XIX IMEKO World Congress
Fundamental and Applied Metrology
September 6–11, 2009, Lisbon, Portugal

PLANTAR PRESSURE DISTRIBUTION MEASUREMENTS: AN APPROACH TO DIFFERENT METHODS TO COMPUTE A PRESSURE MAP

Satu Kärki [1], Jukka Lekkala [1], Tiina Kaistila [2], Heikki-Jussi Laine [3], Heikki Mäenpää [3], Hannu Kuokkanen [4]

[1] Department of Automation Science and Engineering, Tampere University of Technology, Tampere, Finland, satu.karki@tut.fi, jukka.lekkala@tut.fi
[2] Physical and Rehabilitation Medicine Unit, Tampere University Hospital, Tampere, Finland, tiina.kaistila@pshp.fi
[3] Department of Orthopaedics and Traumatology, Tampere University Hospital, Tampere, Finland, heikki-jussi.laine@pshp.fi, heikki.maenpaa@pshp.fi
[4] Department of Plastic Surgery, Tampere University Hospital, Tampere, Finland, hannu.kuokkanen@pshp.fi

Abstract – A variety of methods to process plantar pressure distribution data are available. The aim of this study was to compare alternative methods to compute a pressure map from collected data. Correlation coefficients between the pressure maps were used to ascertain whether the pressure maps contain the same information. The interface pressure data of twenty subjects was collected for the data analysis with commercial GAITRite® walkway system. Stationary pressure distribution and pressure distributions at normal and fast walking speeds were recorded with each subject. The data was analyzed with Matlab® software instead of the GAITRite® software. Three alternative pressure maps (cumulative, maximum and average pressure maps) were computed from the measured data. The cumulative pressure map shows the sum of all pressure values detected with a single sensor. The maximum and average pressure maps, instead, present the maximum and mean pressure values of each sensor. The results of this study indicate that with stationary pressure distribution, both cumulative and maximum or average pressure maps should be presented. With pressure distributions measured at walking, instead, any of the three computing methods can be used.

Keywords: pressure distribution, plantar pressure, pressure map.

1. INTRODUCTION

The mechanical stress between foot and shoe has a clinical relevance to various foot pathologies [1]. Abnormally high plantar pressures, especially in people with sensory deficits of the lower limbs, have been linked with pressure ulcers [2]. The pressure ulcers, also known as pressure sores and decubitus ulcers, occur when tissue is compressed under pressure. An excessive mechanical stress on the plantar area is generally accepted as a major risk factor [3]. High pressures occur due to the poor load distribution as a result of reduced sensitivity of the foot [4]. At particular risk are heavily loaded regions overlying bony prominences, such as under the metatarsal heads, where the majority of plantar ulcers occur [3]. Most common cause for foot deformities and pressure ulcer formation in feet is diabetic neuropathy.

Reduction of peak plantar pressure on foot during walking has become a primary focus on prevention and treatment of pressure ulcers [2]. Information about the loading of the anatomical structures of the foot is obtained and thus the gait disorders can be attributed to a specific region of the foot [5]. The pressure can be relieved e.g. with suitable shoes or insoles. Also, the plantar pressure mapping technology can be utilized when evaluating the possible effect of specialized physiotherapy or a surgery operation by measuring the pressure distributions before and after the treatment. In addition, gait analysis is a useful tool in the design and development of prosthetic devices [5].

A lot of opinions have been stated concerning the best descriptor of interface pressure. Maximum and average pressures are often reported. The average pressure is the mean of all the sensor values, whereas the maximum pressure is the highest individual sensor value [6]. The most commonly reported pressure value is the single maximum pressure recorded at critical areas of body [7]. Stinson *et al.* concluded that the average pressure is a more stable measure and gives a better overall picture of interface pressure in disabled people than maximum pressure, which is a single sensor value [6].

