Research on making foot pressure measuring system and determining comfort pressure of shoe upper made from knitted fabric on the forefoot of the woman's foot

Cao Thi Kien Chung[1,2], Bui Van Huan[1]

Abstract--- This study aims to make the pressure measuring system including pressure measuring device and shelves. The device uses the Flexiforce A301 sensor of Tekscan USA, capable of measuring the pressure on the feet in a static and dynamic state, displaying numerical values in real time on the computer. The equipment system is easy to use, has high stability and gives reliable results, suitable for studying shoe pressure on the feet. *Using this* pressure measuring system *to establish the relationship between comfort and pressure of shoe upper made from knitted fabric on the forefoot of the woman's foot. 10 women without foot pathologies were selected for the study. The degree of perceived comfort of the measuring object was recorded. The pressure of 5 upper shoe material systems made from knitted fabric on the instep in 4 walking positions (phases) is measured by the* pressure measuring system*. The results show that the pressure value from 69.20 mmHg to 79.65 mmHg is the comfort pressure of shoe upper material on the forefoot of woman's foot. This result is the basis for the design and selection of shoe material to ensure comfort for the user and to prevent foot injuries.*

Keywords--- *Pressure measuring device, foot pressure, foot comfort pressure*

I. INTRODUCTION

Pressure on the feet when using shoes is one of the important comfort criteria of shoes, especially specialized shoes such as sports shoes, medical shoes. The peak pressure on the instep and soles is the main cause of diabetic foot ulcers. Therefore, in the world, there are many studies on manufacturing pressure measuring system on feet using pressure sensors.

Shoes are products that have a strong interaction with the feet during use. Therefore, one of the important factors that cause discomfort for the feet is the pressure on the foot. The forefoot on the instep is the most affected area of the shoe upper, because the shoe is tightly fitted to the foot and often cannot be used tools such as shoe laces, velcro, etc. to adjust. In addition, when people walk in shoes, the foot is bent in the forefoot, the dimension of the foot increases and the pressure of the shoe upper on this part increases, too. We feel this feeling very clearly when wearing hard, not fit shoes, shoes with upper made from poor elastic materials. Excessive pressure on the forefoot can affect physiological processes (blood circulation, sensation of nerves, etc.) of the foot that is one of the foot lesion causes.

In this study, the system including pressure measuring equipment and shelves stand is developed. Using this pressure measuring system to determine the comfort pressure of the uppers on the forefoot of the instep as the basis

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for the design and selection of shoe materials, especially shoes for diabetics to ensure comfort, prevention of foot injury.

AI. Literature Review

Research [1] used 8 WalkinSense sensors located in four areas: the hallux, the metatarsophalangeal joint, the middle of the foot, the heel. The study [2] used 6 sensors mounted on the pads at the toe joints, heel to determine average pressure, peak pressure. The microcontroller were mounted on the patient's ankle could connect and display measurement results on computers and smartphones. Saito's wireless shoe pressure measuring system [3] used 7 sensors placing on the heel, the middle feet, the hallux, and the metatarsophalangeal joints of the fingers 1, 3 and 5. The study [4] using 5 sensors attached to the hallux, and the metatarsophalangeal joints of the fingers 1, 2, 4 and heel to determine the pressure on foot plantar to design high heel shoes. The study [5] also used 5 sensors mounted on the pads at hallux, the metatarsophalangeal joints of the fingers 1, 2, 5. In Vietnam, the study [6] has designed and manufactured a device for measuring the pressure of clothing on the body using the MPX10DP gas pressure sensor. In the study [7], the authors used Flexiforce force sensor of Tekscan USA to design and manufacture the device to measure the pressure of clothes on the human body. So far in Vietnam, there has not been any research on designing and manufacturing device for measuring the pressure of shoes on the foot.

