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Image processing based foot plantar pressure distribution analysis and modeling

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Article Info

ABSTRACT

Although many equipments and techniques are available for plantar pressure analysis to study foot pressure distributions, there is still a need for mathematical modelling references to compare the acquired measurements. In order to derive formulas in this concern, this research proposes a measurement-based method which adopts the reference measured parameters such as; the weight of a subject, contact-area size, age, and the pressure level distribution over a plantar image captured by the EMED plantar pressure system. The proposed analysis and algorithm were verified by a group 79 volunteers through data collection with four various measurement conditions. Three mathematical modelling equations have been proposed that describe the relationships between the foot plantar pressure levels and the subject's body mass, foot size, and age. The modelling of foot plantar pressure could be useful for various applications such as gait analysis, hospitals, clinics, custom shoe making, and early detection of ulceration in the case of diabetic patients.

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1.   INTRODUCTION

Plantar pressure distribution analysis is an increasingly popular research area in the study of foot diagnosis and gait evaluation. There are many types of plantar pressure measurement systems that are commercially available and have different constraints such as the high cost, and the data linkages as collected by the computer [1].

Previous studies have classified plantar pressure measuring equipments according to the sensing method used: images or electronic sensor [2, 3]. The ink-based plantar pressure system may not be able to acquire data dynamically, whereas the image-based system derives the plantar pressure distributions from the light intensity of a grayscale image captured through a camera fixed within [4]. Despite some active research in the area circa 1980s, the use of such devices were not widespread due to the limitations in resolution and system cost. However, information extracted from captured images are considered as a useful parameter in gait analysis. One study described the differences for a joint ankle's angles through the use of static and dynamic plantar images [5]. A relationship between foot structure and the static balance system is was studied to investigate a child's footprint image in [6]. Based also on the image measurements, [7] found the

weight bearing area ratio of the foot arch. An individual's plantar shape was considered as a unique parameter for personal identification in [8]. Shine et al. proposed a method to find the relation between the deformation of the foot plantar skin and the gait stability based on foot plantar image [9].

Nowadays, the majority of researchers who adopts the plantar pressure to analyze the data are using electronic sensor based systems. These sensors can be in different configurations such as; mat [10-12], in-sole [13, 14] and treadmill [15, 16]. Conventionally however, these sensors lack the required resolution to measure or predict the pressure of small regions, such as the toes. The distribution of luminance values in greyscale plantar images captured while a subject is walking, was studied and described in the work of [17]. Artificial true color image conversion in RGB system to display the dynamic pressure distribution of plantar pressure was addressed in [18]. Two related research articles that may contribute to the research in this work are [19, 20]. This is because they investigated the distribution of plantar pressure and compared their results with the output from an EMED system.

During regular movement, the main plane of interaction between a human subject and his/her surroundings is represented by the feet. Generally, individuals pay little attention to their feet, but performing activities such as standing for long periods, running quickly or carrying heavy loads can result in physical strain. Thus, foot problems must be diagnosed as early as possible to prevent injuries. Plantar pressure distribution may vary between men and women due to differences in plantar loadings [21, 22]. Foot ulceration is the main consideration for patients with diabetes since this may occur when there is excessive foot plantar pressures in a particular area of the foot [23-26]. The goal is to create an algorithm has the ability to formulate the distribution pattern of plantar pressure accurately and reliably.

2. RESEARCH METHOD

The proposed work Figure 1 for modelling the plantar pressure distribution consists of:
a)   Acquiring data from EMED plantar pressure device.
b)   Image processing module.
c)   Data selection and sepeatability test algorithm.
d)   Data classification and analysis.
e)   Modeling algorithm.

2.1. Data Acquisition through EMED Plantar Pressure Device

This work is based on the plantar pressure images captured by the EMED system and proposes a new method to formulate the relationships between each subject's body mass, foot size, and age with the plantar pressure distribution. This is needed to establish the associated modelling equations. The purpose of this study is to analyze and evaluate the forefoot and rear foot plantar pressures for both feet at a stable standing condition between normal and diabetic patients. Also, the validity of using such data in the prediction of foot ulceration was examined using MATLAB's image processing functions and the in-sole segmentation concept.

Four categories of foot planter measurements have been implemented over 79 participants aged between 20-63, which contributed to 329 feet data to the analyses. The data (using three steps from three walking trails) was recorded using an EMED-X (Novel GmbH, Munich, Germany) pressure platform. The experimental setup and EMED display can be seen in Figure 2. Data captured from the EMED system may be incomplete, contain duplicates, or measurement errors. Data cleaning using MATLAB is performed to correct these errors.

