A Novel Gait Detection Algorithm Based on Wireless Inertial Sensors

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Abstract. Gait event detection has been widely implemented in realtime gait monitoring devices, orthoses and FES system. Certainly, the latency and the accuracy of the gait-even detection under diversities of gait are crucial. However, due to the high detection accuracy usually comes with high time-delay, it is somewhat hard to find a trade-off between high accuracy and low latency. Therefore, this paper presents a real-time algorithm based on wireless inertial sensor placed on the shank for gait-even detection. It combines the use of the cycle-extremum and the updating threshold method to detected the heel-strike (HS), as the minimum of the flexion/extension angle, the toe-off (TO), as minimum of the angular velocity and the mid-swing (MS), as maximum of the angular velocity. The angle and angular velocity were collected from 2 subjects who imitated the patient that suffered from drop-foot for different degrees to validate the algorithm against the wireless inertial measurement system. The results showed that the proposed method achieved comparable levels of accuracy and significant lower detection delays compared with other published methods.

Keywords: event detection; wireless inertial sensor; the updating threshold; the cycle-extremum;

1 Introduction

Gait event is related to some disease characteristics. Detection will be further helpful for some specific condition as a quantitative tool[1]. Therefore, detection has been widely implemented in real-time gait monitoring devices, such as orthoses, and FES system[2]. The extraction for gait events plays a significant role in gait recognition, which has a direct effect on the recognition rates of subsequent point. Generally, a general gait cycle can be divided into stand phase and swing phase[3][4]. Heel-strike (HS) and toe-off (TO) mark the start ofstance phase and swing phase respectively[5], and mid-swing (MS) is the basis of following gait events detection.

As per literature, many algorithms detect gait events by the detection of MS as the beginning of gait cycles followed by TO and HS. Catalfmo et al (CGE), Lee and Park (LP) proposed that once the MS has been detected, the algorithms should wait idle for a period of time to identify TO. As for the algorithms, they were unlikely to be implemented in real-time gait monitoring devices considering the significant delays in the real-time detections. Darwin and Alpha (DA) proposed algorithm uses zero crossing method and the time interval among the adjoin minimum to identify potential points that may qualify as MS, HS, and TO. However, the detection result of accuracy and latency are limited by the difference of time interval caused by the sampling frequency. Above three algorithms relied on predefined temporal thresholds and spatial thresholds[5]. Therefore, the restricted data collected from a specific population sample. (e.g., young and healthy subjects, or patients with a specific pathology) have improved the performance of the algorithms to some extent. Besides, researchers introduced adaptive, real-time algorithm for angular velocity gait event detection using the updating threshold and the angle as references [6], and had higher accuracy compared with other algorithms. However, the latency of angle samples was larger than that of angular velocity gait samples. Researchers introduced off-line advanced artificial intelligence algorithm for gait event detection, and had higher accuracy compared with rule-based algorithms[7]. Yet it is complex and timeconsuming. Other researchers suggested

A. Badnjevic (ed.), *CMBEBIH 2017*,
IFMBE Proceedings 62,
DOI: 10.1007/978-981-10-4166-2_45

spatial-temporal threshold and local search strategy to detect these events[8][9]. In spite of the simplicity, as for the algorithms, they were unlikely to be implemented in real-time gait monitoring devices considering the significant delays in the real-time detections.

In this context, this paper proposed a combination of gait cycle-extremum and threshold-updating method based on wireless AHRS (Attitude and Heading Reference System) inertial sensor to improve accuracy and minimize latency in gait event detection. The proposed algorithm was used to analyze the angle and angular velocity data collected in real-time to validate the accuracy and the delay for the gait events detection. The gait cycle-extremum can meet various gaits to improve the accuracy of HS, MS, TO for normal and abnormal gait. Further, the updating threshold guarantees the real-time detection for gait events to reduce delays and the occupancy of system resources. Comparable levels of accuracy and significant lower detection delays were achieved compared with other published methods, which indicates that the proposed algorithm could be implemented in online or offline processes.

