Modelling of normal pressures distribution in a polymer-made orthopaedic insole for plantar fasciitis treatment

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Abstract. This research is aimed at the developing an optimal design of orthopaedic insole for plantar fasciitis treatment. This article presents a brief description of the experiment performed to analyse the pressure distribution in human foot, and describes the necessary calculations made for the insole construction. A mathematical model was built after the experiment and its further correction was performed, using machine learning algorithms. After the correction of the model, the polymer properties were analysed. The results of the analysis show that to perform the optimal unload of the loaded foot segments there is a need for a polymer thickness change. The respective analysis was performed and a necessary polymer thickness alteration range (1-2 mm) was introduced.

Introduction

Nowadays Plantar Fasciitis (PF) appears to be one of the most wide-spread orthopaedic diseases. Since this disease usually causes a range of problems to different age groups of people [1, 2], there is always a need for an orthopaedic device which can eliminate the source of pain and provide efficient treatment. Despite the fact that the range of treatment methodologies greatly vary [3], some methods may be insufficient for particular individuals due to their personal peculiarities related to musculoskeletal system. Unfortunately, PF can gradually deteriorate if no appropriate treatment is provided.

The main idea of the current research is to develop a specific orthopedic insole which would be able to provide the effective treatment of PF and significantly improve the life quality of people who suffer from this disease. To accomplish this task, there is a strong need for a good model which can represent the pressure distribution in the orthopedic insole and demonstrate the dynamics of this distribution. This article concentrates on the modelling of these pressures and analyses the anomalous pressures on the overloaded human foot segments. Moreover, a machine learning algorithm is used to predict “good” pressures and unload the most loaded insole parts and thus, lessen the load upon the human foot arc in general. The received data is used to change the shape of the insole relief along z axis by changing the thickness of a polymer, and to use this information in further orthopedic insole development. As a result, the provided algorithm changes the insole thickness automatically by calculating the most overloaded parts of the insole and increases the polymer thickness of particular foot segments to decrease the overall load upon the human foot.

The research methodology and experiment description

The current research is based on the theoretical calculations, where the insole is considered as a beam, divided into three equal segments with the respective percentage of the pressure distribution. The total pressures were calculated via weight coefficients, demonstrating a percentage of the pressure distribution and the initial “theoretical” pressure values calculated by [4].
Figure 1. Simplified scheme of the insole for further calculation, where M1, M2 – acting rotational moments, P1…P3 – distributed weight, RA, RB – bearing reaction, Rq1, Rq3 – distributed forces acting inside the insole.

The three segments $l_1$, $l_2$, $l_3$ are equal. According to the theoretical data, the acting pressures in each segment are $\sigma_1$, $\sigma_2$, $\sigma_3$ and equal to $52.6 \times 10^3$ (Pa), $23.5 \times 10^3$ (Pa), $135.7 \times 10^3$ (Pa) respectively [5]. In addition, weight coefficients were used in the calculation: $c_1$, $c_2$, $c_3$, equal to 1, 0.5 and 1. Considering these parameters, it is possible to perform the total pressure calculation:

$$
\sigma_1 \cdot c_1 = 52.6 \times 10^3 \cdot 1 = 52.6 \times 10^3 \text{ (Pa)},
$$

$$
\sigma_2 \cdot c_2 = 23.5 \times 10^3 \cdot 0.5 = 11.75 \times 10^3 \text{ (Pa)},
$$

$$
\sigma_3 \cdot c_3 = 135.7 \times 10^3 \cdot 1 = 135.7 \times 10^3 \text{ (Pa)}.
$$

The weight coefficient $c_1$ illustrates the pressure distribution part in forefoot, $c_2$ – the pressure distribution part in middle foot, and $c_3$ – the pressure distribution part in rearfoot.

Based on the calculated pressure values, a model of the respective pressures distribution was built in MATLAB. Figure 2 represents a graph, where each red mark displays the pressure value in human foot, acting in each 1cm$^2$-sized area of the specific platform [6], which will be described below.

Figure 2. The initial model of the human foot pressure distribution.

Since the graph appears to be nonlinear, it is necessary to perform an approximation of the received data using non-linear algorithms. In this research an algorithm of the fifth-order polynomial regression was used [7]. The polynomial regression equation can be formed using the linear regression cost function equation which will be further minimized:

$$
J(\theta) = \frac{1}{2m} \sum_{i=1}^{m} (h_\theta(x^{(i)}) - y^{(i)})^2
$$

where $h_\theta(x) = \theta^T x = \theta_0 + \theta_1 x_1 + \cdots + \theta_n x_n$ is the hypothesis given by the linear model.

