Modeling Orthotic Insole for Flatfoot using Finite Element Analysis and 3D Scanning

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Abstract

Medical practices are greatly impacted by new engineering technologies. For those who suffer from disordered feet, several engineering tools are used in designing and manufacturing medical insoles. There is a significant percentage of people who need medical insoles due to flat feet, hollow feet, diabetes, etc. The advancement of engineering materials, computer aided design, and computer aided manufacturing gave podiatrists the ability to do their jobs better. Two advanced engineering techniques were used to design and manufacture medical insoles in this study, one is 3D scanning, and the other is finite element analysis (FEA). Podiatrists can create a complete foot solid model using 3D scanning and CAD software. Using the same CAD package, the insole could be designed from this model. Different manufacturing techniques could be used to create a typical insole using the foot model. FEA enables analysis of the disordered foot with different insole designs in order to optimize patient comfort. A statistical analysis was conducted in this paper to prove the unique needs of every foot, even for the same individual. A FEA was conducted to examine the effect of the proposed insole on the plantar pressure of the disordered foot.

Keywords
Orthotic insoles, Flatfoot, FEA and Reverse engineering.

1. Introduction
The anatomy of the foot and its biomechanics are crucial for its functions, including walking, running, and standing (Wang et al. (2021). There are many foot disorders that affect the foot functions to some extent and, sometimes, cause unbearable pain and disablement. Y. Wang and X. Wang (2021) described flatfoot as a deformity characterized by the collapse of the medial longitudinal arch of the foot. The foot arch is very important for providing flexibility, support, and, most importantly, shock absorption (Peter R. and Rodgers 1987).

Because the arch is critical to the foot's function, any medical condition that affects its shape and behavior causes abnormalities in the sole. Some sole abnormalities result in severe knee and foot pain, especially in the older age group when people complain about many foot related issues when walking or running. Foot disorders can be treated with orthotic insoles. An insole is the interior bottom of a shoe that sits directly beneath the foot. In order to ensure that customers will be comfortable, the footwear industry is always working to develop a better insole.

The insole is an essential part of footwear, but orthotic insoles are used by many to limit flatfoot discomfort. As a result, planter pressure during gait is reduced and redistributed, and thus foot functions are significantly improved. The process of designing and building the ideal insole takes a lot of time and requires the expertise of experienced technicians (P. Anggoro et al. 2018). Contrary to commercial insoles available on the market, customized orthotic insoles are expensive and require a long production time (L. Yang et al. 2022). As a result, an extensive effort was made to automate the orthotic insole design and manufacturing process by using CAE and reverse engineering.

A system capable of treating each disordered foot as a unique problem is necessary due to the sophisticated nature of the human foot. In this study, foot scanning using 3D scanners and pedography is used to capture foot details and build its solid model. For the purpose of determining the suitability of the design of a medical insole, a finite element model is constructed using the solid model. In subsequent stages of the project, the solid model of the insole will be used to produce the insole using 3D printing.

1.1 Objectives

In this project, we will develop a systematic approach to using 3D scanning and Pedography to build solid models of disordered feet, design the insoles using CAD tools, build a FEA model to test and validate foot-insole interaction before manufacturing the insole, and test the effectiveness of the proposed system in improving body gait in people with flat feet. The paper covers the preliminary output of the first two objectives.

2. Literature Review

Research in this field indicated that 'fit' is the most important criteria while selecting the footwear, because it will result into comfort, as well as preventing damage and injuries (Cheng & Perng 2000). The perfect fit is required in case of footwear, because loose shoes causes slippage, and tight shoes compress tissues, hence both leading to discomfort and damage to tissues (Witana et al. 2004).

Anthropometry of foot is an important factor while measuring it for customized product. For a good fit, it was suggested that at least two measurements are required in each zone i.e. forefoot, midfoot, and rearfoot (Xiong et al. 2008). Goonetilleke et al. described the important dimensions required for an individual for foot measurement (Goonetilleke, Fan-Ho, & So, 1997). It comprises of, bottom width, instep girth, heel height, and toe box shape. In addition, shape also plays a vital role while designing a customized product (Witana et al. 2004).

