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Finite element modelling of Plantar Fascia response during running on different surface types

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Finite element modelling of Plantar Fascia response during running on different surface types

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Abstract. Plantar fascia is a ligament found in human foot structure located beneath the skin of human foot that functioning to stabilize longitudinal arch of human foot during standing and normal gait. To perform direct experiment on plantar fascia seems very difficult since the structure located underneath the soft tissue. The aim of this study is to develop a finite element (FE) model of foot with plantar fascia and investigate the effect of the surface hardness on biomechanical response of plantar fascia during running. The plantar fascia model was developed using Solidworks 2015 according to the bone structure of foot model that was obtained from Turbosquid database. Boundary conditions were set out based on the data obtained from experiment of ground reaction force response during running on different surface hardness. The finite element analysis was performed using Ansys 14. The results found that the peak of stress and strain distribution were occur on the insertion of plantar fascia to bone especially on calcaneal area. Plantar fascia became stiffer with increment of Young's modulus value and was able to resist more loads. Strain of plantar fascia was decreased when Young's modulus increased with the same amount of loading.

1. Introduction

Plantar fascia is one of the major structures in human foot that acting as a major ligaments connected between foot bones where located underneath the foot bones which it is function as the major stabilizing structures of the longitudinal arch of human foot, sustains a high tensions during weight-bearing[1], [2]. Plantar fascia plays a significant role in the movement of human either in normal walk or running. The injury namely plantar fasciitis occurs when large amount of tension or forces acting toward it [3]. Several studies have been conducted in investigating the mechanical strain of plantar fascia through experiment [4]–[6] and finite element simulation [7]–[9]. Welk et al [10] conducted a study on changes in plantar fascia thickness from tissue creep in runners and walkers by using high resolution ultrasound. The study was conducted in two groups where subject from group 1 need to walk on treadmill for 10 minutes while subject from group 2 need to run on treadmill for 30 minutes. The subjects were imaged by using high resolution ultra sound with 12-MHz linear transducer probe immediately before and after session on treadmill. The changed in mean of plantar fascia thickness where it is reduced about 0.03 mm ± from its original thickness for group 1. The result for group 2 shows that the changed of 0.06 mm ± of the plantar fascia thickness. Moreover, Clark et al [11] investigated about the mechanical strain in the intact of plantar fascia. The frozen intact limb cadaveric was used as experiment's subject. The frozen intact limb was thawed before begin the experiment.

Three-way rosette gauges were used to measure the strain in plantar fascia. The foot of intact limb was dissected to attach six strain gauge. This study resulted the mean of oscillation frequency of the limbs was similar to the data for live subject. It is shows that the plasticity of plantar fascia was similar between live subject and cadaver intact limb.

On the other hand, Cheung et al [3, 4] developed the 3D geometrical of foot bone based on reconstruction of MR images obtained from CT scan. The model comprises of 28 bony segments. A total of 72 ligaments and plantar fascia were included and defined as the attachment point between the bones. Similarly, Cheng et al [7] developed the 3D model of foot bone from images. The DICOM image from CT scan was taken and then reconstructed by using image processing software AMIRA 3.1.1 (mercury Computer System, Germany). The profile of the bones were edited to make it smooth in term of shape and gathered by threshold adjustment. The 3D bones model then imported to the ANSYS software for assembly and further analysis. Cheung et al [3,4] set the mesh for foot bones 3D solid model and soft tissue with total mesh of 50 775 tetrahedral elements (included bony structures, cartilage and soft tissue) and 103 tension-only truss element for ligamentous structure (included plantar fascia). All tissue were set as linearly elastic, homogeneous and isotropic. The meshed for the 3D solid foot bone model with total of 50 482 elements and 72 930 nodes was generated. Cheung et al [12] reported that Achilles tendon forces with 75% of the total weight on one foot was the closest match of the measured centre of pressure during balanced standing of the subject. An increment in tension of the plantar fascia was obtained due to the weight of the foot and Achilles tendon loading. In the previous study by Cheung et al [13], there was a significant increment in the long and short plantar and spring ligament when the value of Young's modulus decreased. The maximum stress was found concentrated near to the medial calcaneal tubercle. Three dorsiflexion angle are selected in the study which is 15, 30, and 45 degree. The stresses of plantar fascia was increased when the dorsiflexion angle is increasing. Hence, kinematics movement of foot was found contributed the biomechanical response of plantar fascia. Since running on different surface could affect the kinematics of foot [14], this study was undertaken to investigate the effect of surface types on plantar fascia response during running.