In patients with foot complications such as gout, diabetes, etc., excessive pressure is the cause of calluses, foot ulcers [10, 11]. There were studies showing different values of the allowable pressure on the foot instep. The authors of studies [12, 13, 14] suggested that pressure values of 4 ÷ 4.7 kPa (30 ÷ 35.25 mmHg) are undesirable and put the tissues at risk from ischemia if left in one position. The results of the study [15] showed that if the continuous impact in the range of 15 ÷ 20 kPa (112.5 ÷ 150 mmHg) interrupts the arterial blood flow and long-term effects of such occlusions include necrosis (skin cell death) and ulceration. Research [16] determined the pressure of 10 males aged of 22.1 ± 0.6 on shoes designed specifically, using the Flexiforce sensor at the metatarsal. As a result, the pressure value were varies from 5 ÷ 25 kPa (37.5 ÷ 187.5 mmHg) and there was a pressure difference between the phases of the foot step. The research [17] summarized the results of the research of Russian scientists and stated that the allowable pressure (the pressure did not change the circulation in blood vessels) at the area 0.448 ÷ 0.68 of foot length to be different with different postures of the foot and reach about 8.7 ± 1 kPa (57.75 ÷ 72.75 mmHg), people feel the pressurizing with pressure from 5.4 kPa (40.5 mmHg). In Vietnam, there have been only a few studies on the pressure of varicose veins [18] on women's legs, the comfort pressure of tight-fitting pants on the human body by numerical simulation and experimental [19] and has not been done to study the comfort pressure of shoes on the feet.

BI. Data Collection

3.1. Design a foot pressure measuring system

The foot pressure measuring system includes pressure measuring device and standing shelf.

3.1.1. Pressure measuring device

Circuit design (fig. 1):

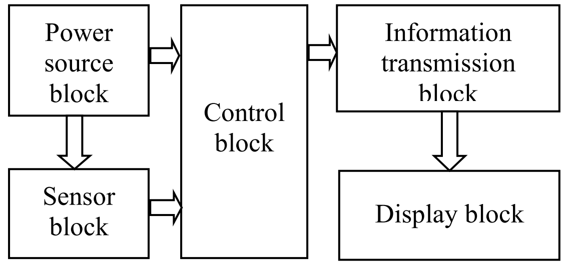
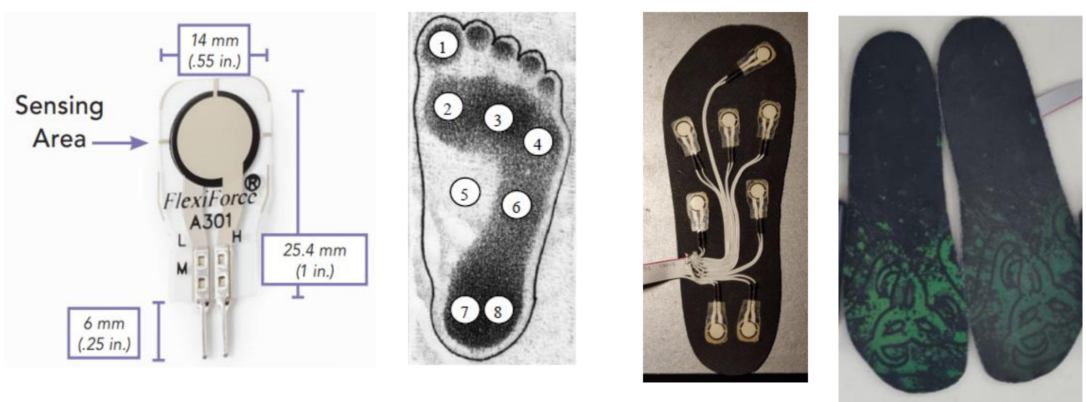


Fig. 1. Block diagram of pressure measuring circuit

Power source: The power supply creates a constant current and voltage that safely supplies the circuit. Using a diode to prevent reverse current from flowing and the IC voltage regulator LM1117 to create a 3.3V supply to the circuit.

Sensor block: The sensor receives data to transfer to the control unit to process it. In this study, Tekscan's Flexiforce A301 sensor (Fig. 2, a) was used. This type of sensor is thin, ensures stability, delay, sensitivity, and is widely used in foot pressure studies [2, 3, 4]. Sensor parameters: Error <± 3%; Non-repeatability <± 2.5%; Latency <4.5%; Temperature range -40 ° C to 60 ° C; Sensing area: 9.53 mm diameter [8].



a b c d

Fig. 2. FlexiforceA301 Sensor[8] (a), Footprint sensor position (b), Sensor placement diagram on the insole (c), complete insoles (d)

The sensors are located on the area of the body's impact on the foot (foot plantar). In this study the foot plantar of Vietnamese woman (average length of foot is 230 mm) was used to locate sensors (figure 2, b). After detecting the pressure areas, pressure sensors implemented on a 1 mm thick soft leather sole by two-sided adhesive tape that considered the first layer (fig. 2, c). A circle layer 9.8 mm diameter of hard texon material 1 mm thick is disposed on the sensor, is aimed to have a global distribution of the force exerted by foot. Then, a second layer the same as first layer is added to protect the sensors and its connection (Fig. 2, d).

