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Research Article

Design of Wireless Device for The Measurement of Plantar Pressure and Study of Its Effect Based on Gender and Body-Weight

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Abstract

Foot plantar pressure is the pressure field that acts between the plantar region of the foot and the supporting ground. The pressure exerted on the various region of the foot was studied using discrete pressure sensors. Information obtained from these sensors are useful for diagnosing and prognosis of various problems associated with the lower limb such as diabetic foot ulceration, footwear design and sports biomechanics. We also studied the plantar pressure distribution between male and female, which will further help in designing a gender-specific foot wear. We studied a variation in pressure distribution based on body weight and gender. The plantar pressure obtained between male and female subjects (aged between 18-25, mean weight for males 63kg and females 52kg) illustrated the significant pressure variation. Males experience higher pressure on hallux and 1st metatarsal than females while the variation is not significant in rear-foot. The device showed variation in the pressure distribution along the foot when compared among males and females with the same body weight. The pressure increases linearly with an increase in body weight and vice versa. The average pressure experienced by people of weight group 45-50kg, 50-55kg, 55-60kg, 60-65kg, 65-70kg and 70-75kg were 313Kpa, 367Kpa, 374Kpa, 397Kpa, 405Kpa, and 448Kpa respectively. The result supported the fact from the literature that females exhibit more pressure in the Heel and males in the Hallux region of the foot. Furthermore, the result suggested linear relation between body weight and plantar pressure. We expect to study the pressure distribution in the foot of diabetic patient in the future study.

Keywords: Foot plantar pressure; Force-sensitive resistor; Gait analysis; Wireless system

Abbreviations: FSR: Force Sensitive Resistor; WHO: World Health Organization; IDE: Integrated Development Environment; PWM: Pulse Width Modulation; UART: Universal Asynchronous Receiver Transmitter; USB: Universal Serial Bus; ICSP: In Circuit Serial Programming; MHz: Megahertz; Tx: Transmitter; Rx: Receiver; CSV: Comma Separated Value

Background

Foot is an essential biomechanical structure which subtly provides support and stability to the entire body [1]. Foot plantar pressure is the pressure field that acts between the plantar region of the foot and the supporting ground. The study of plantar pressure provides adequate information about the forces acting on various regions of the foot. It helps the physicians to diagnose various foot-related conditions and is useful in footwear designing [2]. Plantar pressure mostly depends on the factors such as gender, age, body weight, and walking speed [3-6]. Abnormal and excess pressure on the plantar region of the foot can lead to foot ulceration and neuropathy especially in type II diabetes patients. Micro-vascular complications and neuropathy due to prolonged period of high blood glucose level causes increase in pressure load and shearing forces, which increases the risk of foot ulceration in diabetic patients [1]. According to WHO, in the year 2011 about

300 million people were suffering from diabetic foot neuropathy and foot-related ulceration, which is predicted to rise to 438 million by 2030 [7].

Significant amount of studies have been carried out to study the plantar pressure. Lavary et. al. designed a footwear system for athletes [8]. Praet, et al. designed the shoes with sensors that measured the neuropathic foot pressure and concluded that the use of rocker shoes could reduce the pressure [9]. Queen et al. found that the plantar pressure varies in males and females, and also proposed a gender-specific shoe design to prevent metatarsal stress and ultimately fracture [10]. There are two kinds of system for the plantar pressure measurement: 'platform based system' and 'in-shoe type system'. The Platform-based system consists of a matrix-based sensor placed on a floor for a patient to walk in such that the data will get transferred and recorded on a computer. This system helps doctor to measure patient overall area of the foot, however are limited within a room, require a large area and numerous sensors are required.

To overcome the disadvantages of platform based system, a portable system were introduced which included only few sensors within the sole of the shoes, they are also called 'in-shoe type system'. Shu et al classified foot into 15 regions and used 15 sensors over that region to measure the plantar pressure [11]. Later, Claverie et al. simplified the pressure points to nine regions and used nine sensors for the study of plantar pressure [12]. Based on the above mentioned information, we used pedobarography and characterized pressure regions to six points namely hallux, 1st metatarsal head, 5thmetatarsal head,midfoot lateral, midfoot medial and heel. In comparison with the other studies, we have minimized the number of sensors and used different kind of sensors with unique placement and have observed the results accordingly. There are different types of sensors used in various studies performed so far, namely piezoelectric (ParoTec, Flexiforce), capacitive (Pedarin-shoe systems) and resistive (F-Scanin-shoe systems). However, there is a large variation in the way the data is collected and the way they are analyzed according to different studies.

