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LOW-COST ORTHOPEDIC SHOES BASED ON RECYCLED MATERIALS: MANUFACTURING, PLANTAR CORRECTION EVALUATION

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Abstract

The paper describes a flexible and low cost method regarding the progress of improvement, in terms of foot diseases, in case of wearing orthopedic shoes containing progressive correction orthotic insoles. The research in the field aims at two purposes. The first one is to find an effective method for orthopedic shoe insoles manufacturing, with the role of progressively correcting plantar diseases by using cheap solutions based on the recycled materials. The research focused on an adaptive insole manufacturing, as to obtain a progressive correction of plantar diseases. The same shoe insole could be simply and quickly adapted, since, by wearing it, the foot degree of deformity will reduce progressively. Specifically, the insole would consist of two simple layers of bio-compatible and antiperspirant materials attached to each other. Several elements of recycled rubber may be placed inside it. Inserting or removing such elements, the degree of the plantar correction evolution may be controlled. The second purpose of the research is to assess to what extent the wearing of such adaptive insoles could lead to progressive plantar correction and, both, to stability and postural improvement for subjects with any foot deformities. This involves two aspects: determining the influence of wearing such orthopedic adaptive insoles in terms of center of mass (COM) on the postural control and stability and, evaluating, in terms of measured plantar pressure, the foot deformity correction.

Key words: adaptive insoles, COM, plantar pressure, recycled rubber, stability

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1. Introduction

Due to the fact that human body stability and postural control represents a key aspect reported to daily activities, working, domestic or entertainment activities, the related problem has been lately increasingly analyzed. That is why more and more researches focused on improving methods for testing and analyzing the balance and stability parameters. The evaluation of different internal and external factors influencing the body stability and postural control represents now the main subject of many research projects and scientific papers. One of them could refer to the footwear. Related to factors influencing body stability, many valuable studies were designed to assess the stability parameters of human subjects reported to the shoes. Some of them show how the wearing unstable shoes could improve the postural control as rehabilitation by improving the motor performance (Sousa et al., 2012; 2013; Sousa and Tavares, 2014). Some of them recommend to apply an electromyographic analyze as to illustrate the foot muscle activity leading to the postural control improvement (Sousa et al., 2012; Sousa et al., 2014). In terms of unstable shoes some researches refer to the applying of an electromyography signal affecting the foot muscle activity leading the the postural control improvement (Phillippe et al., 2013).

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Referring to the body stability, many researches focused on the center of mass (COM) and the center of pressure evaluation. Some important address the issue of stability and mobility evolution in different situations of the arrangement of the center of the forces and the COM in relation with the human body support in static and dynamic activities (Tokuno, 2007; Whiting and Rugg, 2012). The work of Panjan and Sarabon (2010) describes several types of tests on human subjects to assess the body stability and balance, using dedicated equipment. It may refer to clinical and simple field tests of human balance consisting of a different number of tasks while the stability is registered in different foot position. These tests allow a good evaluation of forces and pressures developed in the foot plantar in real time. Other valuable and important researches are about the plantar pressure measuring system, due to sensors, dedicated platform bases and PC or microprocessor devices, integrated in wireless systems (Lavery et al., 1997; Razak et al., 2012) the behavior being evaluated in locomotory activities (Razaket al., 2012).

In the Department of Orthopedics and Traumatology (Chinese University of Hong Kong) and Jockey Club Rehabilitation Engineering Centre (Hong Kong Polytechnic University) important and valuable researches on different design insoles were performed, influencing the plantar pressure redistribution during walking, in case of diabetic and normal control subjects (Tsung et al., 2004).

Regarding the influence of certain external factors (brightness, noise), but especially of internal factors (such of neurological, or muscular coordination), more valuable researches were done about the evolution of the center of mass / forces / pressure reporting to the human body support base (Baritz et al., 2008; Tokuno, 2007). For instance, Dominik (2017) highlighted a representative example given by the correlation between music or dancing influence on the body stability and balance.

