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The Effect of Sole Design on Foot Stress Distribution to Runner

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Abstract:
There is an increased stress on the metatarsal when running due to repeated loadings that cause ankle injury. The solid foam structure of the sole may not provide optimum strength and good absorption shock, as demonstrated by previous studies. So, this study aimed to design the shoe sole models of various patterns or topologies and compare the effects of shoe sole design on the foot stress distribution. This study was conducted using three different softwares which were 3-Matic, Solidworks and ANSYS. Three different topologies of sole including circular, elliptical and hexagonal patterns were designed using Solidworks software. A 23 years old female foot with 45 kg weight and 25 cm foot length was scanned using three-dimensional (3D) scanner and modified using 3 Matic software. Foot-sole simulation was carried out in finite element analysis (FEA) platform called ANSYS, considering the nonlinearity and viscoelastic properties of the sole material to reflect the stress distribution on the foot plantar that in contact with three different midsoles of various topologies. The result showed the hexagonal sole pattern has the lowest stress with a maximum of 0.1 MPa. It has the potential to enhance the area of contact between the foot and the sole. The stresses on the foot were more uniformly distributed. The highest stress was found on the elliptical design with 0.19 MPa because the struts will buckle as the compression load changes dramatically thus, it cannot avoid concentrating the stress on the foot. Meanwhile, the circular pattern has a maximum of 0.12 MPa. The increased stress caused by repeated external impact loads when running will cause ankle injury. Therefore, the hexagonal sole design is the most comfortable that will help to reduce ankle injuries. Lastly, more subjects should be involved in the future for the FEA to achieve a solid conclusion.

Keywords: Sole design; Ankle injuries; Foot stress distribution; Finite element analysis; Runner

1. Introduction

Running is the most apparent expression of people's desire to participate in regular physical activity. The number of runners and running events has rapidly increased in recent years because of its low cost and ease of implementation by a wide range of people with minimal equipment [1]. Despite these health benefits, the surge in popularity of running has coincided with an increase in the number of running-related injuries (RRIs) with frequency of incidence ranges from 2.5 to 33.0 injuries per 1000 h of running [2]. Foot injuries make up 10% to 20% of all running injuries and it is identified that most of the injuries among runners or athletes is the ankle sprain with the frequency of runners suffering from recurrent ankle sprains can be up to 73% [3].

On the other hand, there is an evolution of footwear manufacturing as running becomes popular physical activities across years. Footwear has become a demand among runners as it is believed can enhance the performance and give comfort to the runner. This gave the idea to the designer to develop various designs of shoes with various construction. One of the most crucial components in shoe design is the sole where various properties are required for the shoe sole. There are a variety of shoe sole designs and materials developed by footwear manufacturers in order to provide the best running shoes to all runners or athletes. Previous research has shown that the solid foam construction does not provide optimal strength and stress absorption [4]. As a result, biomechanical study on structural design is required to provide new insight into the future development of running soles.

Furthermore, different groups of athletes may require different types of shoe sole design. Even though there are a lot of choices for sole designs, their design needs and requirements remain to be the most crucial challenge for sport shoe researchers and manufacturers in the near future [5]. So, various sole designs can be developed to meet the runners' needs. Every day, individuals are using their feet to perform activities such as sitting, standing, walking, running, jumping, and so on. Each activity needs a distinct amount of weight being exerted on each foot. In this light, choosing the appropriate footwear for each sport or activity is critical yet often neglected [6]. However, athletic shoes should be chosen by taking their functions into account for their suitability with specific types of activities. Footwear design must incorporate comfort features and regard functionality as a key component of its physical appearance.

Therefore, this study aimed to improve the performance of athletes by determining the proper shoes in terms of different types of sole design. The objectives of this research include to design the shoe sole models of various patterns or topologies and to compare the effects of shoe sole design on the foot stress distribution.

2. Materials and Methods

2.1 Development of 3D model of shoe sole

The topology or pattern used for the sole design should also be selected before the model was designed using and generated in computer-aided design (CAD) software, Solidworks (version 2022). In this research, a semi-curved shoe was used to draft the sole by using sketch picture command and sketch feature. The measurement of the sole frame was created according to subject’s foot measurement where the length was about 26 cm. After that, by using extrude boss feature, an outersole and three types of midsole topologies were designed as shown in Figure 1.

