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Heuristic Based Gait Event Detection for Human Lower Limb Movement

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Abstract— Gait event detection is important for intent predication in lower limb prostheses and exoskeletons during different activities. Human gait cycle is divided into two main phases i.e. swing phase and stance phase. Initial contact (IC) with the ground indicate the start of stance phase while Toe Off (TO) is the start of swing phase. This article presents algorithm based on set of heuristic rules for gait event detection using a single gyroscope attached on shank of subjects performing activities of daily living such as normal walking, fast walking, ramp ascending and ramp descending. The algorithm sequentially detected gait events like IC, TO, Midswing (MSw) and Midstance (MSt). Results were compared with the reference pressure measurement system using Flexiforce footswitches (FSW). The mean difference error between the reference and proposed system was for IC is about +4ms and for TO is about -6.5ms. The results showed that proposed algorithm achieved high detection performance compared to the existing algorithms and will lead to powerful tool to develop an intent recognition system for lower limb amputees.

I. INTRODUCTION

Locomotion is crucial for human during activities of daily living (ADLs) as it plays an important role in gait efficiency and task progression. Patients with pathologic gait suffer from higher energy consumption and risk of falls. Gait analysis and event detection has been used in different applications using ambulatory gait systems to evaluate and improve patients' motilities and to control the functional electrical stimulation (FES) [1-3].

Gait events can be detected using either force based measurement systems by means of footswitches such as force sensitive resistors (FSR) [4], or wearable sensor such as Inertia Measurement Unit (IMU) [5]. To perform outdoor activities for longer period of time, it is crucial to use the systems which are reliable, portable, small, inexpensive, and with low power consumption [6-8].

Many researchers have used wearable sensors (accelerometers and gyroscopes) for analysis of spatio-temporal gait parameters during ADLs [9, 20-21]. Gyroscopes have been applied for detecting the gait events for triggering [10] and feedback of FES systems [11]. Gyroscope can be mounted on different body locations. The information from the gyroscope placed on shank can be useful to develop a signal of an intent of gait in lower limb amputees [20]. Locating the gyroscope on shank has many advantages as opposed to other parts of the human body [12], such as less soft tissue muscles at shank compared to thigh. In addition, gyroscope placed at shank is acceptable accurately in healthy and pathological subjects [13, 14].

Sabatini et al. [15] developed a gait event detection system for analysis of incline walking based on a single gyroscope attached on the foot of healthy subjects. However, placing gyroscope on shank provides ease of use as compared to its placement on foot as it provides less signal variability between the subjects. P. Catalfamo et al. [16] used a single gyroscope placed on the shank for detection of initial contact (IC) and foot off (FO) in subjects walking up and down on inclined surface and level ground. The results were compared with a reference system of foot switches. However, the mean time difference error of the two systems was -25ms for IC and 75ms for foot off (FO) for all the three terrains. J.K. Lee et al. [15] reported a quasi-real time method for automatic gait event detection using a uniaxial gyroscope. However, their algorithm detects TO and IC only for level ground walk (LGW). The work in [16] developed a gait event detection algorithm based on a single tri axial accelerometer placed on waist foot and shank. The system detected IC and TO during gait on tactile paving, smooth, flat and inclined, terrains. However, the system is based on accelerometer which may be affected by gravity thereby contain high frequency components [19]. The electrodes used in this experiment were non-contact with the skin and were fixed on specially designed cuffs. However, the experiments were conducted for level ground walking only and detected only two gait events. To the best of our knowledge, no study has been carried out to evaluate event detection within the range of time difference of ±7ms.This work aims to extend the existing research as follows:

- The proposed algorithm does not require any threshold value if compared with rule based algorithms.
- Time difference error for the detection of gait events is minimized.
- MSw and MSt events are detected prior to IC and TO, respectively.

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The remaining paper is organized as follows, section II is about the experimental setup, section III describes heuristic based algorithm and its implementation, section IV presents results and discussion and last section is about conclusion.

II. EXPERIMENTAL SETUP

A. Control Subjects

In this study, 8 healthy male subjects (weight: 76.0+6.9 kg; height: 170.3+4.2 cm; age: 28.9+4years) voluntarily participated. The experimental procedure was performed according to the guidelines of both universities ethical boards. All subjects were required to perform different activities such as normal walking (NW), fast walking (FW), ramp ascending (RA) and ramp descending (RD).

B. Experimental Procedure

The data was collected using a 6-DOF inertial measurement unit (IMU) consisting of a gyroscope and accelerometer (MPU,6050. InveneSense). The IMU has a 24MHz Central Processing Unit (CPU), battery and other circuitry placed on the shank of each subject. Four piezoresistive FlexiForce sensors (Tekscan Inc., Boston, MA, US) were used as reference system. As shown in Fig.1. these sensors were fixed underneath the foot on four different locations.

All the subjects were requested to walk along an 8m pathway at different speeds (normal and fast). For ramp ascending and descending activities the subjects were required to walk up/ down on a 6m long inclined surface with inclination of 5°.