2 Method

2.1 Hardware

The data obtained were processed by Wireless Inertial Sensor unit *(AHRS)* placed on the shank of subjects A B, can measure 3-axis components of acceleration, angular velocity and magnetometer. The sensor coordinate systemlocation diagram is shown in below figl. The *MPU*6050 is the mainly core part in *AHRS* in this experience, which includes acceleration and gyroscopes used to dectect angular velocity and acceleration. For Sensor coordinate system, the gyro direction obeyed the right-hand rule rotated around the XYZ axis acceleration. The direction of walking is for the positive z-axis direction. The angle datas was calculated by angular velocity(Eq.(1)). Angle and angular velocity signals of the sensor measured with a sampling of 50Hz are transmitted via Bluetooth to a PC at a rate of 115.2kbps, where the signals are stored, then processed and analyzed using *MATLAB*®(Math Works, USA, www.mathworks.com). We measure the angle Ø1, Ø2 (Figl) and angular velocity of foot to obtain the gait events such as TO, HS, MS values.

$$\varnothing_T = \varnothing_0 + \int_0^T \omega_0 dt \tag{1}$$

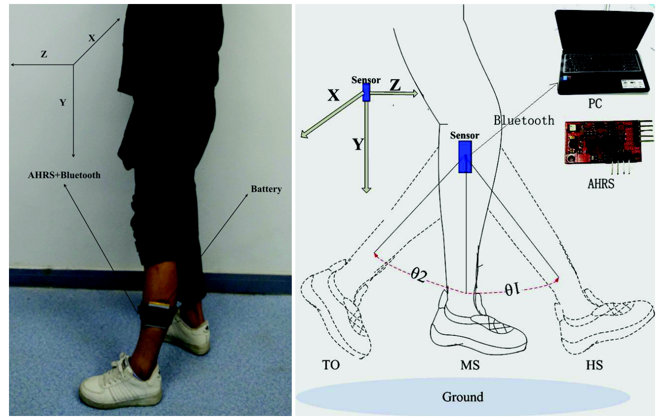

Fig. 1. Outline of the gait measurement system

2.2 Algorithm design.

The algorithm of gait events which detected the MS HS TO values is shown in Fig.2. In order to enhance the feasibility of the algorithm in the new sets of data, the shank angle (fig.2(a)) and the shank angular velocity (fig.2(b)) collected from the subject who imitated patients suffered from drop-foot were used to validate the accuracy for the algorithm. The algorithm consisted of six stages ran automatically with no input. Detail steps are as follows:

1. FIR filter was used to eliminate noise and smooth wave. The higher order of filter is, the higher delay would be achieved. In this work, the 10th order low-pass of FIR filter with linear phase and cutoff frequency of 14Hz was set considering the normal frequency of people walking.
2. After the calibration, the initial values included the MS-Threshold, TO- Threshold and the cycle, was determined to provide a judgment for the peaks and troughs and also for the next threshold updating.
3. The mean value of the former 5 cycle peaks (Eq.(2)) and the variance of the former 5 cycle peaks (Eq.(3)) was calculated as the detection threshold of next peak (Eq.(4)).

$$aver(i) = \frac{1}{5}\sum_{k=1}^{5}\rho(k), 1 < i < N \tag{2}$$

$$S(i) = \sqrt{\frac{1}{5}\sum_{k=1}^{5}(\rho(k) - aver(i))^2} \tag{3}$$

$$MS_{threshold} = \rho_{min} - S(i) \quad (4)$$

Where ρ_{min} is the minimum value of 5 peaks, where N is general data points.

