Numerical Simulation by Finite Elements for Redistribution of Plantar Pressure in Sport Insoles

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Abstract

There are different factors that can cause an injury during the execution of a sport activity, intrinsic elements such as weight, age, height and extrinsic factors, such as type of soil, equipment and footwear. One of the main components of footwear is the insole, which is responsible for contact with the foot, these can have different purposes, such as odor control, plantar arch support, reduce pain, humidity control, cushioning, among others. Based on CAE, Finite Element Analysis (FEA) has become a very popular tool thanks to its versatility and accuracy for modeling different footwear components. The aim of this project is to do a numerical simulation by finite element analysis to prove the redistribution of plantar pressure using insoles of different materials that integrate the anthropometric characteristics of the user. The protocols were created to evaluate the baropodometric characteristics with a Baropodometer and a PodoScan2D (Sensor Medica®). The insole was designed using ABAQUS CAE student version and six materials were tested to obtain their mechanical properties using a universal testing machine (Instron), the combination that best redistributes the plantar pressure was found applying this methodology.

Keywords: FEM, Insoles, Materials, Plantar Pressure.

1. Introduction

There are different activities that require the use of certain orthotics to reduce or avoid different morphological alterations, the use of insoles allows to improve the distribution of plantar pressure and thus avoid deterioration in the structure of the foot and in health in general [1]. The design and development of ergonomic insoles is a time-consuming process that requires expertise and experience to determine the shape, material, and material thickness, which can lead to trial and error to find a functional product that improves footwear conditions for use. This project aims to carry out a numerical simulation by finite elements that integrates the properties of the material and the anthropometric characteristics of the user for the creation of insoles that redistributes the plantar pressure. This document details the theoretical part, experimental part and results.

There are different sports in which the athlete puts great efforts on their physical structure, analyzing the foot in sport is essential for the design of orthoses and sport instruments that allow the athlete to improve the practice. The human foot is a complex structure that consists of 26 bones and 33 joints; plus muscles and ligaments [2]. Seven tarsal bones form the ankle as the connection between the leg and the foot, five metatarsals form the medial and lateral areas of the foot, and fourteen phalanges form the toes [3]. A previous research carried out on Colombian athletes by the biomechanics laboratory of the National Sports School, has determined that there is a tendency to cavus foot in all subjects, regardless of the sport practiced, perhaps caused by the effort required for sports practice [4] this is due to the fact that there was probably not an adequate distribution of plantar pressure during sports practice. The pes cavus does not absorb as much stress as the flat foot does, but it passes to the tibia and femur, the flat foot absorbs more stress on the musculoskeletal structure of the foot compared to the pes cavus,

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so the incidence of stress fractures in the foot structure is higher in individuals with flat feet [5] knowing this, the implementation of an orthosis could reduce the risk of suffering an injury. Furthermore, a recent study has found a high prevalence of pes cavus mainly in females[6].Reliable anthropometric data and technical ergonomics procedures become powerful tools available today for the optimal dimensional matching of designer products [7]. As Smith comment, the use of biomechanics in the design of footwear components provides the resources to know the effects on the lower extremities and find relevant clinical and physical information in order to improve conditions in users [8]. In addition to the anthropometric conditions in product engineering, it is necessary to look for materials technology, since they allow obtaining the functional properties that are required for the activity. In an article published by Braithwaite, the importance of materials and their particular use in technical, functional and sensory matters is mentioned, as natural properties of design [9]. The choice of the best material for the manufacture of the insole represents what properties the material will provide according to its design, thickness, mechanical properties, etc. Therefore, it is important to define what material will be used for manufacturing insoles. In an article developed by Pratt, Reese and Rodgers analyzed five different materials used for the manufacture of insoles and these were subjected to shock absorption tests, it was found that the viscolas (viscoelastic polymer) is the one that best absorbs impacts [10]. One of the problems of the project is to choose the best material for insoles, it seeks to find a material that meets the characteristics to which the product will be exposed during the use, for this the materials engineering allows to identify the mechanical and physical properties of some products through different tests.

The application of the finite element method in the design of the insole will allow to simulate different materials, thanks to this it will be possible to determine if the material and the design of the insole will be able to meet the conditions to which will be exposed.