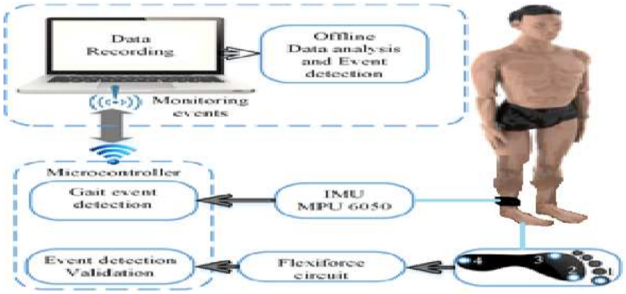

Figure 1. Experiment Setup With IMU and Insole with footswitches; 1: Heel; 2 & 3: 1st & 5th Metatarsal; 4: Toe

III. PROPOSED ALGORITHM

The heuristic based algorithm was written in Matlab 2015 (Mathworks, Inc, Natick, MA). The flowchart of the proposed algorithm and gyroscope signal of one subject are shown in the Fig.2.

A. Preprocessing

During preprocessing, the 2nd order Butterworth low pass digital filter was used and cutoff frequency (fc) of 10 Hz was applied offline to the gyroscope signal. The filtered signal has reduced the oscillations that will avoid false event detection. The selection of cutoff frequency is based on empirical results [5]. The resultant gyro signal was segmented with a window size of 110ms.

B. Gait Events Detection

Fig. 2 provides complete description of the proposed rule based algorithm and its implementation. The algorithm detect the negative peaks for IC (Initial Contact) and TO (Toe off), maxima peak in below zero for MidStance (MSt) and maxima peak above zero for (MSw) Mid Swing as shown in Fig.3(b).

After the preprocessing, if the current time (T) is less than the given time (T_g) the algorithm searches sequentially for MSw in positive slope direction having current sample (g_j) is less than previous sample (g_{j-1}) which means change in slope take place and maxima is detected and marked as MSw. Once MSw is identified, it searches in negative slope direction to detect IC when slope changes from negative to positive slope then minima is detected and named as IC. Having IC marked, the algorithm calculates sum of the total samples of the current window (w_i) and previous window (w_{i-1}). If sum of w_i is less than sum of w_{i-1} the algorithm marked the peak as MSt. Once the Mst is marked, the algorithm again searches for minima peak with condition that slope of the signal changes from negative to positive, minima is detected and marked as TO.

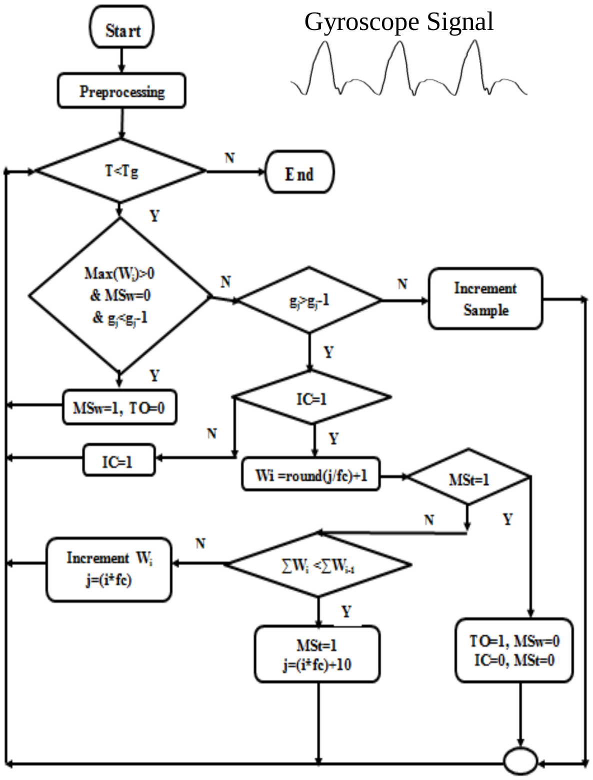

Figure 2. Flow Diagram of Heuristic Based Method

IV. RESULTS AND DISCUSSION

A. Reference System

Validation of the experiment was performed by using an instrumented insole having four foot switches. The insole was placed inside the shoes of each subject during experiment.

TABLE I. COMPARISON AMONG EXISTING AND PROPOSED OFFLINE SYSTEMS.

Ref.	IC (Mean ± Std)	TO (Mean ± Std)	Sensor Position	Activities	CS
[15]	-16.6 ± 11.9	3.7 ± 26.5	Gyroscope on shank	LGW	9
[14]	-8.00 ± 9	50 ± 14	Gyroscope on shank	LGW	7
	-21 ± 15	43 ± 10		RA	
	-9 ± 20	73 ± 12		RD	
[19]	19 ± NA	-8 ± NA	Gyroscope on Shank	LGW(different speeds)	5
Proposed	3.92 ± 1.56	-1.81 ± 4.03	Gyroscope on shank	FW	8
	3.50 ± 1.96	-0.61 ± 3.56		NW	
	3.19 ± 2.44	-6.27 ± 6.50		RA	
	3.63 ± 1.43	-5.94 ± 6.30		RD	

B. Data Analysis Methods

Once the gait events were detected using proposed algorithm then, the time difference (T_{diff}) between the event detection of gyroscope and footswitches was computed using (1), where T_G and T_{FS} indicate the timing of gyroscope and footswitches for MSw, IC, MSt and TO event detection respectively. The mean difference (MD) for all the participants during NW, FW, RA and RD was then computed by averaging their T_{diff}.