Control block: The unit uses Arduino Mini Pro to read and process information from the sensor to produce data and push the collected data into the information transmission block. Arduino is an open source physical computing platform based on simple I/O boards. Arduino can be used to develop interactive objects independently or can be connected to software on computers such as Flash, Processing, MaxMSP.

Information transmission block: Receiving data from the control unit, pushing data onto the application or display block. The diagram of the principle of the device is shown in Fig. 3.

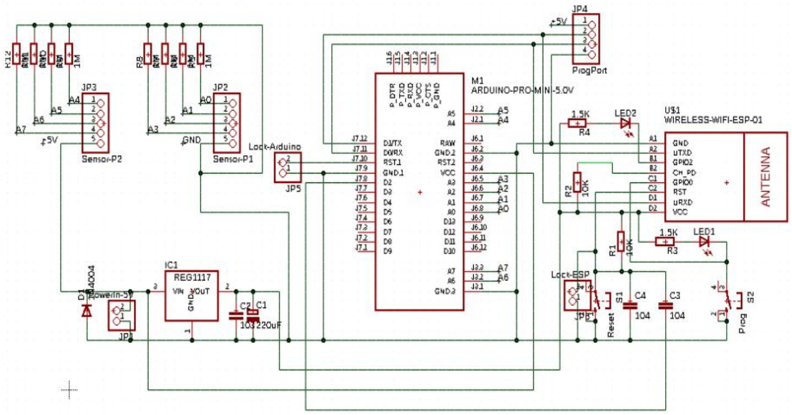


Fig. 3. Diagram of the principle of the system

Display block: When there is force on the sensor, the sensor will transmit the value sent to the processor. The analog pins will read the received value, and then process the data and put it into the Information transmission block for storage. The information transmission unit will store data and push it to the block displaying the results of measurement in the form of graphs and values in real time (quote measurement values with the interval of 0.1 seconds).

Software interface: The measurement system is controlled by computer software in Visual C language, displaying the pressure values at times. The software is convenient to use, allowing simultaneous measurement or separation of each variable in both static and dynamic modes. The pressure results on 8 sensors are continuously displayed in the bar graphs and numerical form, and are stored in file.xls (Fig. 5).

Building calibrated line: Using standard weight set with 10 g, 50 g, 100 g, 200 g, 500 g, 1000 g and 1500 g to build the calibrated line for every sensor. For all sensors, the received calibrated lines have a very high correlation coefficient, $R^2 \geq 0.99$. Fig. 6 showed the the correlation between the input weight (y, kg) and the ADC output value (x) of sensor number 1: $y = 0.0095*x$, ($R^2 = 0.9987$).

Evaluate the accuracy of measurement results: The evaluation of the device's measurement results is carried out in a room with a constant temperature of 25±2°C and an air humidity of 68%±5%. Using the standard set of weights to make 10 measurements (Fig. 6). Error of measurement result δA is determined by the formula: $\delta A = (\Delta\bar{A}/\bar{A})*100$ (%), where ΔA- average absolute error, Ā- average measurement value. The results showed that for small measurement scales (with a load of less than 50 g) $\delta A \leq 14.37\%$, for loads over 50 g, $\delta A \leq 6.65\%$. Table 1 shows (for example) the calculation of errors of sensor 1 (Fig. 2, b).

Table 1. Measurement error of sensor 1

Meas. times	ADC output value for weights, g						
	10	50	100	200	500	1000	1500
1	2	6	13	20	56	105	148
2	1	5	12	20	57	105	150
3	2	6	13	20	57	104	145
4	2	6	12	20	57	104	146
5	2	4	12	21	57	104	143
6	2	6	12	19	57	105	146
7	2	5	13	20	57	105	150
8	2	5	13	20	57	104	147
9	2	5	12	20	57	104	145
10	2	5	13	20	57	105	146
Ā	1.9	5.3	12.5	20	56.9	104.5	146.6

