Instrumented Insoles with Pressure and Acceleration Sensors

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Abstract. This work presents the development of a portable, wireless activity monitoring system for the estimation of biomechanical gait parameters. The system uses a pair of instrumented insoles able to measure pressure from different points of the foot including four commercial piezoresistive pressure sensors and a three-axis accelerometer, all together integrated in the insole to determine foot forces during stance and swing phases. The system allows to analyse the data with a RF communications to a computer or reading from SD memory card.

Keywords: instrumented insoles; plantar pressure; accelerometer; gait; foot

1 Introduction

A system designed to study the gait motion should be able to monitor major gait events: 1) Heelstrike or initial-contact: the first contact of the foot with the ground happens in the heel; 2) Foot-flat: the whole foot lands on the ground; 3) Mid-Stance or tibia-vertical: at this moment, the entire body weight rests on one foot and the leg is extended in the vertical position; 4) Heel off: the heel takes off; 5) Toe off: the big toe takes off; 6) Mid-swing: the foot moves in the air in the direction of movement during the swing phase or flight, and the mid-swing point happens when the tibia of the other leg is in the vertical position and the inclination of the foot changes sign. The next step begins with a new heelstrike [1]. The stance time, considered as the period of time between the heelstrike and the toe off, is an important parameter to determine asymmetries in gait analysis [2] [3]. Traditionally, this study has been done with plantar pressure, that is, the pressure on the sole of the foot. Clinical gait analysis is one of the main applications. The second application is related to athletic training. Given the rapid development of different sensors for portable applications (small size and low energy consumption), in the last years more complex in-shoe systems have been reported, including additional sensors to the traditional pressure sensors. Indeed, the inclusion of accelerometers in this kind of system provides very useful information on foot movement (force and velocity) between foot-ground contacts. Bamberg et al. [4] included an IMU (Inertial Measurement Unit with an accelerometer, a gyroscope and a magnetometer) in order to obtain the foot orientation during swing phase as well as the heel-strike and toe-off for Parkinson patients.

Based on the above, this report focuses on the development of the initial prototype of a portable, wireless activity-monitoring system for the estimation of temporal gait parameters. Our aim has been to develop a compact and comfortable insole which includes all the sensors, and the analysis of the combined data from all these sensors to obtain more complete information, instead of the usual separate analysis of each kind of sensors. The system uses a pair of instrumented insoles able to record pressure from different points on the foot using four commercial pressure sensors. Unlike other works, the three-axis accelerometer has also been included in the insole (under the foot arc) to determine foot forces. The monitor includes an RF transceiver to enable real-time monitoring by computer using a software application. Similarly, the gait-activity data can be stored by the monitor and uploaded to the computer to analyze the data and generate selected reports.

2 Experimental Section

2.1 Sensors and Electronics

The system consists of two instrumented insoles connected to two data-processing and logging modules (Figure 1). The sensors in the insole are powered and read-out by the respective data logger. One of the data-processing modules acts as master and the other as slave. Therefore, the master sends the measurement start and stop commands to the slave, and the data acquired by the slave are then sent to the master and stored on a microSD memory card. Additionally, the results can be sent to a computer via radio depending on the operation mode. The system can operate in two different modes: in manual mode, in which measurements are started or stopped by a button located on the master module; or in remote mode, where the computer controls the experiment and the results are received and displayed in the real-time application. In both operation modes, the results can be stored on the microSD memory card or uploaded via radio or USB.

The master and slave devices are two identical modules differing only in that the master holds the memory card to store the data and the button to start/stop the measurements in manual mode. For wireless communication, we used the MiWi™ protocol (Microchip, USA), which is a low-cost solution for radio communications at 2.4 GHz with a maximum range of 100 m. The master, the slave, and the computer (only in remote mode) constitute a wireless network configured as Peer-To-Peer (P2P) topology, where the master module plays the role of the coordinator. The instrumented insoles are made of a flexible plastic substrate composed of polyethylene terephthalate (PET), where the sensors are affixed. Each insole has a total of four pressure sensors located at the heads

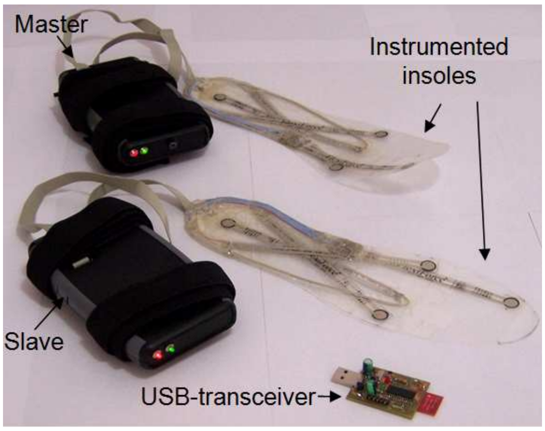


Fig. 1. Measurement System.