2. Materials and Method

2.1. Geometrical Modelling

The foot bone model was obtained from Turbosquid database. The foot model was then imported to Solidworks 2015. The foot bones contains separated 26 bony structures. Between each bone structure, there is a small gap that was filled up to connect all the bone into one single body. The effect of articular cartilages in this study was neglected. The plantar fascia of 1.5 mm thickness was constructed to connect medial calcaneal tubercle to metatarsal head. Five stripes of plantar fascia were connected to metatarsal head as shown in Fig. 1. Each stripe was attached to each metatarsal bone and four connecting bodies were constructed between the stripes. The stripes were then joined to become a single stripe in the middle of foot before connected to calcaneus. Figure 2 shows the ground support with dimension of 150 mm × 300 mm × 20mm that was constructed to act as a base to the foot bone model where it is attached at the top surface of the ground support body.

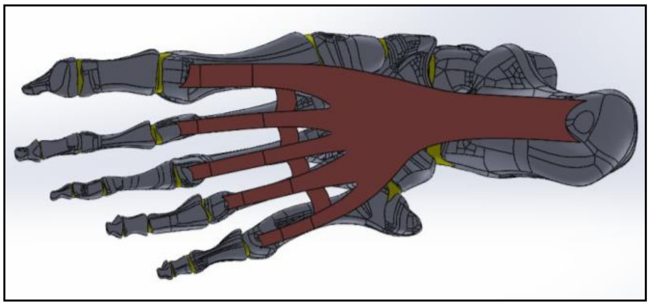

Figure 1. CAD model of plantar fascia with foot bone.

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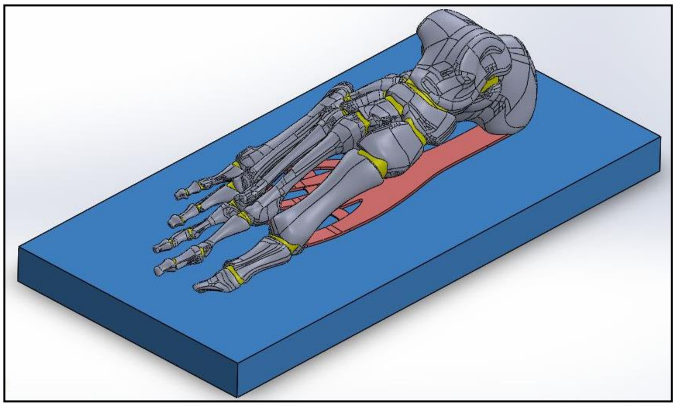

Figure 2. Foot bone model with ground support plate.

2.2. Finite Element Modelling

All materials were considered as isotropic and linearly elastic. The mechanical properties of bone, plantar fascia and ground support plate are listed in Table 2. Three Young's modulus were set on plantar fascia in order to analyse the effect of Young's modulus variation on plantar fascia response. The contacts between bones, plantar fascia and ground support were defined as ‘bonded type’ for the present finite element analysis (FEA). Figure 3 shows a complete meshed model. The element size of 5 mm tetrahedral type was used for foot bones and plantar fascia, whereas 6 mm of 3D-brick element was used for ground support plate. The optimum element size of 5 mm for tetrahedral element were obtained from the convergence test.

Table 1. Material properties of foot bone, plantar fascia and ground support model.

Component	Young's modulus (MPa)	Poisson’s Ratio
Foot bone	7300	0.3
Plantar fascia	350, 500 & 700	0.4
Ground support plate	210 000	0.4

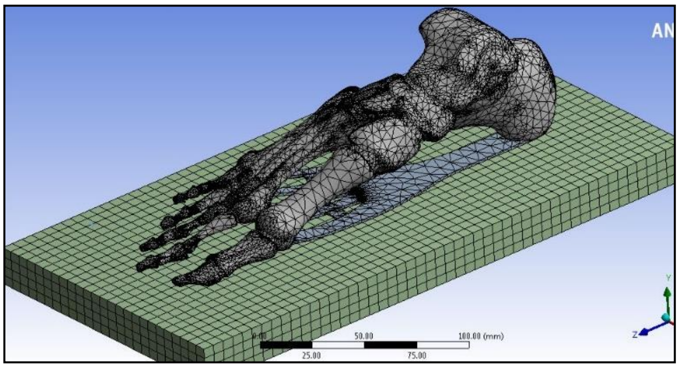

Figure 3. Complete meshed model.