ΔĀ	0.18	0.56	0.5	0.2	0.18	0.5	1.72
δA	9.47	10.57	4.00	1.00	0.32	0.48	1.17

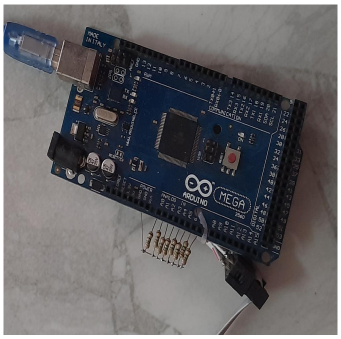


Fig. 4. Microprocessor of device

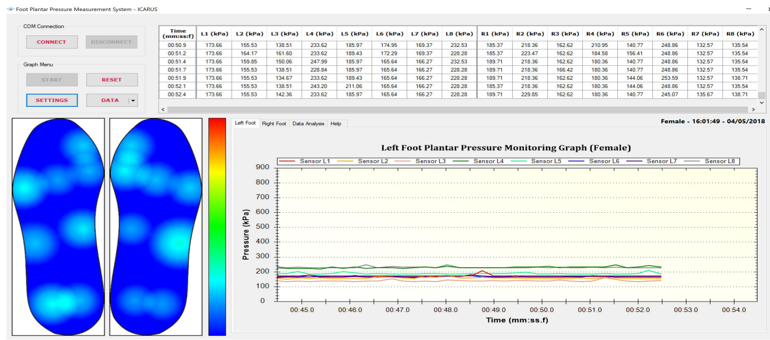


Fig. 5. Software interface of device

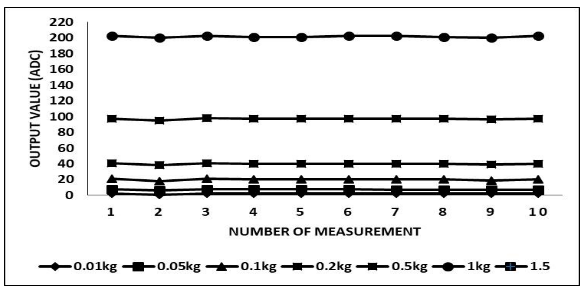


Fig. 6. Chart the average results of 10 measurements of the sensor with loads from 10 g to 1500 g

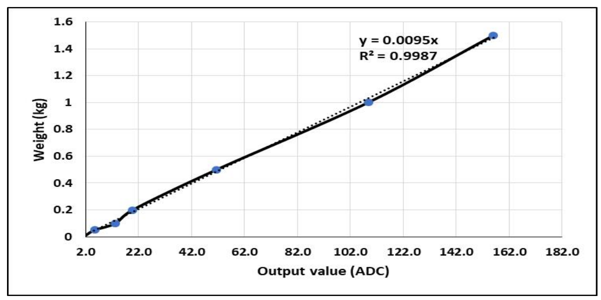


Fig. 7. Chart calibrated line for the sensor 1

3.1.2. Designing and manufacturing stand shelf

Pressure measurement results (accuracy, repeatability) are greatly influenced by gait, posture and standing stability during measurement. In this research the standing shelf has designed and manufactured to help the object stand and balance and maintain the correct gait and posture when measuring. The shelf consists of a wooden pedestal so that the tester can stand while measuring. The abutment is fitted with a fixed buttock to allow the person to maintain a stable posture when measuring; have handrails for the measuring person to keep standing or moving while walking. Above the vertical pillar there is a table to attach the focus that the tester needs to look at when measuring to stabilize the pressure on the foot plantar (Fig. 8, a). Behind the correct post, there are screws that allow adjusting the position of the buttocks and the handle height according to the height of the object (Fig. 8, b).

a b c

Fig. 9. Standing shelf when viewed from the front (a), from the back (b), the standing posture (c)

3.1.3. Measuring Procedure

Firstly the measuring system is connected to the computer via the USB connection port, and then, start the software of the measuring system. The participant stands in the correct posture for about 30 seconds (Fig. 9, c), observing on the display that the measurement results show a stable value, and then saving the measurement result.

For each sample, 30 values are taken and calculated the average as the final measurement result. Measure 5 times and take the average as the measurement result.

3.2. Method of research on determining comfort pressure of shoe upper made from knitted fabric on the forefoot of the woman's foot

3.2.1. Subjects

Knitted fabric samples: Knitted fabric is increasingly used to make shoe upper due to their soft fabric, ventilation, good ventilation, and especially elasticity. In this study, 05 typical knitted fabric samples (material systems) of Taiwan with basic characteristics as shown in Table 2 were studied.