of the first and fifth metatarsals, at the big toe, and at the heel, respectively (Figure 1). Four sensors are considered the minimum needed for a basic plantar-pressure study in accordance with previous studies[5]. The sensors at the big toe and heel indicate the start and end of contact during locomotion. The sensors at the first and fifth metatarsals have been added to determine the lateral pressure distribution in the front part of the foot.

We used the Flexiforce® A201 (Tekscan, USA), which is a piezoresistive sensor connected with a planar flexible wire whose sensing area is a circle with a diameter of 9.53 mm registering pressures of up to 1500 kPa. The manufacturer guarantees at least 10^6 impacts, so the instrumented insoles should last for 700 km, considering a minimum step length of about 70 cm. In fact, these insoles have been used for around 100 km in our combined tests, without damage or appreciable aging in any of the eight sensors. Each sensor was individually calibrated in the range of interest (up to 400 kPa for the metatarsal pressure sensors and up to 1000 kPa for the heel and toe sensors) with a press, obtaining a non-linearity and hysteresis total error of less than 5(%). The pressure and conductance of the sensors were fitted to a linear regression, and the coefficients were used to calculate the pressure in our application. As a novelty, a three-axis accelerometer has been included at the arch foot to monitor movement during the foot flight time and the forces generated. Below, we will use the combined information of both kinds of sensors (pressure and acceleration) for the gait analysis with a very low number of sensors. Moreover, the accelerometer reports useful data about the force undergone and applied by the foot. We selected the ADXL330 (Analog Devices, USA) due to its small package, low power consumption, and sensitivity of 330 $^{\mathrm{mV}}/_{\mathrm{g}}$ in its three-axis measurements, where g is the gravity acceleration (9.2 $^{\mathrm{m}}/_{\mathrm{s}^2}$). The rest of the instrumented insole is 1.0 mm thick, allowing to it be included in normal shoes without modifications (Figure 1). As concerns powermanagement electronics, each data-logger module is powered by two AA alkaline batteries.

The master and slave modules were attached just under the right and left knees, respectively instead of at the waist, with the aim of being suitable in certain sports such as hurdling, where they are a significant safety concern. The coordinate axes are the Y-axis the direction of advance, X-axis in the lateral direction and Z-axis in the vertical. Moreover, with the proposed data-logger location, the connection wires are shorter than in waist systems, notably reducing electrical interference sensitivity. The size and weight of this initial prototype are around 14.5x7.5x2 cm and 210 g per data-logger (mainly due to overweighed enclosure boxes). This undesirable drawback can be improved with lighter enclosures, allowing a 50% reduction in weight.

2.2 System Validation and Specifications

We measured the plantar pressure during gait, and compared data with those recorded using the F-scan system (Tekscan Inc., Boston, USA). To measure plantar pressure in equivalent regions of our sensors, we fixed the insoles F-scan (used adhesive tape) to our insoles. Each FlexiForce sensor covered the area between four or six sensing points on the F-scan insoles. The average of the pressure values for all the Fscan sensing points was calculated and compared to the corresponding FlexiForce sensor value. The variations in the plantar pressure were measured simultaneously by our system and the F-scan system for three participants. Typical plantar pressure curves obtained from both devices are shown on the same graph in Figure 2. The solid line is the result of our device and the dashed line is the F-scan result. The differences in peak pressure ranged from -1.8 kPa to 27.9 kPa, where the maximum difference was in big toe sensor. We can observe a very good agreement between both systems with an error below 8.1% pressure. Moreover, from the dynamic point of view, the average delay between the signal from our system and F-scan system was below 30 ms. Therefore, the developed system was confirmed to provide a quantitative estimation of plantar pressure.

The main technical specifications of this initial prototype are summarized in Table 1. In the present stage of system development, the sampling frequency (62 Hz) obtained allowed the system to be used only for walking analysis[6][7].

