Instrumented Shoes for 3D GRF Analysis and Characterization of Human Gait

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Abstract. The main objective of this work is to develop a computerized system based on instrumented shoes to characterize and analyze the human gait. The system uses instrumented shoes connected to a personal computer to provide the 3D Ground Reaction Forces (GRF) patterns of the human gait. This system will allow a much more objective understanding of the clinical evolution of patients, enabling a more effective functional rehabilitation of a patient's gait. The sample rate of the acquisition system is 100 Hz and the system uses wireless communication.

Keywords: Human gait analysis · Gait pathologies · Ground reaction forces

1 Introduction

The study of the human gait has generated much interest in fields like biomechanics, robotics, and computer animation. It has been studied in medical science [1–3], psychology [4, 5], and biomechanics [6–8] for five decades. Comprehensive measures of gait pathology are useful in clinical practice. They allow stratification of severity, give an indication of the gait quality, and provide an evaluation of treatments outcomes. There are many ways to gauge overall gait pathology. While parent and caregiver assessments are useful and practical, they lack the precision and objectivity provided by three-dimensional quantitative gait data. Gait data can be used to assess pathology in a variety of ways. For example, stride parameters such as walking speed, step length, and cadence provide an overall picture of gait quality. These parameters are especially useful after normalization to account for differences in stature [9]. So, it's important to have systems that provide such kind of information.

To study and analyze the human gait, their patterns must be acquired. During walking, the most common force acting on the body is the GRF that is a three-dimensional force vector. The GRF consists of a vertical component plus two shear components, antero-posterior and medial-lateral directions, acting along the foot support surface. A fourth variable is needed, the location of the center of pressure of this GRF vector.

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In the particular domain of plantar pressure and GRF, there are a variety of pressure mats or insoles [10] like as F-scan©, Emed© or Zebris© systems. Force platforms mounted in the ground are used in many studies on humans to measure GRF during walking or running [11, 12]. However, force plates are expensive, the number of successive ground contacts is very limited, and they are conditioned to certain types of environment.

The first measurement of dynamic ground reaction force and plantar pressure using instrumented shoes was realized by Marey [13]. In [14] is disclosed a system for detecting abnormal human gait using an inertial measuring unit to measure angular velocity and acceleration of the foot, and four load sensors and a bending sensor installed on the insole of the feet to get force and flexural data respectively. It was specifically designed to detect patterns of normal gait, toe in, toe out, over supination, and heel walking gait abnormalities. The system presented in [15] was designed to measure GRF and CoP using six-degrees-of-freedom force sensors, one under the heel and the other on the forefoot. Because there are only two sensors, the determination of the location of the CoP in every moment of the walking phase as well as the behavior of the reaction force at other points of contact between the foot and the ground are restricted.

Another more complete solution is the combination of the kinematics of the body segments with the GRF, like the system presented in [16, 17]. Human walking patterns data are analyzed, especially in the sagittal plane, based on video camera images and an acquisition system of the CoP and the vertical component of GRF using four force sensors in each shoe sole. This system objective was to obtain gait signatures using computer vision techniques and to extract kinematics features for describing human motion and equilibrium. These results have been used afterwards in gait specification of biped robots. Results show that this approach worked successfully.

For an accurate characterization and analysis of the human gait, it is needed a GRF acquisition system to obtain the three components of the GRF, the vertical force, anterior-posterior shear, medial-lateral shear.

2 Data Acquisition System

The system developed for the 3D ground reaction forces data acquisition consists of a prototype shoes with force sensors, hardware, firmware, and acquisition software.

Figure 1 presents the system architecture showing the data flow from the force sensors located in the shoes up to the computer where the data processing software is hosted. The data can be acquired via an Android application and then sent to the computer to be processed or sent directly form the instrumented shoes to the computer.

2.1 Prototype Shoes

The prototype shoes' soles, where the force sensors are located, were built with ABS 3D-printed pieces that were assembled and glued to the shoes garment. A rubber sole was added to the bottom of the shoe. A prototype of the developed right instrumented shoe is shown in Fig. 2.

