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CUSTOMIZED WEARABLE SENSOR-BASED INSOLES FOR GAIT RE-TRAINING IN IDIOPATHIC TOE WALKERS

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Abstract

Idiopathic toe walking is associated with lack of heel strike during the initial contact phase of a gait cycle. Idiopathic toe walking affects 5–12% of healthy children in the US. In the case of idiopathic toe walkers: typically, a child can heel-toe walk, but habitually walk on their toes. A corrective intervention is needed during the early age of a child. In this pilot study, we developed a wearable insole with tactile corrective feedback. A total of five subjects (13±4 years) participated in this study. A customized insole was designed with two pressure sensors, inertial measurement units, a vibration tactor and on-board data storage SD card. A vibration biofeedback was provided to the participants if three consecutive toe-toe strikes were found while walking. We found that the average proportion of heel to toe strikes was 0%,66%,64%,53% and 67 % among participants. We also found median time of return to habitual walk of toe-toe gait was 13 seconds. All analysis was conducted on a walking data ranging from 2 to 20 hours of walking. All five subjects reported that the customized insoles were helpful and motivated them for a corrective gait. This novel research with wearable sensors will help physical therapists to utilize innovative intervention methods for gait training in idiopathic toe walkers.

Keywords

Idiopathic Toe Walkers; gait; wearable insoles; tactors; toe-toe gait; heel-toe gait

INTRODUCTION

Idiopathic toe walking can be described as bilateral toe walking with no orthopedic or neurological cause past the age of two years. In this condition, children can voluntarily

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CHOC IRB Contact Information: IRB # 170870 CHOC Institutional Review Board – Research Institute, 1201 West La Veta, Research Building, 4th Floor, Room 410, Orange, CA 92868, Phone: (714) 509–8869 walk with the normal heel-toe pattern but habitually prefer to walk with the toe-toe pattern for unknown reason[1]. In order for it to be considered idiopathic, the child's medical history should be clear of any neurological, orthopedic, or neuro- psychiatric conditions including other gait abnormalities. Idiopathic toe walking affects 5–12% of healthy children in the US[1, 2]. Children with idiopathic toe-walking have developmental delays and neurodevelopmental diagnoses[3–6]. Several invasive interventions are adopted if the child does not grow out of the toe walking behavior, such as leg braces, serial casting, botox, surgical lengthening of the Achilles tendon[2]. A few studies have explored long-term gait outcomes of toe walking (>5 years) following treatment in childhood [7–10] but are limited in sample size.

Idiopathic toe walkers usually walk subconsciously on their toes and when alerted can produce heel-toe gait. In order to bring heel-toe gait the physicians recommend the parents to watch their children when walking on toes and correct them. Although this practice helps in reducing toe-toe gait in daily life, but automated biofeedback-based interventions are needed to change toe walking behavior in the adolescents. In this study, we have developed a new non-invasive method of correcting toe walking behavior through corrective tactile biofeedback. This method is non-invasive and can be easily and safely incorporated in the life of toe walkers. This can also be used as corrective intervention tool for treatment by pediatric physical therapists. In this study, we have investigated into feasibility of customized wearable sensor-based insoles for gait re-training in idiopathic toe walking adolescents.

