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A FOOT-MOUNTED WEARABLE DEVICE FOR ONLINE IDENTIFICATION OF GAIT PHASES

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Abstract. *Use of wearable devices is an efficient solution to collect quantitative information about gait with lower costs than standard gait analysis systems like motion tracking cameras and force platforms. In this paper, we present the development and testing of a wearable device to be worn on the feet, capable of measure, store and transmit gait data. The device is equipped with two six-axis inertial measurement units (IMUs) to capture foot's kinematics, two force-sensitive resistors (FSRs) to detect contact between foot and ground, and one Arduino Uno board to perform data processing. We demonstrated the utility of the developed device by performing online detection of the gait phases of healthy subjects. To do that, we propose two threshold-based algorithms for phase detection: one based on the FSR signals, and the other based on the sagittal angular velocity of the foot, measured with the IMU placed on the heel. Both algorithms where evaluated during treadmill walking by a healthy subject. Experimental results demonstrated the reliability of the proposed device to measure gait signals and to use those signals for gait phase detection. We also validated the feasibility of the phase detection relying solely on the inertial sensors.*

Keywords: *gait analysis, gait phase detection, wearable devices, robotic rehabilitation, inertial sensors.*

1. INTRODUCTION

Recent technological advances in robotics, especially in exoskeletons, have allowed substantial improvements in rehabilitation, therapy and assistance focused on the recovery of independent walking in subjects with compromised motor skills (Hussain, 2014).

Adaptation of the robot actuation during therapies requires continuous monitoring of the human activity, including timely identification of the different events and phases during gait. Acquisition, monitoring and analysis of gait data can be done using wearable and non-wearable systems. Due to their small size, low cost, high mobility, durability, and low operating power, Inertial Measurement Units (IMUs) have been increasingly used for gait analysis, in replacing of the most commonly used Force Sensitive Resistors (FSR). Lee and Park (2011) proposed examples of similar applications, where sensors were put in the sole of the foot. Sabatini et al. (2005) use IMUs attached to aluminum plates and 3D-printed heel supports.

In this paper, we develop and evaluate a novel wearable device for acquisition and analysis of gait data. It uses two six-axis inertial measurement units (IMUs) to capture foot's kinematics, two force-sensitive resistors (FSRs) to detect contact between foot and ground, and one Arduino Uno board to perform data processing. In order to evaluate the usability of the device in real-time setups, we implemented two threshold-based algorithms for online detection of gait phases. The first algorithm uses the signals from two FSRs placed under the heel and under the second metatarsus. The second algorithm uses the measurement of the foot's angular velocity in the sagittal plane. Due to their low computational cost, we could implement the proposed algorithms directly in the Arduino microcontroller. The proposed device is an improved version of the wearable device that the authors described in Perez-Ibarra *et al*., (2018).

We evaluated the reliability of the developed device through an experimental walking test over a treadmill performed by a healthy subject. In addition, we also demonstrated that an algorithm for detection of gait phases based only in the IMU signals is feasible. Our device showed promising implications that encourage us to use it inside the control loop of an exoskeleton robot, and for the gait analysis of impaired subjects.

The paper is organized as follows: in Section 2, we describe the materials and methods including the wearable device and the phase detection algorithms. In Section 3, we present and discuss experimental results. Finally, we present some conclusions.

2. MATERIALS AND METHODS

2.1 WEARABLE DEVICE

Figure 1 presents the wearable devices constructed for the project. Each device consists of a 3D printed arc that is fixed to a baseplate built in aluminum. Each shoe uses two six-axis inertial measurement units (MPU6050) to capture foot's kinematics, one placed on the back of the heel and the other at the side of the fifth metatarsus; devices also are equipped with two force-sensitive resistors (FSRs) to detect contact between foot and ground, one was placed under the heel and the other under the second metatarsus. Data processing and communication is performed on one Arduino Uno board for each foot. The prototypes can be attached directly to the user's footwear with Velcro straps. Despite the sensitivity of FSR sensors being affected by their position, there is no need to remove the patient's shoes, thus facilitating their use.