Qualitative and quantitative evaluation of plantar pressure is limited due to the technological constraint. Plantar pressure analyzing system is mostly available only in sophisticated hospitals, while in rural areas such analysis is carried out by visual observation, which is relatively less efficient and accurate in determining any deviation in plantar pressure and gait. Therefore, we have proposed a portable and relatively accurate plantar pressure measuring device in order to make difference in the prognosis and diagnosis of various foot plantar related problems.

Results

Data collected from various subjects were classified based on bodyweight and gender. Figure 1 shows the change in pressure with an increase in body weight. It was found that the pressure increases linearly with an increase in body weight and vice versa. Body weight categories were made based on a group of 45-50 kg, 50-55kg and so on to 70-75kg, and each group had 5 person of the respective weight category. The average pressure exerted on each sensor was plotted. There was a linear increase in pressure in hallux, 1st metatarsal, and midfoot lateral while the pressure variation on other regions of the foot were not significant. The average pressure experienced by people of weight group 45-50kg, 50-55kg, 55-60kg, 60-65kg, 65-70kg and 70-75kg were 313Kpa, 367Kpa, 374Kpa, 397Kpa, 405Kpa, and 448Kpa respectively (Figure 1). The pressure distribution along the various parts of the foot among males (mean weight 63kg) and females (mean weight 52kg). Males experience higher pressure on hallux and 1st metatarsal than females while the variation is not significant in rear-foot (Figure 2). On analyzing the results between both genders of similar weight which is from 55 to 60 kg, the result showed that males experience higher plantar pressure in the forefoot as compared to females, while the pressure variation in mid-foot and heel region is relatively similar irrespective of gender (Figure 3).

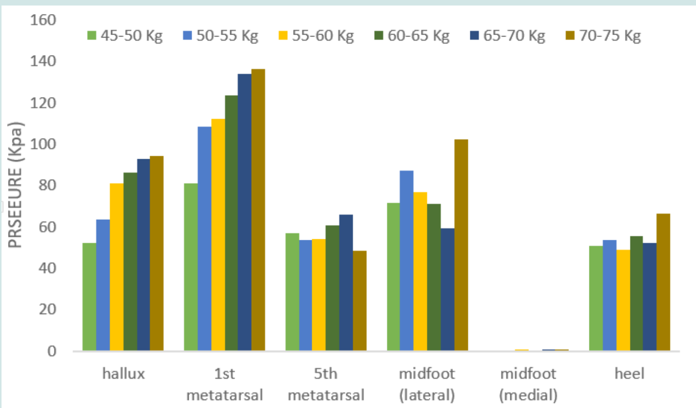

Figure 1: Pressure Variation according to body weight.

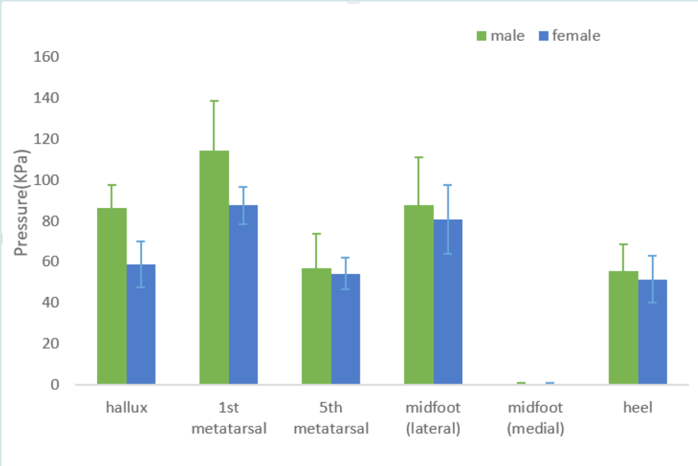

Figure 2: Pressure Variation according to gender.