METHODS

A total of five subjects (3 males, 2 females) of age 13±4 years, participated in this study. All subjects were asked to wear the shoes with customized insoles for at least 30–60 hours per week. The IRB was approved by Chapman University and Children's Hospital of Orange County (CHOC). A physician from the pediatric department at CHOC diagnosed the subjects with idiopathic toe walking symptoms (figure 1). Toe walking is characterized as toe-toe gait with initial contact of the foot whereas normal gait is characterized as heel-toe gait. A customized insole was designed with two pressure sensors, inertial measurement units (accelerometer and gyroscope), vibration tactor and on-board data storage SD card (figure 2). A vibration biofeedback using a vibration motor (11000 RPM, Adafruit product ID 1201) was provided to the participants if three consecutive toe-toe strikes were found. Data from the logger was saved to an SD card using a SparkFun OpenLog. The data was sent to the data logger over UART as raw text at 8600 baud with the UART interface. Openlog separated the files out into separate text files saved to an external SD card. The open logger was mounted with a female header that allowed the UART interface to be accessible from the Ardunio Pro Mini. This allowed for re-programming and tweaking the program as well as verifying problems with assembly. The data from both FSRs (Force Sensitive Resistor, Interlink 402), the raw IMU acceleration and gyroscope data, and an epoch value for timing was recorded in the file. The data logger sampled at 8–10Hz, depending on the processor availability. A ITG/MPU 6050 breakout board containing 6-axis IMU was used. The assembly information is provided in the figure 2a. An Arduino Pro Mini (code E000025, 3.3V, ATmega328, SparkFun, Niwot, CO) was utilized as the processor.

FSRs and a vibration tactor were affixed on the insoles as shown in figure 2b. A small, two pin, JST connector allowed for the lipo battery (500 mAh) to be disconnected and recharged. A 3D printed box was specifically designed to enclose the completed circuitry. The 3D printed case was laced through one of the straps of the shoe as seen with figure 2c.

One of the FSR, was placed at the front around the 2nd metatarsal and another at the back around the heel of the sole and a small vibration tactor (10mm diameter, 2.7 mm thick, product 1201, Adafruit) was used to provide tactile feedback when walking on toes. The complete configuration is shown in figure 2b. The two FSRs were helpful in detecting toe and heel strikes among the subjects. If the toe FSR is consecutively pressed (or activated) without any activation of the heel FSR, the tactile feedback is generated to alert subjects of the toe walking behavior. A pilot lab study revealed that idiopathic toe walkers have good sensitivity to tactile stimuli around the toe region. Thus, the vibration tactor was placed around the toe region.

Data Collection Protocol:

Walking data from all subjects was a collection of multiple walking bouts throughout 3 days. The bouts of gait were collected from different time of day, when the participant wore the shoes. The data from each session was aggregated into a single time series. A threshold-based algorithm was deployed to differentiate walking versus non-walking data.

Each gait cycle was identified using FSR and accelerometer data (figure 3) and was resampled to 100 data points as seen in figure 4 and figure 5.

RESULTS

Development of State Machine for gait events:

Utilizing appropriate thresholding, the heel contacts and toe-off events of gait can be successfully identified. This can be modeled using a simple state machine and a counter. The state machine consists of three states: i) raised state, ii) front-strike state (FSR at metatarsal) and iii) back-strike state (FSR at heel). The state machine starts in the raised state and transitions either on B (Back State) or C (Front State). The transition requires that either sensor at least goes above an upper threshold. The direction is determined by the pressure detected by the FSRs (front and back FSR). If the front sensor has a larger pressure value then the back FSR, the state machine transitions along C else it will transition along B as shown in figure 7.

For the front strike state, if the back FSR goes below the minimum threshold then the model will transition back to the raised state along D. For the back-strike state, if the front FSR goes below the threshold then the model will transition back to the raised state along A.

Accurate identification and analyzing of peaks (or spikes) is necessary to identify gait events such as heel contact and toe off. While it is easy to visually identify peaks in a small univariate time-series, automatic algorithms to detect peaks are needed. A Smoothed z-score algorithm is based on the principle of dispersion. Z-score smoothing uses a sample average and deviation to determine if the point is a peak. If a new datapoint in the timeseries is located x number of standard deviations above from moving mean, the datapoint is considered as peak (z-score). It is a robust algorithm since it creates a separate moving mean and deviation, and do not corrupt the threshold. The peaks are identified with approximately the same accuracy and the changes in the sample do not affect if a peak is detected or not. The gait events were identified using a smoothed z-score algorithm and were confirmed with a rise in pressure from the heel and metatarsal FSRs as show in figure 8. Preliminary analysis revealed the amount of time spent toe walking vs heel walking. We found that the average proportion of heel to toe strikes was 0%, 66%, 64%, 53% and 67% among the five participants. The average time when toe walking stops due to tactile feedback and initiated among the participants was found out to be 13 s.

