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An Insole Plantar Pressure Measurement System Based on 3D Forces Piezoelectric Sensor

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Abstract: In this paper, an insole plantar pressure device based on 3-D forces piezoelectric sensor, integrated into a shoe, was developed for monitoring plantar pressure under real-life conditions. The device consisted of an insole with eight measure points composed of piezoelectric sensor, a wireless data transmission and embedded computer. The piezoelectric sensor with ceramic was embedded into the insole assembled by three different directions (3D) of X, Y and Z. The piezoelectric sensors mathematical model was built, and the layout of these sensors in insole was investigated. Based on the FFT algorithm, the eight measurement points data were collected and analyzed taken by frequency. The plantar changes of the left and right foot in 3D direction were measured, respectively. The results were displayed on the software interface, it showed that the insole system 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, Plantar pressure, Force piezoelectric sensor, Pressure measurement system.

1. Instruction

Insole pressure measurement systems have been widely used in clinical and research environments. Many studies have focused on plantar pressure measurements in healthy and hemiparetic adults or in healthy children, which can provide data that will optimize patient assessments and evaluate the treatment outcomes [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 the pressure measurement systems. Pressure measurement systems are commonly found in two different formats: an insole based or a platform based assessment system. An insole based pressure measurement systems compared with a platform based assessment system have some advantages, such as simple, convenience, real-time and so on. Therefore, they become good way and alternatives to evaluate plantar pressure real-time.

The F-Scan mobile system (Tekscan, Inc., Boston, USA) is one of the most commonly used in-sole 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 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 [12]. Pedar mobile system is a relatively new product among the insole pressure measuring devices. Although these devices have contributed to the basic analysis of human gait, some limitations have been noted from a therapeutic viewpiont. In particular, they are not designed for daily, real-time, and feedback use in therapy-directed research.

For piezoelectric sensors ceramic materials are used. The piezoelectric effect is found in non-conducting materials (e.g. quartz, ceramics, lead zirconate titanate) and in thin flexible PVDF films (polyviny lidenefluoride). 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. Charge amplifiers can be used to convert these charges to voltages. Kärki et al., have developed a new piezoelectric sensor prototype for plantar pressure measurements during gait. The mechanical stress at the plantar surface has two components, pressure acting normal to the surface and shear stress acting tangential to the surface [26]. Gross et al., have designed a system suitable for non-invasive measurement of discrete in-shoe vertical plantar stress during dynamic activities. In the system, eight transducers were constructed, with small piezoelectric ceramic squares (4.83 × 4.83 × 1.3 mm) used to generate a charge output proportional to vertical plantar stress [27].

Piezoelectric sensors (with the exception of PVDF) are highly elastic, show little material deformation and exhibit low hysteresis effects. Therefore, they are suitable for recording of high-frequency loading events. On the other hand PVDF and most piezoceramic materials are temperature sensitive so that the environmental conditions should be controlled and kept as constant as possible.

In this study, we developed an insole plantar measurement system. The piezoelectric sensors were distributed according to human anatomy characteristic. There were 8 measurement points in the insole. Each measurement point had three sensors assembled in 3D directions. Compared with previously literature reported plantar pressure measurement device, this insole 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 be fixed into 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. The piezoelectric sensors mathematical model was built, and the layout of these sensors in insole was investigated. Based on the FFT algorithm, the eight measurement points data were collected and analyzed taken by frequency. The plantar changes of the left and right foot in 3D direction were measured, respectively. The results showed that this insole plantar pressure measurement system can be used to monitor plantar pressure during daily living.

2. Device Design

2.1. Piezoelectric Sensors Mathematical Model

As shown in Fig. 1, pressure sensor can be viewed as a mechanical system, and it is a quality-spring-damper system, belonging to the second sensor.