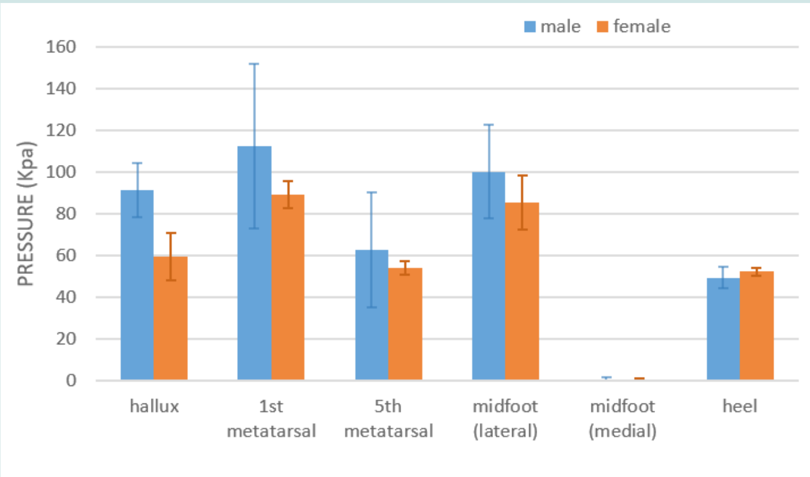

Figure 3: Plantar Pressure Variation of males and females of body weight between 55 to 60 kg.

Discussion

A study on 16 males and 16 females suggested males experience higher plantar pressure on hallux and 1st metatarsal than females, which could be because of the greater weight and walking speed of males [13,14]. The increase in walking speed in male led to higher impact force on the forefoot leading to higher pressure. The t-test among the data acquired from males and females subject resulted $p<0.0001$ and $t=5.17$, which depicts the data are significantly different. The linear increase in pressure with increase in body weight was observed. This increase in pressure with bodyweight is due to a higher load in the foot [15]. Analyzing the plantar pressure distribution in males and females with similar bodyweight, the result showed that males experienced higher pressure in the forefoot as compared to the females. This result supported the fact from the literature that males tend to have higher pressure due to higher contact areas, impact force and force-time integral on 1st metatarsal head, hallux and 3rd metatarsal head [14]. The pressure in the metatarsal head in males is significantly higher due to their shift in the center of pressure towards the forefoot and is the reason for higher chances of foot injuries in males [16].

Conclusion

Many people experience uneven foot and plantar pressure distribution. This can cause problems like ulceration (diabetic patient), neuromuscular disease, sprain, and even gait abnormalities [17]. Uneven foot plantar pressure distribution, if not diagnosed earlier can cause ulceration which can also lead to amputation [15]. Also, uneven foot plantar pressure distribution causes gait abnormalities which directly impact the performance [11].

The result obtained on 16 males and 16 females revealed that males experienced higher plantar pressure than in females. The next study performed based on body weight of 30 subjects demonstrated the 'linear relation' between bodyweight and plantar pressure. With its promising scope in sports, medical and footwear-designing field, this in-shoe system can be used in various industries. This kind of non-invasive system can be used for the diagnosis of foot neuropathy and identification of foot type and abnormal gait upon receiving a clearance.

Methods

The overall system was developed in two stages. The first step included design and development of the circuit. The circuit was a simple voltage divider network with FSR and a 10kΩ resistor in series for the transmitter system. An input voltage of 5v was supplied to this voltage divider network and then the voltage drop across the FSR was amplified and fed into the input pin of an Arduino. Twelve FSR connected in twelve individual voltage divider were connected to 12 analog input pins of an Arduino respectively from A0 to A11. The reading from the Arduino was then transmitted to the receiver system via Bluetooth module, HC-05. While on the receiver end the circuit was simply an Arduino connected to a Bluetooth module and a data processing unit (a laptop or desktop).

In the second phase, software was deployed to receive the data from FSR, record, analyze and display. In Arduino IDE, the code was written to acquire data from the sensors and to transmit it via Bluetooth. Similarly, a code to receive the data was uploaded to the Arduino on the receiver end. Once the data were received, the analysis and data presentation to the user was completed using another platform, Processing IDE. Data from Arduino were linked to Processing IDE and then were displayed in graphical and numerical formats. In the meantime, numeric data obtained were stored in a notepad (as .CSV format) and was finally analyzed using excel and graph-pad prism.

