The Usage of Smart Materials for Development of Rehabilitation Orthopedic Device for Plantar Fasciitis Treatment

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Abstract. This article demonstrates the initial research results, related to the construction of rehabilitation orthopedic device for plantar fasciitis treatment. The results include the calculations of the pressure distribution, considering the human weight and individual gait peculiarities. Three calculation methods are considered: “theoretical” calculation, using the anatomical proportions of load distribution in human foot, empirical calculation, using weights coefficients and human weight distributions, and experimental calculation, using specific medical equipment. Moreover, this article covers the usage of specific smart materials which can be implemented in the insole construction process. Each smart material has particular properties, considered in the functionality of the insole during the construction.

1. Introduction

Nowadays, there are many types of diseases, related to human musculoskeletal system. These diseases may not only bring discomfort to daily life of individual but also provoke a serious threat to the human health. One of these diseases is plantar fasciitis (PF) which can be observed in adults as well as in youth. The disease is the result of the dysfunction of plantar fascia, which main function is to create a special “arc” between the bones on foot and act like a damper, decreasing the load. It consists of soft non-elastic tissue, and therefore it is rather easy to cause its overstrain. PF is a disease, caused by plantar fascia overstrain which provokes the increase of load upon the foot and further excessive tension leads to pain (usually most noticeable in the morning) [1].

The disease is usually caused by a number of factors: overweight (due to wrong lifestyle or pregnancy), “standing” job, flat-footedness, rapid change in physical activity or excessive physical activity (professional sportsmen and dancers) and excessive overstrain of Achilles tendon [2]. All the above causes, either individually or combined together, lead to PF.

The age group which is subjected to this disease more is adults of 40-60 years old but there are also cases among younger group – 18-35 years old. It is possible to note that in recent years this disease became more typical for younger individuals. According to the statistics, each 10\textsuperscript{th} individual in the world suffers from PF during their lifetime, and this risk is 6 times higher for females [3].

Since the PF is spread not only in Western but also in Eastern countries, the question of specific rehabilitation device development remains open. The market analysis shows that the main methods to cure this disease are medical therapy and orthoses [4]. Some cases require special shockwave therapy,
and exceptionally hard cases demand surgical interference. Due to the fact that PF appears quite often, it is easy to predict that during the nearest 10 years, rehabilitation devices for this disease will be popular on the market worldwide [4].

The aim of this research is to develop a device for passive rehabilitation to improve the quality of life of people who suffer from PF and also cure this disease completely. The fundamental tasks of the project include:

1) The analysis of existing methods to reveal normal pressure distribution during the gait of a “healthy” person and a person with PF;
2) Building of the foot pressure distribution model;
3) The development of the shape and surface of the insole to decrease the most loaded foot areas (rearfoot area appears to have maximum pressure);
4) The development of the technological process of samples production by using the fast prototyping technology, considering individual requirements of the wearer;
5) The consideration of a possibility of shockwave generator implementation to actively affect the source of pain.

This article covers the mathematical part of the project including material review and analysis and three calculation methodologies for further insole construction. Based on the results of the calculations, it would be possible to conclude the possibility of the insole construction.

2. Materials review

Before choosing the appropriate material for orthopedic insole, it is necessary to consider a range of factors, which will be used in further insole construction. The material choice is performed considering medical prescription (or after consultation), diagnosis of the specific patient, respective biomechanics and individual requirements without neglecting safety regulations and construction standards.

In general, foot orthotics fall into one of two broad categories: functional or accommodative. Functional orthotics seek to control the subtalar joint (STJ) and foot biomechanics and can help people who suffer from pronation, plantar fasciitis, and heel spur syndrome. Accommodative orthotics minimize changes to foot function while providing relief and/or protection to specific areas of the foot and are suitable for patients with diabetes, early Charcot joint disease, or any form of neuropathy [5].

Knowing the insole type, which should be used for the rehabilitation of a specific patient, it can be possible to choose the base material for the device construction. The final choice may depend on medical specialist, availability of the chose material or patient’s former experience.

For example, thermoplastics include several groups of plastics used in the orthotic industry, and they are sold in many different thicknesses, strengths, and colors [6]. Another material is polypropylene - a plastic with a low specific gravity and high stiffness.

A high-molecular-weight, high-density polyethylene, subortholen is a wax-like, inert, flexible, and tough polymer. These characteristics ensure a high melt strength and deep draw without thinning.

Combining acrylic plastic with carbon fibers creates a rigid sheet material [7]. Known by various trade names such as Carboplast, Graphite, and the TL-series, the "carbons" are good for thin, functional orthotics.