The platform has a spatial resolution of four sensors per cm2 and was sampled at 70Hz. Pressures were analyzed using the Novel multimask software (version 13.3.65) in five distinct regions of the foot based on functional regions/touch areas investigated: the heel, midfoot, forefoot, lesser toes and hallux. The peak pressure from the three trials in the touch areas was used in the analysis as the outcome variables. The test categories are:
a.   Dynamic (normal walking, 3 steps and repeated 3 times)
b.   Dynamic with load (normal walking while carrying load, 3 steps and repeated 3 times)
c.   Static (Standing, repeated 3 times)
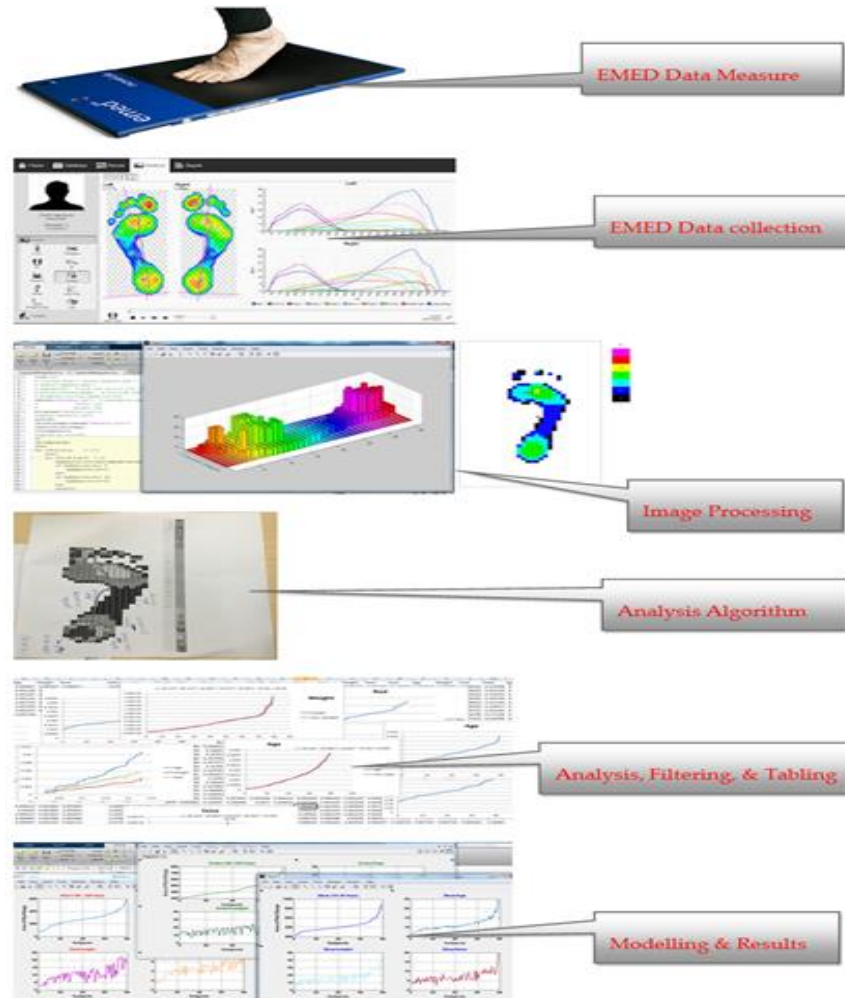d.   Static with load (Standing, repeated 3 times)

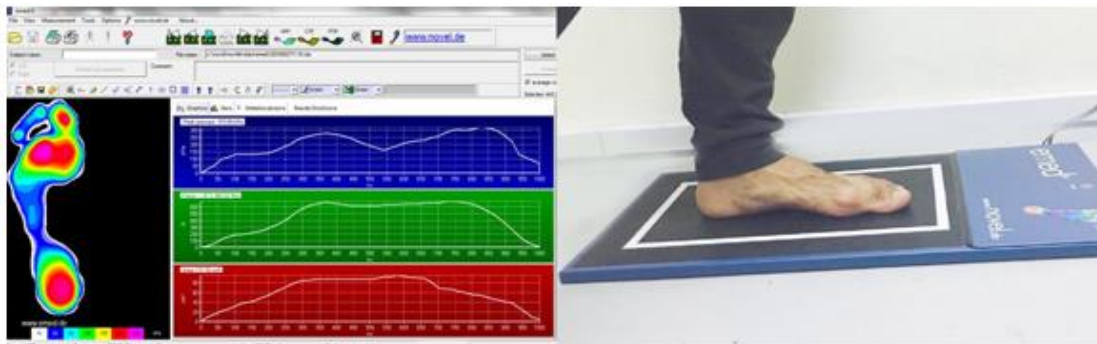Figure 1. Methodology diagram for the proposed plantar pressure