Table 2. Basic characteristics of shoe upper material systems

Symbol	Fabric Type	Weight, g/m^2	Thickness, mm
M1	3D knitted fabric	325,0	2,13
M2	3D knitted fabric	350,0	1,13
M3	Knitted fabric + Foam + Tricot	295,0	2,66
M4	Mesh + Foam + Tricot	325,0	1,98
M5	Mesh 3D knitted fabric	305,0	1,92

Participants: 10 young women aged 21.8 ± 0.63 years, height: 155.9 ± 2.96 cm; weight: 47.5 ± 2.84 kg; ball girth circumference: 223.8 ± 1.2 mm and foot length: 230.0 ± 1.4 mm were selected.

3.2.2. Method of research

Experimental method of determining the pressure on the foot:

Sample preparation: A sample of the material simulates the uppers of the instep (metatarsal) of the feet, the width of sample is 6 cm. The length (circumference) of the sample, keeping the dimension of the sole (6 cm) and the choice of 5 sizes for the material of the instep with an increment between sizes of 5 mm, namely: size 1: 13.7 cm, size 2: 13.2 cm, size 3: 12.7 cm, size 4: 12.2 cm, size 5: 11.7 cm. The sole of the foot (6 cm) uses a non-elastic woven fabric, making sure that the pattern only extends at the instep (Fig. 10). Using Juki DDL - 9000A-SS at Workshop of Hung Yen University of Education and Technology to sew samples.

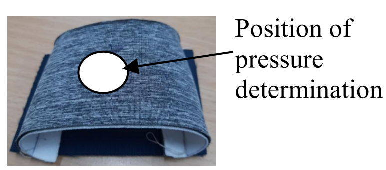


Fig. 10. Image of sample

Measuring postures: Selecting 4 typical measurement phases according to the steps of the foot cycle (Figure 11, a-e).

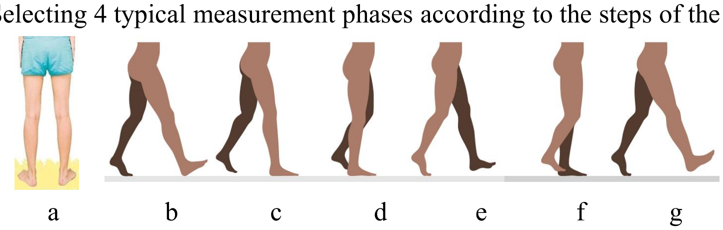


Fig. 11. Phases of foot cycle [20]

Posture 1 (TT1): The legs are upright, the feet are in full contact with the ground (Fig. 12, a).

Posture 2 (TT2): The foot posture is tilted forward, the feet fully in contact with the ground (Fig. 12, c).

Posture 3 (TT3): The foot posture is straight, perpendicular to the ground, feet must be in full contact with the ground (Fig. 12, d).

Posture 4 (TT4): The foot posture is tilted backwards, the whole toe touches the ground (Fig. 12, e).

a b c d

Fig. 12. 4 postures of pressure determination: a. postures 1; b. postures 2; c. postures 3; d. postures 4

Process measurement: Firstly the measuring system is connected to the computer via the USB connection port, and then, start the software of the measuring system. The participant stands in the correct posture for about 30 seconds, observing on the display that the measurement results show a stable value, and then saving the measurement result. For each sample, 30 measurement values are taken and calculated the average as the final measurement result. Measure the girth of the foot when wearing sample to determine the actual elongation of the material. Record the feeling of the subject when taking the sample.

The method of determining comfort pressure on the forefoot:

Using the Quartile value is a quantity that describes the distribution and dispersion of the data set to determine the material pressure thresholds on the forefoot due to the results of the subjective feeling of participants when wear the sample during pressure determination.

$$Q_{p\%} = L_{Qp\%} + \left[\frac{i-F}{f_{Qp\%}}\right] \text{x W} \quad (1) \quad [21]$$

In which: $Q_{p\%}$ is a quartile value corresponding to% of observations; $L_{Qp\%}$ is the lower limit of the quartile group; i is the position of the quartile; F is the cumulative frequency up to the limit of the quartile containing group; $f_{Qp\%}$ is the frequency of the quartile group; W is the width of the quartile group.

In order to determine the pressure thresholds of shoe upper material on the forefoot, the study was based on the analysis of 4 quantities: first quartile value Q_1 (or 25% percentile value); second percentile value Q_2 (percentile value 50%); third quartile value of Q_3 (or 75% percentile value).