3 Results and Discussion

First, tests were carried out in order to assess system comfort and usability. In trials, the instrumented insole was placed on top of and under the sports shoes' insole. It was concluded that the instrumented insole must be under the insole of the sports shoes for maximum comfort. It must be taken into account that the pressure recorded under the shoe insole will be lower. Indeed, the measured pressure depends on the absorption of the sole of the shoes. The absorption coefficient of the used shoe insoles was 1.19, calculated as the ratio of the average

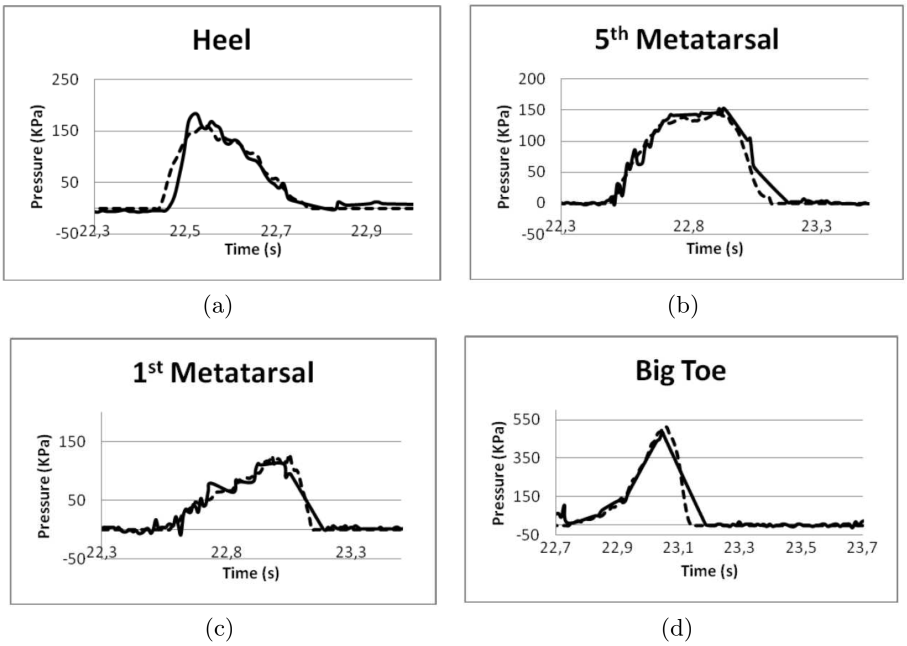


Fig. 2. Pressure patters obtained from our system (solid line) and a F-scan system (dashed line) on the left foot. Heel sensor 2(a) 5th Metatarsal sensor 2(b) 1st Metatarsal sensor 2(c) Big Toe sensor 2(d).

Acceleration linear range (g)	3.6
Acceleration resolution (g)	0.017
Acceleration errors (%)	5
Pressure range (kPa)	1000
Pressure resolution (kPa)	2.5
Pressure error (%)	5
Master/slave weight (with batteries) (grams)	219/213
Master/slave size (cm)	14.5x7.5x2
Insole weight (grams)	32
Thickness of arch insole (mm)	5.6
Thickness of rest of insole (mm)	1.0
Battery time (h)	3
Wireless transmission distance, in open air (m)	60
Sampling frequency (Hz)	62
Recording time in a 2-GB uSD (h)	50

Table 1. Technical specifications of the measurement system.

pressure registered without and with shoe insole. This coefficient was also validated with the commercial system F-scan. Therefore, the pressure values have to be considered as dependent on the shoes used in the study. In addition, it was found that the foot slid less over the shoe insole than directly over the plastic cover of the instrumented insole. The instrumented insole does not significantly disturb locomotion patterns because the thickest area, the board with the accelerometer, is located under the arch of the foot; as a consequence, no modification of the shoes' insoles was required. For the case of participant with low or collapsed arches, the thickness of the shoe insole could be reduced in the arch to increase comfort. Nevertheless, one participant with collapsed arches did not feel any discomfort while using the instrumented insole under the shoe insoles.

Pressure and acceleration were recorded during walking for a total of ten subjects. The participants walked freely on a flat surface without any impositions concerning velocity or other parameters in order to study the participants' natural gait. The characteristics of the participants are summarized in Table 2. By previous biomechanical and medical tests, four of the subjects were diagnosed as walkers who supinate slightly, one pronates, and the rest were considered neutral. In addition, participant 2 has a claw foot and number 9 has collapsed arches. These characteristics are evident in the results, as compared to a normal walker as shown below.