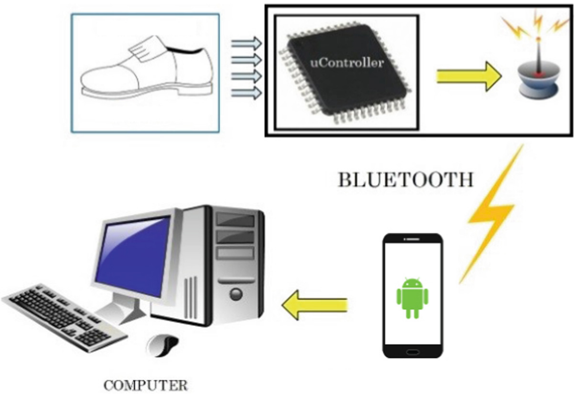


Fig. 1. System architecture.

Fig. 2. Instrumented shoe prototype.

The measures by which the prototype was designed for are shoes sizes from 40 up to 46, according to the European system. The different sizes are obtaining by adjusting the back Velcro strap and sliding the heel forward and backward. The physical characteristics of the shoe are shown in the Table 1 below.

Table 1. Features of the prototype instrumented shoe.

Characteristics	Values
Length	310 (mm)
Height	20 (mm)
Width	100 (mm)
Weight	700 (g)
Sensors	16

The shoe sole consists of two independent parts, the back part that comes into contact with the rear-foot and mid-foot, and the front part that comes into contact with the fore-foot. The upper connection between these parts is made with an insole leather material and a hinge causing the shoe accompanying the dorsiflexion and plantar flexion movements of the foot. Each sole part is made out of a top and bottom platforms. The sensors are placed on the bottom platforms (Fig. 3).

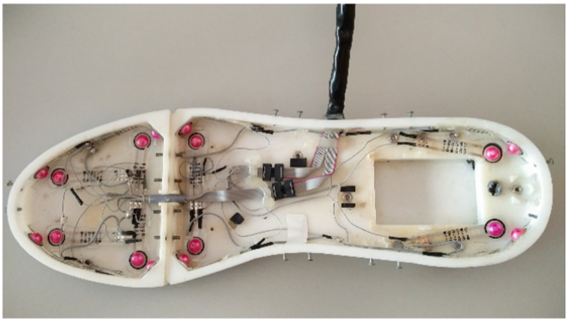


Fig. 3. Interior of the shoe sole prototype. (Color figure online)

In order to centralize the force applied to the sensors and capture 100% of this force, shims (pink semi-spheres) were used between the load and the sensor. Discs with a diameter equal to the diameter of the sensitive area of the sensor and with a thickness of 0.5 mm were also used so that the force is distributed only by the sensitive area of the sensor (Fig. 4).

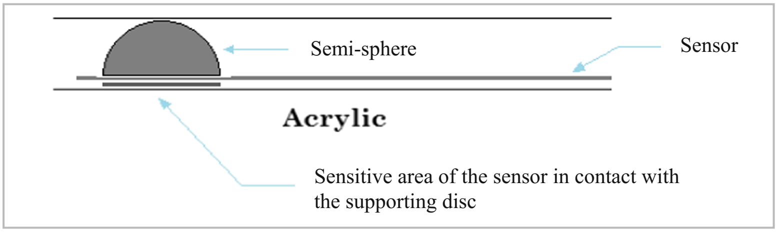


Fig. 4. Semi sphere and disc in contact with the sensor in order to centralize force and distribute the load to the sensitive area of the sensor.

The global system has 32 force sensors, 16 force sensors in each shoe. In each shoe, there are 8 force sensors to measure the vertical component of the GRF, and 8 to measure the horizontal components of the GRF. The sensors are equally distributed by both front and back parts of the bottom platform of the shoe (Fig. 3). The horizontal force sensors at the corners of the soles are each placed at 45°. This way each horizontal force sensor measurement is decomposed in longitudinal (x axis) and lateral (y axis) force components (Fig. 5).

The vertical force sensors are Teskan FlexiForce A201 sensors with a range of 0-440 N, and the horizontal force ones are the same model but with a range of 0-110 N.