The interquartile range (IQR) is a numerical quantity that measures the dispersion of a dataset, which means that the location with the highest frequency of pressure is chosen as the value of the comfort pressure of upper shoe material on the forefoot. The IQR is the range of values from the first to the third quartile = Q_3 - Q_1.

Use the box plot to represent the quartile range. The box is about quartile. Upper antennae = Q_3 + (1.5 x IQR). Lower antennae = Q_1 - (1.5 x IQR).

Data analysis: Use Excel 2013 software to statistic and process measurement results. The statistics were analyzed on Anova to verify the reliability of the measurement results.

VI. Study Results, Summary And Contribution

4.1. The result of determining the pressure on the instep and subjective sensory evaluation

According to the established method, the subjective perception survey was conducted according to 5 levels of elongation, 4 measuring postures of 5 material samples on 10 young females, corresponding to 1000 assessments, 200 assessments on each sample material. Fig. 13 illustrates the results of evaluating subjective sensory levels of pressure on the forefoot of participants.

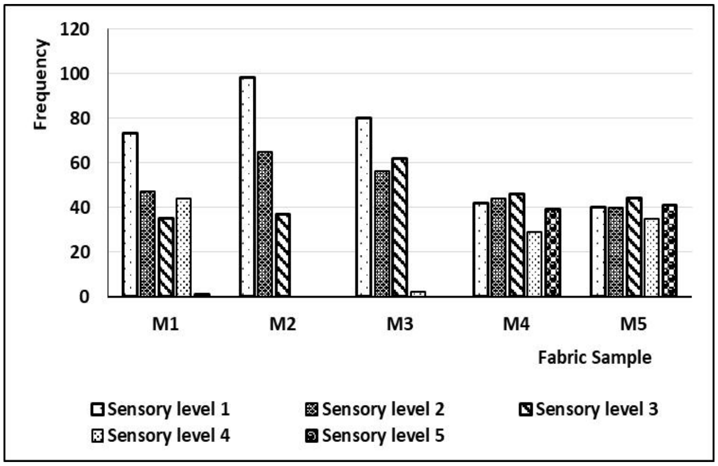


Fig. 13. Frequency with 5 levels of subjective sensory of 5 material samples

Fig. 13 shows that the level of sensory on each sample material is different. The total number of sensory evaluation papers at level 1 is 333, level 2 is 252, level 3 is 224, level 4 is 110 and level 5 is 81. The degree of subjective sensory of each material sample is different, p = 0.03 significant. The samples M1, M2 and M3 have the highest values at sensory levels 1, 2 and 3. The sample M2 do not has any evaluation at perceived sensory levels 4 and 5. The samples M4 and M5 have a perceived value at sensory levels 1, 2, 3 lower, but rating sensory level 4, 5 is higher. This is consistent with the elongation characteristics (with elongation up to 30% by ASTM D4964 - 96) of the 5 studied fabric samples (Fig. 14). The fabric samples M1, M2 and M3 have better elasticity than M4 and M5.

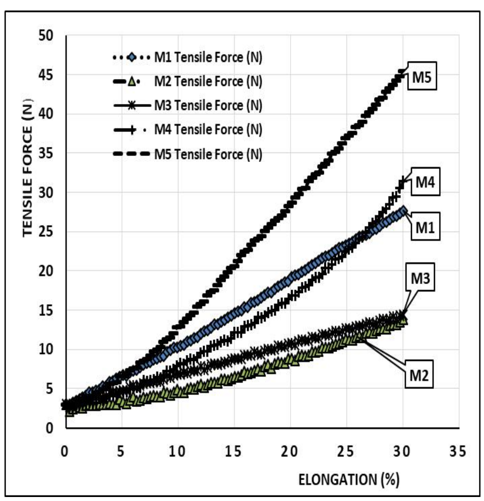


Fig. 14. Diagram of relationship between tensile force and elongation up to 30% of 5 material samples

