a consistent definition of this signal, adding to the description the occurrence of a peak (AP6) during the decline after an IC, this peak is associated with forefoot loading. Auvinet [16,17] described the vertical acceleration from

☆ *Disclaimer*: All the authors were fully involved in the study and preparation of the manuscript. The material within has not been and will not be submitted for publication elsewhere.

* Corresponding author. Tel.: +34 985 18 26 78; fax: +34 985 18 20 68.
E-mail address: amlopez@uniovi.es (A.M. López).

0966-6362/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.gaitpost.2009.11.014

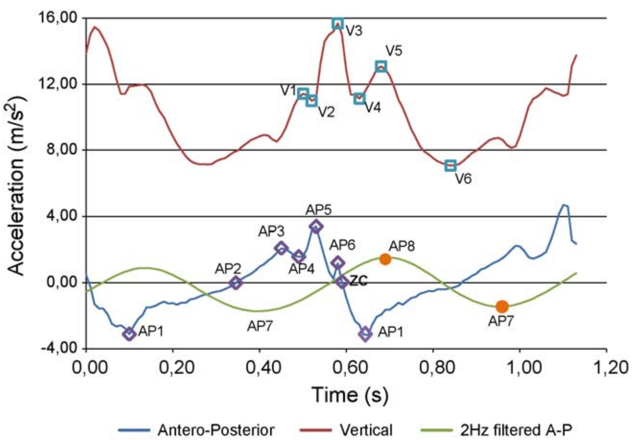

Fig. 1. Gait events and their transcription on lower trunk accelerations: vertical (top), antero-posterior (bottom).

the L3–L4 inter-vertebral space. The IC is located in the first valley (V2) while the second (V4) is associated with FC of the contralateral foot. He also associates peaks V3, V5 and V6 with foot flat, mid-stance and initial push off respectively. This description is consistent with that given by Zijlstra and Hof [14] and Menz et al. [15].

Medio-lateral acceleration has rarely been studied. Principal studies are mainly limited to the description of peaks in the neighborhood of ICs and agree about a high irregularity of the rest of the signal [14,15].

There are works aimed to identify gait events from accelerations registered in the lower trunk [14,15,17]. However, real-time detection has rarely been addressed in spite of its interest in applications such as FES, gait biofeedback or gait-dependent event control applications. An example of such an application is presented in [7], in which the authors present a method to detect IC events, although they do not give their actual time of occurrence. The high variability reported for the detection delay makes the timing of the event very imprecise.

In this paper we report on a novel approach for the real-time detection and timing of IC and FC as they are the main determinants of the fundamental phases of gait. For IC detection, we have modified the timing identification procedure from the antero-posterior acceleration on [14], adapting it for processing in real-time. For the detection of FC, we developed a new algorithm based on the description of the translation of the event to lower trunk accelerations given by [15,17].

2. Methods

2.1. The event detection algorithm

We propose an algorithm based on the location of zero crossings from positive to negative in the output of an 11th order FIR filter applied to incoming antero-posterior acceleration (ZC point in Fig. 2). Each time a ZC is found, we numerically approximate the area enclosed by positive values of the filtered antero-posterior acceleration signal, preceding the detected ZC (A_{ZC} in Fig. 2). If this area is below a given threshold, the ZC is discarded because it is not considered to be associated with the occurrence of an IC event.

If the ZC is not discarded the raw antero-posterior acceleration is analyzed to locate the peak associated with the IC event, thus giving its estimated time of occurrence. For such purpose, we define a search window for local maxima in the same time interval used to calculate A_{ZC}.

The search window may present several local peaks. To identify the peak related to the IC event, we apply the following heuristic rules:

- Vertical acceleration must be higher than gravity.
- The peak must occur before the vertical acceleration reaches 99% of its local maximum value (V3 point in Fig. 1).
- If several peaks satisfy these conditions, the closest to ZC is selected.

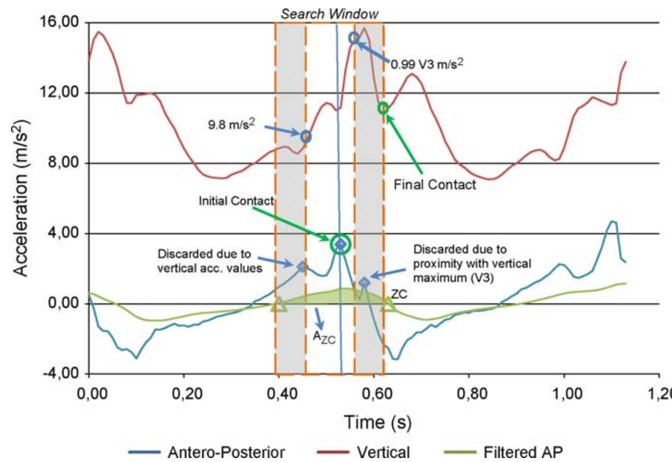

Fig. 2. Detection of events. Vertical (top) and antero-posterior (bottom) accelerations. Zero crossings from positive to negative (ZC) are located in the filtered antero-posterior signal. The area of the lobe preceding a zero crossing (A_{ZC}) is used to identify whether the zero crossing is related to an IC. Once located, the peak related to the IC (AP5, Fig. 1) is searched for in the raw acceleration using a search window of the same length as the positive lobe preceding the ZC in the filtered signal. To establish which of the peaks contained in the search window is that corresponding to the IC, several heuristics are used. The effect of the heuristics is to discard all those peaks contained in the shaded area of the search window. Of the remaining peaks, the last one is associated to the IC and used to define the time of occurrence of the event.

Each IC detection launches a search for the contralateral FC in the raw vertical acceleration. Starting from the sample corresponding to the IC, incoming samples are processed searching for the first local minimum (V4, Fig. 1) that comes after the first detected local maximum (V3 Fig. 1).

3. Experiments

We carried out two independent experiments, one (training data) to define the heuristics used in the algorithm to characterize IC and FC events, and the other to validate the method (validation data).

Training data was based on 1719 steps gathered from 11 subjects (seven males, four females). They were instructed to walk 12 independent excursions along a 25 m long path in a straight flat corridor. Walking speed was calculated from the time taken to complete the central 20 m of each excursion. Time was measured using two synchronized cameras. Walking velocities were freely chosen, with the single condition of walking four excursions at slow, four at preferred and four at fast velocities. Subjects were advised to maintain a constant velocity in each excursion. Acceleration data were gathered by means of an XSens MTx accelerometer fixed close to the L3 vertebra (sampled at 100 Hz, 12 bit A/D conversion). Steps were manually labelled with the actual time of occurrence of IC and FC events using the theoretical descriptions described above. A double check procedure (carried out by two different people) was applied to minimize labelling mistakes.

An independent experiment was designed to validate the results of the algorithm. Six male individuals (ages 34 ± 5.48 years, height 174.17 ± 6.94 cm, body mass 76.83 ± 5.6 kg) were instructed to walk 12 times along a 10 m long path, at three different velocities (indicated as low, preferred and fast) and using their normal footwear. Two force platforms (Digimax MechaTronic®, 2.5 m long) were placed in the centre of the path to record data from each foot independently. Subjects were allowed to rest between different excursions. Raw antero-posterior and vertical accelerations were captured using an XSENS MTx placed close to the L3 and secured through the use of a corset. Measurement axes were aligned to the anatomical ones. All sensors were synchronously captured at 100 Hz. Only steps walked over the force platform were used for validation,