Figure 2. Experimental setup using EMED device screen (left) and platform (right)

2.2. Participant Information

A total of 79 healthy subjects were enrolled in this study. The mean age, body mass and height were 35 years (range of 20–63 years), 84 kg (range 50–132 kg) and 168.83 cm ± 10.696 cm respectively. All subjects were fully informed of the research to be performed and have provided written consent form prior to testing. The first part of recruitment activity was to invite potential participants to attend a foot exam which is accompanied by a lifestyle questionnaire. The purpose of the foot exam was to ensure no participants had lower limb ailments. In addition, the participant must not have any history of previous lower

limb surgery or ulceration or demonstrate other neurological or orthopedic impairments such as severe knee deformations or foot deformities that would adversely affect their gait. This is important since the inclusion criteria requires that all subjects were in good general health prior to and during assessment.

2.3. Image Processing Module

Initial preliminary arrangements have been carried out on the foot plantar data obtained from the EMED platform. For instance, these may involve placing data into rows and columns in a table format as a structured data for further analysis in Microsoft. For further analysis and processing, the MATLAB software was used. Relationships were explored among between the pressure measurements as classified by the image processing algorithm (where pressure over the insole area have been divided into 7 levels) and the continuous predictor parameters (body mass, foot size, age and the gender). The data was inspected in terms of repeatability pooled for left and right feet to increase statistical power and avoid missing relevant feet. The image processing program has been designed to implement several processes on the images obtained from the EMED platform so as to get the suitable interpretation of the image that shows the pressure distribution over the insole plantar for further analysis.

The image captured by EMED is conveyed to the computer by custom MATLAB software developed for this purpose. The image processing algorithm begins by creating a mask to segment only the feet of the acquired image to perform background removal. Then, based on a specific threshold value, the algorithm converts the image from RGB format into Index image format to be able to specify the values of the pressure levels. Each are represented by different colors, where each color refers to a specific range of values. The steps for this process have been illustrated in Figure 3.
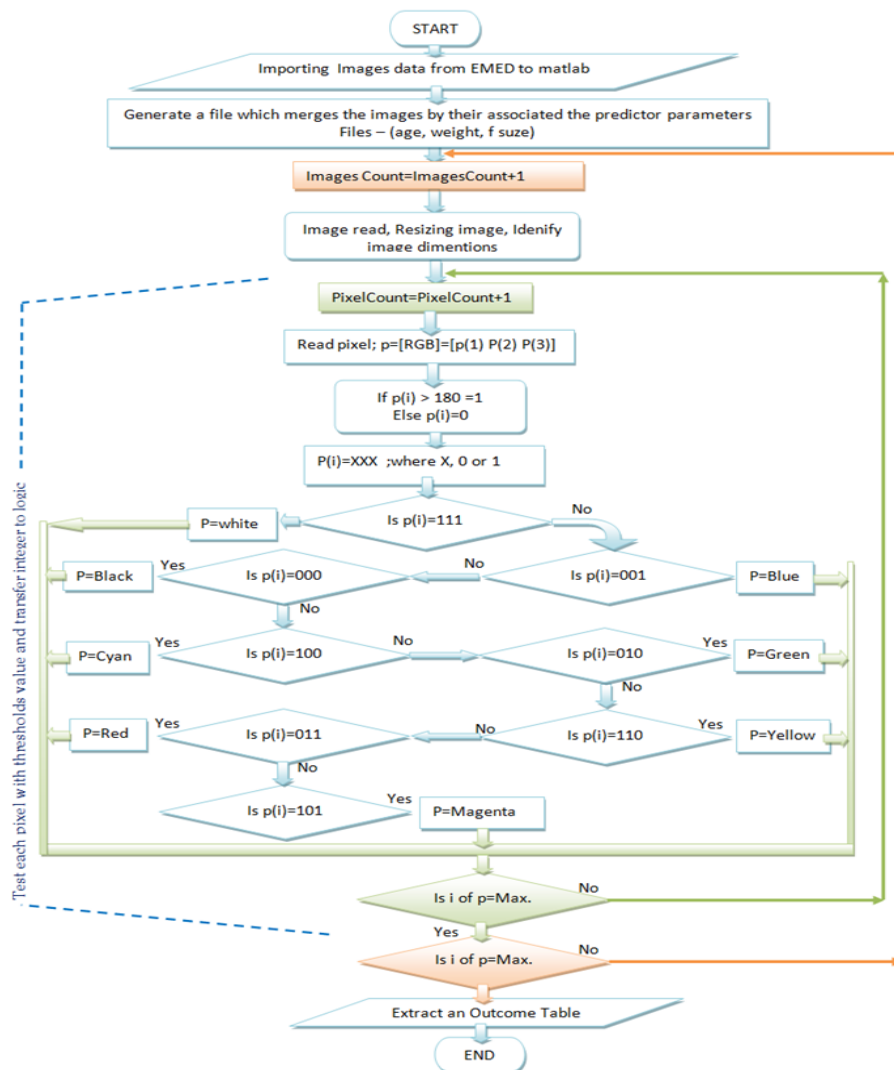