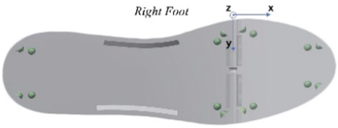


Fig. 5. Sensors position and coordinate system of the right shoe prototype. The left shoe coordinate system is symmetric.

2.2 Hardware

It was chosen to use two commercial boards, one for each shoe, with an embedded Arduino Mega 2560 microcontroller because has a small size and contains 16 analog inputs, meeting the needs of each shoe to read all the 16 sensors. Each board is powered by a battery with 7.4 V and 2250 mAh.

Another two dedicated boards were developed to signal conditioning the force sensors' values. Each of these boards has an RN-42 Bluetooth Module to establish a wireless communication with the Android device or the used computer, operating over the frequency range of 2.402 GHz to 2.48 GHz, and having a signal reception range of about 20 m.

To acquire the values of the sensors, it is used the force-to-voltage circuit of Fig. 6, and the force sensor signals are acquired by 10-bit resolution ADCs integrated in the microcontroller of the Arduino chip board. This circuit uses an inverting operational amplifier to produce an analog output based on the sensor resistance (R_S) and a fixed reference resistance (R_F). The resistance R_F value is 6.81 kΩ for the vertical force sensors and 7.5 kΩ for the horizontal ones.

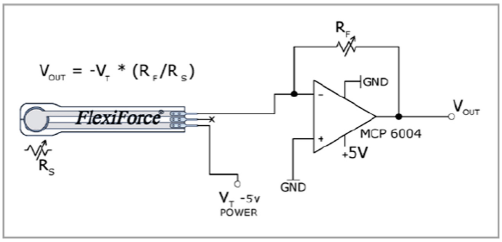


Fig. 6. Force-to-voltage circuit

The force sensors were calibrated. Considering that all sensors of the same type had similar behavior, and since two types of sensors are used in this work, 0-440 N range and 0-110 N range, the calibration process needed to be repeated for both types of sensors. The calibration process consisted in applying different weights with a known mass to a sensor and reading its output voltage. To have more accurate results the sensor should be calibrated in the circuit were it is going to be used. For this reason, the sensor was connected to the Arduino board and the voltage was also read from the same board. With these values, a linear regression was made to obtain an equation that would fit best the behavior of the sensor.

2.3 Firmware

The firmware routines are important parts of the system, allowing the acquisition and transmission of the force values from the shoes to the computer, with error checking.

These routines are hosted and performed by the embedded microcontrollers. The set of operating instructions programmed in the Arduino includes the configuration of the serial communication, reading sensor values from the Analog-Digital Converter (ADC), generating the Cyclic Redundancy Code (CRC), packaging of data to transmit, and sending data via Bluetooth.

There are 4 modes of operation: acquiring the sensor values at a sampling rate of 100 Hz (suitable for the human gait acquisition [18]), acquiring the sensor values at a sampling rate of 1 Hz (for system checking), the tare mode, and idle mode.

The state diagram of the implemented operations (actions) are shown in Fig. 7. In the two acquisition modes, after the interrupt flag is activated, the Arduino draws the Interrupt Service Routine (ISR) to be executed. In the ISR, for each sampling time is determined the current time and read the 16 sensor values. After the acquisition of the sensor values, it is calculated the CRC value for each sensor value and for the time that is later packaged and sent to the Android device. In tare mode, the Arduino reads the sensor values and sets the offsets for each sensor that are sent and stored on the computer which will then be subtracted to the value of the force. In idle mode the system is on standby until it receives a command to start one of the aforementioned modes.

