In-sole plantar pressure device with optimization measurement techniques

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Article Info

ABSTRACT

Doctors and clinicians rely on accurate underfoot pressure data to perform diagnosis of foot diseases. In sole pressure measurement systems are designed to provide such data but its implementation suffers from certain constraints such as the need for a spacer to be placed on the sensor when taking measurements and the need for multiple calibrations due to the fact that the sensor parameters tend to change without it. In this work, we proposed an optimization technique to address these limitations. The results obtained from testing indicate that the proposed device performed measurement of plantar pressure effectively. Also, the calculation of body weight using the proposed optimization technique is improved from 5.07% to 9.06%. For validation, the results are compared with the measurements from a commercial plantar pressure device (EMED system) as benchmark.

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1. INTRODUCTION

Plantar pressure measurement systems are often used to obtain useful data regarding the structure of the underfoot base and the distribution of pressure it exerts to the surface plane. These systems allow for the diagnosis and treatement of various problems related to posture and gait but there are inherent limitations within these systems that need to be addressed such as the lack of precision in body weight calculation, self-calibration improvements and suitability of the physical characteristics of the materials used. The work in [1, 2] studies the effects of obesity or increasing body weight and the resulting disparities in the plantar pressure distribution patterns. Another study found that increase in the human body weight was a significant factor that contributed to the plantar pressure distribution pattern [3, 4]. This leads to recommendation from researchers that the diagnosis and treatment of foot problems in obese patients should consider the effects of increased body mass on their plantar loading [5, 6]. The study in [7, 8] then found that the relationship between mean/peak plantar pressure and increasing body mass was dependent on the affected plantar area.

These prior works show that current insole systems do not consider pressure range in the measurements of plantar pressure. Thus, there is a need for a method to obtain points that can be used to produce a suitable pressure range in the plantar measurement system, specifically the maximum and minimum pressure values during walking and standing, as related to the body mass. The findings of accurate and reliable underfoot pressure ranges based on incremental body weight is needed as a benchmark or

reference to be used by other reseachers for comparison. In addition, these ranges also enable the differentiation of subjects with and without foot complications as studied by [9, 10].

In this paper, we propose an in-sole based plantar pressure measurement device with optimized techniques. The device is designed to measure the range of underfoot pressure and prove its relation to calculations of total body weight and it is expected that the date it produces could be used as a reference or benchmark for other reseachers. In this study, the ethics approval was granted by the Universiti Putra Malaysia Human Research Ethics Committee for the use of experimental subjects.

2. RESEARCH METHOD

2.1. Sensor Selection

The force sensor that is selected for use in the design of an in-sole plantar pressure measurement device must possess some essential characteristics:
a) The force sensitivity range should be appropriate
b) The sensor must be small, thin and flexible to ensure the comfort of the wearer
c) The driving circuit of the sensor must be simple enough for the instrument to be portable [11, 12].

Thus, the piezoresistive force sensor model A201™ from Tek-scan was chosen since it fulfills all the requirements. This sensor was used to measure the underfoot pressure with in-sole applications. It was distributed over the touch area of the foot and was calibrated with the recommended procedure for calibration. For such an in-sole system, the pressure sensor was calibrated for the full range, which means that a 100-lb flexi force pressure sensor A 201 had to be calibrated to measure pressure ranging from 0-4400 KPA [13, 14].

2.2. Sensor Distribution and Calibration

The monitoring of parameters in in-sole systems is becoming a major factor in several fields of scientific research as it may provide useful data on the prevention and treatment of various health conditions, as well as the planning for physical therapy and rehabilitation exercise programs. The parameters for the insole plantar pressure system are set according to the number of sensors and their distribution pattern, which is often determined by the purpose of the in-sole system application. Table 1 summarises the application and number/distribution of sensors in previously developed in-sole systems found in the literature. Since each system has a different aim/application, there is no gold standard for the placement of sensors to measure foot pressure accurately. Cost is also an important factor to consider since increasing the number of sensors could result in a more expensive device. Therefore, it is necessary to find the optimal number and placement of sensors for the in-sole plantar pressure device.