The interface pressure is presented here as a pressure map, as a colour-coded contour map, instead of presenting the pressure as a single value. The pressure map can be viewed as a function of time (movie) or a static pressure map can be calculated. A presentation of the pressure map as movie is useful especially when the gait pattern and pressure distribution during walking are evaluated. To compare different data analysis methods to process the pressure distribution data, three alternative pressure maps (cumulative, maximum and average pressure maps) were computed in this study. Correlation coefficients between the pressure maps were used here to ascertain whether the pressure maps contain the same information. If the alternative methods provide similar results, pressure maps computed with various methods and presented in separate references could be compared. Also, only one of the methods could be used in measurements of future applications.

The structure of this paper is as follows. Section 2 presents the measurement system used in this study as well as the data collection and data analysis operations carried out. In Sections 3 and 4, the results obtained are reported and discussed, respectively. Section 5 concludes the study.

2. METHODS

2.1. Measurement system

We used the commercial GAITRite® system version 3.8 to measure the gait parameters and corresponding interface pressures. The GAITRite® walkway is 0.6 cm thick and has an active area of 488 cm x 61 cm [8]. It consists of eight separate sensor pads, each consisting of 48 x 48 individual sensor elements. In total 18 432 resistive sensors are arranged in a 384 x 48 grid pattern. Each sensor forms a 1 cm x 1 cm square, and the pitch of the sensors is 1.27 cm [8]. Sampling rate of 60 Hz was used in the interface pressure measurements.

The pressure exerted by a foot activates the sensors as the subject walks over the walkway [8]. The walkway detects the geometry of a step in a two dimensional space and also senses the vertical component of pressure exerted by the subject [8]. The pressure values presented by the GAITRite® software are normalized and expressed as a percent of the maximum pressure [8]. These values are then divided into six switching levels. The switching levels are thus relative pressure values and cannot be converted into normal pressure units (e.g. Pa or mmHg).

The GAITRite® software does not present the pressure values for each sensor separately. The footprint is divided into twelve trapezoids, six located in the medial side of the footprint and six in the lateral side. Pressure parameters presented by the software (sectional integrated pressure over time, peak time, area and peak pressure) are calculated for these trapezoids.

The measured files were stored as text files with special GAITRaw® software for further analysis. The text file has four columns consisting of scanning times, x coordinates, y coordinates and relative pressure level values (switching levels). The x and y coordinates define the location of the activated sensor in the sensor pad; the x coordinate can vary from 1 to 384 and the y coordinate from 1 to 48.

2.2. Data Collection

The interface pressure data of twenty subjects was collected for the data analysis. All the subjects were young healthy adults with normal physical development and no history of previous gait disorders. Characteristics of the subjects are shown Table 1. Each subject was assigned with an identification number to preserve confidentiality.

The subjects were bare footed during the data collection. To familiarize the subjects with the test procedure, they were allowed to practice the walking over the electronic walkway before the measurement. Also, the walkway was located so that the subject was able to start walking a few steps before the walkway and develop a normal gait pattern before stepping on the walkway.

Three separate pressure distributions were recorded: relative static pressure distribution, relative pressure distribution at normal walking speed and relative pressure distribution at fast walking speed. The static pressure measurement provides information on the pressure distribution during stationary standing; the subject was asked to stand stationary on the walkway and a 10 seconds section of data was recorded. The GAITRite® system is intended to take dynamic measurements and it does not store the data if the subject only stands on the walkway. Thus the subject had to walk over the walkway after the stationary standing. The section of the relative static pressure distribution was separated from the data for further analysis. The two latter dynamic measurements were carried out to find out whether the walking speed affects the results of correlation analysis.

Table 1. Characteristics of the subjects. Values are presented as the mean ± standard deviation with the range in parenthesis. BMI stands for Body Mass Index (Body mass/Height^2).

No. of subjects	20 (10 male)
Age (years)	23 ± 3 (19-30)
Height (cm)	173 ±10 (158-192)
Body mass (kg)	66 ± 14 (49-90)
BMI (kg/m^2)	21.9 ± 3.1 (16.2-28.1)

2.2. Data analysis

The data was analyzed with Matlab® software instead of the commercial GAITRite® software. The way the GAITRite® software presents the results of pressure measurements is rather limited. It is more useful to see the relative pressure values as individual sensor signal values than values calculated for the trapezoids. The use of Matlab® software also provides more versatile ways to process the pressure data.