Finite Element Analysis (FEA) was successfully applied by many researchers for foot insole analysis. Cheung and Zhang, (2005), investigated the effect of material stiffness of flat and custom-molded insoles on plantar pressure and stress distribution during balance standing. A three dimensional model for human ankle and foot was developed using magnetic resonance (MR) data. MIMICS software was used to segment the MR data. A customized insole was developed using PPT, and other one using Polypropylene. Using the developed FEA model, Foot-support interfacial pressure, Von Mises stress in bony structures, and strain of the plantar fascia were predicted successfully. It was concluded that the insole's custom molded shape is more important in reducing peak plantar pressure than the stiffness of the material from which it is made.

Luo et al. (2011), performed the computational analysis and experimentation to design the optimal insole. The aim was to reduce the pedal tissue trauma. Subject's foot was scanned through magnetic resonance image (MRI) technique to obtain the geometry and morphology of the pedal tissue. The results showed: (a) Flat insoles made of soft material provide some reductions in the maximum stress, strain and SED produced in the pedal tissues. These maximum values were computed near the calcaneus. (b) Flat insoles, with conical/cylindrical reliefs, provided more reductions in these maximum values than without reliefs. (c) Custom insoles, contoured to match the pedal geometry provide most reductions in the maximum stress, strain and SED.

Chokhandre et al. (2012), conducted an inverse finite element analysis of the heel in order to calculate heel-specific material properties. A three-dimensional finite element model was developed. Using inverse finite element analysis heel pad material properties were determined, by fitting the model behavior to the experimental data. The model predicted structural response of the heel pad was in good agreement for both the optimization and validation cases. It was reported that the inverse analysis successfully predicted the material properties for the given specimen-specific heel pad using the experimental data for the specimen.

Ali Zolfagharian et al. (2021) conducted FEA using ABAQUS to study the viscoelastic behavior of various suggested lattice structures of shoe midsoles used in different human activities. FEA helped in selecting the lattice structure with less stress with respect to person's activity.

Wang et al (2021) used CT scan and the reverse engineering software Geomagic Studio to build the solid model of 140 feet of individuals with normal feet, flatfeet, clubfeet and Lisfranc injuries. ABAQUS FEA software was used to construct finite element models of the studied feet. The goal was to analyze the von Mises stresses in the midfoot of under different foot deformity conditions. They concluded that the prediction of von Mises stresses is a promising tool in evaluating the effects of different foot injuries and deformities on the pressure distribution and structure changes in midfoot.

Based on literature, it can be concluded that FEA techniques proved to be significant and reliable tool in terms of predicting the behavior of insoles and orthotic under varying conditions of load, material, thickness, etc. However, more research is needed to relate FEA with reverse engineering techniques such as 3D scanning in order to automate the insole design process and hence facilitate insole manufacturing using additive manufacturing techniques.

3. Methods

3.1 3D Scanning

FaroArm, a 3D portable laser scanner, was used to scan the foot in order to build its solid model. The device projects a laser beam on the scanned object and a camera detects the reflection as the beam hits the object. The individual's foot was scanned several times slowly to capture all the foot details. The Geomagic Studio software was used to build the solid model of the foot and convert it into an IGES file. Figure1 shows the output of the FaroArm scan process.