Other important researches refer to the plantar pressure reducing in the case of different diseases; the developed method invokes the plantar pressure evaluation in case of ulcer or hallux diseases in the metatarsal area when wearing extra-depth, athletic and comfortable shoes with and without viscoelastic insoles. A rubber-soled canvas was used to establish the pressure values (Lavery et al., 1997). Referring to the plantar pressure evaluation for obese and non-obese adults, in the Physical Medicine and Rehabilitation Department of Trakya University Hospital (Turkey) a method was applied to two groups of subjects (obese and non-obese), static and dynamic pedobarographic evaluations being performed during standing and walking. The study was meant to evaluate the impact of different obesity categories on the plantar pressure values (Birtane et al., 2004).

Related to the actual researches on the body stability and plantar pressure evaluation, the paper aims to highlight the method and results obtained when wearing orthopedic shoes with progressive correction insoles. Based on these considerations, regarding the actual stage of research on stability and postural control evaluation methods, the Research and Development Department of Transylvania University of Brasov (Romania), has research studies in progress. Specifically, the research aims to develop some cheaper and environmentally friendly prosthetics and orthotics orthopedic, to solve, in a better way, different problems in terms of posture and locomotion diseases. The main purpose is to integrate the concepts of eco-friendly, low cost and rehabilitation in order to increase quality of life.

2. Methods and equipment

Based on the state of art on plantar pressure control, the proposed method applied in the study and research of the progressive plantar correction impact on body stability implied the following steps:

1) measuring the plantar pressures of ten subjects, aged between 20 and 40, in the same environmental conditions and body posture; the selection of the subjects was ensured with respect of their relatively close shoe numbers and weight (in the ranges no. 41÷44 and 70÷90 kg, respectively); the aim was to identify some people with any plantar foot diseases;

2) electing as a case study a subject who had plantar problems: a person aged 24, weighing 63 kg, 1.65 m high, shoe-number 41-42, with a flatfoot. It is a typical example, in terms of foot deformities such as flatfoot, that could be corrected in a cheap and practical way: wearing shoes equipped with adaptive insoles that could allow the plantar progressive correction;

3) manufacturing of adaptive insoles to be disposed into the shoes of the subject;

4) establishing the conditions recommended for wearing the orthopedic shoes, referring to the body posture and stability;

5) evaluating the stability parameters for the case study subject, for different stages of correction while wearing the plantar orthesis.

For the first step of the research, respectively identifying subjects with plantar diseases, specific equipment for plantar pressure measuring was used for each of the tested person. It consists of a *Foot Scan* plate connected to a dedicated computer system. Its main technical characteristics are presented in Table 1. In terms of software, a LabVIEW interface allows an easy and quick access to the users, provides the ability to perform plantar pressure measurements in real time, both for static (orthostatic posture) and dynamic mode (while running). Software interface ensure rapid image acquisition of plantar pressure charts, as in Fig. 1, by color range, the coldest meaning the lowest value and the warmest the highest value of plantar pressure. The graphic chart is strictly correlated to the measured numeric values in terms of plantar pressures when testing in static and dynamic mode. Static mode means testing when standing and dynamic mode means that the pressure chart is registered during walking or running.

Table 1. Technical characteristics of the used FootScan system

Equipment	***Dimensions: L x B x H** [m]*	***Active sensor surface L x B** [m]*	***Amount of sensors***	***Sensitivity range** [N / cm²]*	***Max frequency** [samples / min]*
FootScan 3D Gait Scientific plate	2 × 0.4 × 0.02	1.95 × 0.32	16.384	0.27 ÷ 127	500