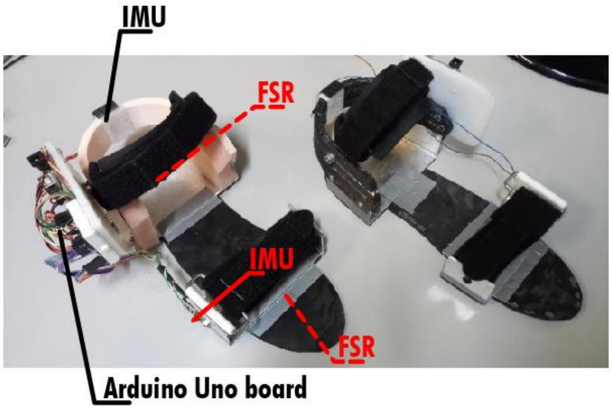

Figure 1. Phase detection devices developed with resistive and inertial sensors

Data acquisition occurs in the Arduino Uno at 100 Hz. A C routine receives serial packets of data from both Arduinos and creates a file containing all inertial signals and FSR outputs; system architecture is illustrated in Fig. 2.

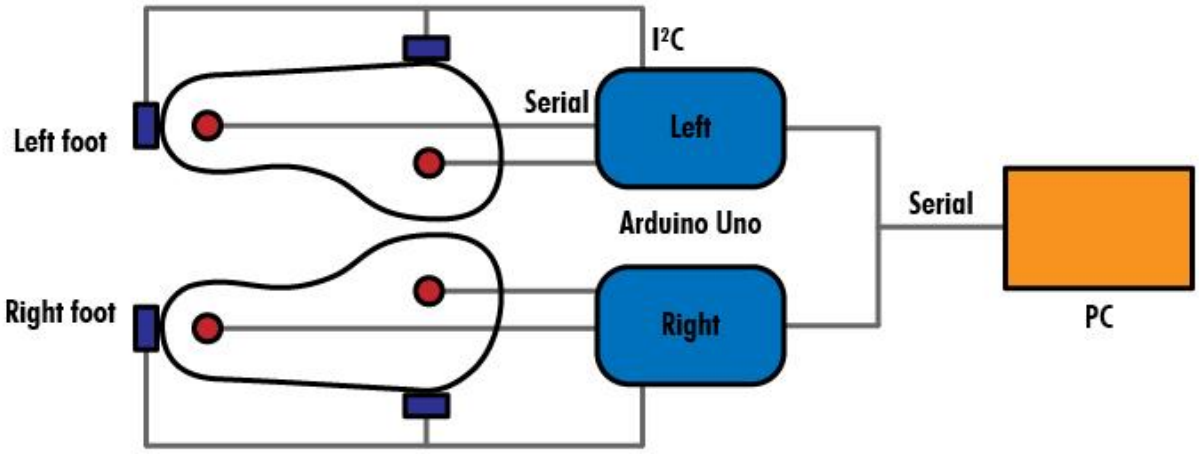

Figure 2. Schematic of the system architecture, with its four IMUs, four FSRs and two Arduino Uno. Inertial data of each foot, as well as FSR readings, are acquired by an Arduino, which then sends those to a PC.

2.2 PHASE DETECTION ALGORITHMS

Phase detection algorithms were implemented in the Arduino itself, where detection occurred during the healthy subjects' walk, and verified offline in Python (Python Software Foundation), with mathematical and data processing libraries. These algorithms consider a gait cycle with the following four phases: *stance* (ST), *terminal stance* (TS), *swing* (SW), and *loading response* (LR), as shown in Fig. 3. Detection of the transitions among phases occurs respectively with the identification of the following four events: *toe strike* (TSt), h*eel off* (HO), *toe off* (TO), and *heel strike* (HS).