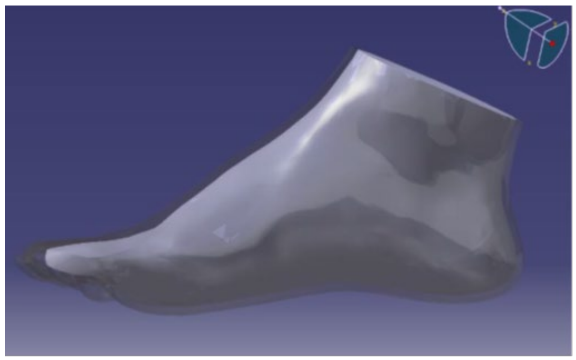


Figure 1. The foot solid model produced using FaroArm

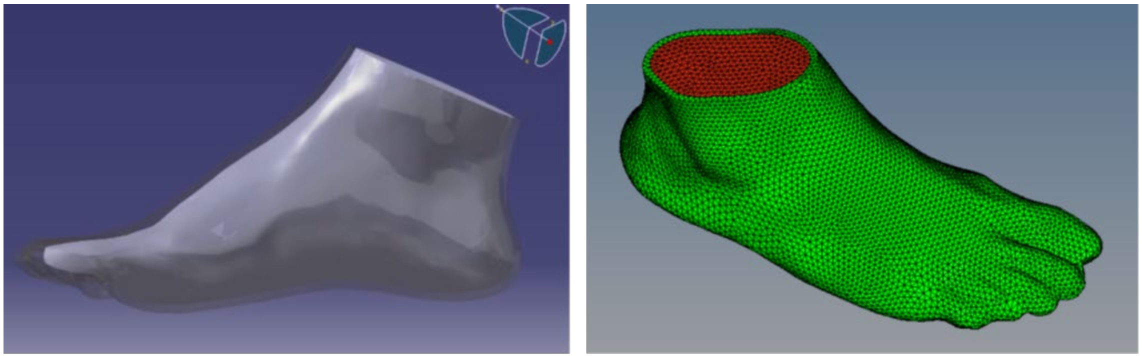
3.2 Pedography

Pedography is a known tool that is used to measure the pressure distribution and contact area under the foot in order to diagnose foot disorders. Static and dynamic pedography are two available methods to conduct the test. In this method a soft rubber mat is laid down on the ground and the person is asked to walk normally and put one or two steps on this rubber pad. Under the rubber pad, sensors and are installed; these and connected to computer system. The measured pressure, force and area are plotted and the distribution of their value on the foot is shown by different color coding. From the output drawings, the effected portion of the foot can be identified.

3.3 FEA

As mentioned in previous section, 3D scanning was conducted on both flatfoot and normal foot. The normal foot images were converted into 3D solid model using Geomagic Studio software. The solid model was meshed in HyperMesh software, where all bad elements were fixed, boundary conditions were applied and contact surfaces were defined. The normal foot model was used to simulate both the normal foot and flat foot in finite element analysis. The reason to use the same model is to keep similarity between the two cases for the sake of comparison. Also, since the differences between both feet appear in the internal structure, it was not possible to depict these details without using CT scan and special advanced software. The time domain and budget allowed for the project do not allow this type of complicated research. The boundary conditions of the foot solid model were adjusted differently to match the normal foot and the flatfoot.

Figure 2 (a) shows the solid model of the foot split into bones (the inner dense structure) and skin (outer light structure). Figure 2.b shows the mesh of the foot with bones colored in red and skin colored in green. Tetrahedron solid elements were used to create the FE mesh with element size ranges between 0.55 and 2.77 mm.



(a) (b)

Figure 2. (a) Foot solid model, (b) foot mesh

The boundary conditions were defined as a contact between a rigid surface, the floor, and the foot as shown in figure 3. The plate was fixed in all degrees of freedom. A load of 84 kg (the weight of the subject) was applied on the top surface of the foot (colored red in figure 1.a) as a distributed load. Table 1 demonstrates the material properties given to the bone and skin structures in the model.

Table 1. Material properties of foot elements

Material	**Modulus of elasticity**	**Poisson's Ratio**
Bone	10 GPa	0.34
Soft tissue (skin)	1.15 MPa	0.49

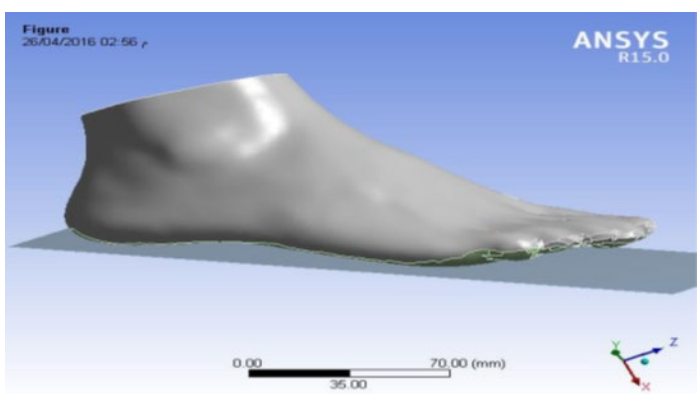


Figure 3. The foot model in contact with a rigid surface

4. Data Collection

A sample of 9 adults with flatfoot disorder was selected randomly to analyze their flatfoot problem and its characteristics. The sample included four males and five females with ages range between 20 and 51 years. The foot sizes range was 37 to 40 for females and 41 to 47 for males. For each case in the sample the planter pressure was measured and plotted, the peak plantar pressure, the maximum contact force and the total contact area between the foot and the test rig were extracted from the database stored test equipment. These measurements and data extraction were repeated for both right and left feet. For each foot the test is replicated five times and the average values are calculated automatically by the testing equipment. The tests were conducted on a plantar pressure testing mat with built in load cells. Table 2 shows the results for the 9 cases.