Hardware

Force Sensitive Resistors (FSR)

Force-sensitive resistor (FSR) sensors are piezo-resistive sensors, a resistor that changes its value depending on how much force is applied. Its electrical resistance decreases with an increase in load weight or pressure. They are low in cost and convenient to use. FSR are placed underneath the sole to assess the pressure distribution. When the sensor is pressed or the force is applied, the electrodes and piezoelectric elements are compressed causing the change in the output resistance or voltage (Figure 4).

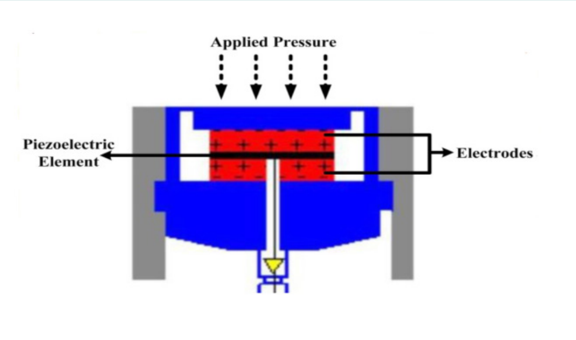

Figure 4: Illustration of working of the piezo-resistive sensor.

Arduino Mega (ATMEGA 2560)

The Arduino Mega is a microcontroller board based on the ATMEGA1280. It has 54 digital input/output pins (of which 14 can be used as PWM outputs), 16 analog inputs, 4 UARTs (hardware serial ports), a 16 MHz crystal oscillator, a USB connection, a power jack, an ICSP header, and a reset button. Arduino Mega allows 16 analog inputs which are ideal for reading data from 12 FSR placed on the sole of two feet.

Bluetooth Module (HC-05)

The HC-05 is a module that can add two-way (full-duplex) wireless functionality. The use of HC-05 in this system enables the wireless transmission of the data from the test subject to the base workstation. This will allow the data collection and analysis of gait parameters without any disturbance to the subject while walking around during the test. Hardware have been selected in a way they produce the accurate data without any interference to the subjects' normal activity. The thin filmed FSR cannot be felt even if they are placed on the sole and ATMEGA 2560 can accommodate all the sensors, with 16 input pins and is readily available and portable.

Software

Two software were used for data collection, interpretation and output visualization. They are:

a) Arduino IDE - a programming platform

b) Processing IDE

The Arduino IDE provides a user interface to write the code and upload it to Arduino hardware. Processing IDE is a graphical library for electronic and visual designing. The Processing IDE allows easy communication with Arduino IDE for data transfer from Arduino and process it for visualization. After the data acquisition from Arduino the graphical and animated visual output can be produced.

Block Diagram

ATMEGA 2560 at the transmitter end receives the data from the sensors placed on the sole. These data are transmitted to the base station, via Bluetooth (Figure 5). At the base station these data are collected by ATMEGA2560 through Bluetooth. Data are processed and visualized in Processing IDE either on a laptop or in the mobile application (Figures 6 & 7). The user friendly interface of processing allowed the users to visualize the pressure points easily and identify the region of highest pressure. This 'processing' platform helped in better visualization of data from the sensors, both in numeric and graphical forms, which have an add-on benefit to analyze the data in real-time through graphs and in future via numeric recorded values.

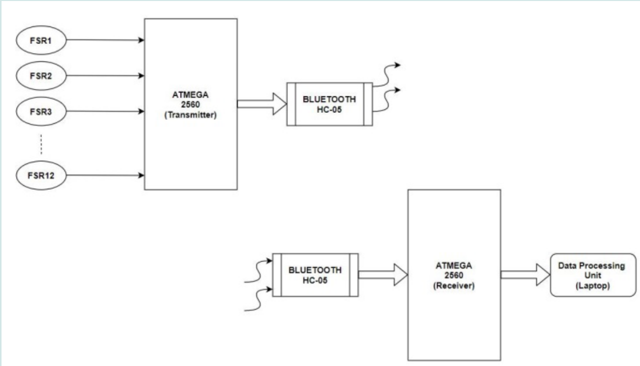

Figure 5: Overall Block Diagram of the system.