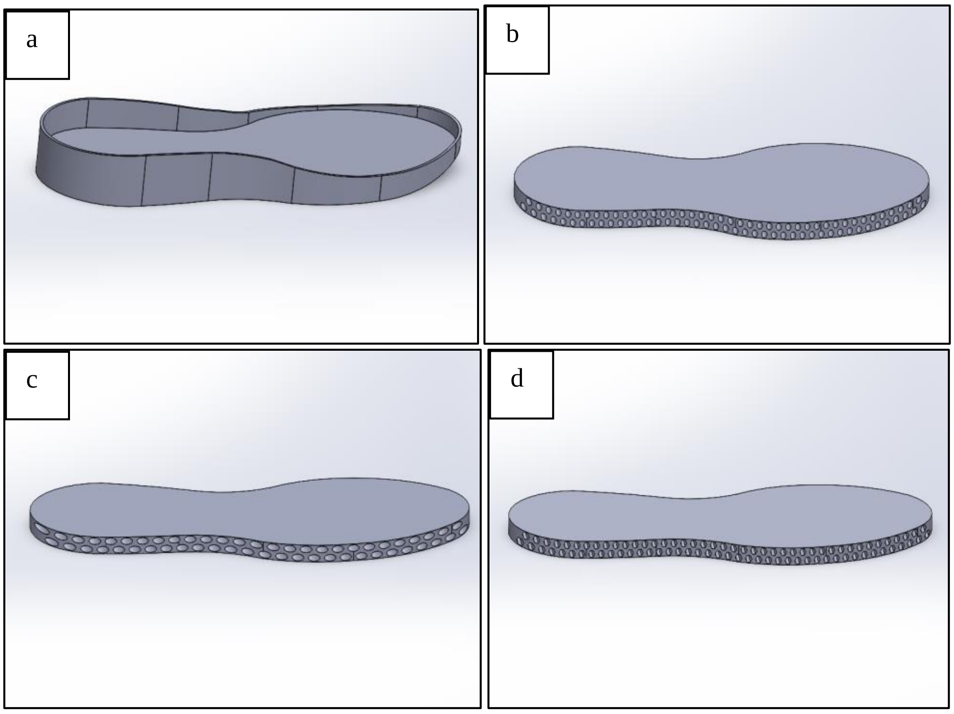

Figure 1 (a) Outersole design, (b) circular pattern of midsole, (c) elliptical pattern of midsole and (d) hexagonal pattern of midsole

2.2 Foot model modification

The SenseTM 3D Scanner was used to create 3D representations of the foot. 3D scanning provided better information of the 3D model, particularly in terms of geometry. The scanner was held roughly 38 cm away from the foot. To avoid tracking loss of 3D scanned models, the scanner was moved gradually. The post-processing of 3D scanned models of the human foot was performed by using 3-Matic (Materialise, Leuven, Belgium). This process consists of the surface smoothing without the removal of the foot features. On the other hand, the same programme was used to eliminate foreign entities from the 3D scanned model. Meanwhile, the design of midsole and outsole was constructed according to the foot geometry. In this study, the subject foot of 23 years old female with 45 kg mass and 25 cm foot length were scanned. The model was then saved in stereolithography (STL) file for future processing.

2.3 Finite element modelling

For mesh production and refining, all 3D models in STL format were imported into 3-Matic. The models' surface and volume mesh were produced first before being imported into Solidworks for the sole-foot assembly and subsequent analysis. The Young's modulus and Poisson ratio of the foot were set at 7300 MPa and 0.3, respectively [4]. Meanwhile, the material of the soles was set where midsole was set to ethylene vinyl acetate (EVA) material while outersole was polyurethane (PU). Next, the foot and the sole were assembled together using Solidworks software before the file is being exported to ANSYS software (student version) in order to run the study. The assembly of sole-foot model, was created using assemble features in the Solidworks.

2.4 Finite element analysis

Using ANSYS software, FEA is used to numerically investigate the mechanical response of the compression of the human foot under the various patterns of the shoe sole. The simulation models are shown in Figure 2 where the force load of 225N is added on the top of the foot. The load was added based on the subject's mass (45 kg) where it should be divided by two since there are two legs; right and left. The bottom surface of the shoe sole is fixed. After that, the interaction between the shoe sole and the foot is generated. During the simulation, the response forces on the foot are saved. The distribution of the plantar stress was presented in the simulation result.