Participant	Sex	Mass (Kg)	Height (m)	Age (years)	Body Mass Index	Foot Type
1	Male	76	1.82	30	22.9	Neutral
2	Male	80	1.81	33	24.4	Supinated, claw feet
3	Male	75	1.78	27	23.7	Supinated
4	Male	94	1.83	35	28.1	Neutral
5	Male	73	1.77	41	23.8	Supinated
6	Male	72	1.71	23	24.6	Neutral
7	Male	73	1.76	18	23.6	Over-Supinated
8	Male	79	1.85	38	23.1	Neutral
9	Female	61	1.60	17	23.8	Supinated, collapsed archs
10	Female	54	1.65	17	19.8	Pronated

Table 2. Participant characteristics.

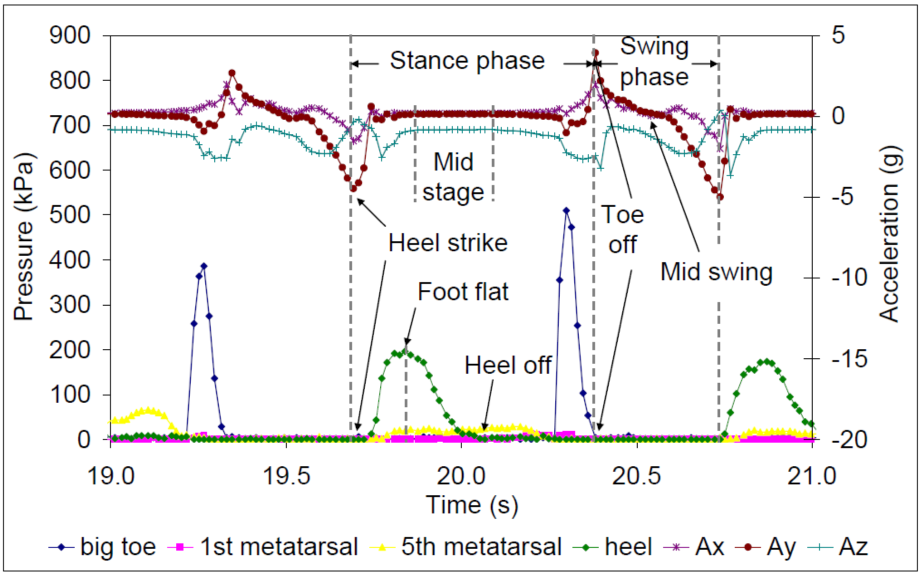
The results from the experiment of participant 1 are plotted in Figure 3(a), where A_X, A_Y, A_Z represent the acceleration components. The major events in gait can be observed. The step starts with the heelstrike, during which acceleration in the direction of movement, A_Y, reduces to its minimum value, and pressure in the centre of the heel starts to increase [2][6][7]. The maximum pressure value in the centre of the heel is recorded during the flat-foot stage, when the foot reaches horizontal and the fifth metatarsal touches the ground. When the foot is totally resting on the ground, the acceleration components are constant, and the inclination of the accelerometer can be zeroed. Then, the mid-stage starts, and pressure decreases in the rear of the foot and increases in the front due to the mass centre movement of the subject. The mid stage phase ends when the foot acceleration changes, as the Figure 3(a) shows. During the mid stage the pressure in the heel drops down to zero; and ends with the heel-off. The acceleration in Z-axis changes due to heel elevation movement, as Figure 3(a) shows. During the heel-off the sensor at the fifth metatarsal reaches a maximum, and after falls to zero when the pressure in the big toe starts to increase. The contact of the foot with the ground, the stance phase, finishes with the big toe take off (toe-off). Finally, the foot advances through the air in the swing phase, or foot flight, until the next heel contact. During the swing phase, the foot inclination changes, and the point where A_Y is equal to zero can be considered the mid-swing.

The set of four pressure sensors could be enough to detect certain anomalous gait parameters. As an example, Figure 3(b) shows the results of participant 2, who presented a slight claw foot. During the heel-off phase, the pressure increases in the first and fifth metatarsal, but when the first metatarsal makes contact with the ground, pressure in the big toe is reduced for a moment, and then increases once again at the end of contact with the ground. In fact, the pressure of the big toe for the participant 2 (Figure 3(b)) shows two maxima of the big toe pressure (at the middle point, the big toe is not in contact with the floor practically) due to the claw foot. However for neutral foot (participant 1) a unique maximum is found for the pressure measured at the big toe (Figure 3(a)). The stance time and swing time per step have been calculated over ten steps after the first ten seconds, and the average and the standard deviations are summarized in Table 3.