4. The algorithm use zero crossing method by judging of the value of a (Eq.(5)), which can find the potential MS,HS or TO as pp.Unless a < O. Then finding the maximum data whose amplitude were higher than MS-threshold as a peak, and determining the maximum data which was identified as a starting of gait cycle, then the command MS-event=0 should be written to shorten the running time and guarantee that there is one peak in a period.

$$a = (datapoint(i) - datapoint(i-1)) * (datapoint(i-1) - datapoint(i-2)) \quad (5)$$

5. According to the summary from many experiments and the complexity of the gait, the mode of human walking, running, jumping were uncertain. The relationship among the several gait cycles can provide a reference to detect the next trough. Calculating the mean between data(i) (the last trough of gait cycle) (fig.2) and data(i+1) (the first trough of the cycle) (Eq.(6)). Then adding the standard deviations of the 5 data points (Eq.(7)), which can be used to detect the new threshold of TO value.

$$S(k) = \sqrt{\frac{1}{5}\sum_{i=1}^{5}\left(\frac{data(i) - data(i+1)}{2}\right)^2}, 1 < k < N \quad (6)$$

$$TO_{threshold} = \frac{data(i) + data(i+1)}{2} + S(k) \quad (7)$$

6 After identifying the first MS, the first trough was stored in the MV(m) as data(i+1). Once data(i+1) was identified, the data amplitude lower than the TOthreshold would be detected for a while, until the detecting data was out of the threshold range. During the interval, every sample was estimated to check for the possibility of TO value. For a sample to be recognized as TO, it has to satisfy a combination of the following rules: The minima pp was stored in the array of MV(m). During the delay time shown in fig2, the minimum value in array MV(m) was determined as TO. then the command MS-event=1 should be written as the beginning of the peak detection. The algorithm of gait detection for angular and angular velocity analysis was shown in fig.2 and fig.3, respectively.

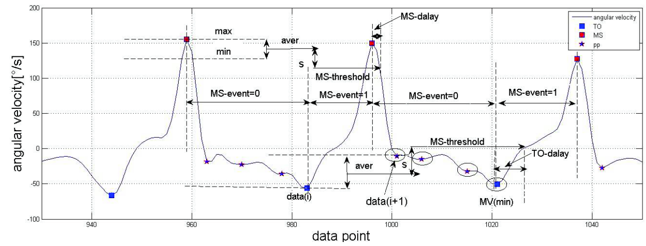

Fig. 2- The details of the algorithm for abnormal angular velocity gaits detection

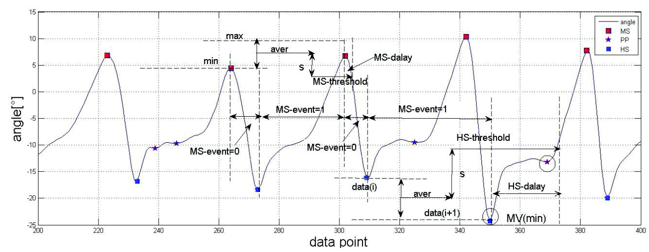

Fig. 3. The details of the algorithm for abnormal angle gaits detection

2.3 Experiment

In the experiment, we had 2 volunteers participated in the experiment named A and B, (1 males, 1 females). 2 volunteers were healthy adults, who imitated the patient suffered from drop-foot for different degrees. Once the device was securely strapped on subject's shank as show in Fig. 1. The subject were requested to walk for approximately 1 minutes, to ensure that the devices were fitted snugly on subject's shank. Volunteers began for the walk at a straight line for about 30 ± 0.5m (about 30 gait cycles) in the indoor environment. Volunteers opened the wireless inertial measurement node, then they were required to stand for 3 seconds, before he can start to walk in order to obtain initial attitude of wireless inertial measurement nodes. The MATLAB routine was used to analyze the signals from the wireless inertial sensor to identify the gait events of TO, HS, MS by using the cycle-extremum and the updating threshold method. Gait events (MS, HS, TO) would be marked only when the detection process satisfy the rules as Table 1 shows.