Figure 2 Simulation of sole-foot model

3. Results and Discussion

Based on the previous research from Zolfagharian *et al*. [7], the three different shoe sole model were designed with various patterns which are circular, elliptical and hexagonal. According to the findings, the elliptical lattice has the highest stress and, as a result, has the greatest displacement. This is owing to the lattice's distinct structure when compared to the circular and hexagonal ones. However, in this study, PU and EVA material were used by looking their advantages despite lattice material.

Koike and Okina [8] have been studied the effects of sole designs on the plantar stress and the ground reaction force over a period of time. The results revealed that changing the stiffness and damping structure influences the reaction force value. It was also discovered that the elastic and viscosity properties of the sole provide torque to the ankle and knee joints, causing the body to propel itself. The goal of midsole design is to lessen the amount of plantar stress that is generated on various foot regions and to allow the person's body to relax more while engaging in physical activity.

The simulation result of the plantar stress distribution on the bottom surface of the foot is shown in Figure 3. From this analysis, the effects of three different sole designs of various patterns on the foot stress distribution were observed. The greatest stress of the hexagonal sole pattern is found to be around 0.1 MPa, which is the lowest of all the results. The stress distribution is likewise more uniform in this pattern or topology than in the others. The elliptical sole design, on the other hand, has a higher stress of roughly 0.19 MPa than the other designs. The stress concentration is also more obvious in the elliptical design. Meanwhile, the stress distribution of the circular pattern sole design is around 0.12 MPa. In summary, the shoe sole with the hexagonal topology is the best choice since it has a smaller and more uniform stress distribution than the other designs as stated in Table 1.

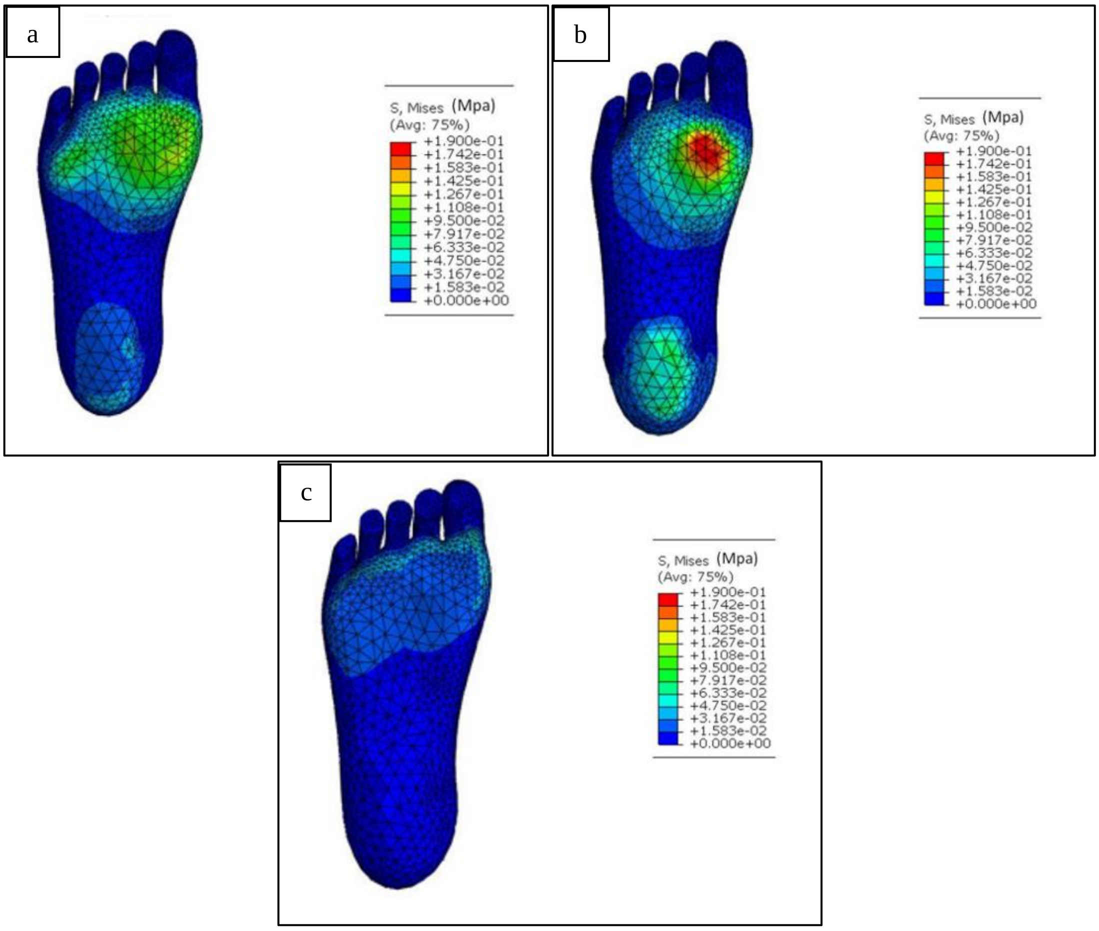

Figure 3 Simulation results for (a) circular pattern, (b) elliptical pattern and (c) hexagonal pattern