Table 1. Sensor Numbers and Distribution with Different Application

Number of sensor and Distribution	Application
Eight sensors with positions located at the toe, 1st metatarsal, 3rd metatarsal, 5th metatarsal, 2 positions at the lateral forefoot, the medial heel, and the lateral heel [14]	Monitoring the balance of the physical body, identifying the mechanical dysfunction path, evaluating treatments, and improving sport skills performance
6 units of insole pressure sensors, with three units placed in the heel area and three units in the metatarsal area [15]	Analyse the COP of the body
Eight sensors [16]	Dynamic movements in real time, and are used for clinical gait analysis
Eight sensors divided into five positions [17]	Detect a fall and classify the direction of a serious backward fall
Five sensors located on the insole [18]	Estimate the foot load with reasonable accuracy, reduce the cost of the system and monitor the plantar pressure for daily activity exercise stress assessments
Eight sensors for the in-shoe derived from natural rubber (Hevea brasiliensis) and equipped with a pressure control [19]	Customised for people who have a diabetic foot with neoformation of tissues

The proposed in-sole plantar pressure device (IPPD) system, which was designed to measure underfoot pressure ranges, is illustrated in Figure 1. The sensors were distributed for 15 positions, as shown in Figure 1(a), which are namely (1) back heel, (2) inside of the heel, (3) lateral heel, (4 & 5) plantar middle, (6 to 10) 1st to 5th metatarsal head, (11 to 15) 1st to 5th toe [11].
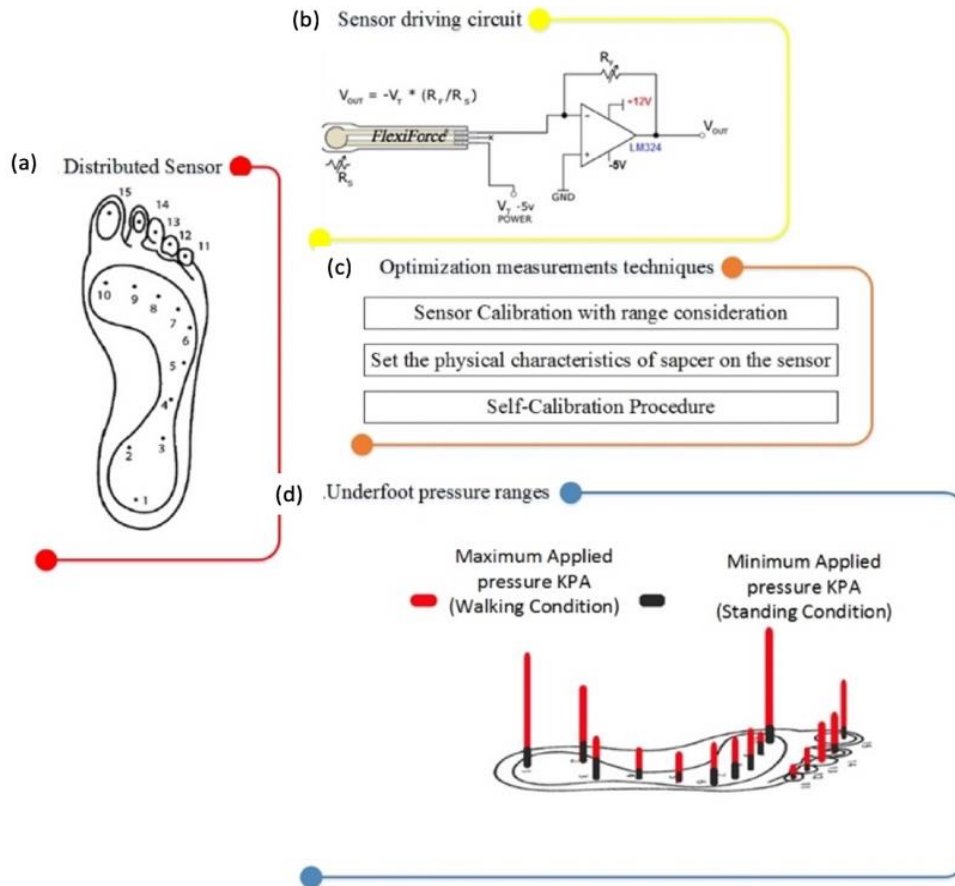
Figure 1. Diagram of proposed insole system (a) Sensor distribution (b) Sensor driving circuit,
(c) Optimization measurement techniques (d) Underfoot pressure ranges