DISCUSSION

This paper quantitatively identified the severity of idiopathic toe walking, and also demonstrated intervention in adolescents. The intervention consisted of a customized shoe insole with two FSRs and one vibration tactor. The whole circuitry was programmed using an Arduino Pro Mini. In the intervention, after five toe-walking steps a tactile feedback was provided to the participant.

We found that for each gait cycle, the deviation from the mean for toe walking was much higher when compared to normal walking (figure 4 and 5). As shown in figure 4, for a normal gait cycle, 0% is the foot strike event and 0% to 10% is the roll of the foot onto the front toe. The 10% to 50% is the full plant of the foot transition before the raise of the heel and 60 % to 80% is the raising of the heel and 80% to 100% is the swing of the foot. For toe walking, in about 10% to 50% of the gait cycle we expect the foot to be fully planted on the ground, but this isn’t true for toe walker. This adds slight variation in accelerations during the single stance phase of gait. At 10% of the gait cycle, where the front foot strike is expected to occur (figure 4). We found that in toe walking acceleration profiles, the front strike is missing. We also found that in angular velocity profiles from gyroscope do not show foot roll up during the initial foot strike during the toe walking (Figure 5, initial 0–10% of gait cycle).

During walking, gait events are generated repeatedly in a particular sequence. As seen in figure 6, during heel contact when the center of pressure is near the heel, a pressure spike is generated by the heel FSR. This heel pressure spike is followed by a spike in pressure of the FSR situated at the meta-tarsal during the toe-off. During toe-walking, the heel FSR does not get activated since there is no heel contact. However, in normal gait we expect alternate activation of the heel FSR (back) and meta-tarsal FSR (front). We found that smoothed z-score algorithm could successfully discriminate heel contact and toe off through peaks and troughs. It was also found that the median time of return to habitual walk of toe-toe gait was 13 seconds.

Various degree of severity of toe walking characteristics were seen among participants as the participants exhibited the average proportion of heel to toe strikes as 0%, 66%, 64%, 53% and 67% for their entire walk time with the shoes. All five subjects reported that the customized insoles were helpful and reminded them for a corrective action during walking.

This research with wearable sensors will help physical therapists to utilize innovative intervention methods for gait training in idiopathic toe walkers.

Limitations:

Biofeedback based interventions are dependent on patients willingness to correct the behavior themselves. We also suspect that some patients will acclimatize to the stimuli and ignore the intervention. This can be mitigated up to some extent through introducing variation in vibration of tactors such as i) length of the time for vibration of tactor ii) random offset when the tactor is triggered iii) random variation in amplitudes of vibration.

CONCLUSIONS

In conclusion, new non-invasive interventions can be designed for the spectrum of severity of idiopathic toe walking among adolescents. In-home interventions like shoe-insole based biofeedback have potential to bring behavioral change in idiopathic toe walking adolescents. This customized insole can track natural history and explore toe walking severity type and allow for greater understanding of idiopathic toe walking.

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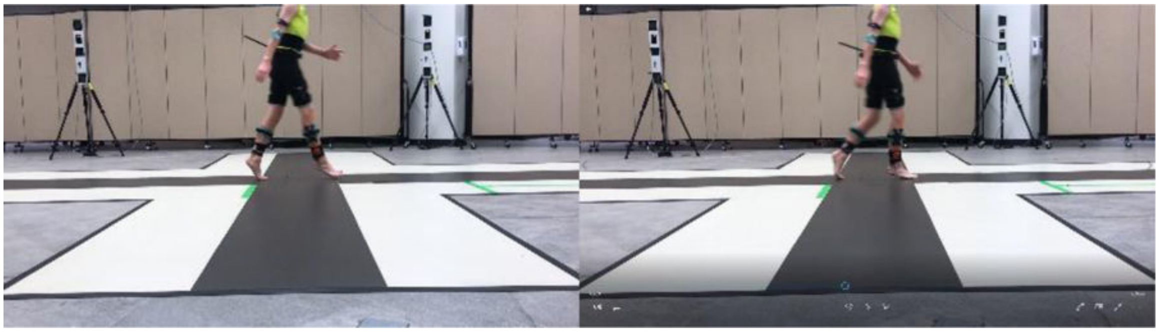