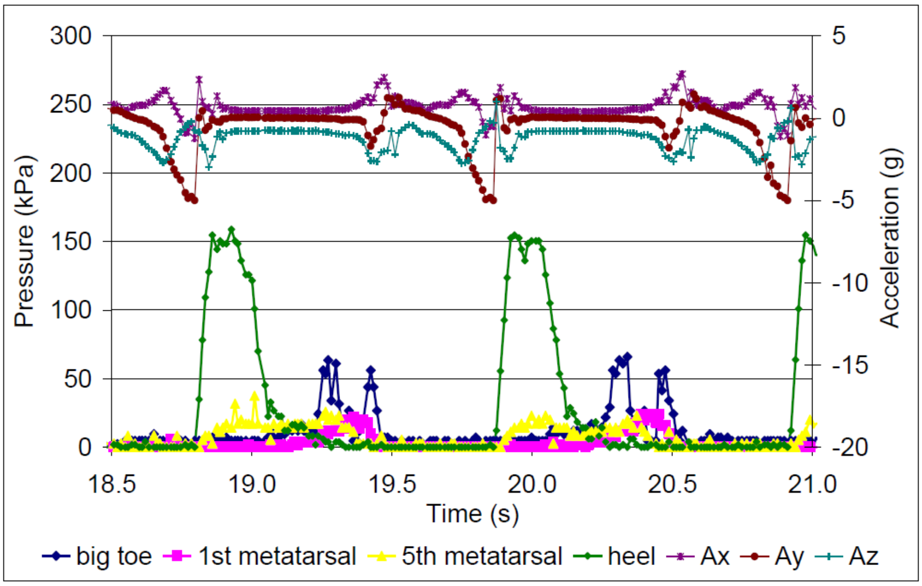
The period of a step is practically equal for the different participants when they walked freely, and the averaged cadence is (0.92 ± 0.05) Hz, very similar for all the subjects. In addition, the ratio between the stance time and the time per step (duty) has been calculated, resulting in around 2/3 for most of the participants walking freely without restrictions which is in agreement with the literature [8]. The mean stance time for the set of participants (global) is (0.727 ± 0.034) s.

	RIGHT FOOT							LEFT FOOT						
	Time per Step(s)		Stance Time(s)		Swing Time(s)		Duty(%)	Time per Step(s)		Stance Time(s)		Swing Time(s)		Duty(%)
	Mean	SD	Mean	SD	Mean	SD		Mean	SD	Mean	SD	Mean	SD	
1	1.030	0.009	0.685	0.017	0.346	0.011	66.4	1.030	0.011	0.675	0.016	0.356	0.015	65.5
2	1.058	0.028	0.712	0.017	0.346	0.022	67.3	1.056	0.023	0.706	0.016	0.350	0.014	66.8
3	1.048	0.027	0.717	0.018	0.331	0.020	68.4	1.050	0.013	0.716	0.016	0.334	0.008	68.2
4	1.097	0.015	0.745	0.014	0.352	0.006	67.9	1.114	0.040	0.716	0.029	0.397	0.025	64.3
5	1.086	0.010	0.712	0.012	0.373	0.014	65.6	1.085	0.022	0.701	0.019	0.385	0.015	64.5
6	1.117	0.017	0.758	0.015	0.359	0.016	67.8	1.112	0.018	0.742	0.008	0.369	0.019	66.8
7	1.023	0.013	0.686	0.014	0.337	0.011	67.1	1.025	0.012	0.679	0.019	0.347	0.014	66.2
8	1.201	0.020	0.791	0.019	0.410	0.017	65.9	1.201	0.030	0.835	0.020	0.366	0.015	69.5
9	1.052	0.016	0.713	0.013	0.339	0.013	67.8	1.053	0.016	0.723	0.011	0.330	0.008	68.7
10	1.113	0.021	0.754	0.012	0.359	0.019	67.7	1.097	0.022	0.710	0.014	0.387	0.013	64.7
Global	1.082	0.053	0.727	0.034	0.355	0.023	67.2	1.082	0.052	0.720	0.045	0.362	0.023	66.5

Table 3. Temporal parameters in gait test for the ten participants.



(a)



(b)

Fig. 3. Right plantar pressure and accelerations during walking: Participant 1 3(a) Participant 2 3(b).

4 Conclusions

The system presented in this work can simultaneously provide the pressure values for the big toe, first and fifth metatarsals, heel and the acceleration components in the three spatial axes including, for the first time, all the sensors in the instrumented insole. The data analysis can be carried out with a software program or with a standard spreadsheet. Moreover, the accelerometer readouts report additional information during swing and stance time in walking tests.

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