When there is no pressure being applied, the Flexi force pressure sensor does not produce any output since due to an infinite resistance value. From the detailed specifications of the sensor, it was found that without any load, the amount of resistance in the sensor is at a minimum of 5 MΩ. As the load applied increases, the sensor resistance value would decrease. An accompanying electrical circuit with an operational amplifier (Figure 1(b)), is needed to produce an output voltage that linearly correlate with the force applied on the sensor. In order to ensure that the voltage output is equal to the sensor output, the sensor is calibrated to have the same value as the total feedback resistance. The sensor output voltage is given by the equation:

$$V_o = V_{in} \frac{Rf}{Rs}$$

The Flexi force pressure sensor from Tek-scan company requires calibration to reduce errors in the pressure measurements [20-22]. It was essential to condition the Flexi force pressure sensor before the calibration and testing to achieve accurate results. Unlike previous in-sole systems, the sensors for the proposed IPPD were calibrated for specific values. These specific values represent the maximum force that was applied to each point under the foot for the maximum sample weight. The calibration procedure can be represented by a Simulink circuit as shown in Figure 2.
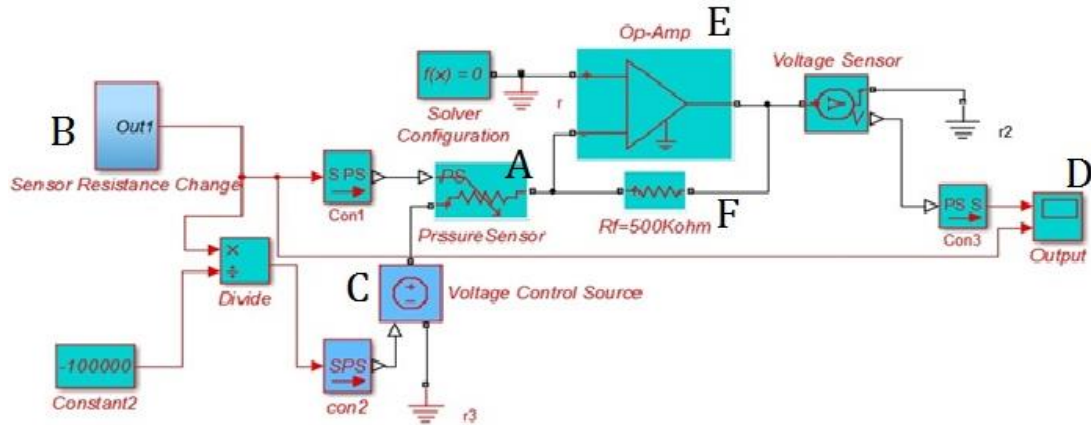
Figure 2. MATLAB simulink circuit representing the calibration procedure

Whare:
A: Pressure sensor with adjustable resistance
B: Variation in sensor parameters after certain period of time
C: Input voltage controller which relates to sensor parameter changes
D: Sensor output voltage
E: Operational amplifier circuit driving the sensor
F: Feedback resistance.

Once the calibration is performed, future users are advised to repeat the calibration process after a specific amount of time. The calibration procedure is required to analyse the linearity of the applied force with with output voltage produced by the sensor. Figure 3 shows the design of the proposed IPPD and the driving circuits for the sensors.

An important factor that had to be considered in the implementation of the in-sole system was determining the parameters of the spacer to be placed on the effective area of the sensor. This spacer was recommended by the manufacturing company to evenly distribute the pressure applied to the sensor [20]. Preliminary tests and also previous work [23, 24] have showed that without the use of a spacer on the effective area, a higher measurement error will be produced compared to when a spacer is used. However, the suitable material and dimensions of the spacer to obtain accurate measurements were not specified. Rigid materials, such as plastic and rubber were considered as possible candidates for the spacer material. The thickness of this material should be suitable and unobtrusive for the user. Experiments were carried out to examine which material is suitable and able to produce minimum measurement error. A Universal Testing Machine (UTM) was used to apply a force of 10 kg (98N), as shown in Figure 4.
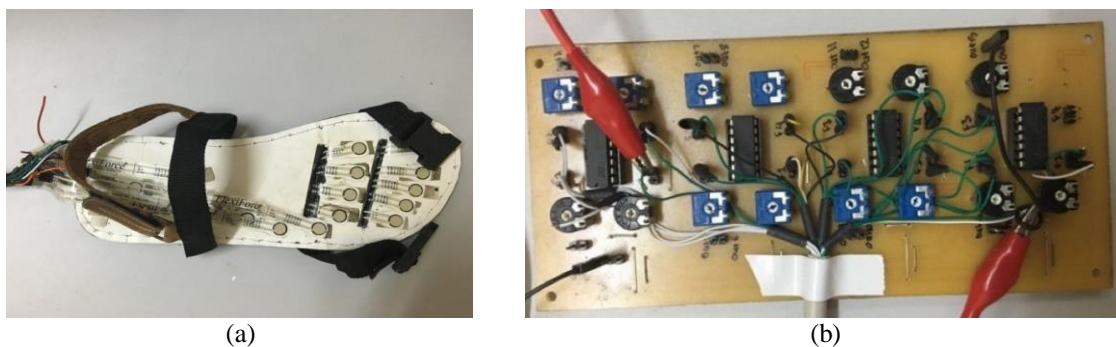