Boundary conditions were set out to represents the foot condition during running by applying the peak ground reaction force (GRF) vertically from the bottom of the ground support plate. The peak

GRF for running on three different surfaces; concrete, rubber and artificial grass, was obtained from the previous experimental study [15]. The top surface of the foot was fixed. The peak GRF load was applied with 1373 N for concrete surface, 1490N for artificial grass surface and 1620N for rubber surface.

3. Results and Discussion

Figure 4 shows the result of equivalent (von-Mises) stress for plantar fascia under running on three different surfaces with Young's modulus of 350 MPa. The highest value for maximum equivalent stress is 0.92285 MPa which occurred during running on rubber surface. Whereas running on concrete and artificial grass have the maximum equivalent stress of 15.2% and 8% less than the value from running on rubber tile respectively. Figure 5 shows the result of equivalent elastic strain under the same boundary conditions. Similarly, running on rubber surface contributes to the highest value for maximum equivalent elastic strain which is 0.0026772 mm/mm.

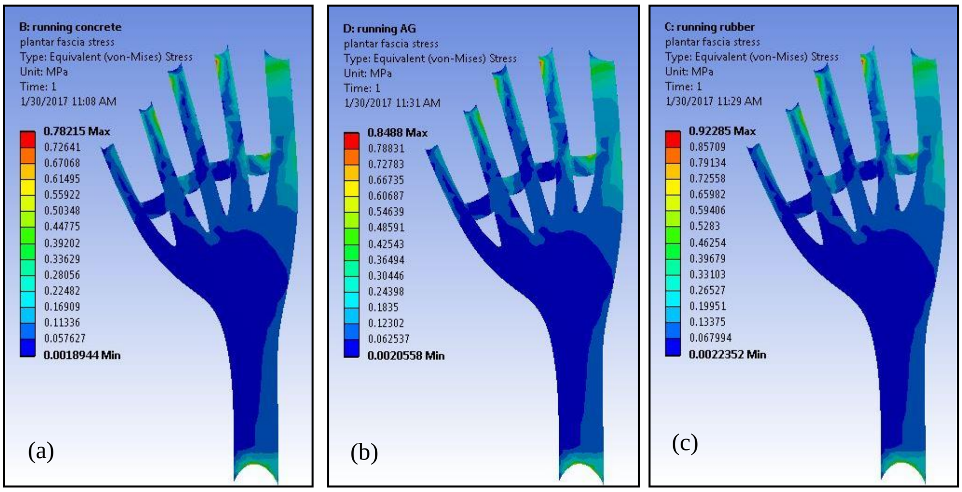

Figure 4. Equivalent (von-Mises) stress for plantar fascia when running on three different surfaces with Young's modulus of 350 MPa: (a) concrete, (b) artificial grass, (c) rubber.

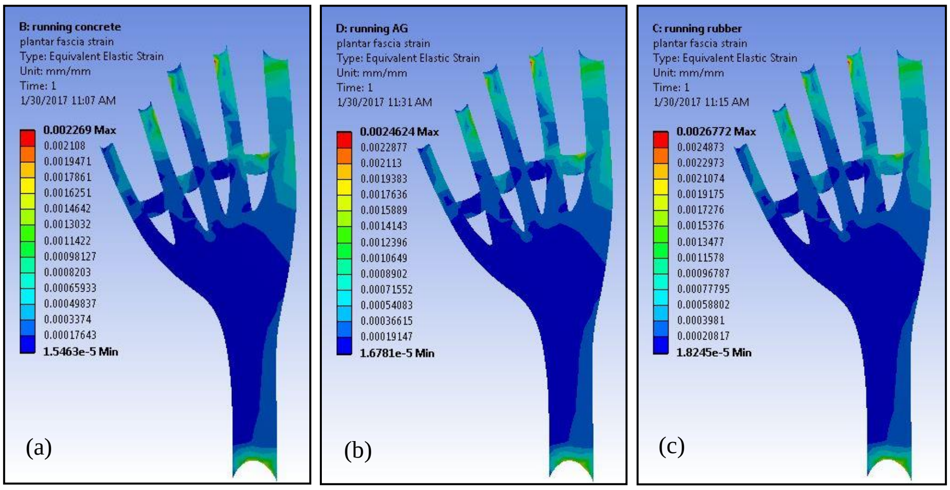

Figure 5. Equivalent (von-Mises) stress for plantar fascia when running on three different surfaces with Young's modulus of 350 MPa: (a) concrete, (b) artificial grass, (c) rubber.