Figure 1.

Representative subject showing toe-toe walking characteristics in adolescents. The subject's foot strike and foot off gait phases are shown.

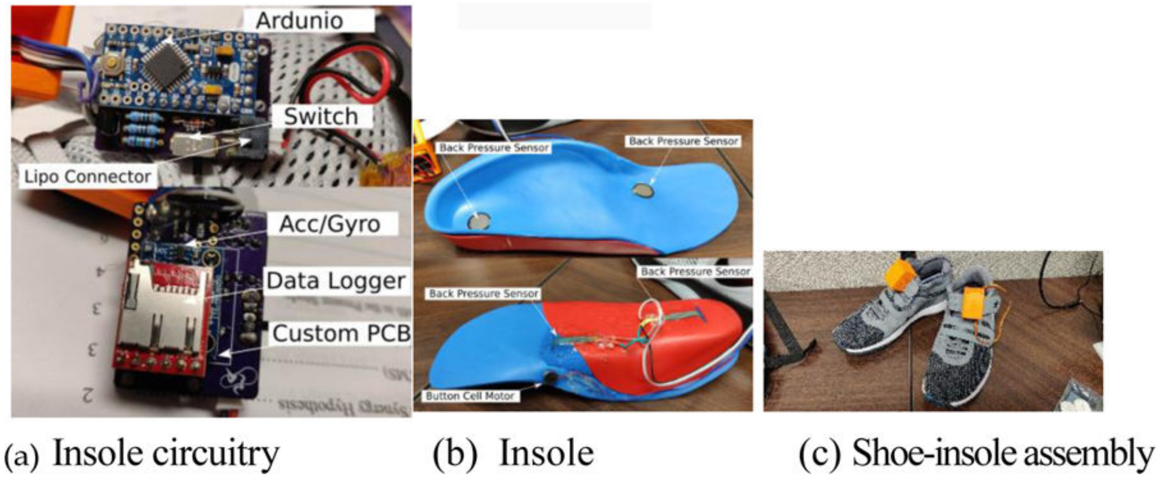

Figure 2.
a) Insole circuitry, b) Insole with FSR and vibration tactor c) shoe-insole assembly