Figure 3. Image processing algorithm

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The seven level ranges as well as the Plantar Pressure Ranges (PPR) of the pressure over the in-sole area have been described in Table 1. Based on the analysis algorithm for the plantar pressure distribution, the proposed image processing outcome can be displayed as a 3-D representation of one subject, as shown in Figure 4.
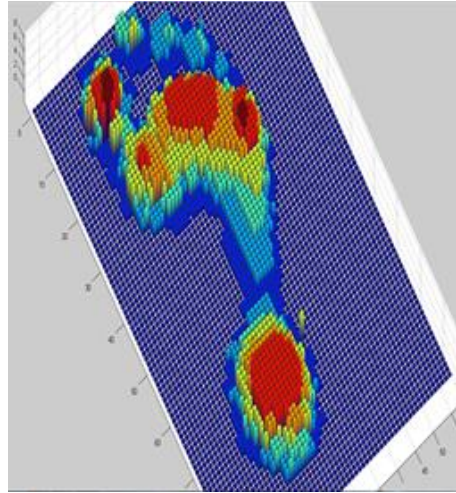

Figure 4. 3D Image processing outcome of one subject test

Table 1. List of Colors with Associated Range of Pressure Measurement

Weight's level	Pressure indicator	Pressure Range (kPa)
7	Magenta	>300
6	Red	220~295
5	Yellow	150~215
4	Green	100~145
3	Cyan	60~95
2	Blue	30~55
1	Black	10~25

2.4. Data Selection and Test-Retest Reliability / Repeatability

The data selection depends on the results of the Test-Retest Reliability which measures test consistency, the reliability of a test measured over time. In other words, given the same test twice or more to the same subject (person) at different times, but under the same conditions to see if the EMED measurements produced are the same to select one of the data categories.

This research adopts the second category, which is the dynamic with load category, according to the repeatability results for the four measurement categories that were shown in Figure 5. The results of this process which were applied to the three measurement categories (Dynamic (walking), Dynamic with load, Static (standing), and static with load) can be shown in Figure 6. Therefore the selecting of DL based on the lower fluctuating data that results from the following equation:

$$P_i = \sum_{i=1}^{k} Mag_i * 7 + Red_i * 6 + Yel_i * 5 + Gr_i * 4 + Cy_i * 3 + Blu_i * 2 + Blk_i \qquad (1)$$

where i, (1-k) represents the number of subjects and Mag_i, Red_i, Yel_i, Gr_i, Cy_i, Blu_i, Blk_i represents the pressure levels starts from the maximum respectively.

```
                              START

                    import data from excel to matlab

    Generate a weighted equation according to pressure level measurement;
```

$$P_i = \sum_{i=1}^{7} Mag_i * 7 + Red_i * 6 + Yel_i * 5 + Gr_i * 4 + Cy_i * 3 + Blu_i * 2 + Blk_i$$