(a)   (b)

Figure 3. (a) The proposed IPPD and (b) driving circuits

Figure 4. Universal testing machine with plastic spacer with flexi force pressure sensor

2.3. Underfoot Pressure Measurement Methodology using Proposed IPPD

The measurement of underfoot pressure using the IPPD plays a role in the understanding and detection of certain problems in relation to foot complications. The proposed IPPD was designed to measure the underfoot pressure for 15 positions that are considered as important positions for supporting the body weight [25, 26]. Following the application of the optimization measurement techniques with the proposed IPPD, this section explains the methodology for the measurement of the underfoot pressure to obtain the data regarding the minimum and maximum pressure from each point under the foot. The underfoot pressure measurement methodology involved several steps. Firstly, the IPPD was set up and the participants were requested to wear the proposed IPPD. Next, the peak pressure (maximum applied pressure) was measured by asking the participants to walk for two steps at a normal walking speed using the proposed IPPD. Then, the touch pressure (minimum applied pressure) was measured during the standing condition. Finally, the body weight was calculated using (1):

$$
\begin{cases}
Sample\ Body\ Weight = \sum_{n=1}^{n=15} \frac{P_n}{A} * \frac{1}{Effective\ area\%} * 2 \\
Sample\ Body\ Weight = \sum_{n=1}^{n=15} W_n \frac{1}{Effective\ area\ \%} * 2 \\
Sample\ Body\ Weight = \sum_{n=1}^{n=15} \frac{X_n}{5\ v} V_n * \frac{1}{Effective\ area\ \%} * 2
\end{cases}
\tag{1}
$$

n : Number of sensors
P : Pressure measured during standing condition in (KPA)
W : Extracted weight of each sensor (kg)
V : Output voltage from each sensor under the foot (V)
X : The particular value of the weight range in which the sensor was calibrated based on its position (Kg)
A : Factor = 98, which converts $1kg/cm^2$ to KPA.
Effective area: The sensors covered around 8.6 % of the whole area of the foot.

After extracting the underfoot pressure ranges for the different samples, the body weight of each sample was also calculated. Finally, the minimum and maximum pressures under the foot in relation to the increasing body weight were determined. After that, the participants were requested to use the current in-sole system again and the novel EMED system for the measurement of touch pressure and the calculation of the body weight.

3. RESULTS AND ANALYSIS
3.1. Spacer Material and Dimensions Test

The experiment for calculating the standard weight to be applied using a UTM was explained in methodology section. After the sensors had been calibrated for a specific value, and the effective area of the distributed sensors had been calculated, a verification process was carried out using a spacer. Table 2 shows the percentage of error between the applied weight using the UTM and the calculated weight using the distributed pressure sensors with three different conditions (using a plastic spacer with a thickness of 0.55 mm, using a rubber spacer with a thickness of 0.55 mm, and without using a spacer).

Table 2. Weight Calculations using Pressure Sensors with and Without Applying A Spacer

	Measured force using pressure sensor with a plastic spacer (N)	Measured force using pressure sensor with a rubber spacer (N)	Measured force using pressure sensor without a spacer (N)
Calculated force, N	94.4321185	91.559518	85.2659276 N
Percentage of error	3.12 %	6.57 %	12.4 %

The error of measurement between the applied weight using the UTM and the measured weight obtained using the distributed sensor measurements without using a spacer was 12.4%. Meanwhile, the measurement error between the applied weight and the measured weight reached 3.12 % when a plastic spacer was used, and 6.57 % when a rubber spacer was used. It was concluded that, during experiments, it is necessary to place the spacer made of plastic material, with a thickness of 0.55 mm, onto the sensors to obtain precise and accurate measurements.