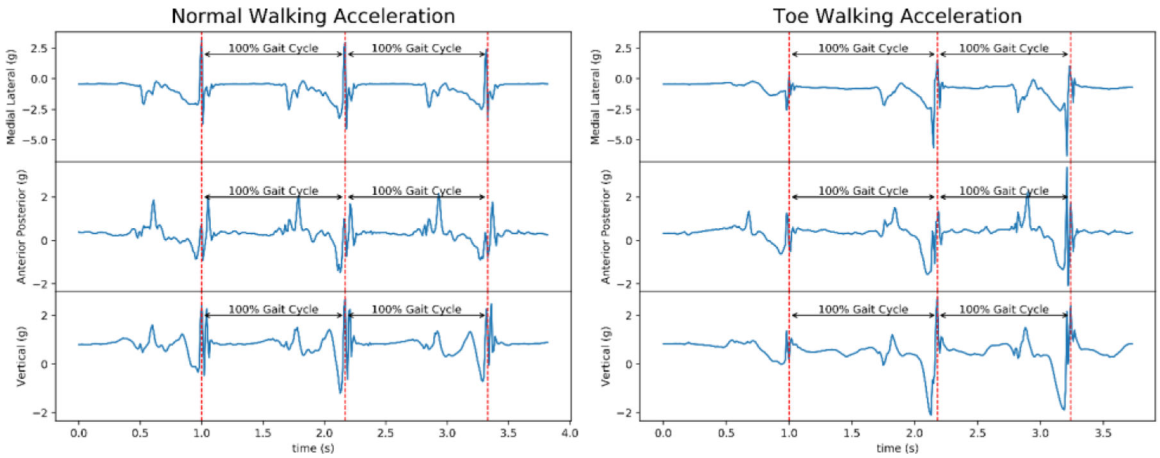

Figure 3.
Acceleration profiles from normal walking versus toe walking

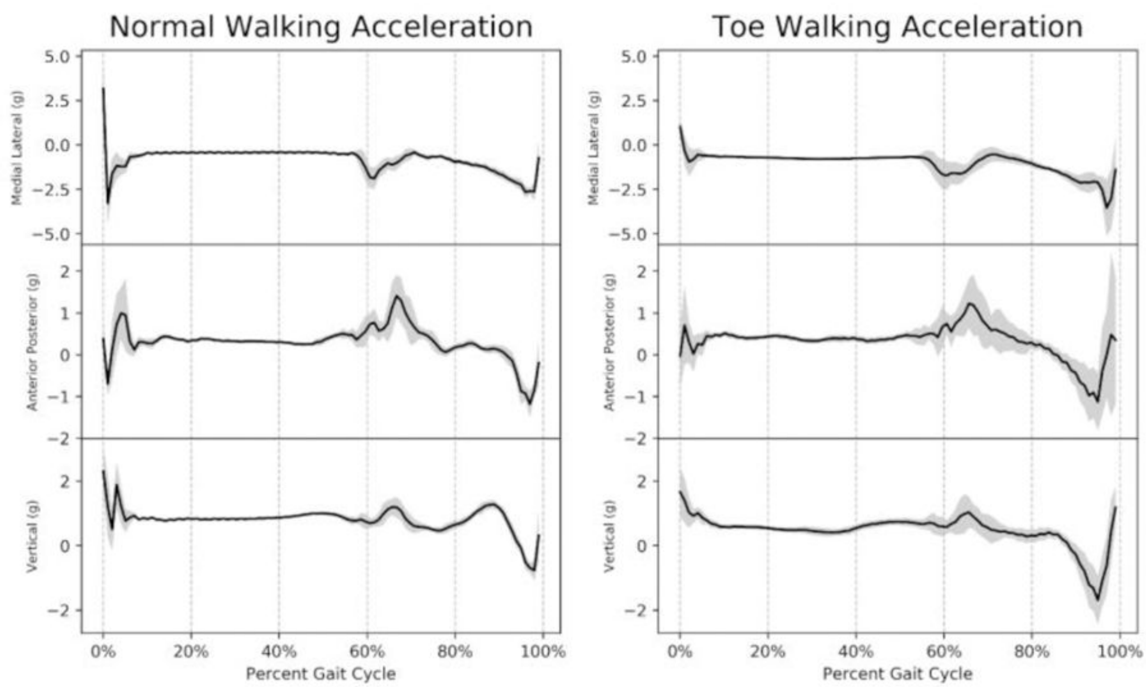

Figure 4.
Normalized acceleration profiles during a complete gait cycle during normal walking and toe walking.