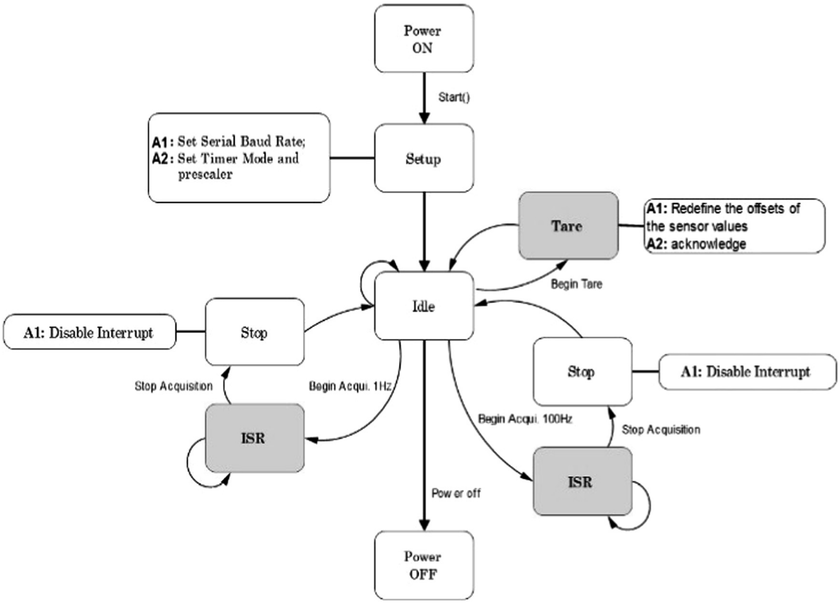
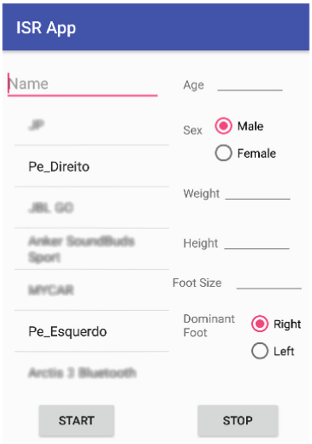


Fig. 7. State diagram of the actions (Ax) implemented in the firmware.

2.4 Acquisition Software

To acquire the human gait, an Android application was developed to obtain the force sensor values. The acquisition is performed at a sampling rate of 100 Hz, and this acquired data will be used to characterize the human gait. Before starting the acquisition, the user needs to fill in data fields related to the person whose gait is going to be analyzed and select the Bluetooth devices corresponding to the two instrumented shoes (Fig. 8). The files produced by the application are stored on the "Downloads" folder of the Android device.



Name

Age

Sex ● Male ○ Female

Pe_Direito

Weight

Height

Foot Size

Pe_Esquerdo

Dominant Foot ● Right ○ Left

Fig. 8. Layout of the Android application to acquire the human gait.

The processing of the acquired force values is done using a Matlab application. On each foot, the anterior-posterior shear force, corresponding to F_x force, and the medial-lateral shear force, corresponding to F_y force, are calculated using the 8 forces exerted on the horizontal force sensors. The positioning of the horizontal force sensors are at $m \times 45$ degrees around the z axis of the reference system of each foot, where m is an integer. Therefore, the absolute values of the horizontal components of the forces of the sensor n are given by

$$F_{n,x} = F_{n,y} = F_n \times \sin\frac{\pi}{4} = F_n \times \frac{\sqrt{2}}{2} \qquad (1)$$

where F_n is the absolute value of the force of sensor n. The anterior-posterior shear force is then calculated by

$$F_x = \left(\sum\nolimits_{i=1}^{4} F_{i,x} - \sum\nolimits_{j=1}^{4} F_{j,x}\right) \times \frac{\sqrt{2}}{2} \qquad (2)$$

where $F_{i,x}$ is the absolute value of the ith anterior sensor of each shoe part and $F_{j,x}$ is the absolute value of the jth posterior sensor of each shoe part. The medial-lateral shear force is calculated by

$$F_y = \left(\sum_{i=1}^{4} F_{i,y} - \sum_{j=1}^{4} F_{j,y}\right) \times \frac{\sqrt{2}}{2} \tag{3}$$

where $F_{i,y}$ is the absolute value of the ith lateral sensor and $F_{j,y}$ is the absolute value of the jth medial sensor.

The values of the vertical sensors are used to calculate the vertical component of the GRF corresponding to the F_z force:

$$F_z = \sum_{i=1}^{8} F_{i,z} \tag{4}$$

where $F_{i,z}$ is the absolute value of the ith vertical sensor.