Table 2. Results from 9 flatfoot subjects

							Left foot			Right foot		
Case	Sex	Age	BMI Kg/m^2	Weight Kg	Height Cm	Foot Size	Peak Pressure KPa	Maximum Force N	Contact Area Cm^2	Peak Pressure KPa	Maximum Force N	Contact Area Cm^2
Case 1	F	20	29	75	161	40	770	1710.7	171.2	690	809.0	155.8
Case 2	F	51	31	74	154	39	365	751.8	165.0	360	818.8	170.8
Case 3	M	28	27	91	182	47	605	1967.9	218.6	545	2103.7	235.4
Case 4	F	50	43	120	167	39	235	2155.5	181.1	285	2210.1	178.4
Case 5	M	25	30	95	180	43	590	1664.4	221.6	740	1740.0	174.0
Case 6	M	20	35	100	168	41	345	1924.9	161.0	590	1983.2	162.6
Case 7	F	36	41	94	152	38	1020	1972.3	148.3	455	1808.9	144.9
Case 8	F	30	36	80	149	37	615	1965.5	170.7	870	2039.9	173.8
Case 9	M	47	34	90	163	41	965	2005.5	187.9	725	2132.7	195.3

Figure 4 shows sample planter pressure distribution from Case 1 for both feet. Apparently there is a difference between both feet with respect to maximum value and pressure distribution. Figure 5 shows a column chart for the maximum plantar pressure in all cases in relation with contact area. Some cases have very severe peak planter pressure (cases 7 and 9) compared to other cases. Also the differences between the left and right feet are very clear in the chart. Planter pressure for all cases is given in the appendix.

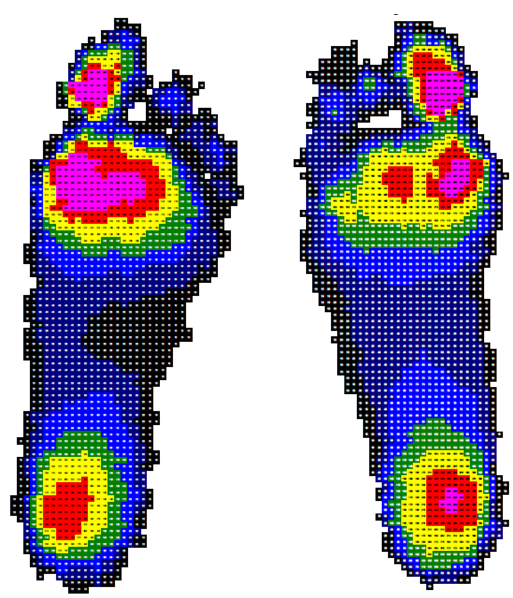


Figure 4. Plantar pressure for Case 1

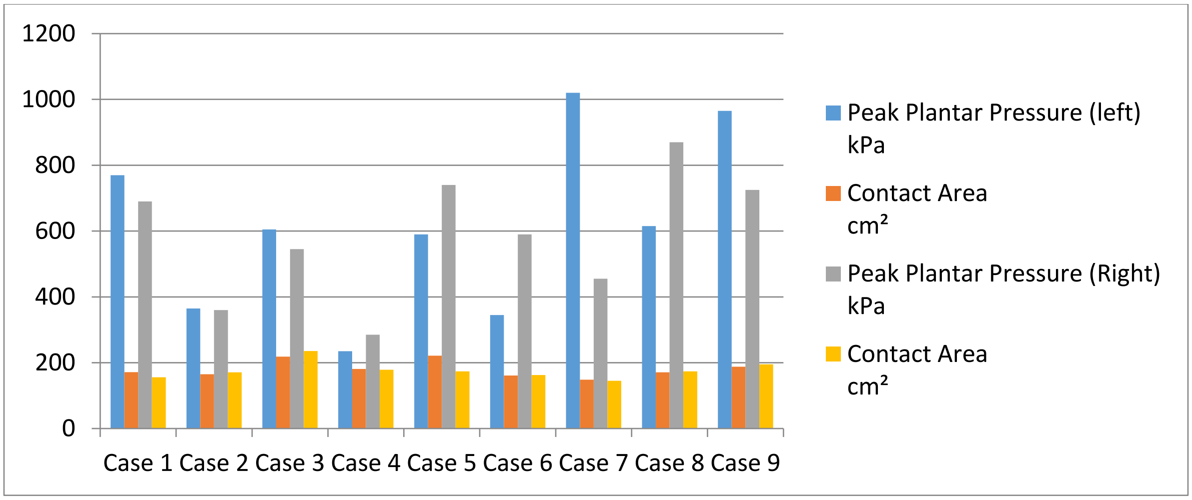


Figure 5. Column chart for the peak pressure and contact area for all cases

5. Results and Discussion

5.1 Numerical Results

Significance analysis

Paired t-test was used to test the significance of the differences between both feet of the same subject case. The test was conducted for maximum plantar pressure, maximum force and contact area. The data were organized such that the difference is estimated between the high and low value of each tested variable regardless of being left or right foot. Table 3 summarizes the data for the paired t-test, and the results for the three studied variables.