In this study, three alternative methods to compute a relative pressure map were compared: cumulative pressure map, maximum pressure map and average pressure map. In the cumulative pressure map (Fig. 1), the sum of all relative pressure values measured with a single sensor is calculated. The cumulative pressure p_{cum} of a single sensor is:

$$p_{cum} = \sum_{n=1}^{k} p_n \,, \tag{1}$$

where k is the total number of scanning times. Instead, the maximum pressure map (Fig. 2) determines the maximum relative pressure p_{max} of each sensor. In the average pressure map (Fig. 3), the mean of all relative pressure values measured with a single sensor element is calculated. The average pressure p_{avg} of a single sensor is:

$$p_{avg} = \frac{1}{k}\sum_{n=1}^{k} p_n \qquad (2)$$

The relative pressure distribution data presented in Figs. 1-3 is measured from a 22-years-old male (height 188 cm and body mass 74 kg) during stationary standing. The horizontal axes in the pressure maps show the x coordinate and the vertical axes the y coordinate. The colours in the pressure maps and the corresponding relative pressure values are shown in the colour bars located on the right side of the figures. The unit of pressure is the relative switching level. Also, the pressure values of the single activated sensors are marked in the figures. Especially in the cumulative pressure map, very high relative pressure values may appear and thus it is useful to see the value also as a number. Since the cumulative pressure map is calculated as a sum of all individual pressure values measured with a single sensor, the cumulative pressure values in the stationary pressure map are much higher than in the maps of the dynamic measurements due to the duration of the measurement.

Fig. 4 shows an example of maximum pressure maps computed from the data measured at normal (velocity 160.9 cm/s) and fast (velocity 263.9 cm/s) walking speeds. The walking velocities are obtained from the GAITRite® software. The data is measured from the same subject (22-years-old male) as the data in Figs. 1-3. Otherwise, similar markings are used as in the previous figures.

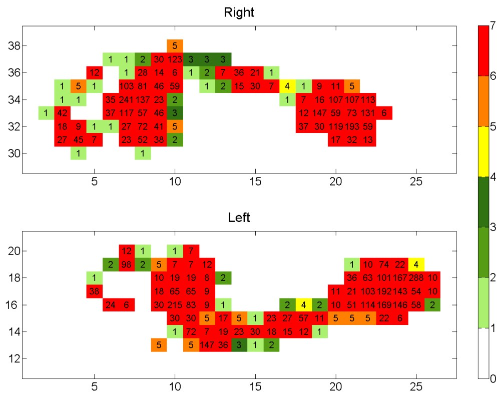

Fig. 1. Cumulative pressure map shows the sum of all pressure values measured with a single sensor.

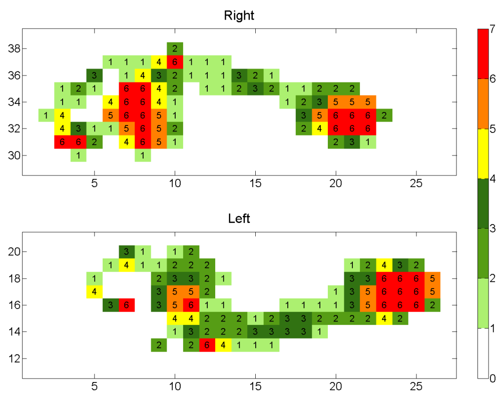

Fig. 2. Maximum pressure map determines the maximum of the values measured with a single sensor.

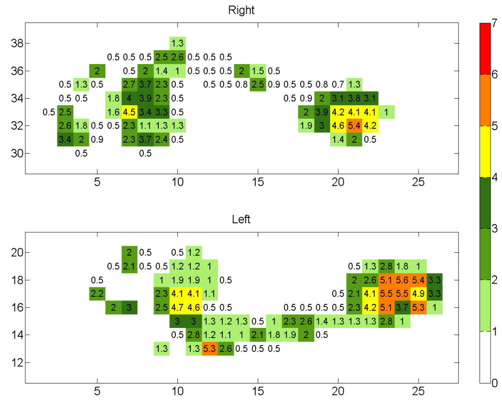

Fig. 3. Average pressure map determines the mean of the values measured with a single sensor.