3 Experiments and Results

The experiments with the instrumented shoes were performed with one 23 years old person, with 76 kg and 1.79 m of height. The experiments consisted in walking at different speeds to acquire the patient's 3D GRF. At the beginning of each experiment the patient had to stand on each feet for a few seconds in order to use the total registered force as the person's weight reference. Then the patient had to walk six times along the corridor starting with a normal speed, then a little faster and then even a faster speed. During the fourth walk the patient should walk at a normal speed again, followed by a slower speed and finally an even slower speed. The experiments were carried out using the shoes without any attachment (friction coefficient of 0.47) and using a 0.25 mm PVC sheet underneath the rubber sole (friction coefficient of 0.27).

In Figs. 9 and 10 it is possible to see the vertical component of the GRF for the five speeds and for the two friction coefficients. All the graphics were normalized for the person's weight. It is noticeable from the graphics that the faster the walking speed was, the higher the first peak corresponding to the contact of the heel on the ground (heel strike). The second peak corresponds to the push-off (toe off). It is also visible that the faster the person walked the shorter is the duration of the step. Comparing the patterns with different friction coefficients, it is possible to see that the vertical component of the GRF is higher for the higher friction coefficient, corresponding to a more confidence walking, as expected.

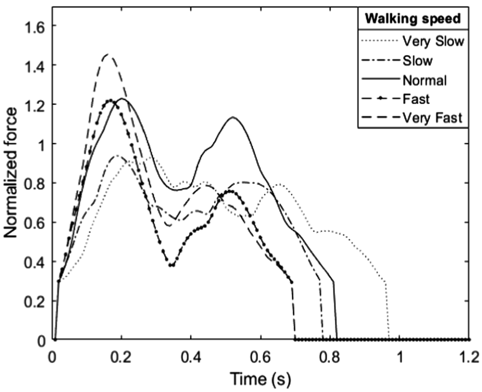


Fig. 9. Vertical component of the GRF with a 0.47 friction coefficient.

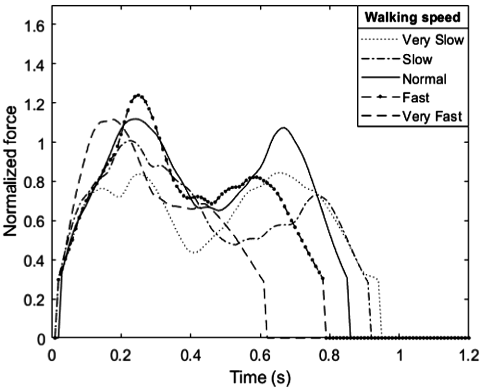


Fig. 10. Vertical component of the GRF with a 0.27 friction coefficient.

In Figs. 11 and 12 are represented the antero-posterior components of the GRF for the two friction coefficients. The amplitude of the forces is about 3 to 4 times smaller than when these forces are measured using horizontal static platforms [7]. This is due to the fact that in the used instrumented shoes, when these antero-posterior forces are higher, the shoe is with its greater inclination to the ground, having its sensors inclined to the horizontal. In other words, these instrumented shoes' sensors coordinate system rotates in the sagittal plane during the gait. These force profiles cannot therefore be compared with the horizontal static platforms results.

In Fig. 11, for the 0.47 friction coefficient, the curve corresponding to the fastest walking speed shows the typical pattern of the antero-posterior component of the GRF, with well-defined heel strike and toe-off forces [7]. As the speed decreases, the amplitude of the antero-posterior component of the GRF also decreases, as expected. At slow speed, the gait is more irregular and the forces absorbed on the heel strike and those created on toe-off are smaller, causing more irregular patterns.

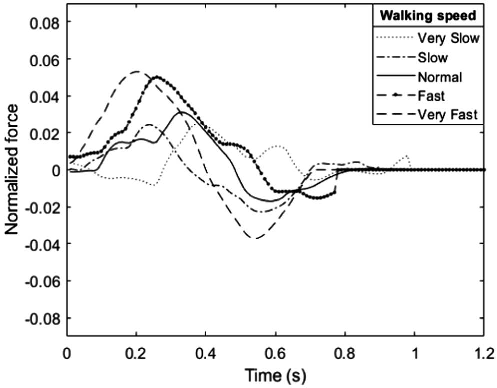


Fig. 11. Antero-posterior component of the GRF with a 0.47 friction coefficient.