Table 3. Data organized for the paired t-test and the test output (p-value)

Cases	Peak plantar Pressure (kPa)		Maximum Force (N)		Contact Area (cm²)	
	High value	Low value	High value	Low value	High value	Low value
Case 1	770	690	1710.7	809.0	171.2	155.8
Case 2	365	360	818.8	751.8	170.8	165.0
Case 3	605	545	2103.7	1967.9	235.4	218.6
Case 4	285	235	2210.1	2155.5	181.1	178.4
Case 5	740	590	1740.0	1664.4	221.6	174.0
Case 6	590	345	1983.2	1924.9	162.6	161.0
Case 7	1020	455	1972.3	1808.9	148.3	144.9
Case 8	870	615	2039.9	1965.5	173.8	170.7
Case 9	965	725	2132.7	2005.5	195.3	187.9
P-value	0.012		0.07		0.045	

The null hypothesis in all tests is that there is no significant difference between the two feet of each subject. The alternate hypothesis is that there is a significant difference between the two feet. As default, p-value of less than 0.05 results in rejecting the null hypothesis and proves strong evidence towards the alternate hypothesis. This is a two tailed test since it measures the significance of the difference in both directions of the probability distribution curve.

For the peak plantar pressure, the p-value equals 0.012 showing a significant difference between the two feet in the selected random sample of subjects. The same result was concluded for the contact pressure with p-value equals 0.045. The maximum force had a p-value of 0.07 showing insignificant difference between both feet.

Correlation analysis

Correlation analysis was used to study the relation between the differences in both feet and several subject characteristics, namely, weight, height, age, BMI and foot size. The values of these characteristics are given in Table 1. Correlation test yields a normalized value between -1 and +1. As the yielded value approaches zero, the test result proves no correlation. In contrary, the test approves high correlation as the yielded value approaches -1 or +1.

Regarding the correlation with weight, it turned out that differences in both plantar pressure and contact area are not correlated with subject weight, while the difference in maximum force is moderately correlated with correlation value of -0.44. The age had no correlation with differences in contact pressure and moderate correlation with differences in forces and contact area.

High correlation was found between differences in contact area and foot size, while moderate correlation was found with difference in peak pressure. No correlation was found with difference in forces. The body mass index (BMI) had a strong correlation with differences in both peak pressure and contact area, and moderate correlation with difference in forces.

Subject height had a high correlation with differences contact pressure, moderate correlation with differences in peak pressure and no correlation with differences in maximum forces. Table 4 summarizes the correlation test results.

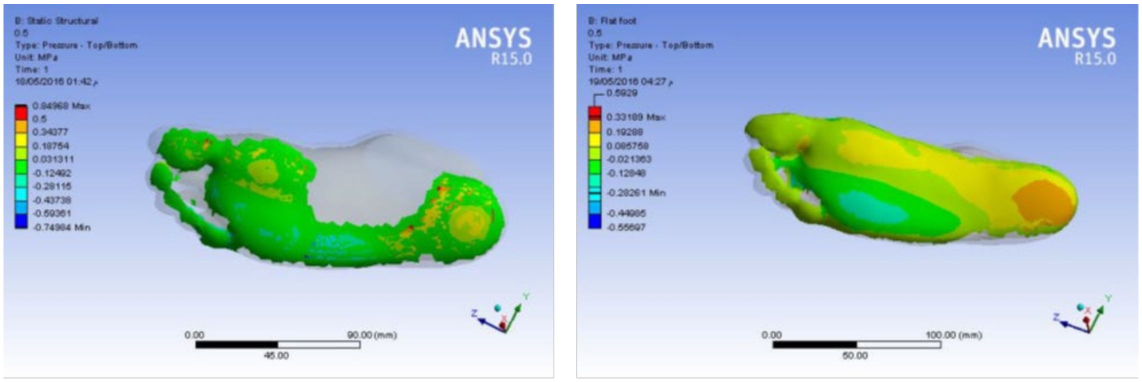
Table 4. Correlation test results

Variable	Body characteristics				
	Age	BMI	Weight	Height	Foot size
Difference in plantar pressure	-0.13	0.5	0.08	-0.4	-0.37
Difference in maximum force	-0.42	0.35	-0.44	-0.09	-0.04
Difference in contact area	-0.38	-0.55	-0.06	0.65	0.53