The leather was the original material used for "arch supports." Shoemakers took sole leather and wet-molded it to casts. These devices typically had high medial flanges to support the midfoot, and relatively low heel cups. Leather laminates are still used today when patients want good support but cannot tolerate firmer plastics. Their bulk and weight usually necessitates an extra-depth shoe, work boot, or sneaker.

The most popular and relevant materials for this research are polyethylene foams (including such trade names as plastazote [8], pelite [9], aliplast [10], dermaplast, and nickelplast [11]). These closed-cell foams are ideal for total-contact, pressure-reducing orthotics although some are subject to compression with continued wear. Ethyl-vinyl acetates (EVAs) [12], crepes/neoprenes [13], and more
recently silicones are other groups of man-made materials that are ideal for making accommodative foot molds.

3. The construction calculations and material choice
The orthopedic insole can be schematically described as a beam with a rectangular section in Fig.1, which is affected by distributed load (human weight) and two rotation moments at the ends of the beam, which have opposite directions. Moreover, there is bearing reaction at the ends of the beam. The nominal approximate sizes of the beam are 250 mm length and 25 mm width. The beam is divided into three equal parts which refer to the basic parts of human foot: forefoot, midfoot and rearfoot. Three calculation methodology are introduced with the aim of choosing the right material for further insole construction.

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

4. The theoretical calculation methodology
This methodology is based on the following procedure. According to the theoretical research [14], the distributed pressure ratio in human foot is 2.6/1 rearfoot/forefoot respectively. These are average numbers, gained during the experiments with 107 individuals involved. However, the authors of the research do not exclude any abnormalities in pressure distribution and explain it with personal peculiarities of gait or individual lifestyle. It is scientifically proved that the abnormalities worsen in dynamics and may be observed clearer [15, 16]. Moreover, all the changes may also occur due to the shoe wear of the patient [17].

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. In addition, weight coefficients were used in the calculation: $c_1, c_2, c_3$,equal to 1, 0.5 and 1 respectively. Considering these parameters, it is possible to perform the pressure calculation:

$$\sigma_1 \times c_1 = 52.6 \times 10^3 \times 1 = 52.6 \times 10^3 \ (Pa),$$

(1)

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

(2)

$$\sigma_3 \times c_3 = 135.7 \times 10^3 \times 1 = 135.7 \times 10^3 \ (Pa).$$

(3)

The data from the research are compared to the data which were received during the experiment, using the emed platform [8].

5. The empirical calculation methodology
Consider the second calculation methodology. Suppose that the subject has a mass of 85 kg, then their weight is:
\[ P = m \times g = 85 \times 9.8 = 833 \text{ (N)}, \] \hspace{1cm} (4)

Since the beam was divided into three equal segments, it is possible to find the area of each beam segment:

\[ S_1 = S_2 = S_3 = 25 \times \left(\frac{250}{3}\right) = 0.0021 \text{ (m}^2\text{)}, \] \hspace{1cm} (5)

For each insole segment, the pressure on the segment equals to:

\[ p = \frac{833}{0.0021} = 132223 \text{ (Pa)}, \] \hspace{1cm} (6)

Applying the weights coefficients, the pressures are:

\[ \sigma_1 \times c_1 = 132223 \times 10^3 \times 0.5 = 6612 \times 10^3 \text{ (Pa)}, \] \hspace{1cm} (7)

\[ \sigma_2 \times c_2 = 132223 \times 10^3 \times 0.5 = 6612 \times 10^3 \text{ (Pa)}, \] \hspace{1cm} (8)

\[ \sigma_3 \times c_3 = 132223 \times 10^3 \times 1 = 132223 \times 10^3 \text{ (Pa)} \] \hspace{1cm} (9)

6. The experimental calculation methodology
The third calculation methodology was performed with the data, collected from the pedographic platform by eMed [18]. 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 Fig.2. The red lines show the foot areas and each of them contains maximum value which was used in calculations.

\[ \text{Figure 2. The pressure measurements in the foot during statics and dynamics} \]
The calculation included the weight coefficients respectively:

\[
\sigma_1 \times c_1 = 140 \times 10^3 \times 1 = 105 \times 10^3 (Pa),
\]

(10)

\[
\sigma_2 \times c_2 = 90 \times 10^3 \times 0.5 = 45 \times 10^3 (Pa),
\]

(11)

\[
\sigma_3 \times c_3 = 105 \times 10^3 \times 1 = 105 \times 10^3 (Pa),
\]

(12)

Walking:

\[
\sigma_1 \times c_1 = 370 \times 10^3 \times 1 = 370 \times 10^3 (Pa),
\]