Where i, referred to the subjects (person's index)

```
                    select data and data filtering
                    (Delete non numeric values)

                    Reshape P_i into C(3,i/3)

                    Measure the Range of
                    variaition = peak2peak(C);

                    Reshape into C(4* i/4) &
                    check D,DL,S,SL

                    Check
                    Repeatability

                    Data Drawings

                              END
```
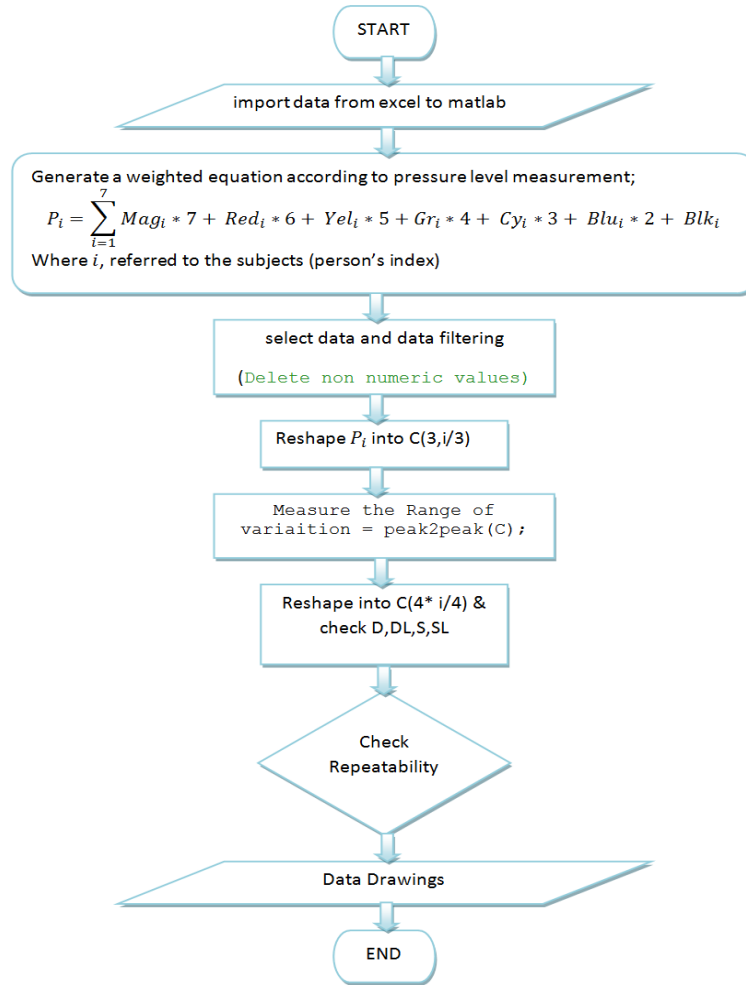
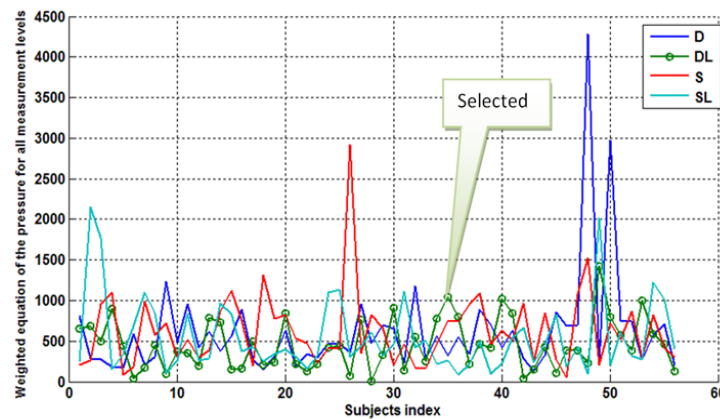Figure 5. Data selection and repeatability test diagram

Figure 6. Selecting a category (DL) from the results of the weighted equation of the pressure for all
measurable levels

3. RESULTS AND ANALYSIS

3.1. Modeling and Algorithms

Mathematical formulas or models called algorithms may be applied to the data to identify relationships among the variables. In general terms, models may be developed to evaluate a particular variable in the data based on other variable(s) in the data, with some residual error depending on model accuracy (i.e. Data = Model + Error). In this research, a statistical technique was considered to measure relationships between the potential predictor parameters (age, foot size, body mass, gender, diabetes) and the pressure distribution levels. After the image processing and the data selection stages, regression analysis was used to model whether a change in advertising (independent variable;age, foot size, and the body mass) explains the variation in the plantar pressure distribution levels (dependent variablePi). In mathematical terms, Pi (PPR) is a function of (age, foot size, and the body mass). It may be described as:

$$P_i = a * age + b * fsize + c * weight + d + error \qquad (2)$$

Where the model is designed such that (a, b, c, and d) minimizes the error when the model predicts P_i, for a given range of values of (age, foot size, and the body mass). The research analysts also attempted to build models that are descriptive of the data to simplify analysis and relative results. Each pressure level range for all the subjects has been analyzed with the three independent parameters (age, foot size, and the body mass) to evaluate the relationship and to interpret the variation. The basis used for data analysis, which is the number of pixels at each pressure level, has been formulated as in (3).