Moreover, the stress and strain contour of plantar fascia with Young's modulus of 500 MPa and 700 MPa was found similar to the contour obtained when Young's modulus is 350 MPa as shown in Figs. 6 to 9. However, the increase of Young's modulus of plantar fascia reduced the equivalent elastic strain and increased von-misses stress as shown in Fig. 10 (a) and (b), respectively. Obviously, the plantar fascia became stiffer with the increase of Young's modulus and was able to resist load and prevent large deformation.

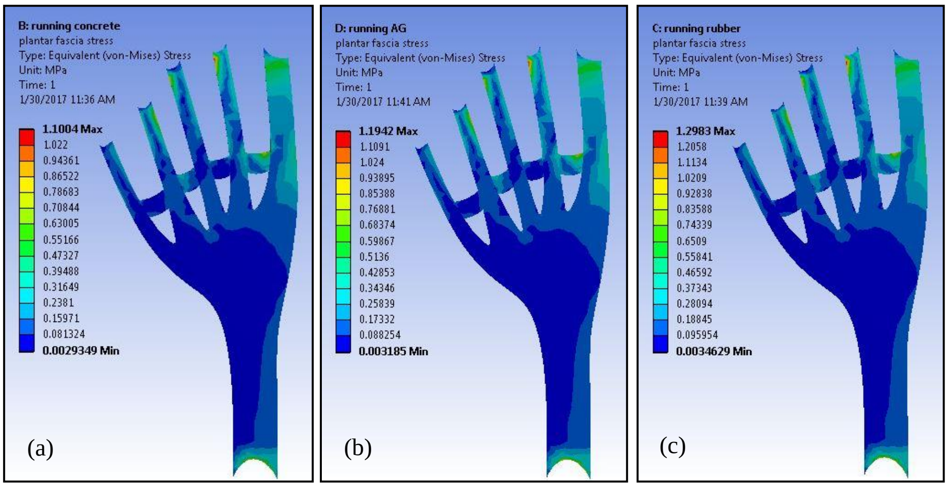

Figure 6. Equivalent (von-Mises) stress for plantar fascia when running on three different surfaces with Young's modulus of 500 MPa: (a) concrete, (b) artificial grass, (c) rubber.

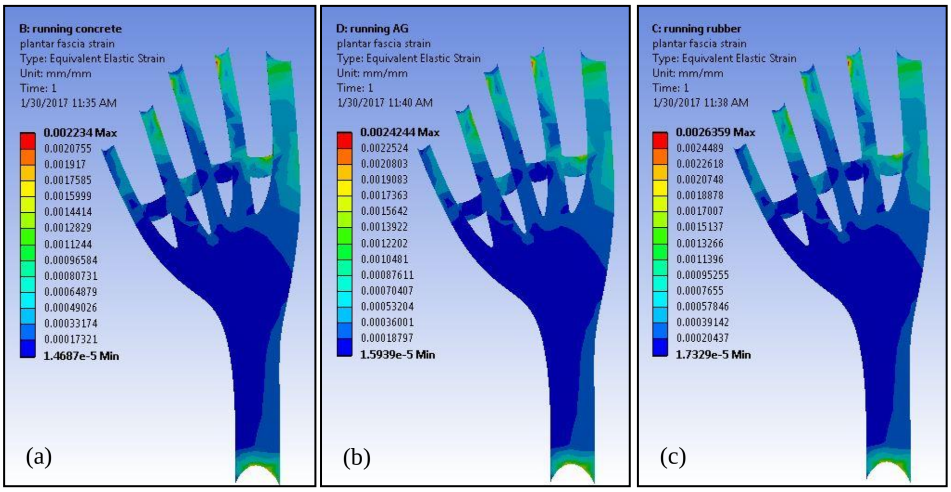

Figure 7. Equivalent (von-Mises) stress for plantar fascia when running on three different surfaces with Young's modulus of 500 MPa: (a) concrete, (b) artificial grass, (c) rubber.