3.2. Analysing Measurement Precision with Applied Calibration Technique

As mentioned in the introduction, there is an inherent challenge with the use of the Flexiforce pressure sensor, where the sensor parameters would change after a period of time following the calibration. In this research, the change in sensor parameters was analysed by studying the variance in measurements after a period of time following the calibration. Table 3 shows the changes in the sensor parameters in terms of the relationship between the applied force and the sensor output voltage after a period of time following the calibration. The relationship between the applied force and the output voltage was determined from Figure 5, which showed that the characteristics curve of the sensor after a period of time following the calibration was affected only by the sensor output, while the relationship between the applied force and the output voltage remained linear.

Table 3. Sensor Output vs. Applied Force After a Period of Time Following the Calibration

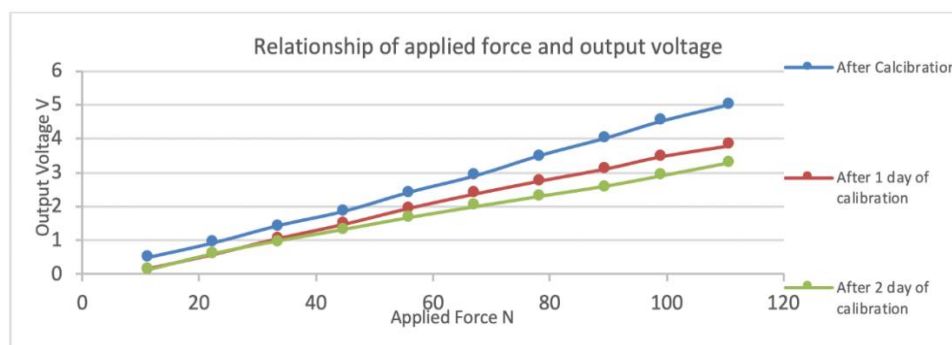| Applied Force (N)	Output Voltage (V) from sensor after calibration	Output Voltage (V) from sensor after one day of calibration	Output Voltage (V) from sensor after two days of calibration
111	5.00	3.8	3.3
99	4.50	3.471	2.9
89.6	4.01	3.115	2.6
78.4	3.50	2.759	2.3
67.2	2.90	2.3763	1.99
56	2.42	1.958	1.67
44.8	1.86	1.4863	1.32
33.6	1.44	1.068	0.98
22.4	0.93	0.5963	0.6
11.2	0.50	0.178	0.12

Figure 5. Relationship between the applied force and output voltage after a period of calibration

The simulation results of the calibration procedure, represented by the MATLAB model in methodology section, are shown in Figure 6. Based on the calculated values, it was concluded that the calibration procedure for the Flexi force pressure sensor needs to be performed routinely to maintain the same low measurement error. The time required to apply the calibration procedure was determined by applying the procedure on the sensor and tracing the relationship between the applied force and the output

voltage. Figure 7 shows the sensor parameters after applying the calibration and after one hour of calibration. This shows that the sensor parameters remained the same after one hour of application of the self-calibration technique. Thus, it is recommended that the self-calibration be repeated after one hour to maintain the same measurement from the sensor.

There was an improvement in the calculated body weight using the insole system after the sensor had been calibrated for the maximum applied pressure (range considerations). As shown in Table 4, the percentage of error between the actual body weight and the calculated body weight using the IPPD system with the sensor calibrated for range considerations amounted to 7.10 %. This is lower than the percentage of error when the sensors had been calibrated without range considerations which amounted to 8.79 %. This variance in terms of the calculated body weight highlights the importance of calibration with range considerations to ensure more precise and accurate measurements can be obtained.
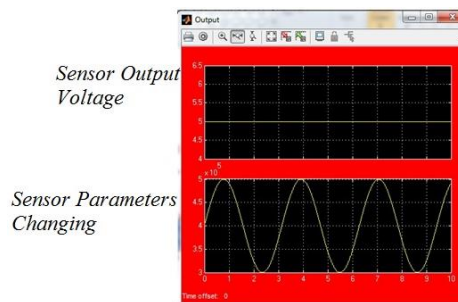

Figure 6. Calibration output

Table 4. Body Weight Calculation using Insole System with Two Considerations of Sensor Calibration