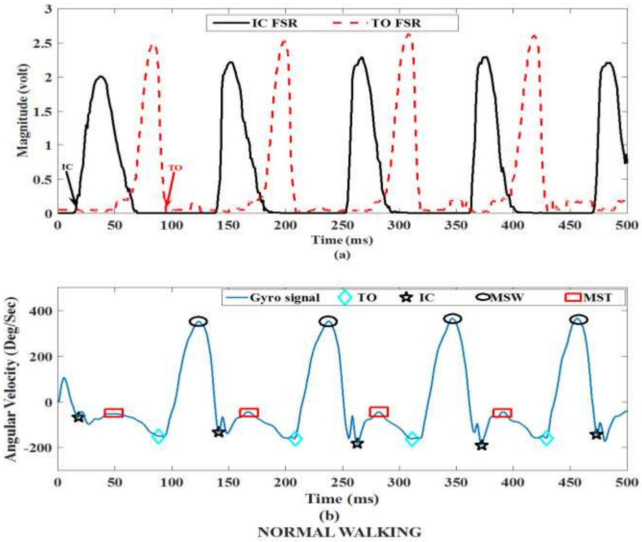

Figure 3. Gait event detection: (a) IC and TO FSRs (b) Gyroscope signal

In order to compare the results of the proposed method with existing algorithms, the mean difference, standard deviation (std) and 95% confidence interval (CI) were calculated for each activity using (2)

$$T_{diff} = T_G - T_{FS} \tag{1}$$

$$CI = Y \pm t_{1-\alpha/2}\ s/\sqrt{n} \tag{2}$$

Where Y is the mean, n is the number of samples to calculate the mean, s is the standard deviation and $t_{1-\alpha/2}$ is corresponding value of t-test. Furthermore, the positive time difference indicates the post-detection and negative time difference indicate pre-detection.

C. Discussion

The results were expressed in millisecond (ms) for all the activities. The rule based algorithm is applied offline and each window sample evaluated sequentially. The rule based algorithms are faster as compare to the machine learning based gait event detection. The machine learning algorithms are based on learning of gait event pattern and then detect the events accordingly.

During experiment, eight control subjects participated and five trials were carried out for each activity. The average time difference for IC was 3.92±1.56 ms, 3.50±1.96 ms, 3.19±2.44 ms, 3.63±1.43 ms and for TO -1.81±4.0 ms, -0.61±3.56 ms, -6.27±6.50 ms, -0.94±6.30 ms during FW, NW, RA and RD respectively. The experimental results showed post-detection for IC and pre-detection for TO. The pre-detection will be useful for early triggering the system to perform the task/activity.

The results of proposed study were compared to the existing work which successfully validated results by FSR and implemented offline. Catalafamo et al. [16] detected the gait events and found a mean difference error and standard deviation for IC -8.0± 9.0 ms, -21±15 ms, -9±20 ms for LGW, RA and RD respectively. Lee et al. [17] showed mean difference error of -16.6±11.9 ms for IC and 3.7±26.5 ms for TO during LGW activity.

Table I shows a comparative analysis of the proposed algorithm with exiting algorithms. The proposed system shows significant improvement in results for IC and TO. Which implies best results for the detection of MSw and MSt as it early detected before IC and TO for all four activities.

A limitation of this algorithm is the implementation in offline environment and start gait event detection from MSw. However, the algorithm has the ability to modify in online mode and will include amputee with different prosthesis during all the activities.

Table II provides confidence interval (CI) for event of IC and TO for four activities i.e. FW, NW, RA and RD. For IC the CI is positive which means that IC will be detected later while for TO CI is mostly negative which means that TO is detected early.

Activity **Event**	**Fast walking**	**Normal Walking**	**Ramp Ascending**	**Ramp Descending**
IC	[2.7 5.1]	[2.1 6.0]	[1.4 5.0]	[2.6 4.7]
TO	[-4.7 1.2]	[-3.3 2.0]	[11.0 -1.45]	[-10.6 -1.3]

TABLE II. CONFIDENCE INTERVAL FOR DIFFERENT ACTIVITIES

V. CONCLUSION

The accurate and reliable gait event based systems would be useful in many ambulatory applications. This study presents a rule based method for the detection of gait events, based on the use of a single gyroscope attached on the shank. The proposed system is fast, reliable and does not require any threshold value for the detection of gait events. The mean difference error between the reference and the gyroscope based system was found to be in range of ±7ms. Future research work will focus on the evaluation of the proposed system with lower limb amputees and on different terrains.

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