Finite element modelling is very useful tool to enhance the understanding on biomechanics response. Based on the result obtained in the present analysis, we found that the stress and strain were concentrated on the insertion area of plantar fascia towards the foot bones which is near to the calcaneus and metatarsal head regardless of the value load applied to the model. This result in correlation to the common injury of plantar fascia namely, plantar fasciitis which is always occurred on the heel area around the insertion area of plantar fascia to calcaneus. The contour of these result were same because the boundary conditions applied for all three model are same. The only difference for these models are Young's modulus values. It contributes to the difference in minimum and maximum value of equivalent stress for all models. The stress and strain were concentrated on the insertion area of plantar fascia which is on calcaneal and metatarsal area. The stress and strain concentration were very low in the medial area of plantar fascia.

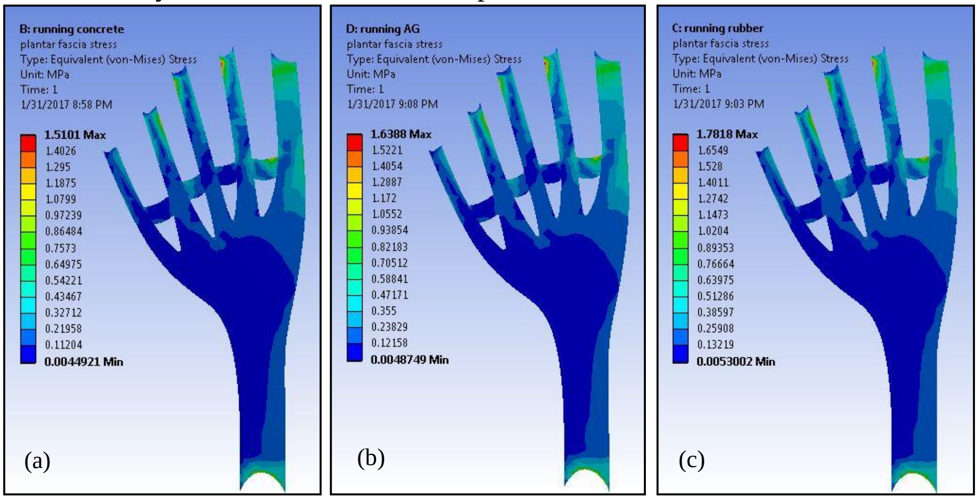

Figure 8. Equivalent (von-Mises) stress for plantar fascia when running on three different surfaces with Young's modulus of 700 MPa: (a) concrete, (b) artificial grass, (c) rubber.

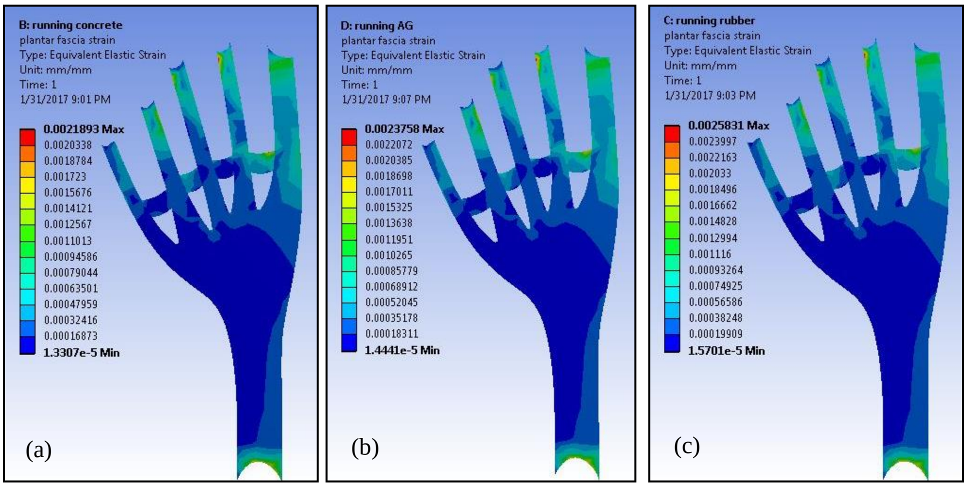

Figure 9. Equivalent (von-Mises) stress for plantar fascia when running on three different surfaces with Young's modulus of 700 MPa: (a) concrete, (b) artificial grass, (c) rubber.