$$Color_{i,j} = \frac{Color_{i,j} * (\frac{p_{maxj} - p_{minj}}{2})}{Total_{i,j}} \qquad (3)$$

Where i, j represent the subject and the color are indexed respectively. The Total (i, j), given by (4).

$$Total_{i,j} = \sum_{j=1}^{7} Color_{i,j} * (\frac{p_{maxj} - p_{minj}}{2}) \qquad (4)$$

The relative four figures for each pressure level ($Color_{i,j}$) of the subject foot planter was based on the selected colors sort. They are often sorted in ascending order to simplify the interpretation and evaluate the data as can be shown in Figure 7.

3.2. Body Mass and Plantar Pressure Distribution.

The effects of the pressure applied to the foot can be investigated to study the relationship between the body weight and the plantar pressure distribution over the insole area. The analysis in this research, finds that a nonlinear polynomial equation can be considered to govern this relation. The relation formula that has been conducted is in (5), while the graph which interprets that formula can be shown in Figure 8.

$$W(p) = a1p^4 + a2p^3 + a3p^2 + a4p + a5 \qquad (5)$$

where the a1,a2…a5, are the coefficients of the weight formula.

The result of Figure 9 shows that there are several measurement points that have fluctuated above the modelled curve (in red). Upon further investigation, it is found that these data points subjects belong to subjects with medical problems. Therefore, a more detailed analysis is required to process such data. As a result, efforts have been made to solve this issue through adopting one of two methods. Either abnormal subjects are excluded from the study or they are asked to perform a retest with the other foot which is assumed to be healthy. The three effective continuous predictor parameters (body mass, foot size, and age) have been analyzed to extract their related modelling equations as they have a direct effect on dynamic peak plantar pressure in healthy subjects. The relations were formulated for best fitting with the measured data over one base of variation represented by the index of the total average pressure levels in (6).

$$Pt_i = \sum_{i=1}^{k} Mag_i * p_7 + Red_i * p_6 + Yel_i * p_5 + Gr_i * p_4 + Cy_i * p_3 + Blu_i * p_2 + Blk_i * p_1 \qquad (6)$$

