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An Insole Device Based on Piezoelectric Sensor to Assess Plantar Pressure during Daily Human Activity

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Abstract: In this work, we reported the development of a novel device, integrated into an insole, to monitor plantar pressure during stand and natural walking. The device consisted of an insole with eight measure points composed of pezoelectric sensors and a wireless data transmission based on Zigbee technology incorporated into a smaller measurement unit. There were three sensors arrayed at each measurement point, and the three sensors were assembled in three different directions (3D) of X, Y and Z. Changes in the plantar pressure during standing and walking were recorded in order to validate the function of the insole device. These results showed that the measurement of plantar pressure based on the piezoelectric sensor is satisfied. The insole device can be used to monitor plantar pressure during daily living and is expected to be useful in various clinical applications. *Copyright* © 2012 IFSA.

Keywords: Insole, Device, Ceramic piezoelectric sensor, Plantar pressure.

1. Introduction

Plantar pressure measurement systems are being used increasingly during gait analyses when investigating the effectiveness of foot wear and orthotic interventions [1, 2]. To date, a number of devices have been developed to measure plantar pressure. However, there are significant variations in the data acquisition systems, such as the type of pressure sensors and the number and arrangement of the sensors used in these devices. A number of existing devices, such as the F-scan system and the Pedar Mobile system, measure plantar pressure via a thin sheet of matrix pressure sensors [3-5].

The F-Scan mobile system (Tekscan Inc., Boston, USA) is one of the most commonly used in-shoe pressure measurement system for gait analysis. Several studies have evaluated the accuracy and reliability of force and pressure measurements using the F-Scan@system and reached different conclusions. While some authors concluded that F-Scan demonstrated good to excellent reliability in measuring plantar pressures, others concluded that the system was not entirely suitable for accurate and repeatable absolute pressure measurements or that the system could be used only in a sample large enough as to allow the detection of the real effect of the treatment. Other studies suggested that errors could be greatly minimized by adequate preparation and use of the system [6-8]. This system utilized relatively low-cost and thin in-shoe sensors which can be easily trimmed to fit the size and shape of a shoe.

While the F-Scan system is less superior in comparison to another commercial product-the Pedar system, its accuracy and precision can be greatly improved by using appropriate pressure for calibration [9-12]. Pedar mobile system is a relatively new product among the in-shoe pressure measuring devices. As clinical decisions and treatment strategies are planned based upon data from these invaluable systems, no more emphasis is needed for utilizing highly dependable equipment. Repeatability is one of the elements which may define such dependability.

These devices have been used in dynamic applications that require high-resolution pressure measurements in specific settings [13, 14]. Although these devices have contributed to the basic analysis of human gait, some limitations have been noted from a therapeutic viewpoint. Usually, the design and usability currently available systems still exists many limitations, like (i) Improper place of device components. The data-recording device is regularly positioned on the subject's hip using a belt with wires running the length of the leg, to connect the foot sensors to the data recording unit [15-17]. The design and usability of can also be a limitation due to the placement of device components. (ii) Having a limited operating time (25min or 6h), which depends on the device's or PC's data memory. (iii) The device cost is relatively expensive [18, 19]. Therefore, the insole device needs design further for daily, simpler, low-cost and real time use in the therapy-directed research.

Hermie et al. have developed an insole device equipped with eight pressure sensors that could be attached and removed from the subjects own shoes. The eight sensors were arranged to cover the entire shoe insole; two sensors were located on each the great toe and the heel, and the remaining four sensors were equally spaced on the insole. Pressure data was recorded at a sampling rate of 50 Hz and stored on a wired desktop personal computer. Thus, use of the device was limited to indoor environments [20].

Wersch et al. developed a device that was equipped with seven conductive polymer pressure sensors. This inexpensive sensor is thin and flexible and does not interfere with natural human gait. The device was portable and had a longer continuous operation time (8 h), and data were stored in a data recorder [21]. However, this device was limited by the size (200 mm×180 mm×70 mm) and mass (800 g) of the data recorder, which needed to be placed in a backpack on the subject.

Authier et al. developed a shoe device equipped with four load sensors that used a wireless data acquisition system to collect force data. The wireless device was capable of continuous data acquisition and recording for 7.5 h [22]. However, a belt around the ankle was still used to connect the foot sensors to the wireless transmitter in order to record data.