(13)

\[
\sigma_2 \times c_2 = 75 \times 10^3 \times 0.5 = 37.5 \times 10^3 (Pa),
\]

(14)

\[
\sigma_3 \times c_3 = 282.5 \times 10^3 \times 1 = 282.5 \times 10^3 (Pa),
\]

(15)

Running:

\[
\sigma_1 \times c_1 = 545 \times 10^3 \times 1 = 545 \times 10^3 (Pa),
\]

(16)

\[
\sigma_2 \times c_2 = 140 \times 10^3 \times 0.5 = 70 \times 10^3 (Pa),
\]

(17)

\[
\sigma_3 \times c_3 = 155 \times 10^3 \times 1 = 155 \times 10^3 (Pa).
\]

(18)

After these calculations the task of choosing the material was performed. Before the material analysis and further choice, some calculations related to the bending moments and forces, acting on each segment of the insole. According to Hall, the ratio of the spreading load on the insole is 0.6 (rearfoot), 0.08 (midfoot) and 0.28 (rearfoot) [19]. Furthermore, the force, acting on each segment was calculated, using the ratios above. The force and moments calculations were performed based on the methodologies outlined above and are demonstrated in Table 1 and Table 2.

### Table 1. The calculation of forces in each insole segment

| Foot Segment | Theoretical Calculation [N] | Empirical Calculation [N] | Experimental Calculation [Nm] |
|--------------|-----------------------------|---------------------------|-------------------------------|
| Forefoot     | 71.66                       | 77.75                     | 73.17                         |
| Midfoot      | 20.47                       | 22.21                     | 20.91                         |
| Rearfoot     | 153.56                      | 166.60                    | 156.80                        |

### Table 2. The calculation of moments in each insole segment

| Foot Segment | Theoretical Calculation [Nm] | Empirical Calculation [Nm] | Experimental Calculation [Nm] |
|--------------|-----------------------------|---------------------------|-------------------------------|
| Forefoot     | 5.95                        | 6.45                      | 6.07                          |
| Midfoot      | 1.70                        | 1.84                      | 1.74                          |
| Rearfoot     | 12.75                       | 13.83                     | 13.01                         |

One of the most necessary ratios which needs to be checked before the material choice is the strength condition which can be calculated via the following formula:

\[
\sigma_{\text{max}} = \frac{M_{\text{max}}}{W} \leq [\sigma],
\]

(19)

where \( W = 2.87 \times 10^{-5} \) which was calculated, using the length and the width of the rectangular section across the insole. Table 3 demonstrates the received values for further material choice.
Furthermore, these values satisfy the restriction of permitted values for the moments, where the margin of safety equals 2.

### Table 3. The strength condition in each insole segment

| Foot Segment | Theoretical Calculation [MPa] | Empirical Calculation [MPa] | Experimental Calculation [MPa] |
|--------------|-------------------------------|-----------------------------|-------------------------------|
| Forefoot     | 0.21                          | 0.22                        | 0.21                          |
| Midfoot      | 0.06                          | 0.06                        | 0.06                          |
| Rearfoot     | 0.44                          | 0.48                        | 0.45                          |

The maximum value 0.48 is the peak value of bending strength and based on this value, it is possible to choose an appropriate material. After the material research it was discovered that polylactic acid (PLA) or foaming PLA are the best materials for the orthopedic insole construction due to its specific properties. It is a versatile polymer made from renewable agricultural raw materials, which are fermented to lactic acid. PLA has a slow degradation rate and it allows to produce the long-term orthopedic implants. Different configuration polymers from PLA are given by the crystallinity, with different melting points, from 185,175 and 235 °C. Because the PLA has a hydrophobic nature, its degradation in the body decrease the PH of surrounding tissue, therefore, it is being changed into polymers with a more hydrophilic nature [20].

### 7. Conclusion

Thus, the results of the theoretical research and initial hypotheses regarding force, human weight and bending moments were proved to be successful. Since the bending strength of PLA is 55.3 MPa and modulus of bending elasticity is 2.3 GPa, it is possible to state that the orthopedic insole can be constructed, using any PLA material. Considering these factors, it is claimed that there is elastic strain in the material and there is an absence of residual stress in inner layers of the material. Therefore, not only PLA but also foaming PLA can be used in the construction.

Obviously, the experimental results differ from the theoretical results. This can be explained by individual foot position (individuals tend to correct the position on their own, considering their illnesses and restrictions) either in statics or in dynamics. The obtained data require the further research and possible correction but the existing results can definitely help in the orthopedic insole construction and smart material choice. In addition, the analytical equations may require additional correction and it is also possible to calculate new proportions.

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