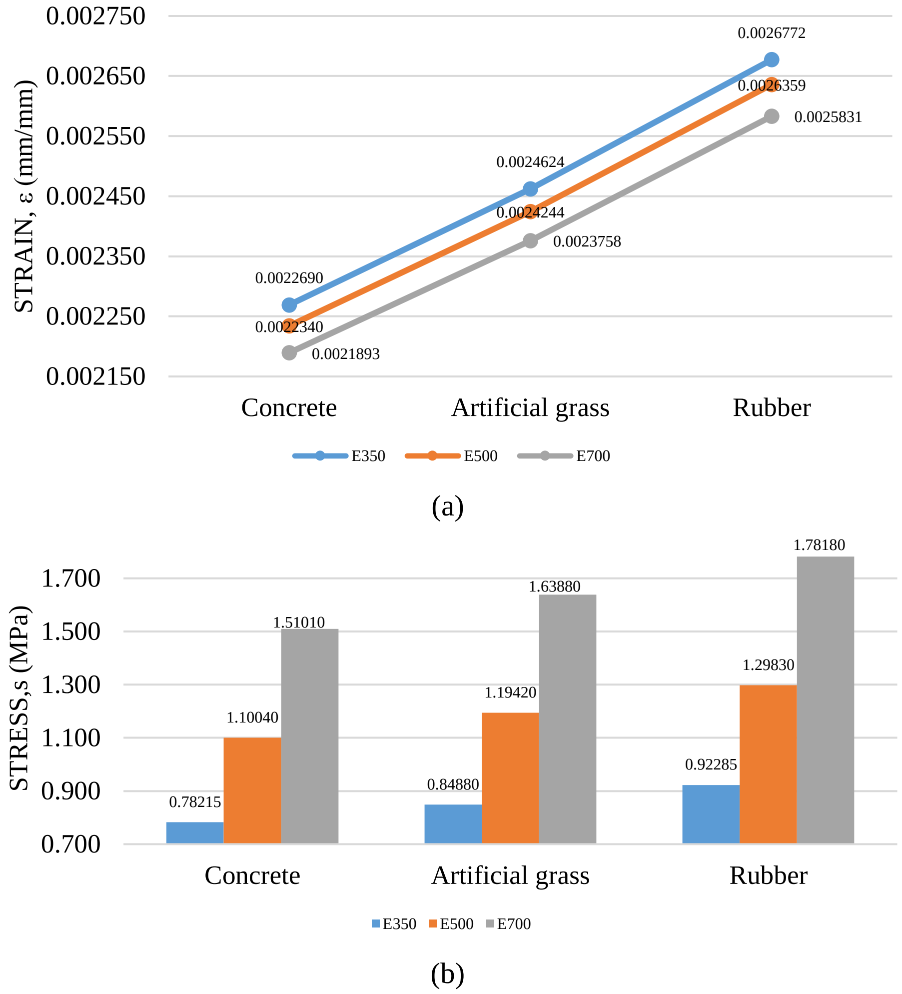

Figure 10. Effect of surface types on plantar fascia response with Young's modulus variation. (a) Equivalent elastic strain. (b) Von-misses stress.

Since there is no experimental study conducted to validate the result of the present finite element study, the result was compared to other published finite element studies[16]. The equivalent stress obtained in this study was found in agreement with other published results when Young's modulus of 350 MPa was used on plantar fascia. Hence, Young's modulus of 350 MPa predicted well on the stress response of plantar fascia. There are some limitations associated to the present study. All materials of the analyzed model were assigned to linearly elastic. The soft tissue and other connective tissue such as other ligaments and tendons other than plantar fascia were not included. However, these limitations did not compromise the general findings of the present study. The predicted stress and strain response of the plantar fascia was found similar to other published results.

4. Conclusion

The plantar fascia was observed to have high concentrated stress and strain at the insertion area that connected to calcaneus and metatarsal. The highest stress and lowest strain response of plantar fascia was found when running on rubber surface. The increase of plantar fascia's modulus contributed to the increase of equivalent stress and reduce the elastic strain. The present study could provide additional insight on study of plantar fascia response due to forces reacted during running with different surfaces that could lead to plantar fasciitis.

5. Acknowledgments
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