Moreover, the measurement of plantar pressure distribution is now possible by commercial platforms or thin insoles integrating matrices of load cells and is used widely for clinical evaluation [23, 24] and biomechanical studies [25, 26]. However, existing pressure insoles for ambulatory measurement of plantar pressure distribution are only sensitive to vertical forces acting on the insole, which can not reflect the plantar pressure distribution completely.

As mentioned above, current plantar pressure measurement systems for daily use have many limitations in terms of usability and features, such as the size, mass and the limited recording time. Therefore, we developed a novel device to overcome current plantar pressure measurement systems' limitations.

Based on these considerations, we used three pressure sensors arrayed by three different directions (3D) as a measurement point to measurement a point plantar pressure under real-life conditions. The device consisted of an insole with twenty-four measure points composed of piezoelectric sensors and a wireless data transmission based on Zigbee technology incorporated into a smaller measurement unit to decrease the size and mass of the device. Compared with previously literature reported devices, this novel device is smaller and lighter (the measurement unit was 10 mm×20 mm×8 mm in size, with a mass of 10 g, excluding the power source), therefore, the pressure sensors can fixed on the shoe insole, the device can be inserted into the subject's own shoes. Thus, the user wears one's own shoe, which is comfortable and does not interfere with the natural gait. Furthermore, various changes in the plantar pressure during standing and walking are recorded in order to validate the function of the insole device, and the device can record the data for more 24 h. These results showed that insole measurement based on the piezoelectric sensor is satisfied. The insole device can be used to monitor plantar pressure during daily living and is expected to be useful in various therapy and clinical applications.

2. Device Design

2.1. Pressure Sensor Select and Design

The piezoelectric effect is found in non-conducting materials (e.g. quartz, ceramics, lead zirconate titanate) and in thin flexible PVDF films (polyvinylidene fluoride). The electronic dipoles in the material react under the influence of an external load with a displacement of charges on a molecular level generating electrical charges at the sensor surface. Therefore, the piezoelectric ceramic sensors have the following strong points: high sensitivity, wide working frequency, high good SNR (signal to noise ratio), low mass, good stability of temperature and so on. Here, we selected the piezoelectric ceramic sensors as plantar pressure sensor for measuring plantar pressure. The detailed parameters were selected as following.

2.1.1. The Span of the Sensor

The span of sensor depended on the subjects' body weight, walking speed and the array position of sensors. In normal case, the plantar pressure of a normal person does not exceed 100 kg at the normal walking speed. Moreover, when the least contact area between plantar and support surface was about 2 cm×1 cm, the plantar pressure was largest. When the sensor's sensitive force area was 0.5 cm×0.5 cm, the sensor was in the largest force area. Thus, the sensor can bear maximum force was calculated by the followed formula:

$$f_{max}=100\text{ kg}/(2\text{ cm}\times 1\text{ cm})\times 0.5\text{ cm}\times 0.5\text{ cm}=12.5\text{ kg}$$

Based on the mentioned above consideration, we used 20 kg as the span of the sensor.

2.1.2. The Linear Characteristic of the Sensor

The relationship of force of sensor and output voltage was linear, which was fitted by method of least squares. The fitted equation was as following:

$$y=b+kx,$$

where y is the output, x is the input, b is the intercept and k is the slope.

The calibration data and the real data of experiments were all substituted in the above equation, and derived the value of k and b , and then method of least squares fitting equation was obtained. Finally, the maximum deviation ($\pm\Delta_{\max}$) between real value and theoretical value was calculated. The nonlinear error was as following:

$$e_f=\pm\Delta_{\max}/V_{fs}\times 100\%,$$

where e_f is the nonlinear error, $\pm\Delta_{\max}$ is the maximum deviation and V_{fs} is the output voltage of scale span. The test results showed that the nonlinear error of the sensor was less than 0.8 %.

2.1.1 2.1.3. The Sensitivity of the Sensor

The sensitivity of the sensor was the ratio between small incremental of output and input. If the ratio value is more large, the sensitivity of the sensor is more higher. Here, we selected sine comparison standards method to make sure the sensitivity of the sensor. The calculated formula as following:

$$K=V_2/V_1\times k_I,$$

where k is the voltage sensitivity of calibrated sensor, k_I is the system voltage sensitivity of standard sensor's charge amplifier, V_I is the system output voltage of standard sensor's charge amplifier, and V_2 is the output voltage of calibrated sensor. We detected the sensor's sensitivity by this method, it was 0.11V/N. The results showed that the sensor had a good sensitivity and stability.