Table 1. Gait event detection heuristic conditions

Gait events	Conditions
MS	$a).MS >= MS_{threshold}$ $b).a <= 0$ $c).MS_{event} = 1$
HS(angle)	$a).TO <= TO_{threshold}$ $b).a <= 0$ $c).MS_{event} = 0$ $d).TO = min(MV)$
TO(angular velocity)	$a).TO <= TO_{threshold}$ $b).a <= 0$ $c).MS_{event} = 0$ $d).TO = min(MV)$

2.4 The accuracy and latency

Algorithm validation was based on the accuracy and the latency. The accuracy was defined as a detection rate of identifying manually the gait events (MS HS TO) by the algorithm (Eq. (8)). Latency is the time required for an algorithm to identify a specify gait event. To get sensible results, the first and last gait cycles were removed, the accuracy and latency were calculated individually inevery experiment.

$$Accuracy = \frac{turepoints}{turepoints + falsepoints} * 100\% \qquad (8)$$

The study focused on comparing latency caused by the inherent characteristics of an algorithm. Therefore, latency from data filtering was not considered, as well as the delay of implement for MATLAB commands. The latency of the proposed algorithm included MS-delay HS-delay, and TO-delay. After MS Points were detected, the MS-delay time were calculated, until the angle and angular velocity was reaching MS-threshold. When the data(i+1) was detected, HS-delay time for angle was calculated, until the angle reached the TO-Threshold. The method for calculating TO-delay was similar to that HS-delay.

3 Results

The proposed algorithm was able to identify all MS, HS, TO in spite of the variation of angle and angular velocity resulting from the drop-foot. The detection rate for angle and angular velocity for the normal gait or the abnormal gait can reach 100%. High accuracy of the algorithm is usually only for normal gait[5]. However, our algorithm can be applied to irregular gait. The angular velocity about normal gaits and abnormal gaits for MS-delay was shown as Tab2. Table3 was the angle or angular velocity for normal gaits and abnormal gaits on HS/TO detection latency after experiments. The data shown in Table2 and Table3 as follow, have indicated the performance of the algorithm, where A1, A2 and B1, B2 in the Tables were selected from

Table 2. MS detection latency for angular velocity (ms)

times	normal gaits	abnormal gaits
A1	23.512	22.125
A2	21.863	23.156
B1	23.420	21.896
B2	22.942	23.691

Table 3. HS/ TO detection latency (ms)

times	normal gaits		abnormal gaits	
	Angle(HS))	Angular velocity(TO)	Angle(HS)	angular velocity(TO)
A1	68.730	64.566	65.858	65.037
A2	64.566	64.462	65.242	64.800
B1	69.497	64.085	65.116	64.803
B2	64.666	64.663	65.073	65.242

various data of subjects A and B respectively. The smaller delay on the algorithm than DA, CGE, LP was achieved, specific TO of DA minimum delay was 125ms, CGE delay was 120ms, LP was 380ms[5]. In Lee's algorithm,TO-delay was 52.37ms. In this work, the minimum delay for TO was 64.085ms in our algorithm. In Lee's algorithm,delay for HS was 104.5ms. While the minimum delay for HS was 64.56ms in our algorithm. Moreover, the minimum delay for MS was 21.863ms in this work, which have not been mentioned clearly in other research.

4 Conclusion

This paper proposed an algorithm which can be used for online real-time gait events detection. Though the gait of angle and angular velocity is in varied forms for the algorithm, the correct accuracy reaches a certain advantage. Comparable levels of accuracy and significantly lower detection delays were achieved with respect to other published methods. This method can be implemented in further FES devices development. Future works is about to start clinical trials carried out on the drop-foot patients to validate the algorithm.

Acknowledgement

The authors would like to thank to the funds support from the Cooperation Project of Chinese MOST (S2016G3107, 2013DFG32530), the National Natural Science Foundation of China (U1505251), and the Inter-governmental S&T Cooperation Proposal of China and Croatia.

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