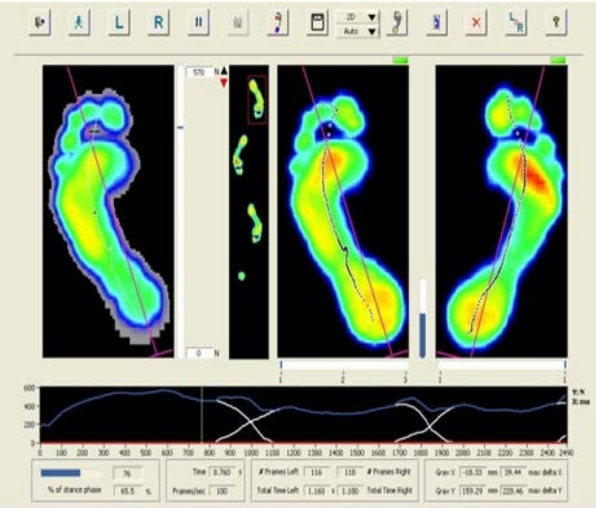

Fig. 1. Example of plantar pressure chart generation in dynamic mode

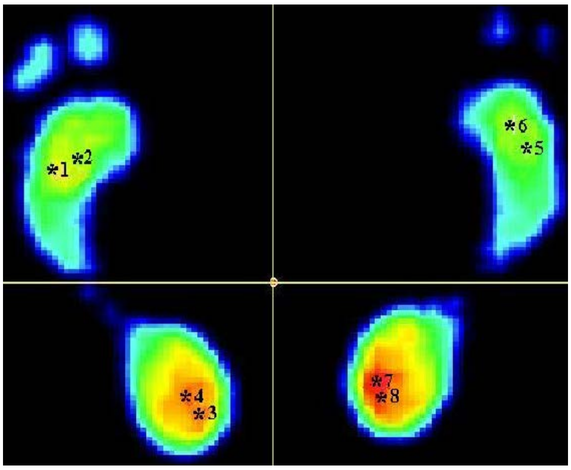

Fig. 2. Plantar pressures chart distribution using color range

This type of chart helped us to have a clear starting point regarding the plantar orthoses prototyping. In addition to image acquisition, the LabVIEW software interface also allows generating numeric data files, of plantar pressure values, which can be further processed.

As a working procedure, the plantar pressure distribution for all tested subjects (experimentally, ten persons being found to be a relevant number of cases) in the same age group was registered, both in orthostatic posture and during walking across the plate. In the first stage, numerical data from all tested subjects were recorded and processed. During the analysis and data processing, there has been noted that a group of 10 subjects with relatively close recorded values can constitute an adequate/ starting basis to determine values – limit of normal plantar pressures in healthy subjects. In comparison with the average values determined for the above-mentioned group, there was noticed a special situation of a person whose plantar pressure values were completely different from the normal plantar pressures values.

The data processing procedure was chosen on the basis of the study of computational image analysis of the plantar pressures. Among used computational methods: the planting pressures image analysis using B-Splines and the pedobarographic image analysis method can be mentioned (Oliveira et al., 2009: Oliveira et al., 2011a,b; Oliveira et al., 2012 a,b).On these computational imaging studies, we established a processing algorithm, based on the analysis of distributed pressures on six relevant plantar areas (Fig. 3). The simple and fast method consisted in converting the image data into digital data (automatically, via Foot Scan software environment), and in processing them in Excel.

The aim was to get quickly, as relevant information, some concrete numerical results in terms of pressure for each plantar area. The division of the planting area in the six zones was done by taking into account the correspondence between the plantar footprint and the specific bone structures: the phalanges, the metatarsal, the calcaneal etc. For this reason, the anatomical foot image and fingerprint image were super-posed. The mentioned division of the planting area above was done because each person may have some deviations from normal conformation (Razaket al., 2012). Each person was tested separately, both the left and right foot plantar areas being analyzed in 6 different zones, as in Fig. 3, in order to have a more conclusive evaluation; the six plantar zones refer to: toes, metatarsal, inner and outer foot arc, middle foot and heel. Besides, the entire plantar area, including toe area and without toe area, was taken into consideration at evaluation.

