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Technical Note

A robust real-time gait event detection using wireless gyroscope and its application on normal and altered gaits

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ABSTRACT

Gait events detection allows clinicians and biomechanics researchers to determine timing of gait events, to estimate duration of stance phase and swing phase and to segment gait data. It also aids biomedical engineers to improve the design of orthoses and FES (functional electrical stimulation) systems. In recent years, researchers have resorted to using gyroscopes to determine heel-strike (HS) and toe-off (TO) events in gait cycles. However, these methods are subjected to significant delays when implemented in real-time gait monitoring devices, orthoses, and FES systems. Therefore, the work presented in this paper proposes a method that addresses these delays, to ensure real-time gait event detection. The proposed algorithm combines the use of heuristics and zero-crossing method to identify HS and TO. Experiments involving: (1) normal walking; (2) walking with knee brace; and (3) walking with ankle brace for overground walking and treadmill walking were designed to verify and validate the identified HS and TO. The performance of the proposed method was compared against the established gait detection algorithms. It was observed that the proposed method produced detection rate that was comparable to earlier reported methods and recorded reduced time delays, at an average of 100 ms.

1. Introduction

Heel-strike (HS) and toe-off (TO) mark the start of stance phase and swing phase. Accurate detection of HS and TO is required in aiding analysis of gait and development of gait assistive devices e.g. functional electrical stimulation (FES) systems [1–3] and drop-foot stimulators [4]. In clinical settings, gait events are used to evaluate treatment progression of patients with pathological gait [5–7] and cerebral palsy [8,9], to refine alignment or fit of prosthesis and orthoses [10], and to assess fall risk of elderly [11]. They are also used to assess functional performance of a patient's lower extremity after hip or knee arthoplasty [12].

Advancement in miniature sensing technology has seen body-mounted inertial sensors being widely considered as a reliable and mobile alternative for gait monitoring [13]. Of late, gyroscopes gained greater popularity in gait event detection. Measurements from gyroscope are not susceptible to assessors' skill and not affected by minor differences due to variation in attachment sites [14,15]. More importantly, peaks (local maxima) and troughs (local minima) from gyroscope measurements corresponds to mid-swing (MS), HS and TO [7,8,15,16].

Researchers previously proposed spatio-temporal thresholding and local search strategy to determine these events [14,16–20]. Despite their simplicity, they were not suitable for real-time gait event detections due to significant delays in the algorithms. These delays are an inherent nature of current gait event detection algorithms and can be present in offline processes too. The algorithm proposed by Catalfamo et al. required 120 ms to identify TO. Lee and Park's algorithm required prior detection of MS before identifying TO and the average time difference between TO and MS is 320 ms.

This paper proposes a combination of heuristics and zero crossing method to minimize latency in gait event detection. The proposed algorithm uses real-time measurements collected by two wireless gyroscopes attached to the subject's left and right shanks. Many literatures reported the reliability of using gyroscope to determine HS and TO [14,16–21]. Time difference between gyroscope, foot switch and pressure insoles were reported to be ranging from −25 ms to 14 ms and from 19 ms to 75 ms, for HS and TO respectively [16,19–21]. Therefore, this paper intends to compare the capability of the proposed algorithm against algorithms proposed in [19,20] in term of gait event detection rate and latency. [19] and [20] used gyroscopes mounted on the shank to identify HS and TO and can be implemented in online and offline processes. The natures of these algorithms are