Assessment different insoles represents a high cost in development, through a finite element analysis it is possible to analyze different designs, materials and situations. Different works have been developed to analyze the plantar pressure distribution with insoles manufactured with polymeric foams [11]**.** The different designs of the insoles can affect the way in which the plantar pressure is distributed, depending on the needs of the patient. San Tsung *et al*., compared the effectiveness of different designs of insoles to redistribute the plantar pressure during gait [12]. The contact area is important during each stage of the gait cycle to determine at which points the plantar pressure is having an effect. In a study developed by Murphy, the relationship between the contact area and the plantar pressure was studied [13]**.**

2. Methodology

2.1 Procedure

For the design of insoles and its analysis by FEM is necessary to determine the methodology to be followed. This with the aim of creating a standardized process to identify key areas of interest. The proposed methodology for designing insoles, consists in performing the evaluation of the anthropometric characteristics, physical tests, data analysis, development of insoles in CAD, characterization of the material and the numerical simulation by finite elements. Fig. 1 shows the methodology for finite element analysis for insoles.

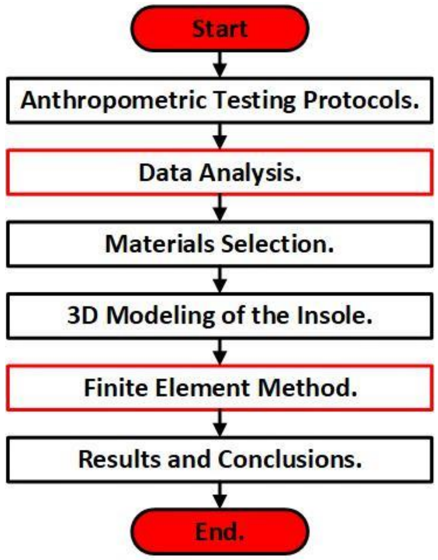

Fig. 1. Methodology for finite element analysis for insoles.

2.2 Anthropometric Testing Protocol

A study was done in 29 women's basketball participants from the sports teams of their educational institutions and from teams belonging to the COMUDE León, with an age between 15 and 25 years. Convenience sampling was performed which allows selecting a sample from the population due to the fact that it is accessible and there is availability on the part of the individuals of interest to carry out the necessary tests for the investigation.

The procedures, risks and benefits were explained in order to obtain the consent for voluntary participation in writing, in accordance with the General Health Law of Mexico, and considering the principles of the Declaration of Helsinki.

Two equipment were used to take the measurements, a Baropodometer (Sensor Medica®, Guidonia Montecelio, Rome, Italy) that is in charge of taking the plantar pressure tests in its different phases and a 2D PodoScan (Sensor Medica®, Guidonia Montecelio, Rome, Italy) in charge of taking the image of the footprint. Once the operation of the equipment had been explained and the informed consent was signed, the tests were recorded. First, the static test was performed, the user stands at the beginning of the platform barefoot, standing upright with his hands at his sides and the plantar pressure distribution is recorded for 10 seconds. Then the dynamic test took place, the participant was instructed to walk naturally, complete two round-trip cycles and start with the right foot, the execution time of the dynamic test was 30 seconds.

After the tests with the Baropodometer, the patient took a break of 3 minutes to finally perform the scan of the footprint with the PodoScan2D. The participant stood on the PodoScan2D platform with his hands on his sides, the scan was started using the device and the participant was informed when it ended.

2.3 Data Analysis

Once the anthropometric tests were done on the equipment, a test report was generated in which important variables were obtained for modeling the insole. This report is automatically generated by the integrated Baropodometer and podoscan2D Freestep software. First, a user identification card is generated with general data such as age, weight, height and sex, which were captured by the person in charge at the time of recording the tests. In addition, a detailed summary is generated indicating the main alterations that were detected in the tests. The main values obtained in the study of baropodometry consist of: Contact surface, percentage of the applied load and anthropometric values. To determine the loads that were applied in the simulation, the foot was divided into six regions where the contact surface in that area is known, as well as the percentage of the load in that area, an example is shown in Fig. 2.