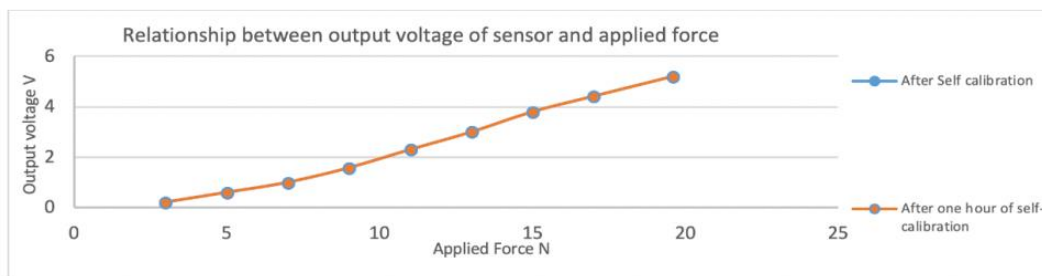| Body weight (kg) using weighing scale	Insole system sensors calibrated with range considerations	Percentage of error	Insole system sensors calibrated without range considerations	Percentage of error
100	91.8	8.20%	91.5	8.50%
95	87.9	7.47%	86.5	8.95%
92	85.5	7.07%	83.5	9.24%
87	80.5	7.47%	79.2	8.97%
83	77.5	6.63%	75.8	8.67%
75	70.1	6.53%	69.5	7.33%
73	67.9	6.99%	65.8	9.86%
68	63.2	7.06%	61.4	9.71%
63	58.8	6.67%	57.85	8.17%
60	55.8	7.00%	55.1	8.17%
58	53.9	7.07%	53.1	8.45%
55	51.1	7.09%	49.8	9.45%
Percentage of error		7.10 %		8.79%

Figure 7. Relationship between output voltage of sensor and applied force after one hour of calibration

3.3. Underfoot Pressure Measurements using Proposed IPPD

The underfoot pressure range measurements obtained with the implementation of the IPPD are presented in this section. The relationship between the maximum and minimum applied pressure by way of increasing body weight for healthy subjects (i.e. subjects without any foot complications) was represented by

a linear correlation with increasing body weight, as shown in Figures 8 and 9. The former showing the results for male subjects and the latter for female subjects. The procedure for calculating the body weight was applied, and the result was compared with a standard insole system (insole system designed without optimization techniques) and another commercial device (novel EMED system). The novel EMED system is regarded as an accurate electronic system for recording and evaluating the underfoot pressure distribution in static and dynamic conditions [20].
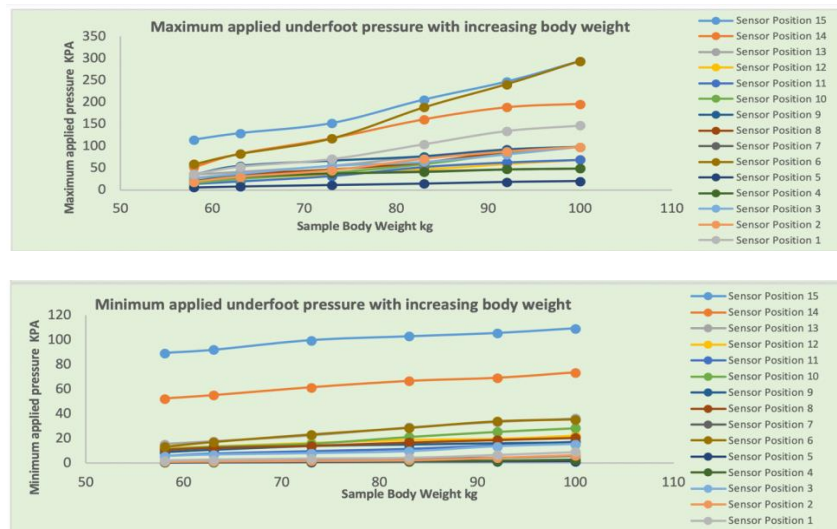