The next step was to calculate/to determine the average plantar pressure for each area separately. Data processing was done in Excel, using the specific function for calculating the average value. The calculation procedure was applied to all planting areas for both left and the right foot, of each tested subject. Then there was taken into consideration the problem of statistical information on the average pressure values of the plantar areas of all the healthy subjects tested, according to the Eq.(1), where $AVG(P_{Si\_toes})$, $AVG(P_{Si\_metatarsal})$ etc. represents the averaged value on the toes/metatarsal/... area for all healthy subjects and N is the number of tested subjects without any plantar diseases.

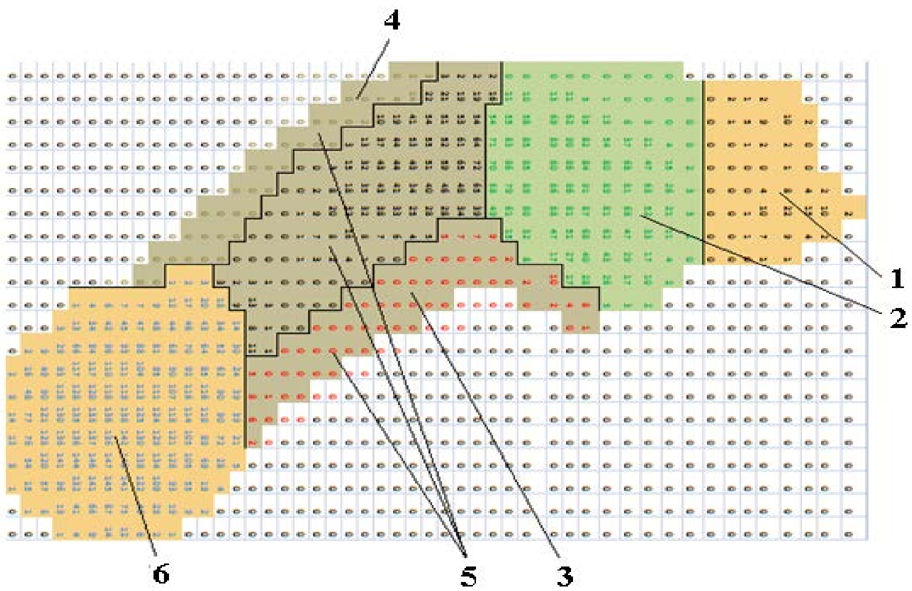

Fig. 3. Plantar surface zoning: 1 - toes; 2 - metatarsal; 3 - inner arch; 4 - outer arc; 5 - middle zone; 6-heel

$$\begin{cases} AVG\left(P_{S_{i\_toes}}\right) = \frac{1}{N}\cdot\sum_{i=1}^{N} P_{S_{i\_toes}} ; \\ AVG\left(P_{S_{i\_tmetatarsal}}\right) = \frac{1}{N}\cdot\sum_{i=1}^{N} P_{S_{i\_metatarsal}} ; \\ AVG\left(P_{S_{i\_inner\_arch}}\right) = \frac{1}{N}\cdot\sum_{i=1}^{N} P_{S_{i\_inner\_arch}} ; \\ AVG\left(P_{S_{i\_outer\_arch}}\right) = \frac{1}{N}\cdot\sum_{i=1}^{N} P_{S_{i\_outer\_arch}} ; \\ AVG\left(P_{S_{i\_mid}}\right) = \frac{1}{N}\cdot\sum_{i=1}^{N} P_{S_{i\_mid}} ; \\ AVG\left(P_{S_{i\_heel}}\right) = \frac{1}{N}\cdot\sum_{i=1}^{N} P_{S_{i\_heel}} , \end{cases} \quad (1)$$