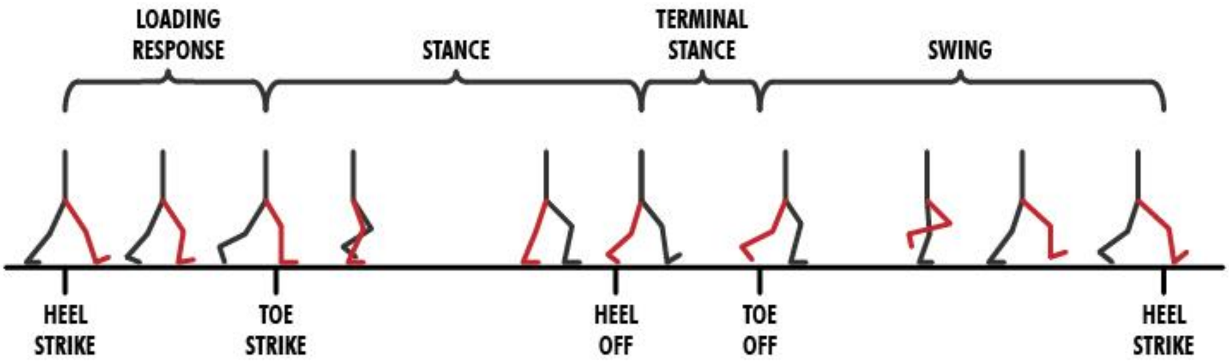

Figure 3. Gait cycle with its four phases and triggering events.

We proposed and evaluated two algorithms: the first algorithm uses the voltage signals read by the force-resistive sensors; and, the second uses the measurement of the sagittal angular velocity of the foot by the heel's IMU. The first algorithm was also utilized to provide labels with current gait phase for validation of the phases detected by the other.

2.2.1 Algorithm 1: Event detection using the output voltage of the FSRs

In the first approach, current gait phase is identified by evaluating the state of the FSR sensor, according to its output voltage. We defined an experimental threshold (T) and the sensor state is determined as explained in Table 1 and as presented in Algorithm 1.

Table 1. Association of sensor states (1 = posterior, 2 = anterior) indicates the gait phase.

	FSR 1 < T	**FSR 1 > T**
FSR 2 < T	SW	LR
FSR 2 > T	TS	ST

Algorithm 1. Event detection using the output voltage of the FSRs.

```
if (fsr1 < T) and (fsr2 < T) then
        phase ← SW
end if
if (fsr1 < T) and (fsr2 > T) then
        phase ← TS
end if
if (fsr1 > T) and (fsr2 < T) then
        phase ← LR
end if
if (fsr1 > T) and (fsr2 > T) then
        phase ← ST
end if
```

2.2.2 Algorithm 2: Threshold-based detection using angular velocity of the foot

The second algorithm consists of a *Switch-Case* logic evaluating the sagittal angular velocity of the foot (ω), where at each time sample is evaluated the current state and the transitions between these phases are determined using the finite state machine (FSM) described in Fig. 4.

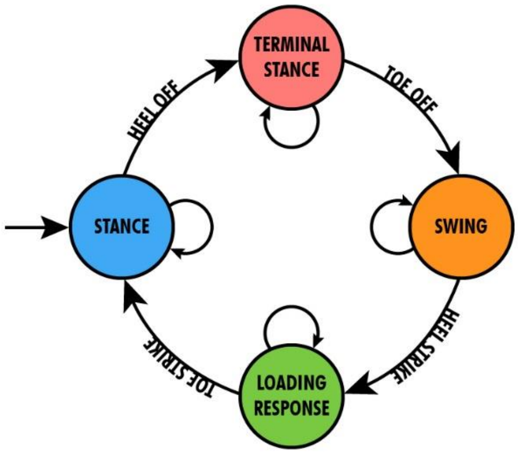

Figure 4. State machine representing the phase-detection system based on angular velocity thresholds.