Figure 8. Maximum (top) and minimum (below) applied pressure with increasing body weight for male group
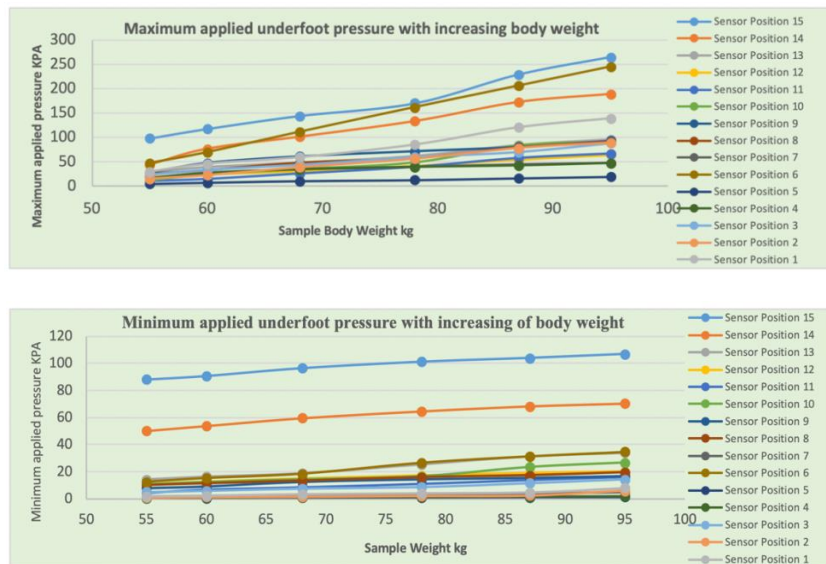

Figure 9. Maximum (top) and minimum (bottom) applied pressure with increasing body weight for female group

Table 5 shows the comparison between the novel EMED system, the current insole system and the IPPD in terms of the body weight calculation and the percentage of error between the real and measured values. It was observed that the estimated body weight from the IPPD system with optimization techniques had a similar percentage of error to the estimated body weight from the EMED system, with a difference of only 0.14%.

Table 5. Comparison between the Novel EMED System, the Current Insole System
and the IPPD in Terms of the Body Weight Calculation

Body weight (kg) using weighing scale	Body weight (kg) calculated using EMED system	Percentage of error	Body weight (kg) calculated using current insole system	Percentage of error	Body weight (kg) calculated using proposed IPPD	Percentage of error
100	91.0	9.0%	91.5	9.00%	94.9	5.10%
95	86.0	9.4 %	86.2	9.26%	90.2	5.02%
92	83.5	9.2%	83.4	9.35%	87.4	5.00%
87	79.0	9.2%	79.4	8.74%	82.6	5.10%
83	75.3	9.3%	76.1	8.31%	78.8	5.06%
78	71.0	8.9%	71.2	8.72%	74.1	5.03%
73	66.5	8.9%	66.3	9.18%	69.5	4.79%
68	61.5	9.5%	61.4	9.71%	64.7	4.79%
63	57.0	9.5%	57.2	9.21%	59.9	4.87%
60	54.5	9.1%	54.2	9.67%	57.0	5.00%
58	52.5	9.4%	53.2	8.28%	54.5	6.03%
55	50.0	9.0%	49.6	9.82%	52.2	5.09%
Percentage of error		9.2%		9.06 %		5.07 %

4.   CONCLUSION

Underfoot pressure ranges were measured using the proposed IPPD with the applied optimization techniques and these experiments led to several findings. Firstly, it was shown that there was an improvement in the calculation of the weight following the use of a spacer onto the sensors during the experiments. The experiments showed that a spacer made of plastic, with a thickness of 0.55 mm, can help to produce measurements with less error than when a spacer is not used. Secondly, it was proven that the optimization measurement techniques, especially the calibration of the sensor with range considerations, resulted in an improvement in the pressure measurements. The measurement error percentage improved from 8.79 % (calibrated without range consideration) to 7.10% (calibrated with range consideration).

Thirdly, the experiments showed that the calibration was useful for maintaining the same measurement error. This is important since the measurement error tends to increase after a period of time. Fourthly, using the IPPD with the optimization techniques to estimate body weight, it was found that the percentage of error was 5.07 % from the actual weight. This is a significant improvement since the percentage of error reached 9.2 % using the novel EMED system and 9.06 % using the current insole system without the mentioned optimization techniques.

It is hoped that the findings of this research will benefit society based on the fact that plantar pressure measurements could potentially play an important role as key health indicators. In addition, this research will contribute to the industrial sector by providing an IPPD with optimization measurement techniques that can produce precise measurements of underfoot pressure, in terms of estimating body weight, as compared to existing commercial devices, such as the novel EMED system. Future work should focus on improving the IPPD further either by adding more pressure sensors that are strategically placed or by implementing an algorithm to the system that could predict any occurrence of foot complications based on current underfoot pressure data.

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