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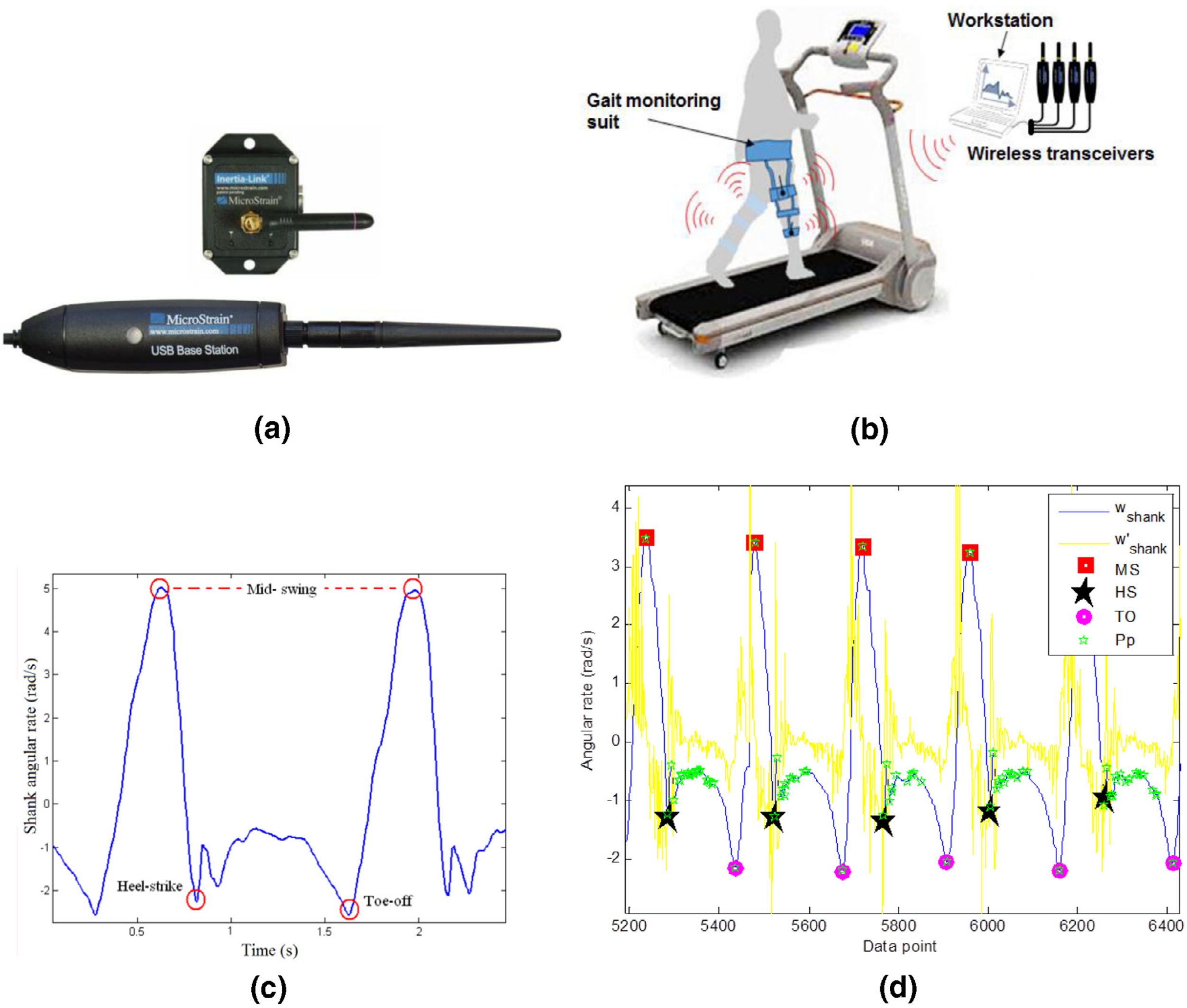

Fig. 1. (a) Inertia-Link wireless sensor and its wireless transceiver; (b) overall system setup; (c) MS, HS and TO in ω_{shank}; (d) proposed algorithm the identification of *Pp*, MS, HS and TO.

the most similar to the algorithm proposed in this study, making them a good comparison benchmark. This paper also examines robustness of these algorithms in both normal and abnormal overground and treadmill gaits, in which abnormal gaits were induced by having the subjects to wear knee brace and ankle brace.

2. Method

2.1. Wireless gyroscope network

A wireless sensor network is setup to measure human lower extremity motion during walking. This network has four wireless Inertia-Link sensors (Microstrain, Inc., Cary, NC, USA) and four transmitters, which are connected to a workstation (Fig. 1(a)). Inertia-Link sensor is equipped with a triaxial accelerometer and a triaxial gyroscope. In this study, readings were only taken from the gyroscope, which has a measuring range of ± 5.235 rad/s with bias stability ± 0.00349 rad/s and nonlinearity of 0.2%. Each wireless gyroscope has an onboard microprocessor performing fundamental data filtering therefore minimal jitter is expected in the data. It has sampling rate of 200 Hz and transmission range of up to 10 m.

For ease of mounting, a gait monitoring suit was designed to attach gyroscopes to the lower extremity (Fig. 1(b)). This suit has straps that can be adjusted to fit any individual by adjusting the length of straps to ensure a good and secure placement so that sensors do not sway freely. The aim of this study is the identification of gait events derived from the shank angular rate, ω_{shank} along the sagittal plane. Therefore, only the angular rates of left (ω_{shankL}) and right shanks (ω_{shankR}) were acquired.

2.2. Real-time gait event detection algorithm

Human shank angular rate during walking, ω_{shank} has prominent peaks and troughs that correspond MS, HS and TO (Fig. 1(c)). Gait event detection algorithms proposed by Catalfamo et al. (CGE) [19] and Lee and Park (LP) [20] utilized these characteristics to identify them. CGE implements a second order Butterworth low-pass filter with cutoff frequency of 35 Hz [19]. CGE then searches the signal for the swing phase ($\omega_{shank} > 0.2$ rad/s). Upon identifying the first instance of swing phase, the immediate negative trough is identified as HS. Once HS is identified, the algorithm waits idle for a period of time, after which every sample is evaluated to check for possible TO. For a sample to be recognized as TO, it has to satisfy a combination of the following rules:

(a) $\omega_{shank}(t-1) < -0.2$ rad/s
(b) $\omega_{shank}(t)$ is the minimum in the window $[t-80\text{ ms} : t+120\text{ ms}]$
(c) In the window $[t-80\text{ ms} : t]$, at least five samples of ω_{shank} are less than the previous sample