In Fig. 12, for the 0.27 friction coefficient, the curves present lower amplitudes and are more irregular than with the 0.47 friction coefficient, showing a lower confidence in the walking. Unlike with the 0.47 friction coefficient, the amplitudes of the antero-posterior components of the GRF are not clearly related with the speed.

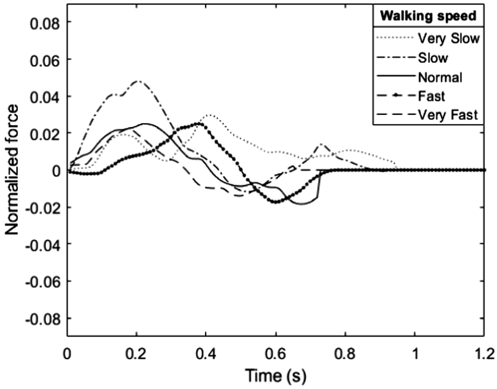


Fig. 12. Antero-posterior component of the GRF with a 0.27 friction coefficient.

The medio-lateral component of the GRF (Figs. 13 and 14) is the most imprecise of all the components because of its low value, about 1–2% of the person weight, similar to the instrumented shoe weight. When the shoe is not fully grounded, the medio-lateral component of the GRF readings suffer from the shoe dynamic forces. These force profiles cannot therefore be compared with horizontal static platforms results. The experiments with the lower friction coefficient, Fig. 14, present lower values of the medio-lateral component of the GRF, as expected.

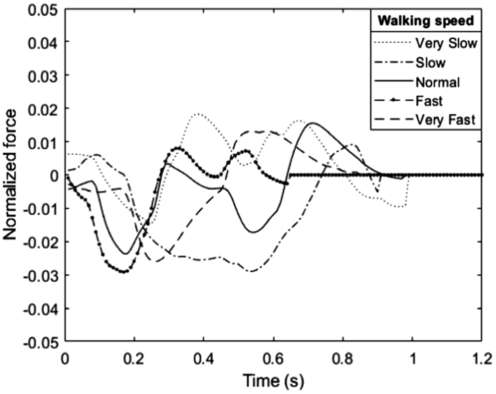


Fig. 13. Medio-lateral component of the GRF with a 0.47 friction coefficient.

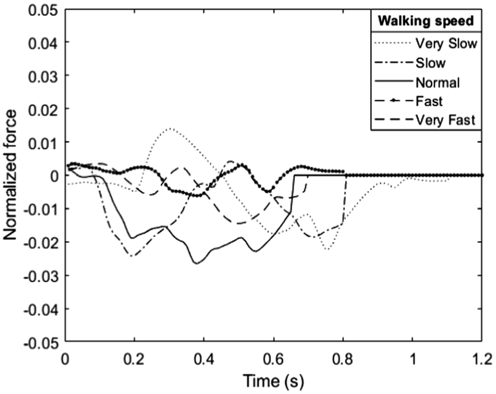


Fig. 14. Medio-lateral component of the GRF with a 0.27 friction coefficient.

4 Conclusions and Future Work

This paper presents an instrumented shoe that measures both medio-lateral and antero-posterior GRF as well as the GRF vertical component. The medio-lateral and antero-posterior GRF are measured in an innovative way by using force sensors placed at 45°.

The measured antero-posterior forces are smaller than when these forces are measured using horizontal static platforms. This is due to the fact that these instrumented shoes' sensors coordinate system rotates in the sagittal plane during the gait. Also, when the shoe is not fully grounded, its weight influences the medio-lateral component of the GRF readings. These force profiles cannot therefore be compared with horizontal static platforms results.

The system can be used in medical areas particularly in diagnosing the degradation of one or more leg joints, by detecting walking disturbances in a patient gait.

In the future, to make a full validation of the prototype and to develop a classification and diagnosis system based on 3D GRF, it is intended to acquire gaits of a large number of people, comparing with results obtained using static force platforms and similar instrumented shoes.

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