The results of the data processing and calculus application pattern described by the equation 1, were considered as reference for the healthy people. Reported to these, a special case for the plantar pressure values was identified, especially for the foot median area. The registered data, corresponding to a person with flatfoot, proved to be the most representative case of the foot diseases rehabilitation by wearing adaptive orthopedic shoes. As a result, this person was chosen as the subject of further research that is the next step – manufacturing specific orthopedic shoes and then a gradual evaluation of the body stability during different stages of wearing the orthopedic shoes. To assess one of the orthopedic shoes for the subject, the following steps were taken: 1 - manufacturing footprint molds respecting the conformation sole; 2 - manufacturing a base pocket, made up of two classic antiperspirant insoles of bio-compatible materials, attached to each other; 3 - tailoring several items obtained from recycled rubber; their size was reported to the initial size of the area median planting; the size of the first item corresponded to the plantar median area dimension, while the sizes of the following items were established on a scale of 90%, 80% compared to the first item; there were made seven items; the sizes of the items and their number was determined according to the subject, by repeated testing; 4 - laying one by one the tailored rubber items into a pocket, composing the core of the adaptive insole; 5 –disposing of a pair of two classic insoles to the core, one above and under it; these elements were made by bio-compatible and antiperspirant materials; in this way the adaptive insoles were obtained; 6 - arranging and placing the adaptive insoles inside the shoes of the subject. In this context, the waste management becomes an increasingly pressing issue every day. Bartolacci et al. (2017), describe an empirical analysis in terms of waste collection rate, in Italy. For manufacturing the core of orthotic, as seen in Fig. 4, was obtained from recycled rubber, in 7 elements arranged in layers, which could be placed in a pocket sheath type. The pocket was made from recycled leather, 2 pieces, fastened together with sewing Velcro. Then, the orthotic core was placed on two insole type elements, as in Fig. 5, the latter being made of a spongy material with the role of increasing the cushioning and comfort while wearing. Once this was obtained, it could be inserted into the subject’s footwear. The main feature of this special orthotics is that it can provide a progressive correction of the flat feet on the foot median area, by gradually introducing rubber mobile elements into the orthotic core, seen in Fig 5.

In this way, we actually have got a family of orthotics planting contained in a single element with progressive correction that can be inserted into the shoe. The next stage of the research was to evaluate the body stability of the subject, wearing the orthesis in various stages of correction (gradually increasing the number of featured rubber inserts into the core). This step was necessary in order to find out at what extend the wearing of the orthesis could improve or, on contrarily, could worsen the subject stability.

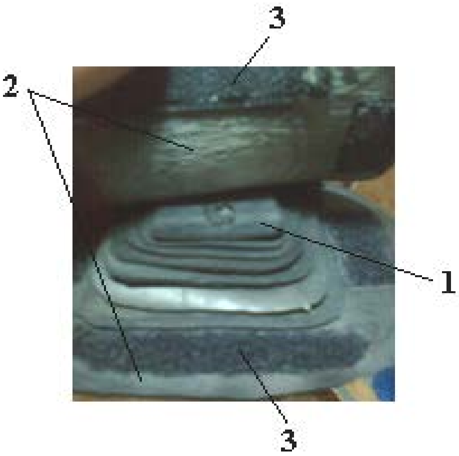

Fig. 4. The orthotic core adaptive insoles manufacturing: 1 – recycled rubber elements; 2 –pocket; sewing Velcro fastening elements; 3 – fixing elements

This could be considered a preliminary stage as to prevent possible stability risks after wearing the orthesis for longer time, during various stages of correction. In this respect, first there were performed stability tests by stimulating the wearing the orthesis and only secondly we proceeded to conduct the effective orthesis wearing in different stages of correction, assessing the evolutionary plantar pressure.