Table 1 - Summary of simulation results on circular, elliptical and hexagonal patterns

Pattern	**Stress (MPa)**	**Stress distribution**
Circular	0.12	Less obvious
Elliptical	0.19	Obvious and concentrated
Hexagonal	0.10	Small and uniform

The greatest stress of the hexagonal sole pattern is found to be around 0.1 MPa, which is the lowest of all the results. The stress distribution is likewise more uniform in this pattern or topology than in the others. Meanwhile, the elliptical sole design has a higher stress of roughly 0.19 MPa than the other variants. In the elliptical form, the stress concentration is also more visible. Meanwhile, the circular pattern sole design has a stress distribution of roughly 0.12 MPa.

The same pattern of stress region was also shown in previous studies that investigated the maximum stress distribution of midsoles for the three patterns of sole (circular, elliptical and hexagonal) at running scenario [7]. Except for numerical simulation, experiment was also can be conducted to investigate the differences among the mechanical responses of the lattice sole. The sole with highest stress, which in this study was the elliptical design, was usually buckled during the compression test. The circular and hexagonal pattern have same stiffness at the beginning however the hexagonal pattern was less stiff than the circular when the compression force increase [7].

As reported in the study and from the analysis obtained, the results proved that the elliptical pattern has the highest plantar stress with 0.19 MPa as shown in Figure 3 (a), compared to the circular, 0.12 MPa (Figure 3 (b)) and hexagonal ones, 0.1 MPa (Figure 3 (c)). The elliptical sole topology is not appropriate for the shoe sole application. The reason for this is that the struts will buckle as the compression load changes dramatically thus, it cannot avoid concentrating the stress on the foot [7]. The hexagonal sole pattern, on the other hand, is the softest of these three topologies.

The increased influence of elliptical geometry is owing to the topology of this construction, which is more prone to crushing and hence experiences a greater quantity of displacement, stress, and energy. The increased stress caused by repeated external impact loads when running will cause ankle injury [2]. The simulation testing results demonstrate that the shoe sole with the hexagonal pattern moves more under the same stress. It has the potential to enhance the area of contact between the foot and the shoe sole. The stresses on the foot are more uniformly distributed. By this mean, running using the elliptical shoe sole pattern has high contribution for the ankle injuries to occur compare to circular and hexagonal sole pattern. As a result, the hexagonal topology shoe sole is the most appropriate since it has a smaller and more uniform stress distribution than the other designs.

Insoles are now widely utilised as devices to reduce the impact on the human foot in a variety of applications, including sports, clinical use, and normal daily living. The biomechanic data of the human foot and the soles can be used to explore a number of potential areas for creating pleasant insoles for athletes, and this new knowledge could serve as a reference for future sport device development [9]. Furthermore, for the limitations, the finite element models of the bones, insoles, and skin were considered to be isotropic, linear, and homogeneous. This did not resemble actual human bones (a bilayer of human bones with a cortical and cancellous area). Hyper-elastic materials are used for the skin and insoles. It is suggested in future study that models with genuine properties be addressed during model construction.

4. Conclusion

In conclusion, sole is the crucial component in shoe construction which can help to give comfort and enhance runners' performance. The objectives are achieved to design different shoe soles; circular, elliptical and hexagonal. The simulation testing results demonstrate that the shoe sole with the hexagonal pattern moves more under the same stress. It has the potential to enhance the area of contact between the foot and the shoe sole. The stresses on the foot are more uniformly distributed. By this mean, running using the elliptical shoe sole pattern has high contribution for the ankle injuries to occur compare to circular and hexagonal sole pattern. As a result, the hexagonal topology shoe sole is the most appropriate since it has a smaller and more uniform stress distribution than the other designs.

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Conflict of Interest

The authors declare no conflict of interest.

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