However, the input argument is an only one parameter – the pressure values in the region of interest, which is not enough to create a sufficient machine learning algorithm and perform a good approximation. Therefore, there is a need to add more features into the model to form a fifth-order polynomial regression algorithm to
provide a correct algorithm. 4 other arguments were added: the arguments were calculated using power function from 1 to 5. These features were added the following way:

\[ x_1 = X, \ldots, x_5 = X^5 \]  

(5)

where \( X \) is the input matrix with the argument values. Thus, the polynomial regression hypothesis for the model is:

\[ h_\theta(x) = \theta^T x = \theta_0 + \theta_1 x_1 + \theta_2 x_1^2 + \theta_3 x_1^3 + \theta_4 x_1^4 + \theta_5 x_1^5 \]  

(6)

Due to the difference in the order of the features, the normalization procedure was also performed to provide correct scaling.

\[ x_{n,norm} = \frac{x_n - \frac{1}{m} \sum_{i=1}^{m} x_n^{(i)}}{x_{n,max} - x_{n,min}} \]  

(7)

where \( \frac{1}{m} \sum_{i=1}^{m} x_n^{(i)} \) is the average values of \( x_n \) feature values and \( x_{n,max} - x_{n,min} \) is the range of \( x_n \) feature values.

The cost function for the model is similar to the one applied for the linear regression.

Considering the remarked calculation, a new graph was plotted. Figure 3 shows the graph with the “learning data” – the initial data, and the resulting approximation.

**Figure 3.** The model with the approximation.

Most of the research is based on the experiment, where human foot pressure distributions were investigated. The experiment can be briefly described as following. An individual was standing on the special pedographic platform by Emed for a few seconds and the sensors in the platform were registering foot pressures in each area of the platform sized 1 cm\(^2\). A few subjects participated in the experiment, and each of them had an individual foot position and different lifestyle. The experiment is illustrated with one of the examples in Figure 4. The red lines show the foot areas and each of them contains maximum value which was used in calculations. Red and pink colors illustrate overloaded parts of the human foot, colder color show the less loaded areas respectively. The three images show the pressure distribution during statics – standing on the platform for 2-3 seconds and during dynamics – human walking and running.
Figure 4. The pressure measurements in the foot during statics (the left picture) and dynamics (the middle and the right pictures).

The calculations of the total pressures were performed via the similar method introduced above. To calculate the pressures, special weight coefficients, which define the percentage of the load distribution inside the insole, were added. The loads in dynamics are significantly higher than in statics, and therefore, there is a need to consider this in the further insole construction. The model correction and further values prediction should be performed, considering the maximum pressure values in the insole to prevent any material deformation.

**Prediction model description and analysis**

As a result of the polynomial regression algorithm implementation, “predicted” optimal pressure values in the insole were received. The most crucial point in the model construction was the critical pressure values in the insole. Based on each critical values, the predicted value was calculated. Figure 5 demonstrates the initial values, marked via red and predicted values, marked via blue.

Moreover, based on the received data, the difference model was built, where the differences between the initial and predicted values are depicted. The green values on the Figure 6 illustrate these differences. These calculations may be used for further calculation of forces, acting on the insole area, sized 1 cm². These force values demonstrate which force a person with particular weight characteristics can produce on the insole, and how it affects different insole areas.
However, during the development of the insole, it is necessary to consider friction forces within polymer, which is used for the insole construction, on the intermolecular level [8]. To overcome the forces of inner friction inside the polymer, a polymer thickness alteration along z axis within 1-2 mm should be performed.

**Polymer thickness alteration**

The values of inner intermolecular forces of the polymer are 57.8 MPa [8]. In order to overcome these forces, it is essential to increase the force acting on the material since during the device construction a work with real material is performed, and the real material may contain not only defects but also impurities. To calculate the polymer thickness change, a few following equations should be used:

\[
\sigma = \varepsilon \times E
\]

\[
\varepsilon = \frac{\Delta l}{l_0}
\]

\[
\Delta l = l_0 \times \frac{\sigma}{E}
\]

The equations above demonstrate the relation between pressure and Young modulus, and the relation between the polymer height change along z axis to the initial height of the polymer. The resulting values \(\Delta l\) were calculated for each area, sized 1 cm\(^2\), considering the pressure values, mentioned above. Then the received data were multiplied by the safety factor coefficient which is necessary for correct insole development. The polymer alteration is illustrated via the Figure 7.
The graph demonstrates the difference between the polymer thickness with and without safety factor coefficient, which equals to 3 in the calculations. The red line shows the maximum thickness of the polymer to provide an optimal unload of the insole by lifting its relief. Both lines depict so-called borders for polymer alteration to provide optimal unload of the foot arc unload. Last but not least, it is important to note that this alteration should be provided automatically within the device.

Conclusion
Thus, a mathematical model of pressure distribution was introduced and its further approximation and correction was performed. Since the main material used for the insole construction appears to be a polymer (PLA), there is a need to make a range of considerations during the device development. First and foremost, physical qualities of the polymer should be analyzed to prevent any polymer deformation. Considering this, a special model with approximation was developed, which included the initial values, predicted values and the differences between them. Secondly, necessary polymer thickness alterations were made to provide the optimal unload of especially loaded human foot segments. The range of the thickness alteration is 1-2 mm, which significantly lessens the total load influence on the human foot arc.

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