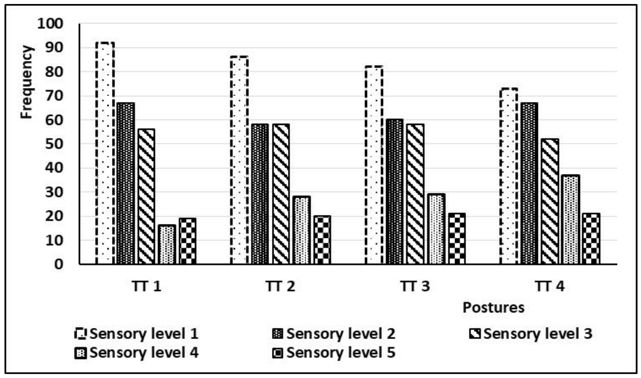


Fig. 15. Frequency with 5 levels of subjective sensory of 5 material samples in 4 measuring postures

The statistics in Fig. 15 shows that each posture is measured for different levels of sensory. The total number of evaluation perceived in each posture is 250. The frequency of evaluation at senses of level 1, 2 and 3 tends to decrease with measurement postures. In contrast, the perceived levels 4 and 5 have the frequency of evaluation increasing with the measurement postures. This is because, compared to posture 1 (Fig. 12, a) the body weight is spread steadily onto the feet, poses 2 and 3 (Fig. 12, b, c) feet are subject to a bigger load (full the body load on one foot) that increases the foot girth. In posture 4 (Fig. 12, d), in addition to being subjected to heavy loads, the foot is bent in the area of the toe joint so ball girth circumference is largest. The degree of subjective sensory of each material sample has a quite difference, using anova control to obtain a statistically significant $p < 0.0005$. Thus, the results of determining the pressure value and the level of sensation between the postures during the measurement received differently.

The pressure value of the material on the forefoot corresponding to the sensory level according to participants by formula (1) is shown in Fig. 16.

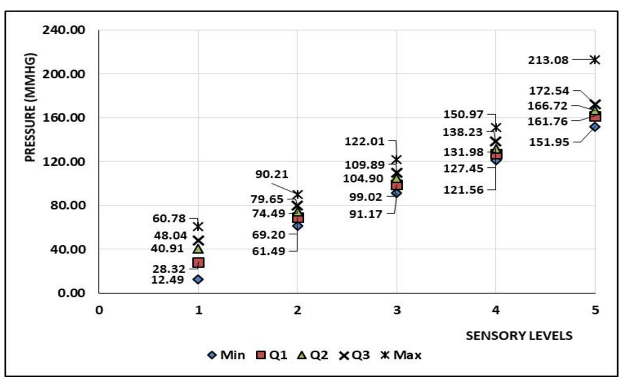


Fig. 16. The pressure of the material on the forefoot corresponding to sensory levels 1, 2, 3, 4 and 5

The results in Fig. 16 shows that the pressure value is proportional to the level of sensation, the level of sensation 1 (very comfort) corresponds to the result of the lowest measured pressure, the level of sensation 5 (very discomfort) corresponding to the highest measured pressure. The measured pressure along with each subjective sensory level is markedly different, $p < 0.0005$ significant. Thus, the comfort sensory gradually becomes uncomfortable sensory when the pressure increases.

Table 3. Comparison of pressure value between sensory level 2 and sensory level 4

Quartile	Pressure, mmHg		Ratio
	Sensory level 2	Sensory level 4	
The first quartile Q_1	69.60	127.45	0.55

The second quartile Q_2	74.49	131.98	0.56
The third quartile Q_3	79.65	138.23	0.58

The results in table 3 shows that the pressure value in sensory level 2 (comfort) is only equal to 0.56 pressure value at sensory level 4 (discomfort). Thus, the threshold of pressure acting on the instep from comfort to discomfort is large difference.

4.2. Determination of comfortable pressure on the forefoot

In order to determine the comfortable pressure of the material on the metatarsal, the study selected the pressure value at the points corresponding to the sensory level according to the subjective pressure level 2 (comfort) for statistics, analyze and calculate the quartile values and IQR. The results are shown in table 4 and box plot (Fig. 17).

Table 4. Value of material pressure on the forefoot corresponding to sensory level 2 at 4 measuring postures

Quartile	Pressure, mmHg, with sensory level, on measuring postures			
	TT1	TT2	TT3	TT4
The first quartile Q_1	67.64	71.16	71.88	69.38
The second quartile Q_2	70.59	73.96	75.74	76.58
The third quartile Q_3	80.88	78.18	79.65	81.07