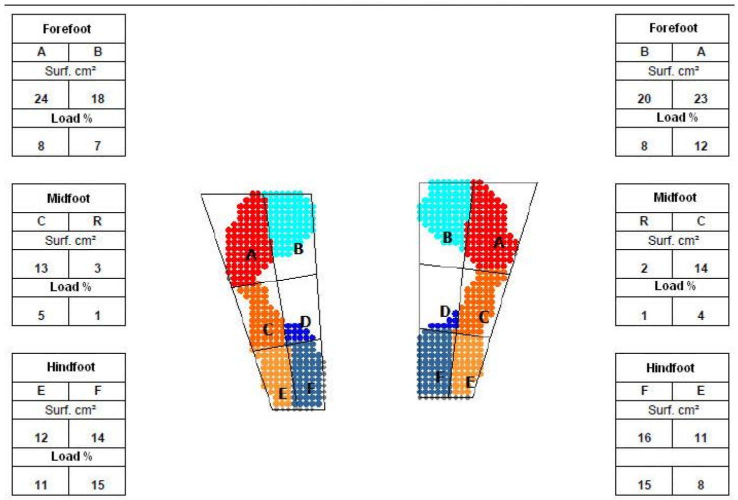

Fig. 2. Division of areas of the foot surface in Freestep Software.

To determine the load that was applied in the simulation, the load (mass in kilograms) is multiplied by the distribution of the load in that area and divided by the contact surface, multiplied by the gravity to obtain the result in Pascals. Equation (1) shows the procedure to obtain the plantar pressure per section in the foot.

$$Plantar\ Pressure = \left(\frac{m*l}{s}\right) * g \quad (1)$$

Where:
m=mass in kilograms
l=percentage of load
s=surface in square meters
g=gravity in meters / square seconds

During the static test, a mean maximum plantar pressure of 1061.54 ± 192.18 g/cm^2 was found in the left foot and 970.09 ± 180.34 g/cm^2 in the right foot, during the dynamic phase a mean maximum plantar pressure of 3458.54 ± 680.71 g/cm^2 was found on the left foot and 3180.54 ± 441.89 g/cm^2 on the right foot.

For the acquisition of the footprint the PodoScan2D was used. A mean size of footwear (Europe) was detected by the 2D PodoScan of 36.8±1.5 in the left foot and 36.68±1.30 in the right foot. A mean length of the left foot of 234.45±10,074 mm and 234.22±10,018 mm in the right foot. In addition, an average width of the left forefoot of 91±5.06 mm and 91.59±5.12 mm was found in the right foot, an average width of the left heel of 60±4.17 mm and a right heel of 61.09±4.86 was found. In relation to the morphology of the plantar footprint, a high prevalence of pes cavus was found, 39% of the participants present this condition, 22% present different degrees of flat foot.

2.4 Material Selection

The literature shows that the selection of the materials for the manufacture of insoles is based on the orthopedist's preference or their experience, the cost and the availability of resources; for the choice of material, a literature search was done and in the current market analyzing the materials used for redistribution of plantar pressure in different contexts. For the location of the suppliers of these materials, ANPIC (Asociación Nacional de Proveedores de la Industria de Calzado) was visited, the most important supplier fair in the country for the leather-footwear sector organized by CICEG (Cámara de la Industria del Calzado del Estado de Guanajuato) attended by 350 exhibiting companies and more than 11000 buyers and visitors. Table 1 shows the suppliers and the materials that most commercialize for the manufacture of insoles, it is intended to use these materials for the ease of access to suppliers according to their sales volume and the supplier's positioning in the local market, these are the materials that are mostly used in the region for the manufacture of insoles.

Table 1. Suppliers and materials for insole manufacturing.