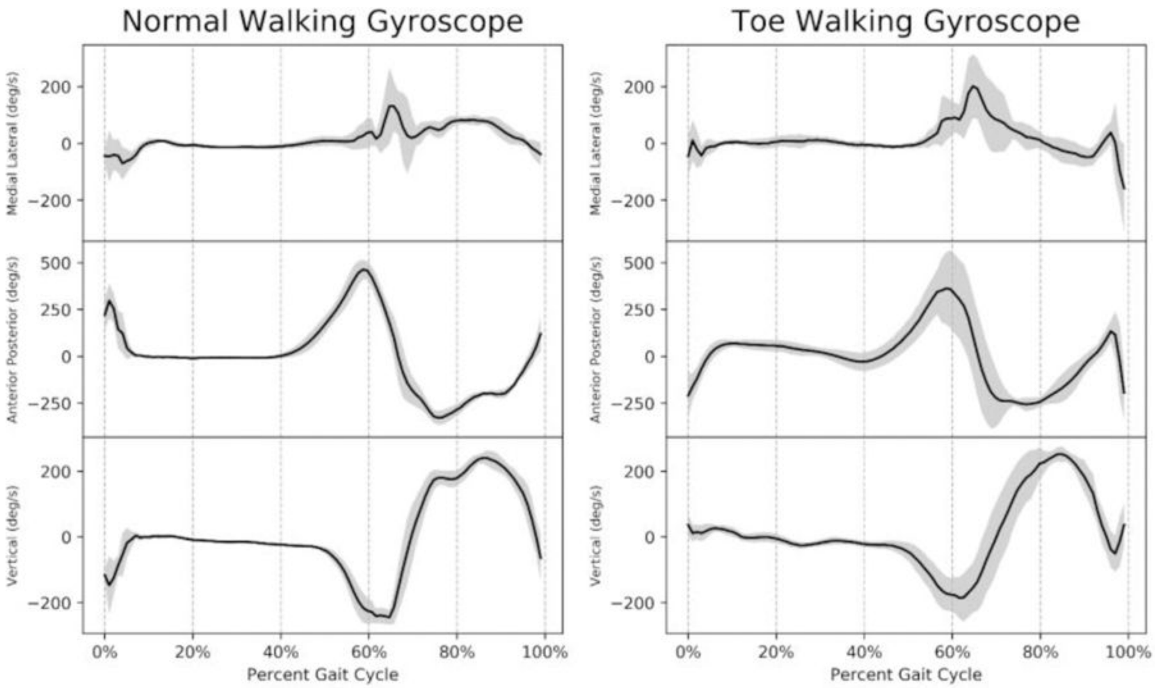

Figure 5.

Normalized angular velocity profiles during a complete gait cycle during normal walking and toe walking.

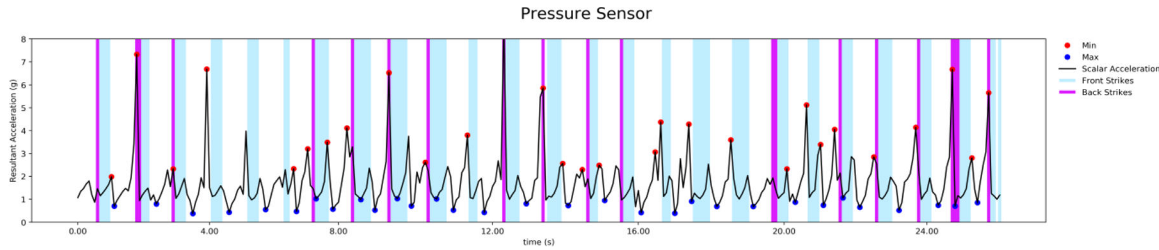

Figure 6.
Resultant scalar acceleration plot with imprints of front and back FSR activation Frequent shifting to the front strike state will increase a toe walking counter while the back-strike state will reset the counter. A minimum of five consecutive toe strikes triggers the vibration tactor and the amount of time the tactor runs increases for each time toe walking is detected. This will reset to the initial time of the vibration after certain (N=10) periods of triggering. We use a minimum of three toe walking steps before tactile biofeedback since there are chances of error in detecting heel FSR activation.