where Pt_i, denote the total pressure of a subject denoted by the index (i), while the the p_1, p_2, p_7, denote the average level of the associated pressure that were presented in Table 2. The developed modelling equations of the three considered predictor parameters are listed in Table 2, while the curves of the parameters' relations are shown in conure 9.
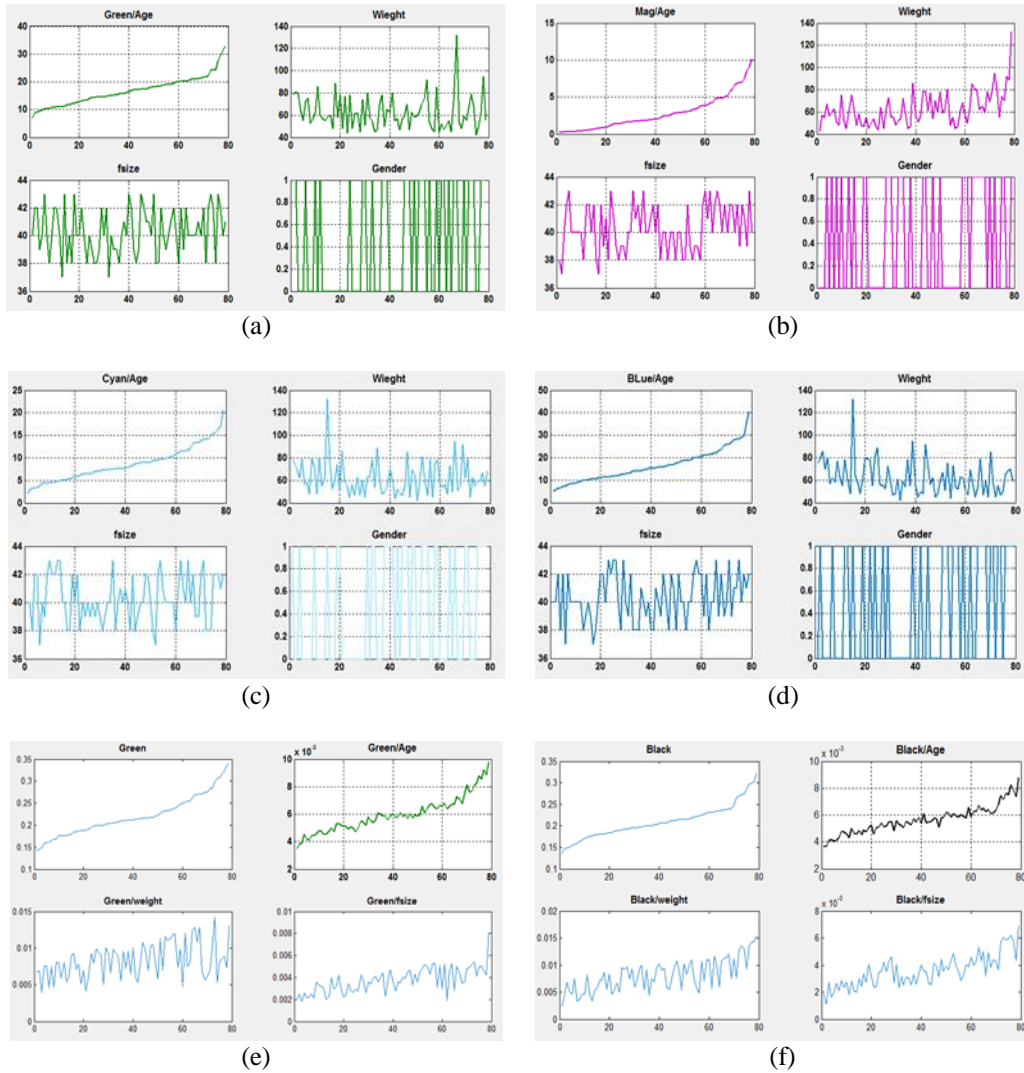
Figure 7. The 7 plantar pressure range levels with each level in an ascending order
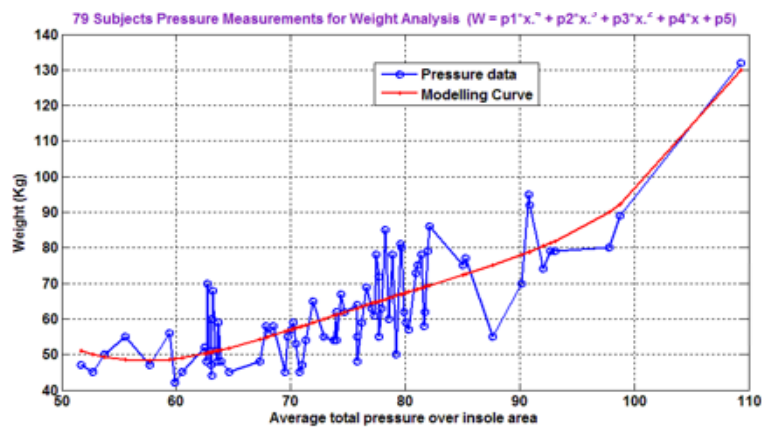versus a number of subjects

Figure 8. The relationship between the body mass and the total weighted plantar pressure over all the
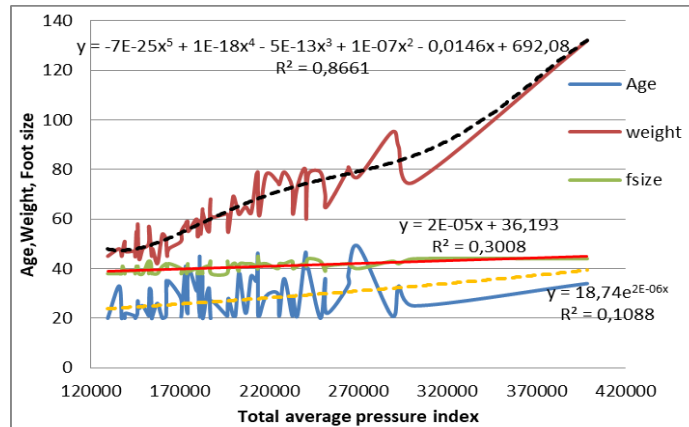considered subjects