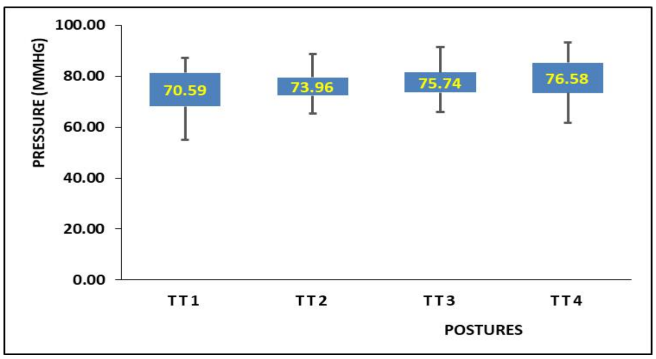


Fig. 17. Pressure at sensing level 2 of 4 measuring postures

The results of table 3 and Fig. 17 show that, in addition to posture 1, the pressure value at sensing level 2 in the remaining 3 measuring postures is equivalent. Maximum value of all 4 postures is 90 mmHg (Fig. 16). The results of studies [16, 17, 22] showed that there are many factors that influence the pressure of shoes on the feet and feel the comfort pressure of shoes on the feet of each person is different. Therefore, in order to ensure the representability of the comfort pressure value range for the whole group of participants in the study, in this study, the pressure was selected in the range of Q_1 to Q_3 (table 4), (the box area as shown in Fig. 18). This is the area with the most concentrated comfort pressure value of all 4 measuring postures. Summing up the pressure value at 4 postures are measured at sensing level 2, the first quartile values of Q_1 is 69.20 mmHg; Q_2 is 74.49 mmHg; Q_3 is 79.65 mmHg (Fig. 18).

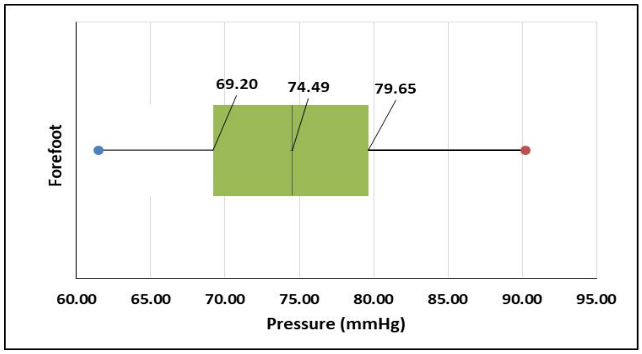


Fig. 18. Pressure comfort range with sensing level 2 on the forefoot

Thus, the IQR (the interval with the highest frequency of pressure) with pressure values from 69.20 mmHg to 79.65 mmHg was chosen as the comfort pressure value of the shoes upper material on the forefoot.

The authors of the study [12, 13, 14] determined the pressure values of 30 ÷ 35.25 mmHg to act locally on a point leading to tissues that could become anemic. According to research [17], the permissible pressure on the instep ranges from 57.75 ÷ 72.75 mmHg. According to European standards [23] for patients with type 4 varicose veins (heavy type), the recommended pressure at the ankles of socks is 59 mmHg. Thus, the comfort pressure threshold (79.65 mmHg) receives in this study that is greater than the recommended allowable pressure on the instep (72.75 mmHg).

Therefore, in this study we consider that the maximum allowable pressure on the metatarsal of the instep of the female foot should be the lower threshold of comfort pressure and is 69.2 mmHg. This pressure ensures comfort and does not affect the physiological activity of the user's foot.

4.2. Conclustion

Using Flexiforce A301 sensor has designed and manufactured a device system that is suitable to measure pressure on the feet including measuring equipment and standing shelf. This system is controlled by computer software in Visual C language, displays the measurement results in real time so it is possible to measure foot pressure both in a static and dynamic state. The results of using the device to measure the pressure of the material on the instep show that it gives high stability and reliable results. The device system is easy to use and highly flexible, suitable for studying shoe pressure on the feet when shoe designing and selecting shoe materials, as well as selecting fit shoes.

Subjective sensory values when taking samples during pressure measurement gave different results among 5 sensory levels. The pressure value of the material on the forefoot is proportional to the subjective sensory levels of the participants being measured. Within the scope of this study, pressures in the range of 69.2 mmHg to 79.65 mmHg are the pressure comfort values of shoe upper material on the forefoot of woman. The upper threshold of comfort pressure is greater than the recommended allowable pressure on the instep by published studies. Maximum allowable pressure value on the forefoot of the instep should be 69.2 mmHg. This result is the basis for design and selection of shoe material to ensure comfort, and does not affect the physiological activity of the user's foot.

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