5.2 Graphical Results

Figure 6 shows the planter pressure of the normal foot (a) versus the flatfoot (b). The contact in flatfoot covers more area than in normal foot as the foot arch almost vanishes when the foot is loaded with the body weight. As the area of contact increase, the maximum pressure value decreases as illustrated in the Figure. In normal foot, the maximum planter pressure is 0.5 MPa, while in flat foot the maximum planter pressure is 0.33 MPa. At some points the pressure exceeds these values due to stress concentrations resulted from the model and the elements rather than the loading conditions. Thus these isolated high values are ignored in the discussion.

Several types of insoles are used to keep the foot arch in position when the foot is loaded with body weight. In this analysis a simple insole design was used to test its effect on planter pressure. The insole, shown in Figure 4, was made of Sorbothane. The material properties of the Sorbothane are: modulus of elasticity 3.84 GPa, Poisson Ratio 0.486 and yield strength of 0.49 MPa.



(a) (b)

Figure 6. Planter pressure in; (a) normal foot, (b) flatfoot

Figure 7 shows the shape of the insole with contact of the foot arch and Figure 8 shows the planter pressure resulted. As illustrated in the figure, adding the insole redistributed the planter pressure over the foot bottom and elevated the maximum pressure to 0.49 MPa, which is very comparable to the values seen in normal foot. However, the insole design needs to be optimized in order to achieve a planter pressure distribution that matches precisely that of the normal foot.

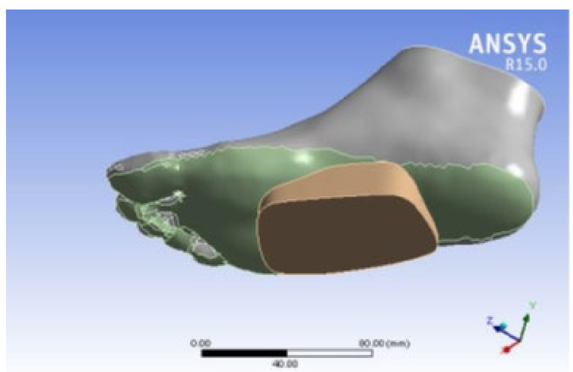


Fig 7. Insole in contact with foot arch.

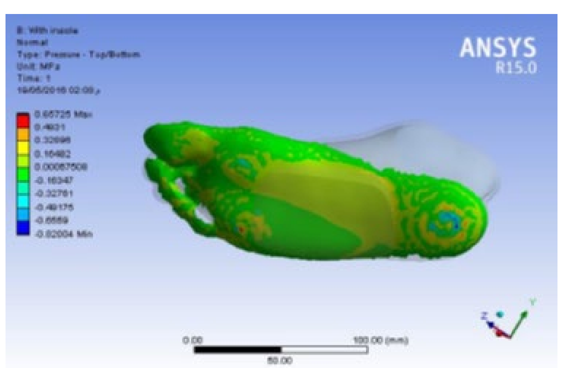


Figure 8. Plantar pressure resulted from the model in Figure 7

6. Conclusion

Nine subjects with flatfoot defects were randomly selected and tested. Their results showed notable differences. Statistics showed significant differences between the two feet of the same subject. The differences are affected by the subject's body characteristics. According to this study, a standard insole for flatfoot would not be a good choice for all subjects. A personally costumed insole should be used for every subject. Moreover, different insoles may be needed for each foot of the same subject.

Based on the range of experiments and verifications conducted in the present work, the following conclusions could be drawn:
1.The decrease in pressure while using insole, give relief to patient as he can walk without pain.
2.Due to the increase in contact pressure the patient feels more comfort and the posture of the body is balanced and more stable.

With respect to results of this research it is recommended to:
1.Use customized insoles for people with ill foot, particularly those who suffer severe syndromes, as commercial insoles may not match their needs.
2.Although FEA is a time consuming process, it might be needed in some cases to assure the comfort of ill foot under different conditions. FEA has the advantage to predict the stresses in foot structure under different conditions.

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Biography

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