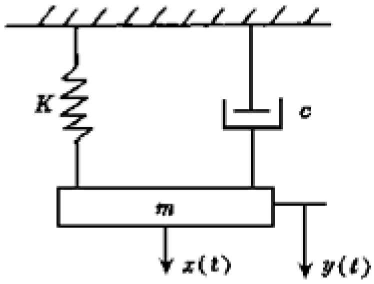

Fig. 1. Piezoelectric sensors mathematical model

Its differential equation is:

$$m\frac{d^2y(t)}{dt^2}+c\frac{dy(t)}{dt}+ky(t)=kx(t) \quad (1)$$

It can be rewritten as:

$$\frac{d^2y(t)}{dt^2}+2\xi\omega_n\frac{dy(t)}{dt}+\omega_n^2y(t)=\omega_n^2x(t), \quad (2)$$

where m is the portion of its mass during system movement, c is the damping coefficient of this system, k is the stiffness of the spring, ω_n is the natural frequency of this system, and here, $\omega_n=\sqrt{k/m}$. ζ is the damping ratio of this system.

Equation 1 can be expressed with the second of differential equation, which is following:

$$(a_2D^2+a_1D+a_0)\ y=b_0x \quad (3)$$

It can be rewritten as:

$$(\frac{1}{\omega_n^2}D^2+\frac{2\xi}{\omega_n^2}D+1)\ y=kx, \quad (4)$$

where k=b0/a0 is the static sensitivity; $\omega_n=\sqrt{a_0/a_2}$ is the undamped natural frequency: $\zeta=a_1/2\sqrt{a_0a_2}$ is the damping ratio, D is differential operator. a_1, a_2, a_0, b_0 are the system constant, usually, we take $a_0=b_0=1$.

Therefore, the transfer function of the second system is following:

$$H(s)=\frac{1}{\frac{a_2}{a_0}s^2+\frac{a_1}{a_0}s+1}, \quad (5)$$

Let $a_0/a_2 = \omega_n^2$, $a_1/a_0 = 2\zeta/\omega_n$

Therefore, the transfer function changed into:

$$H(s) = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} \quad (6)$$

where $\omega_n = \sqrt{\frac{k}{m}}$ and $\zeta = \frac{C}{2\sqrt{mk}}$ are viewed as two major parameters in the piezoelectric sensor.

The frequency response function of frequency characteristics of the second order system is following:

$$H(j\omega) = \frac{1}{1 - (\frac{\omega}{\omega_n})^2 + j2\zeta(\frac{\omega}{\omega_n})}, \quad (7)$$

Amplitude frequency characteristic is the following:

$$A(\omega) = \frac{1}{\sqrt{[1 - (\frac{\omega}{\omega_n})^2]^2 + [2\zeta(\frac{\omega}{\omega_n})]^2}}, \quad (8)$$

Phase frequency characteristic is the following:

$$\Phi(\omega) = arctg\frac{2\zeta(\frac{\omega}{\omega_n})}{1 - (\frac{\omega}{\omega_n})^2}, \quad (9)$$

As above mentioned, after the known transfer function, we can easily find out the characteristics of the system parameters ω_n and ζ, the frequency response function, the amplitude frequency and phase frequency characteristics can be gained. Therefore, we can analyze the difference between output and input to reduce the dynamic error. Therefore, we can select the suitable vale of ζ and $\frac{\omega}{\omega_n} \supsetneq$ to ascertain the scope of frequency.

Usually, $\zeta \leq 0.04$, $\frac{\omega}{\omega_n}$ is in the flat section of the amplitude frequency curve.

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. As shown in Fig. 2, 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. 2.

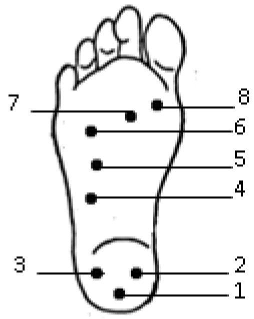

Fig. 2. Measurement points distribution on foot according to anatomical structure of foot: HL, heel lateral (1,3); HM, heel medial (2); M5, metatarsal 5 (4); M4 metatarsal 4 (5); M3, metatarsal 3 (6); M2, metatarsal 2 (7); M1, metatarsal 1 (8).