Defining four empirical thresholds and two delay parameters, the conditions needed for these changes are:

1. Case 1 (HO): ω less than threshold.
2. Case 2 (TO): ω greater than the threshold.
3. Case 3 (HS): ω less than the limit within a predetermined time window.
4. Case 4 (TSt): absolute value of ω less than a threshold, considering a time window.

Algorithm 2 presents the pseudo-code used for this detection.

Algorithm 2. Threshold-based detection using angular velocity of the foot.

```
switch (state):
      case ST:
            if (velocity < threshold_ho) then
                  state ← TS
            end if
      case TS:
            if (velocity > threshold_to) then
                  state ← SW
            end if
      case SW:
            if (velocity < threshold_hs) then
                  delay_hs ← delay_hs + 1
                  if (delay_hs > delay_threshold_hs) then
                        state ← LR
                  end if
            end if
      case LR:
            if (abs(velocity) < threshold_tst) then
                  delay_tst ← delay_tst + 1
                  if (delay_tst > delay_threshold_tst) then
                        end if
            end if
      default:
            delay_hs ← 0
            delay_tst ← 0
            state ← state
end switch
```

3. RESULTS AND DISCUSSION

3.1 Typical Signals

Data collection consisted of a healthy subjects' walk on a treadmill for 2 minutes, at two different speeds: 1 and 2 km/h. Typical signals for the angular velocity and acceleration measurements of the inertial and the resistive sensor outputs of the left foot are shown in Figures 5 and 6, respectively.

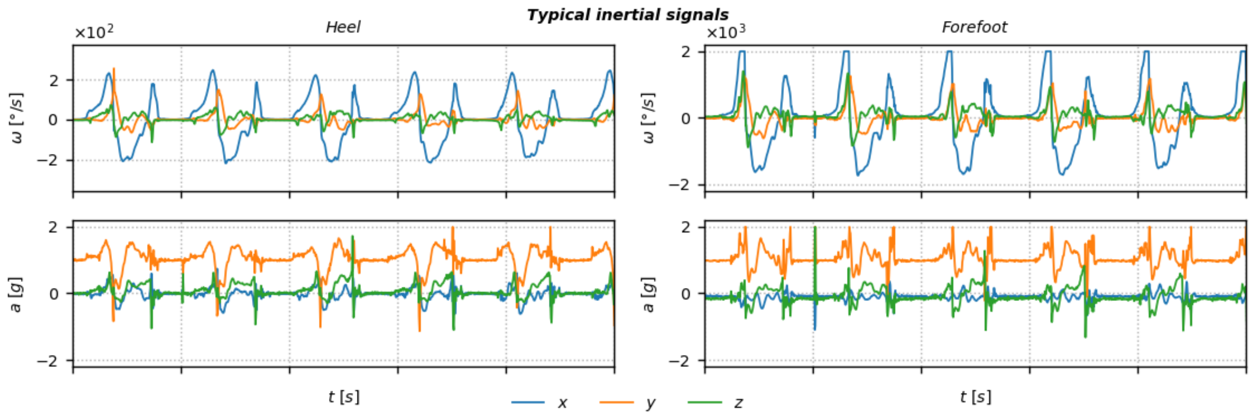

Figure 5. Inertial signals. Graphs show representative signals for the angular velocities in °/s (above), and linear accelerations in *g* (below), measured by the IMUs placed back on the heel (left) and at the side of the forefoot (right).

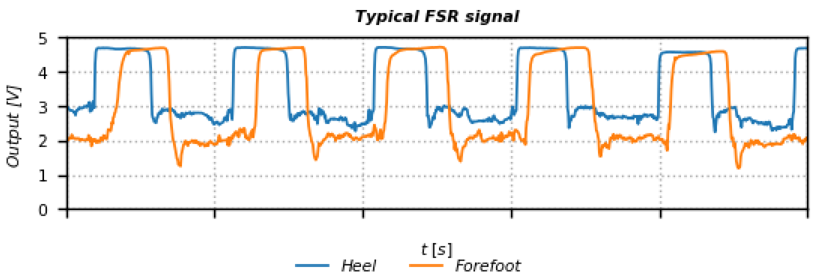

Figure 6. Example of an FSR response curve under normal gait. In such condition, the heel makes contact with the ground first, as illustrated by the blue curve, representing the output of the heel sensor.