Supplier	Material	Volume(cm^3)	Mass (g)	Density (g/cm^3)
S1	EVA 2.5mm	6.25	0.518	0.083
	EVA 3.0mm	7.5	0.680	0.091
S2	Latex generic	11.25	2.131	0.189
	Latex antibacterial	8	3.411	0.426
	Latex activate carbon	8	2.629	0.329
S3	EVA 3.2mm	8	0.838	0.105

The tensile test was done on the Instron universal testing machine which measures the load supported by the material before breaking. The tests were done under ASTM 638 (Standard Test Method for Tensile Properties of Plastics) because with this method the mechanical properties of the plastic can be obtained and according to the standard it is useful for engineering design, and to determine the Poisson's ratio, it was performed under ASTM E132-17 (Standard Test Method for Poisson's Ratio at Room Temperature). Table 2 shows the main results of the tensile test.

Table 2. Results of material tests

Supplier	Material	Young's Modulus (MPa)	Tension Max (MPa)	Deformation Break (%)	Tenacity (MPa)	Tension at break (MPa)	Poisson *v*
S1	EVA 2.5mm	1.995	0.833	139.25	0.750	0.833	0.31
	EVA 3.0mm	1.650	0.916	231.55	1.383	0.916	0.29
S2	Latex generic	0.540	0.247	227.88	0.399	0.224	0.11
	Latex antibacterial	0.580	0.312	266.73	0.574	0.310	0.14
	Latex activate carbon	0.561	0.239	218.90	0.366	0.233	0.19
S3	EVA 3.2mm	2.458	1.060	138.45	0.932	1.060	0.36

2.5 Modeling & Simulation

ABAQUS CAE Student's Version was used for modeling the geometry of the insole. The measurements were taken from the footprint study. Moreover, the insole was divided into six sections where the pressures found in the baropodometer was applied. In the Fig. 3 the insole model with its divisions is shown.

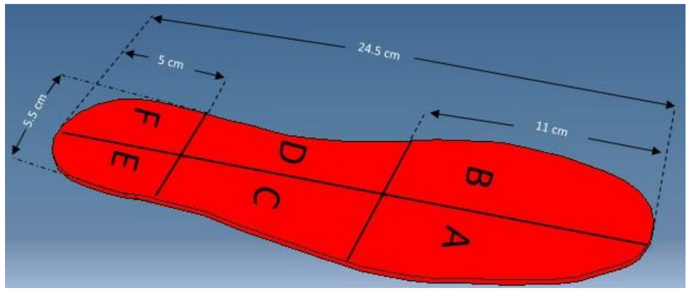

Fig. 3. Insole model with its divisions.

Once the insole was modeled and the mechanical properties of the materials determined, the insole model was meshed, using the type of element "C3D8R: An 8-node linear brick". This type of element was selected because is a general purpose element with reduced integration that helps with the limitation on the student's version in ABAQUS CAE, and was used by Cheung and Zang for the simulation of high-density ethylene vinyl acetate and others similar materials [14].

For initial conditions a reference node was created for each foot zone that served as an initial observation point and to determine the deformation in that node, this works to make the comparisons of the deformations of each material. Boundary conditions were applied to limit the displacements and rotations of the insole placed on the ground, and the loads were applied in each of the regions according to the pressures found in the Baropodometer. Fig. 4 shows the application of the boundary conditions and applied pressures. Six simulations were done on the left foot and six simulations on the right foot, adapting the characteristics of each material to the model and applying the loads in each region of the foot.

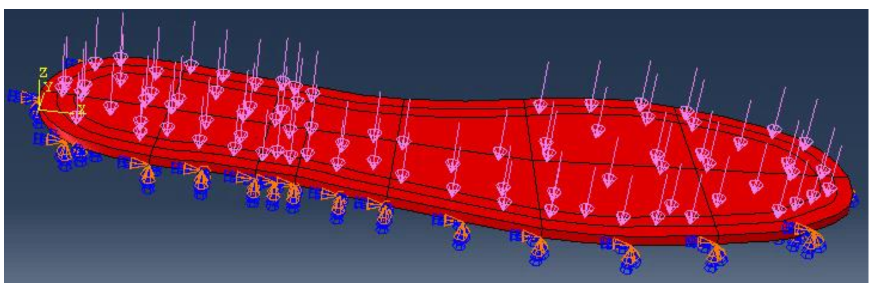
Fig. 4. Application of the boundary conditions and applied pressures.