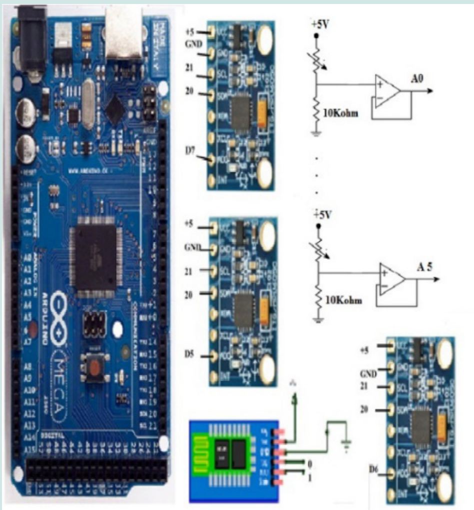

Figure 6: Circuit Diagram of the system (Transmitter side).

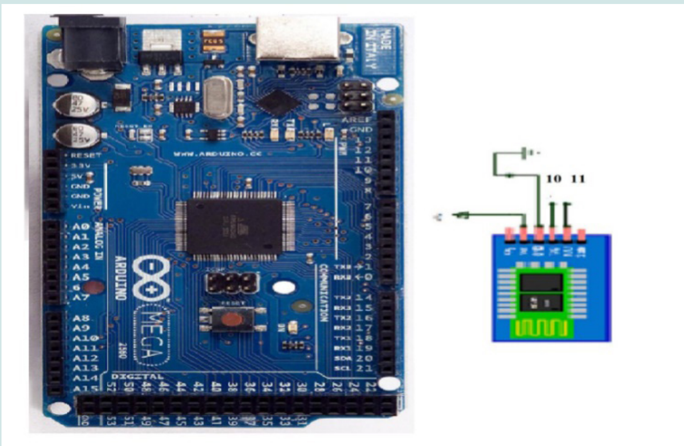

Figure 7: Circuit Diagram of the system (Receiver side).

Figure 8: User Interface for data visualization.

Sensor Testing

The data from the sensor was received as a change in resistance of FSR as the various load was applied to them while walking. So, to quantify the amount of load applied, it needed to convert the obtained value of resistance change to force. For which the testing of FSR was done using a weighing machine and a multimeter. Various known loads were applied on FSR and the resistance values were noted. Then using those readings, a graph was plotted between the force applied and the resistance, which was obtained as a decaying exponential graph (Figure 9). Finally using a trend line and technique of interpolation formula to convert the resistance into force was developed, which is given in equations 1 and 2.

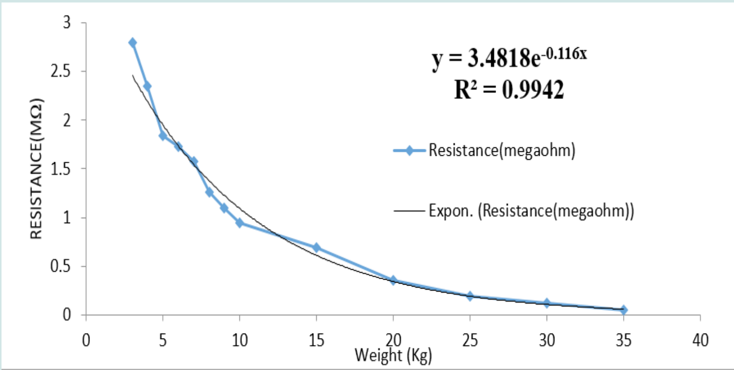

Figure 9: Change in Resistance with applied load.

Figure 10: Sensor Placement in the sole.

Resistance(y)=3.4818*e-0.116*Force(x) (1)

Force= 10.77-8.62*Ln(Resistance) (2)

Sensor placement

Sensors were placed based on the pedobarography and previous studies. Lin et al classified foot into fifteen regions based on pressure point [18]. While Claverie, et al. reduced the functional areas in the foot to nine regions [5]. In this study, the major pressure points are classified into six points, which were hallux (big toe), 1st metatarsal, 5th metatarsal, midfoot (lateral and medial) and heel. Six FSR were placed on each sole on the outer part, which is the plantar part, on those pressure points (Figure 10).

Ethics approval and Consent to Participate

Not Applicable.

Consent for Publication

Not Applicable.

Availability of Data and Materials

Please contact the corresponding author for the data requests.

Competing Interests

The author declares that they have no competing interests.

Funding

Not Applicable.

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