3.2 Comparison between both methods

The algorithms previously described were applied to both angular velocities measured by the heel sensor and FSRs outputs. Figure 7 compares the results obtained by those approaches.

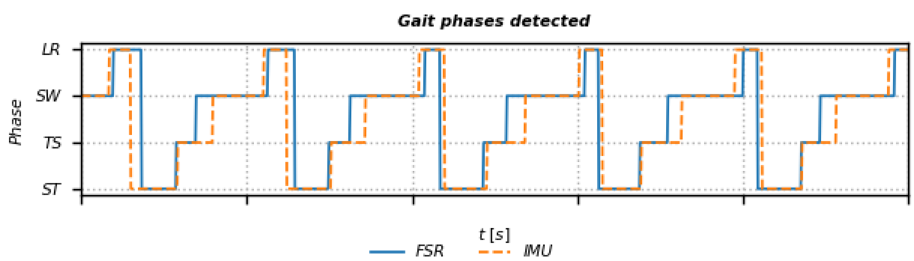

Figure 7. Comparison of the two methods.

The labels defined with the FSR detection method were then used for validation of the IMU algorithm; the confusion matrix in Table 2 summarizes its performance.

Table 2. Confusion matrix evaluating the performance of the IMU algorithm. FSR detected phase was used as true label.

FSR (actual)		IMU ST	IMU TS	IMU SW	IMU LR
	ST	1986	0	141	116
	TS	118	928	10	50
	SW	13	723	2168	368
	LR	230	2	179	772

Based on the confusion matrix above, the following performance metrics are evaluated for each individual phase: precision, recall, and their harmonic mean, the F1-score, defined as

$$\text{Precision} = \frac{\text{True Positive}}{\text{True Positive} + \text{False Positive}} \tag{1}$$

$$\text{Recall} = \frac{\text{True Positive}}{\text{True Positive} + \text{False Negative}} \tag{2}$$

$$\text{F1-score} = \left(\frac{\text{Precision}^{-1} + \text{Recall}^{-1}}{2}\right)^{-1} = 2 \times \frac{\text{Precision} \times \text{Recall}}{\text{Precision} + \text{Recall}} \tag{3}$$

Accuracy metrics presented in Eq. 1-3 are assessed for each phase, and the results presented in Table 3.

Table 3. Precision, recall and F1-score regarding the identification of individual phases. Detection of loading response had the worst performance among them.

	Precision	**Recall**	**F1-score**
ST	0.85	0.89	0.87
TS	0.56	0.84	0.67
SW	0.87	0.66	0.75
LR	0.59	0.65	0.62

Information summarized in Table 3 strongly suggests that parameters adopted here should be reconsidered for performance enhancement. As shown, LR phase is highly misidentified: either SW or ST are detected instead, meaning that the algorithm's threshold and time window for this transition are not adequate. The same happens with TS, where almost 50% of the events are misclassified; Fig. 7 indicates that TS detection is delayed, thus the threshold should be decreased to better identify that event. On the other hand, ST-TS transition is detected simultaneously.

4. CONCLUSIONS

A novel wearable device for acquisition and analysis of gait data, which consists of two six-axis inertial measurement units (IMUs), two force-sensitive resistors (FSRs) and one Arduino Uno board, is presented. Two threshold-based algorithms for online detection of gait phases were evaluated considering walking tests on a treadmill. The results indicated that phase detection using only inertial sensors is feasible and can be applied for rehabilitation purposes when integrated with exoskeletons.

5. ACKNOWLEDGEMENTS

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7. RESPONSIBILITY NOTICE

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