3. Results & Discussion

Among the main results to be analyzed is the Von Mises stress, it was found that the material that best distributes the plantar pressures is the EVA 3.2 mm of thickness. Overall, the EVA is superior to latex, in Fig. 5 it can be seen the comparisons of each of the materials analyzed in each foot, it is observed that with any material there is a redistribution of the plantar pressure. Fig. 6 shows the right foot insole simulation made from 3.2 mm EVA, during the stresses to which it is exposed during the static phase under normal conditions. The material with the least displacement was the EVA of 3.2 mm of thickness for the two feet and in each zone. The material with the greatest deformation was the generic latex 5.5 mm of thickness for both feet and in each area. It was observed that there was a distribution of plantar pressure on the surface of the insole, placing greater effort on the heel.

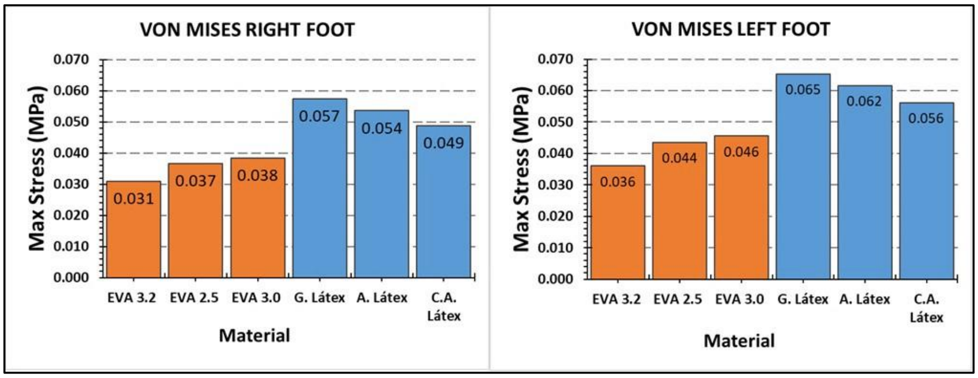

Fig. 5. Comparisons of each material.

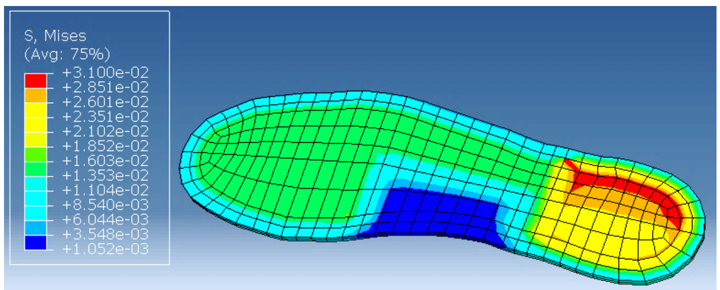

Fig. 6. Right foot insole simulation made from 3.2 mm EVA.

The current research presents some limitations. First, the number of elements available for meshing is limited for the student version of ABAQUS, and this avoids the analysis of complex insoles geometries and verify if this is a significant factor at the time of plantar pressure distribution. Second, there is a sample limited to the Leon Guanajuato region and the sampling was not random due to the complexity of the recruitment of participants, that is why it cannot be generalized for a population. It was observed that Young's modulus and Poisson's ratio influence the redistribution of plantar pressure, the same result that occurs in the work of Berroter et al. [11]. In any case, the results of this study indicate that the material is an important factor in the design of insoles for the redistribution of plantar pressure as Pratt et al. [10] found it must provide good shock absortion. And it must be created based on users who perform the same activity as it was the case with women's basketball.

4. Conclusions

It is observed that with the use of any insole made from the materials described in this work, plantar pressure is redistributed. In relation to the finite element analysis and the mechanical tests of the materials, the best material to use is the EVA. It can be observed that EVA has better mechanical properties compared to latex in its different formulations. The design phase involved the evaluation and analysis of the anthropometric characteristics of the participant to later make the modeling of the insole and perform simulations with different materials. Therefore, the objective of performing a numerical simulation by finite element analysis for probing the redistribution of plantar pressure with insoles that integrates the materials and the anthropometric characteristics of the user was achieved.

Declaration of conflicts of interest

The authors declare that they have no conflict of interest for this work.

Acknowledgments

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