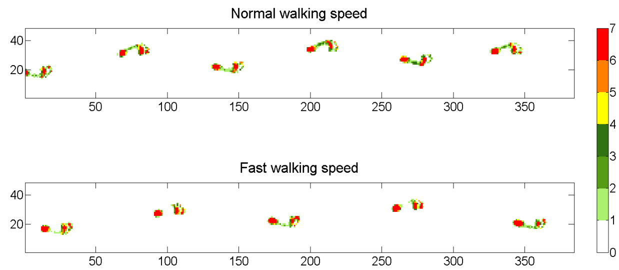

Fig. 4. Maximum pressure maps computed from the data measured at normal and fast walking speeds.

Correlation coefficients were used to ascertain whether the pressure maps contain the same information. In the literature, correlation coefficient is used e.g. as an objective comparison criterion for evaluating the quality of image restoration by comparing the original image to the restored one [9]. The same method can be used here to compare the pressure maps calculated with alternative methods. The correlation coefficient between two pressure maps $x(i, j)$ and $y(i, j)$ can be defined as [10]:

$$\rho_{xy} = \frac{C_{xy}}{\sigma_x \sigma_y} = \frac{\sum_{i=1}^{N}\sum_{j=1}^{M}\left(x(i,j)-\mu_x\right)\left(y(i,j)-\mu_y\right)}{\sqrt{\sum_{i=1}^{N}\sum_{j=1}^{M}\left(x(i,j)-\mu_x\right)^2 \sum_{i=1}^{N}\sum_{j=1}^{M}\left(y(i,j)-\mu_y\right)^2}}, \qquad (3)$$

where C_{xy} denotes the covariance between $x(i, j)$ and $y(i, j)$, σ_x is the standard deviation of $x(i, j)$, σ_y is the standard deviation of $y(i, j)$, μ_x is the mean value of $x(i, j)$ and μ_y the mean value of $y(i, j)$ [10]. The indices $i = 1 \ldots N$ and $j = 1 \ldots M$ refer to the x and y coordinates of the sensors in the pressure maps, and where N and M are the total numbers of sensors in the x and y directions, respectively. The correlation coefficient is 1 if the two pressure maps are identical, and less if some differences exist [10]. The value $\rho = 0$ implies independence while the interdependence increases until $|\rho| = 1$. Here the correlation coefficient is calculated with Matlab® function R = corrcoef(x,y). The function returns a matrix of correlation coefficients calculated from vectors *x* ad *y*.

Correlation coefficient between maximum and cumulative pressure maps (AB), correlation coefficient between maximum and average pressure maps (AC) and correlation coefficient between cumulative and average pressure maps (BC) were determined from the data of each subject. With the pressure distributions measured at walking, the entire relative pressure maps were used in the calculation of the correlation coefficients. With static pressure distributions, instead, only the period of stationary standing on the walkway was used.

3. RESULTS

The correlation coefficients between the alternative pressure maps were computed from the data of each subject, see Fig. 5. The correlation coefficient between maximum and cumulative pressure maps (AB) is shown with black, correlation coefficient between maximum and average pressure maps (AC) with white and correlation coefficient between cumulative and average pressure maps (BC) with grey colour. Test I corresponds to the relative static pressure distribution measurement, test II to relative pressure distribution measurement at normal walking speed and test III to relative pressure distribution measurement at fast walking speed. Correlation coefficient on the vertical axis is shown with range from 0.6 to 1 to distinguish differences between the correlation coefficients. The horizontal axis shows the identification number of the subjects.