2.3. Eight Measurement Points Data Collection

Based on the FFT algorithm, the eight measurement points data were collected and analyzed taken by frequency. The FFT algorithm was shown in Fig. 3.

The 8 measurement points data were shown on the software interface (Fig. 4). The user can observe each measurement point onsite by the software interface.

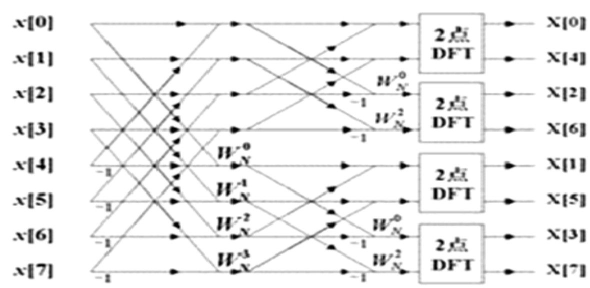

Fig. 3. Eight measurement points data collection based on the FFT algorithm.

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 experimental procedures.

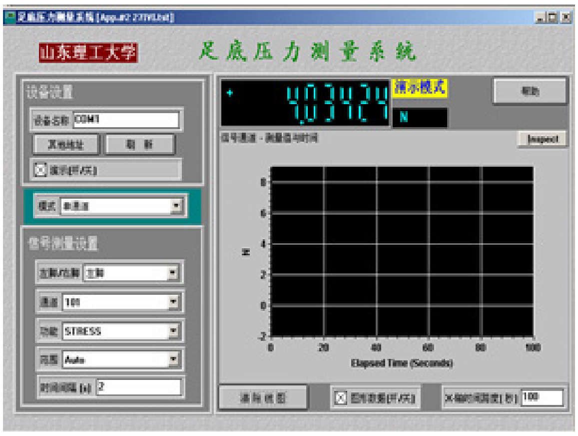

Fig. 4. The software interface of the plantar pressure measurement system.

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

Based on the FFT algorithm, the eight measurement points data were collected and analyzed taken by frequency. Table 1 and Table 2 were the plantar measurement data about right foot and left foot during the subjects were standing posture, the results showed that the pressure of Z direction were the maximum and the pressure of X direction were the minimum at left and right foot plantar pressure same measurement point, The forefoot fifth and third metatarsal head region of pressure were the maximum pressure. 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 3D piezoelectric sensor can satisfy the actual plantar pressure measurement during daily human activity.

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

Direction	1	2	3	4	5	6	7	8
X	1.98	1.80	1.84	0.42	0.20	1.47	1.47	2.15
Y	8.71	6.88	7.14	1.24	1.02	10.25	10.23	12.34
Z	40.56	36.45	30.25	8.82	6.75	70.48	68.42	76.32

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

Direction	1	2	3	4	5	6	7	8
X	9.76	10.21	19.45	0.03	0.01	4.63	5.69	8.92
Y	6.52	8.20	7.31	0.27	0.19	10.47	10.55	11.21
Z	83.17	82.21	78.15	6.54	4.98	10.29	9.97	76.32

5. Conclusion

In the present study, we developed an insole plantar pressure device based on 3-D forces piezoelectric sensor, integrated into a shoe for monitoring plantar pressure under real-life conditions. The device consisted of an insole with eight measure points composed of piezoelectric sensor, a wireless data transmission and embedded computer. The piezoelectric sensors were distributed according to human anatomy characteristic. There were 8 measurement points in the insole. Each measurement point had three sensors assembled in 3D directions. Because pressure sensors are fixed into 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. The insole device is small and light (the measurement unit was 10 mm×20 mm×8 mm in size, with a mass of 10 g, excluding the power source). The piezoelectric sensors mathematical model was built. Based on the FFT algorithm, the eight measurement points data were collected and analyzed taken by frequency. The plantar changes of the left and right foot in 3D direction were measured, respectively. The results showed that the insole system can be used to monitor plantar pressure during daily living and is expected to be useful in various clinical applications.

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