2.2 2.2. Pressure Sensor's Layout in an Insole

Feet, as the body's base of support, often endure ground reaction forces during daily activities. Fig. 1. Anatomical structure of foot: HL, heel lateral (1, 3); HM, heel medial (2); M5, metatarsal 5 (4); M4, metatarsal 4 (5); M3, metatarsal 3 (6); M2, metatarsal 2 (7); M1, metatarsal 1 (8); The purpose of assessing peak plantar pressures during dynamic gait was to quantify the highest pressures applied to each region of the plantar surface of the subject's feet as they occur at any point during foot contact in typical activities of daily living. The entire sensors are inserted into two insoles equally. Each insole has 8 measurement points, its distribution was shown in Fig. 1.

As shown in Fig. 2, there are 3 sensors that are placed onto each specified measurement points specified as the anatomy zone. Therefore, we selected piezoelectric ceramic sensors to measure plantar pressure, and assembled them in three different directions (3D) of X, Y and Z at our laboratory and inserted into insoles. Fig. 3 was the actual piezoelectric ceramic sensors distribution inserted into an insole.

2.3. The Insole Device

Fig. 3 showed the external view the insole device, and the location of eight measurement points. Each measurement consisted of three piezoelectric ceramic sensors assembled in three different directions (3D) of X, Y and Z.



Fig. 1. Measurement points distribution on foot according anatomical structure of foot: HL, heel lateral (1, 3); HM, heel medial (2); M5, metatarsal 5 (4); M4, metatarsal 4 (5); M3, metatarsal 3 (6); M2, metatarsal 2 (7); M1, metatarsal 1 (8).

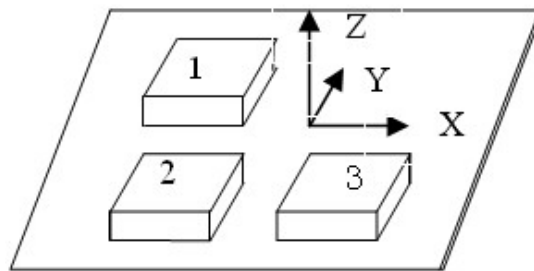


Fig. 2. Each measurement point assembled three sensors distribution in three different directions (3D) of X, Y and Z. (1, 2 and 3 represented three piezoelectric ceramic sensors in a measurement point, respectively).



Fig. 3. The picture of actual piezoelectric ceramic sensors distribution inserted into an insole, among them, red points are measurement points and grey points are piezoelectric ceramic sensors distribution place.

The eight measurement points were placed based on gait kinetics as well as normal and pathological foot anatomy. The insole device also included a wireless transmission unit (2.4 GHz), a pressure measurement unit, and a power source. The measurement unit was 10 mm×20 mm×8 mm in size, with a mass of 10 g, excluding the power source. The power source had a life of approximately 24 h during continuous operation. Pressure values from each sensor were digitized by a 12-bit analogue-digital converter at a sampling frequency of 20 Hz and transmitted to a mobile personal computer. The maximum transmission distance was approximately 100 m. Several devices were fabricated to fit a variety of shoes sizes (18 cm, 22 cm, 23 cm, 24 cm, and 25 cm).

3. Materials and Methods

3.1. Subjects

Three healthy young subjects (male, 20 years old, body weight: 65 kg) participated in this experiment. All subjects participated in plantar measurement after providing informed consent for the experimental procedures.

3.2. Experimental Protocol

Each subject wore the device and performed stand and straight walking trial at a comfortable speed for 10 m. The plantar pressure during stand and straight walking were measured continuously. The pressure data during transitional gait (i.e., the first 4 steps and the last 4 steps) were excluded from analysis, so only data obtained during steady gait were analyzed during straight walking.

4. Results and Discussion

Table 1 and Table 2 were the plantar pressure measurement data about right foot and left foot during the subjects were standing posture, the results showed that the forefoot fifth and third metatarsal head region of pressure were the maximum pressure between 109.87 and 143.22 kPa. While walking, the second metatarsal head region had the maximum pressure between 402.21 and 465.03 kPa (Table 3 and Table 4). The measurement data were conducted in accordance with the previous literature reported conclusions [22-23]. The results also showed that the proposed plantar pressure measurement system based on the piezoelectric sensor can satisfy the actual plantar pressure measurement during daily human activity.

Table 1. Right foot plantar pressure measurement data during the subjects were standing posture.