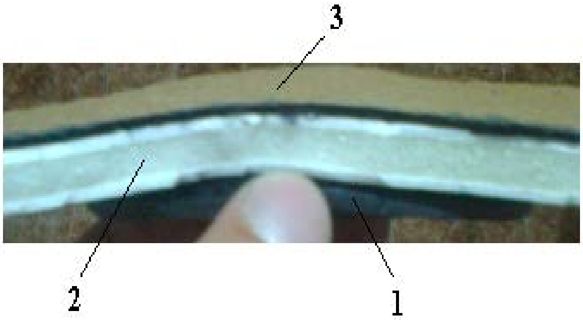

Fig. 5. Arrangement of two orthotic insoles over core: 1 - orthotic core; 2 – special insole, spongy material with shape memory; 3 –bio-compatible and antiperspirant insole material

Referring to the stability testing, the person identified with flat feet (low degree) was evaluated in terms of center of mass (COM) displacement in the sagittal and lateral plane respectively, in orthostatic position. The equipment used for testing stability was a Kistler force plate provided with four piezoelectric sensors. This allowed the measurement of the reaction force along OX and OY axis (F_x and F_y) relative to the support base. Besides, the Kistler plate allowed the measurement of moments and of displacements along both axes. It can be considered that during the evaluation, the subject was positioned on the plate so that the projection of its COM had to be coincident with the center of the support base. Thus, by the values of body displacements and of force distributions along the axes OX and OY, the Bioware software automatically determined the amplitude of the COM displacement.

As a result, the amplitude of the COM, along the two axes (meaning in sagittal and lateral planes) could thus be monitored during a predefined time, representing the time for the subject's stability evaluation on Kistler plate. The software also allowed the exporting of data to Excel files, to be further processed.

Stability assessment was done both in orthostatic position and during walking, because these are the situation which may show best any problems that influence the conformation plantar support base and hence the body stability. In terms of bipedal position, for a more complete and accurate evaluation, each person was tested three times, as in Fig. 6, in three different postures: with small, medium and large support base (BOS) (Baritz et al., 2008).

(a)

(b)

(c)

Fig. 6. Stability evaluation in the three postures: a) in small BOS; b) in medium BOS; c) in large BOS

To test the subject's stability, the recording length was set to 15 seconds; there was noticed that a longer time lead to a loss of stability due to body fatigue and to the subject's concentration during testing.

Regarding the subject with the flat feet, considered as a case study, for the stability evaluation, he was first tested wearing regular shoes. For each stage of testing, were obtained three pairs of two values representing the center of mass displacement in sagittal plane (A_x[mm]) and in lateral plane (A_y[mm]). For each phase of testing there was calculated the COM displacement average, according to the Eq. (2).

$$\begin{cases} AVG(A_x) = \frac{1}{3} * (A_{x\_small\_BOS} \\ + A_{x\_med\_BOS} + A_{x\_big\_BOS}) \\ AVG(A_y) = \frac{1}{3} * (A_{y\_small\_BOS} \\ + A_{y\_med\_BOS} + A_{y\_big\_BOS}) \end{cases} \quad (2)$$

where: $A_{x\_small\_BOS}$ / $A_{x\_med\_BOS}$ / $A_{x\_big\_BOS}$ are the center of mass (COM) displacements amplitude in sagittal plane for testing in small / medium / large BOS; and $A_{y\_small\_BOS}$ / $A_{y\_med\_BOS}$ / $A_{y\_big\_BOS}$ are the center of mass (COM) displacements amplitude in lateral plane for testing in small / medium / large BOS.

Subsequently, the subject was tested wearing the orthopedic shoes containing adaptive insoles, previously manufactured. Stability evaluation was performed for different conformations of the inserts. This means that the test was repeated under identical conditions by introducing one by one recycled rubber items into the adaptive insoles, each time the testing being repeated in similar conditions. Thus, it was determined the optimal conformation for adaptive insoles in terms of the best stability and postural control (what is the number of recycled rubber items for the best stability). The evaluation procedure for wearing orthopedic shoes was similar to that when wearing regular shoes.