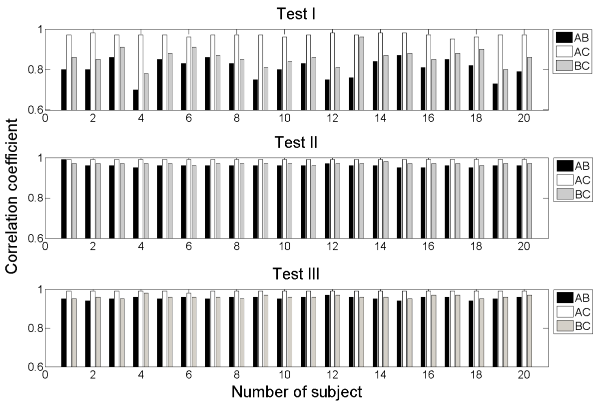

Fig. 5. Correlation coefficients computed from the pressure distribution data measured with the subjects.

With the static pressure map, the highest average correlation coefficient was found to be between the maximum and average pressure maps (AC = 0.97 ± 0.01). The correlation coefficients between maximum and cumulative pressure maps (AB = 0.81 ± 0.05) and between cumulative and average pressure maps (BC = 0.86 ± 0.04) were lower.

At normal walking speed all the correlation coefficients had almost the same magnitude. The average correlation coefficient AC = 0.99 ± 0.00 had the highest value even though the average correlation coefficients AB = 0.96 ± 0.01 and BC = 0.97 ± 0.00 were almost equal. At fast walking speed the results were similar, AC = 0.99 ± 0.00, AB = 0.95 ± 0.01 and BC = 0.96 ± 0.01, respectively.

4. DISCUSSION

With the static pressure distribution data, the correlation coefficients between maximum and cumulative pressure maps and between cumulative and average pressure maps were lower than the correlation coefficient between maximum and average pressure maps. The cumulative pressure map adds information on the concentration of pressure on the plantar area over time when compared to the maximum or average pressure maps. The maximum and average pressure maps, instead, reveal almost the same information. Hence, with the static pressure measurement, both cumulative and maximum or average pressure maps should be presented to evaluate the plantar pressure distributions.

With the data measured at normal and fast walking speeds, the correlation coefficients between the three alternative pressure maps had similar magnitudes. Therefore, to present the pressure distribution data measured at walking, any of three pressure maps can be used. Differences between the correlation coefficients computed from the data measured at normal and fast walking speeds were not found.

The pressure measured by the GAITRite® system is presented as a switching level. The switching level is a relative pressure value and the maximum pressure is always scaled at 6. The drawback of the GAITRite® system is thus in the way it presents the pressure values. Hence, it is not the best possible system to be used in the data collection. The way to present the pressure values as switching levels presumably originates from the elimination of the effect of body weight variations from person to person. Tibarewala & Ganguli used the same method with their system [11]. Also, the sensors in the walkway are quite large at 1 cm x 1 cm with the pitch of 1.27 cm. The sensor always measures the average pressure over the whole sensor surface and thus for small anatomic structures a large sensor underestimates the real pressure values [5].

A variety of devices for plantar pressure distribution measurements are commercially available. For instance, Rahman *et al*. used a commercial Tekscan F-Scan in-shoe pressure sensor to measure the pressure [12]. The sensor consists of 960 resistive sensing elements with a spatial density of 4 elements per square centimetre providing an output pressure with a range from 1 to 150 PSI (from 6.9 kPa to 1034 kPa) [12]. Zequera *et al*. measured the pressure distribution with a commercial Parotec pressure registration system containing 24 sensors [13]. The Parotec is an electronic system used for measuring the pressure distribution on the plantar surface of the foot within the shoe while a subject is standing or walking [13]. However, despite the system used to collect the data, the correlation analysis carried out here can be used to compare the pressure maps computed with alternative methods.

5. CONCLUSIONS

In this study, three alternative methods to compute a pressure map were compared. Correlation coefficients between the cumulative, maximum and average pressure maps were computed to ascertain whether the pressure maps contain the same information. The interface pressure data of twenty subjects during stationary standing and at normal and fast walking speeds was collected with commercial GAITRite® walkway system and analyzed with Matlab® software.

The results of this study indicate that with stationary pressure distribution, both cumulative and maximum or average pressure maps should be presented. With pressure distributions measured at walking, instead, any of the three computing methods can be used. The results will be utilized in future in the analysis of plantar pressure distribution measurements.

ACKNOWLEDGMENTS

The authors wish to thank the subjects participated in the data collection.

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