Figure 9. The modelling equations for the three considered parameters (body mass, foot size and age) over the total average pressure range

Table 2. The Developed Model Equations of (Body Mass, Foot Size, and the Age)

Parameter	Modelling equation	Model Name	(R^2)
Age (years)	$Age(Pt) = 18.74e^{2E-06x}$	Exponential	0.1088
Body mass (Kg)	$Weight(Pt) = -7E - 25Pt^5 + 1E - 18Pt^4 - 5E - 13Pt^3 + 1E - 07Pt^2 - 0.0146Pt + 692.08$	Polynomial	0.8661
Foot size (cm)	$Fsize(Pt) = 2E - 05Pt + 36.193$	Linear	0.3

where R^2 represents the coefficient of determination, which is a number that indicates the proportion of the variance in the dependent variable that is predictable from the independent variable.

3.3. Software Graphical User Interface (GUI)

The software GUI was designed for the Microsoft Windows environment and implemented using MATLAB code. The main purpose of the GUI design is to validate and visualize the relationships between the actual values of the three considered parameters in this work: Age, Body mass and Foot size and between the predicted values of those parameters as a result of the proposed model. The MATLAB code is divided into two branches: the data accessing branch and the user input branch.

The designed GUI display contains "Static Texts" for naming and titles, "Edit Texts" for data input and real-time editing, "Check Boxes" for selecting between two options, and two X/Y axes displays to monitor the 3-D image as a geometric representation of data as well as the EMED attained image. The proposed GUI design for the work can be seen in Figure 10.
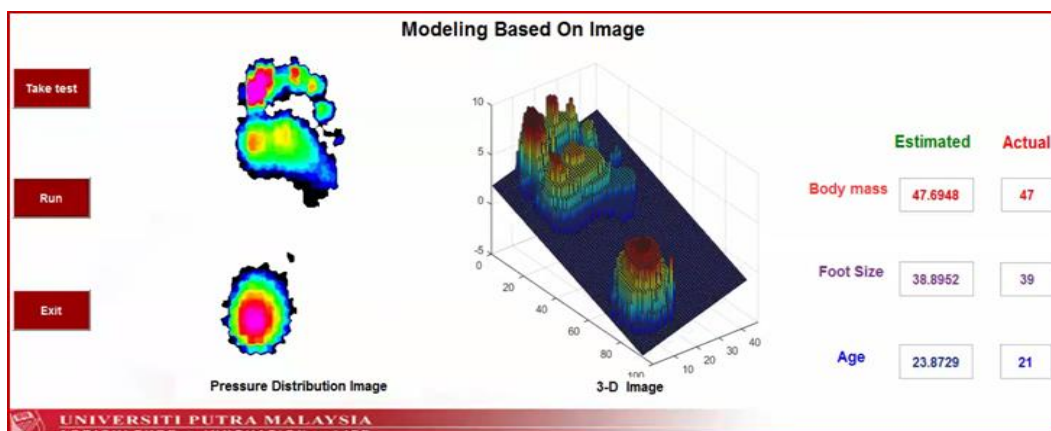

Figure 10. The proposed Graphical User Interface (GUI)

The steps of the GUI functionality can be described as follows:-

a)   The EMED created image is imported into the designed MATLAB image processing program.
b)   Once the image appears in one of the two displays, the actual data stored (containing parameters such as age, weight, foot size) are also displayed.
c)   Next, the Run button is pressed. This will start the algorithm and calculate the estimated values of the subject's Age/Weight/Foot size as well as show a 3-D image that is a geometric representation of the data.

4.   CONCLUSION

Although many equipments and techniques are available for plantar pressure analysis to study foot pressure distributions, there is still a need for mathematical modelling references to compare the acquired measurements. In order to derive formulas in this concern, this research proposes a measurement-based method which adopts the reference measured parameters such as; the weight of a subject, contact-area size, age, and the pressure level distribution over a plantar image captured by EMED plantar pressure. The proposed analysis and algorithm was verified by a group 79 volunteers through data collection with four various measurement conditions. Three mathematical modelling equations have been proposed that describe the relationships between the foot plantar pressure levels and the subject's body mass, foot size, and age. The modelling of foot plantar pressure is valuable for gait analysis, hospitals, clinics, custom shoe making, and early detection of ulceration in the case of diabetic patients. For future work, more data analysis is required. It is then believed that new approaches, such as Nonlinear Autoregressive Network with Exogenous inputs (NARX), could then be used to extract the modelling equations.

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