3. Results and discussion

The data of the tests were exported to Excel files to be further processed. In terms of plantar pressures, the data imaging processing consisted of their conversion into digital form. For each of considered six plantar areas (see Fig. 3), there were determined the average and maximum values, using the Excel computing functions. Average values can be considered as indicators for a mean value of plantar pressure for each of the six areas. Each plantar area has multiple field assigned values (Fig. 3). There were obtained pairs of values for each of the six plantar areas in the case of each tested subject. By comparing these pairs of values, there could be identified one pair of higher values for the medial, inner and outer arch plantar areas. The pressure values were lower for toes, metatarsals, and heel areas (Table 3). These pairs of pressure values were associated with the person with flatfoot. Besides, as statistic information, applying Eq. (1) there were determined the global values for all tested subjects without plantar diseases (Table 2).

As far as the progressive correction by the orthesis wearing is concerned, there was done a simulation for the subject in case. This simulation was meant to test the subject's stability for different plantar orthesis conformations (as it can be seen in chapter 2). The aim was to find the extent to which the orthopedic shoes could influence posture and stability during their wearing for plantar correction. It should be noted that each stability test supposed three recordings of the subject's testing on the Kistler plate. The result of each test was an average of these three records. The results of the evolution of the subject's stability while wearing the orthesis at various stages of correction are shown in Table 4. The data were obtained by processing the Excel numeric data files previously generated by the BioWare software and applying the Eq. (2).

Table 2. Statistical results of plantar pressures for all tested subjects without plantar diseases

Mentioned plantar area	*Average pressure value /each plantar area* [N/cm^2]
Toes area	8.99
Metatarsal area	44.3
Inner arch area	0.76
Outer arch area	1,49
Median area	14.1
Heel area	52.85

Table 3. Statistical results of plantar pressures for the subject with flat feet

Mentioned plantar area	*Average pressure value /each plantar area* [N/cm^2]
Toes area	1.16
Metatarsal area	26.49
Inner arch area	2.29
Outer arch area	10.86
Median area	42.48
Heel area	49.77

Analyzing the results related to the stability evolution, connected with the state of comfort indicated by the mentioned person, the following conclusion could be drawn: the subject is recommended to wear the orthopedic shoes with adaptive insoles containing no more than four recycled rubber items. Wearing the orthesis with a higher degree of correction may cause both embarrassment and a slightly loss of stability for the subject. The subject wore the orthopedic shoes for three months. During the first month the adaptive insoles contained three rubber items. During the next two months the adaptive insoles contained only two rubber items. The number of the adaptive insoles was diminished because after the first month, the subject registered a slight plantar pressure decrease at the median area (Table 5). At the end of each of these two stages of wearing the orthopedic shoes, the subject was shoes off tested in terms of plantar pressures evolution. Just as in the case of testing postural and stability, there were performed three recordings, using Foot Scan in the evaluation of plantar pressure. The results are presented in Table 5, as average values provided by the three measurements. Consulting the results of plantar pressures evolution due to the progressive orthesis wearing for three months, there could be seen that they were closer to average statistical values for the 10 tested healthy persons.

There was found an improvement of about 17.5%, in terms of plantar pressures after three months of orthesis wearing, as compared with plantar pressure before orthopedic shoe wearing. In Fig. 7 there are presented the results in terms of plantar pressures evolution due to the orthopedic shoes wearing, after one month and after three months.