Channel number	101	102	103	104	105	106	107	108
Plantar pressure (kPa)	10.06	5.95	4.20	3.39	2.56	50.03	33.35	87.30
Channel number	109	110	111	112	113	114	115	
Plantar pressure (kPa)	66.70	54.93	109.87	128.51	122.62	108.89	143.22	

Table 2. Left foot plantar pressure measurement data during the subjects were standing posture.

Channel number	201	202	203	204	205	206	207	208
Plantar pressure (kPa)	10.07	5.22	4.20	3.36	2.56	50.02	33.34	87.30
Channel number	209	210	211	212	213	214	215	
Plantar pressure (kPa)	66.71	54.93	109.87	128.51	122.62	108.89	143.22	

Table 3. Left foot plantar pressure measurement data during the subjects were walking.

Channel number	101	102	103	104	105	106	107	108
Plantar pressure (kPa)	463.03	304.11	206.01	99.08	96.13	336.48	351.19	314.90
Channel number	109	110	111	112	113	114	115	
Plantar pressure (kPa)	233.47	152.05	117.72	186.39	399.26	393.38	402.21	

Table 4. Right foot plantar pressure measurement data during the subjects were walking.

Channel number	201	202	203	204	205	206	207	208
Plantar pressure (kPa)	465.03	314.11	207.98	100.07	96.58	339.44	357.14	304.97
Channel number	209	210	211	212	213	214	215	
Plantar pressure (kPa)	234.97	154.40	118.99	185.96	403.62	397.81	405.64	

3. Conclusion

In the present study, we developed a prototype insole device to monitor plantar pressure during stand and natural walking. At each measurement point, we used three assembled sensors to construct three different directions (3D) pressure sensors array to monitor plantar pressure. The device consisted of an insole with twenty-four measure points composed of piezoelectric sensors and a wireless data transmission based on Zigbee technology incorporated into a smaller measurement unit to decrease the size and mass of the device. Various changes in the plantar pressure during standing and walking were recorded in order to validate the function of the insole device. These results showed that insole measurement based on the piezoelectric sensor is satisfied. The device was designed to be user-friendly and to record natural stand and walking plantar pressure easily and safely. We found no technical failures of the device during the plantar pressure tests, and it functioned as intended in all subjects. The wireless transmission worked reliably when tested indoor as well as outdoor. Furthermore, the device could be inserted into the subject's own shoes to monitor gait. The insole device can be used to monitor plantar pressure during daily living and is expected to be useful in various clinical applications.

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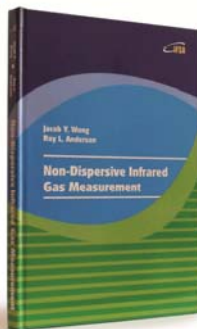
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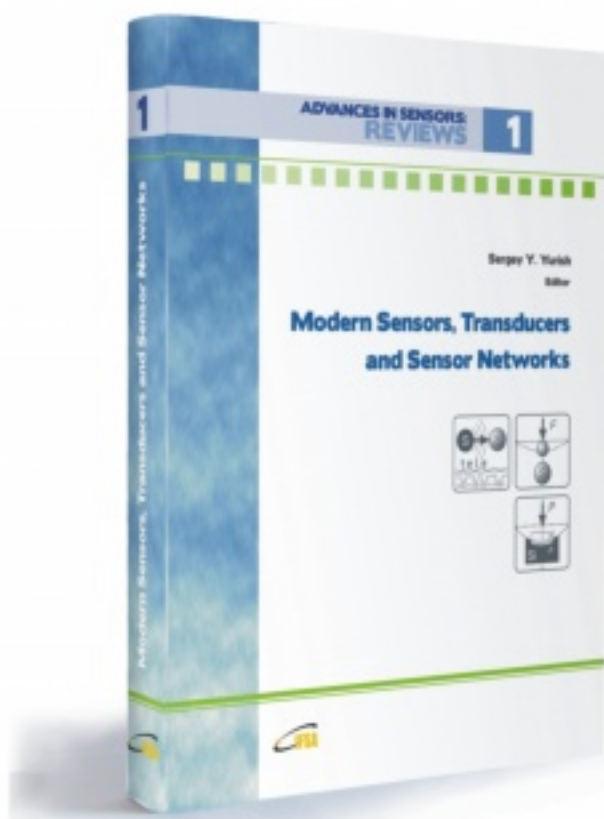
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