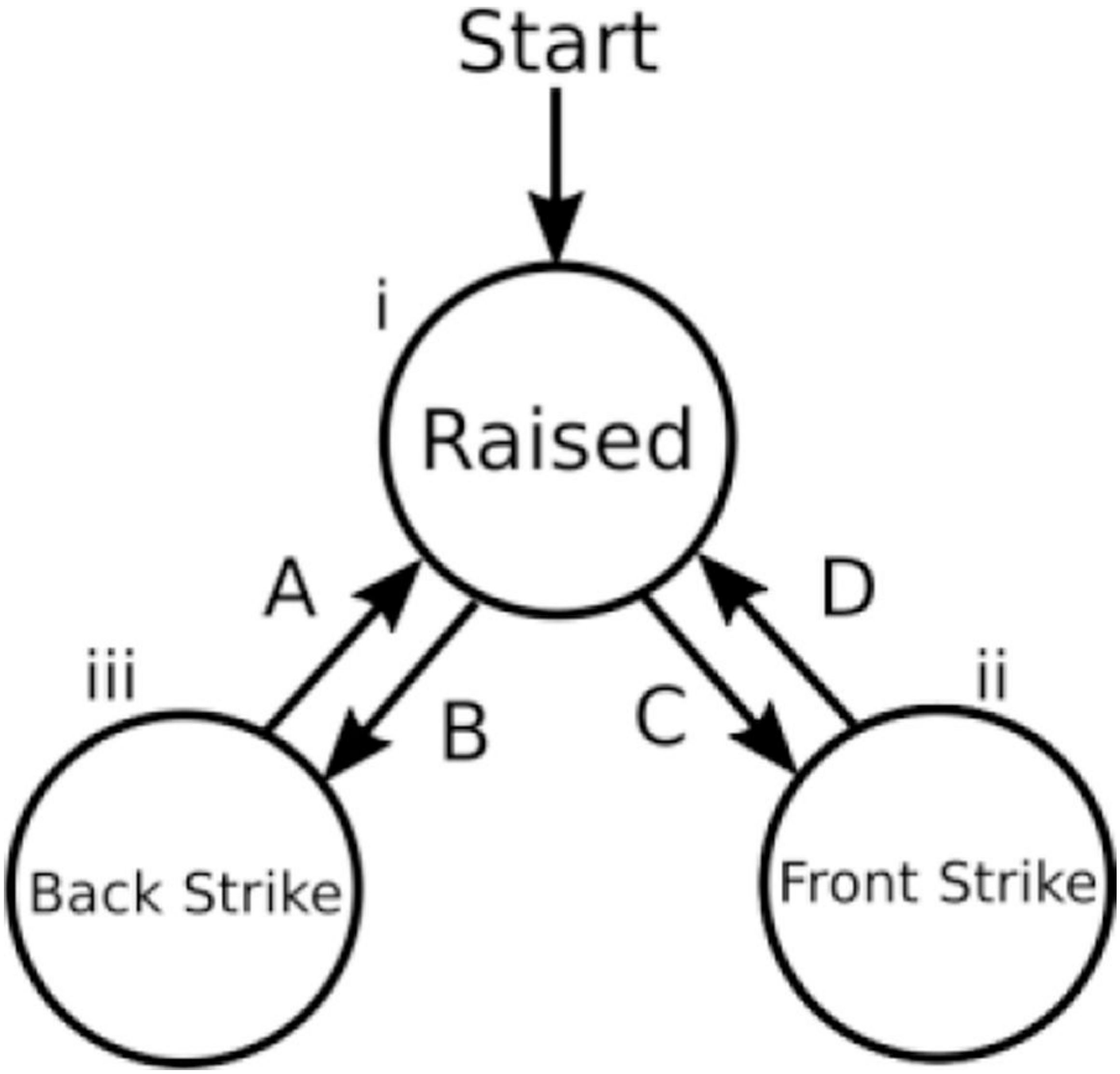

Figure 7.
State machines for gait event detection

Figure 8.

(a) Z-Scoring for peak detection (b) Peak Detection Gait event (heel contact and toe off) identification from accelerometer scalar magnitude (or resultant acceleration) and the pressure FSRs