Table 4. Results of stability simulation for different conformation of the adaptive insoles, three registrations for each test

Different conformation of the adaptive insoles	***COM displacement in sagittal plane (A_X)*** *[mm]*	***COM displacement in lateral plane (A_y)*** *[mm]*
wearing regular shoes	8.56	10.64
wearing shoes with adaptive insoles containing one rubber item	8.52	7.65
wearing shoes with adaptive insoles containing two rubber items	7.91	7.38
wearing shoes with adaptive insoles containing three rubber items	7.91	7.03
wearing shoes with adaptive insoles containing four rubber items	7.95	8.03
wearing shoes with adaptive insoles containing five rubber items	11.35	9.24
wearing shoes with adaptive insoles containing six rubber items	13.57	10.05
wearing shoes with adaptive insoles containing seven rubber items	15.65	12.38

Table 5. Results of plantar pressures evolution due to the first two progressive stages of plantar correction, by wearing the orthopedic shoe on the left foot, three registrations for each registration

Plantar area	***Plantar pressures before wearing orthopedic shoe P_{pl}*** *[N/cm²]*	***Plantar pressures after one month P_{pl}*** *[N/cm²]*	***Plantar pressures after three months P_{pl}*** *[N/cm²]*
toes	1.16	1.31	1.43
metatarsal	26.49	29.08	30.83
inner arc	2.29	2.04	1.86
outer arc	10.86	9.51	8.56
foot median	42.48	37.72	34.22
heel	49.77	53.7	56.88

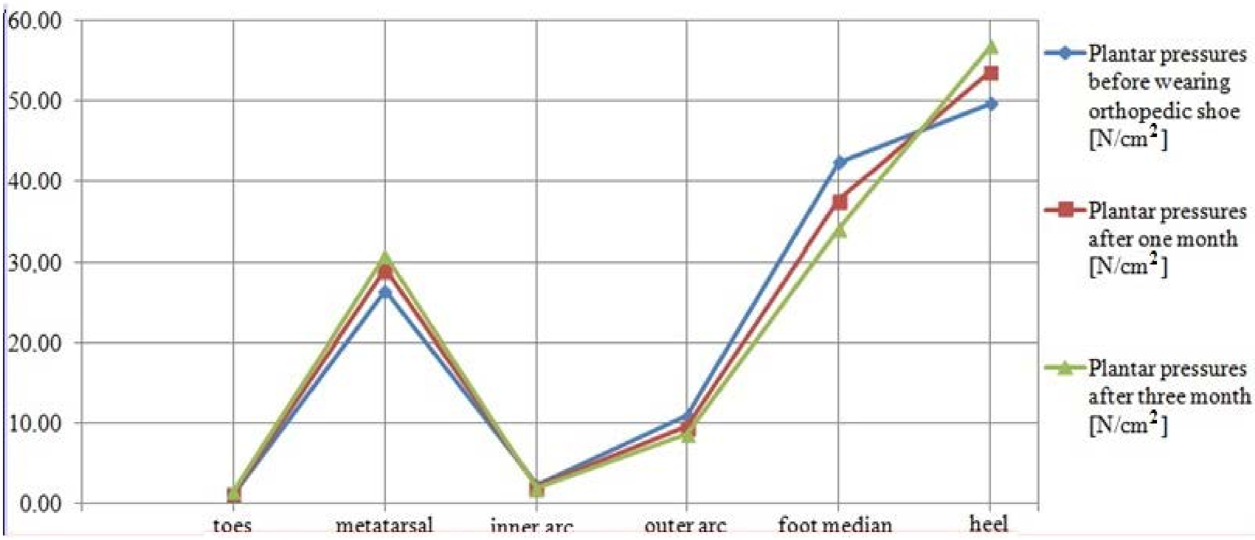

Fig. 7. Evolution of the pressures for all six plantar areas in case of the subject with flatfoot, as a result of wearing orthopedic shoes

4. Conclusions

Wearing such orthopedic shoes for a period of time can lead to a plantar correction and postural control improvement even for adults. As a result, future research will be focused on athlete children.

As far as manufacturing, the adaptive orthopedic shoe insoles could be profitable due to some advantages: the solution is green because recycled materials can be used; the adaptive insoles manufacturing is simple and fast; it seems to be a cheap solution because the procedure involves materials and technologies to achieve costs; the solution is a practical one because the adaptive insoles can be quickly and easily used with any type of footwear.

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