ASSESSMENT ON MECHANICAL STRESS AND STRAIN OF PLANTAR FASCIA: A REVIEW

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Abstract— Plantar fascia plays a major role as superficial to the muscle of the plantar surface of the foot and the most important arch stabilizing structure. Excessive stress and strain on plantar fascia may result in local inflammatory response that could cause plantar fasciitis. Therefore, the purpose of this paper is to review recent studies that focuses on the assessment to investigate the mechanical stress and strain of plantar fascia that could lead to plantar fasciitis. This review also highlights both experimental and computational analysis for enhance understanding of plantar fascia response under daily activities load.

Keywords—plantar fascia, plantar fasciitis, mechanical stress, elastic strain.

I. INTRODUCTION

Plantar fascia is one of the major structures in human foot. 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 high tensions during weight-bearing [1]. Plantar Fascia play a significant role in the movement of human either in normal walking or running. The ligament often experience injuries when large amount of tension or forces acting toward it. Study about stress and strain in plantar fascia has been carried by many researchers [2]–[4], especially investigation on the injury related to plantar fascia. The most common injury related to plantar fascia is ‘plantar fasciitis’ which is one of the common heel pain. Commonly this injury occurs during the activity that gives high stress directly towards foot such as sports [5]. There many research were carried out on plantar fascia with similar objective which is to examine the causes and solution of plantar fasciitis [6]–[8]. The limitation of the investigation upon plantar fascia is the ligament itself located underneath the soft tissue (skin) thus has contribute difficulties to investigate directly on plantar fascia. Thanks to modern technology in computer has solve these difficulties in investigation on plantar fascia. The plantar fascia can be modelled in the software to carry out an analysis using computational method.

In general, assessment of injury risk on plantar fascia can be conducted either using finite element method (FEM) or experimental method. In FEM, the plantar fascia can be developed through CAD software. Development of the plantar is based on the foot bones that functions as a foundation for this ligament. The model of plantar fascia might be vary according to the researchers on how to develop the most similar model compared to actual ligament. The complete model of plantar fascia will then imported to FEM software to perform the analysis. The model will then be discretized into finite elements before the boundary conditions was applied.

Experimental studies upon this type of ligament was very limited since it is located underneath human soft tissue (skins). The experiment can be conducted with or without undergoing surgery procedure. Through the surgery method, the experiment needs cadaveric intact limb as a subject. The limb must be undergo minor dissection to reach the ligament before the experiment can be conducted. The other way to conduct experimental method is using alive subject. The ligament can be analyzed by using high resolution ultra sound to imaging the changes of plantar fascia before and after experiment.
II. OVERVIEW OF PLANTAR FASCIA

Plantar fascia is kind of ligament found in human foot structure located beneath the skin of human foot. It has a strong and thick central part which covers the central of the 1st layer muscle [1]. As an important connective tissue in foot bone, plantar fascia is made up from a longitudinally oriented dense collagen fibers that formed a fibrous structure of ligament similar like the composition of other ligament. Plantar aponeurosis is the other name of plantar fascia. Plantar fascia is connecting calcaneal (more specified to be attached on medial calcaneal tubercle.) to all five metatarsal and extended to proximal phalanges of toe. Illustration in Fig. 1(a) shows the plantar fascia structure in human foot whereas Fig. 1(b) shows the illustration of plantar fascia from side view.

The major function of plantar fascia is stabilized longitudinal arch of human foot as well as give a robust supportive base during standing and absorbs dynamic reaction forces during gait, gait brings meaning during normal walking and running [2]. Acting as major supporting structure for the arch of human foot, plantar fascia has a great mechanical strength as well as biomechanical properties that able to sustain high tensions during weight-bearing of human body [9].

Another function of plantar fascia is a ‘windlass mechanism’. This mechanism is very important during gait (walking or running) to provide stability of human body and help to avoid the foot arch from collapse. Imagine the foot bones as simple trusses with three main components which is plantar fascia as a tie rod (structure 1), calcaneus as a rear foot (structure 2) and metatarsal as fore foot (structure 3) in triangular structure as illustrated in Fig. 2(a), with a pulley connection on structure 1 and 3 [8]. Windlass mechanism will be activated when toe lift up on weight bearing of the body especially lifting up the great toe [11]. During standing situation, vertical forces from the load of the body weight is transferred downward to this triangular trusses through tibia bone and causes the structure 2 and 3 to be flatten. So, the function of plantar fascia is to avoid the trusses from collapse or in other words to stop the toe spreading away from heel. When the toe is dorsiflexed (rising up the toe whilst the heel stay on the ground), the plantar fascia will wrapped around the head of metatarsals as shown in Fig. 2(b), thus increasing the height of longitudinal arch and shorten the distance between heel and metatarsal head as well as it will become rigid [12].
Fig. 2 Mechanism of plantar fascia. (a) Windlass mechanism illustration [11]. (b) Windlass mechanism when toe dorsiflexed [12].

III. OVERVIEW OF PLANTAR FASCIITIS

Plantar fasciitis is an injury on the plantar fascia due to thickening of the ligament itself. As one of the most common heel injury, plantar fasciitis would be painful injury to individual. This injury usually take a long period to get worsen. It usually caused by repetitive microtears on the plantar fascia thus prevent the ability of the body to repair the affected areas [13]. Plantar fasciitis usually occur near the same location on plantar fascia (localized) where the area of occurrence near the insertion of plantar fascia into the medial tubercle calcaneus as shown in Fig. 3.

Fig. 3 Location of occurrence microtears lead to plantar fasciitis [14].

The major causes that often lead to plantar fasciitis are excessive stretch on plantar fascia, repetitive and abnormal stress applied on plantar fascia, overweight (obesity), having a flat feet or unusual high arch, walk or run for a long period especially on hard surface and tight Achilles tendon [15]. The people who has daily routine in bearing body weight for a long period such as athlete, soldier and labor workers for example. People in middle age has a greater risk to suffered plantar fasciitis rather than younger people in normal demographic condition. Sport activities that often lead to this injury are football, basketball, tennis, dances as well as long distance running [1].

Plantar fasciitis will goes into significant pain when individual bearing body weight after a prolonged period rest for example during morning wake up after sleep especially on the first step. The pain will gradually relief after a few steps but will getting worsen as the day progresses. Other situation that the pain often occur are the first step after sitting for certain period, climbing the stairs and after finish doing any activity especially sports. Untreated plantar fasciitis will lead to chronic injury and the patient will not be able to do daily activity as usual and make a movement such walking feel uncomfortable. The ordinary treatment for initial stage of plantar fasciitis is taking a rest from doing risky activity that lead to worsen the injury of plantar fascia.
IV. EXPERIMENTAL STUDIES ON PLANTAR FASCIA

Only a few experimental studies on assessment of plantar fascia are available in the literature since it has many limitations to conduct in depth analysis. Welk et al. [16] studied about a measure changes in plantar fascia thickness from tissue creep in runners and walkers by using high resolution ultrasound. The study involved 61 independent samples of participant that were divided into 2 groups which consist of 36 and 25 each with range of age from 20 to 51, involving 29 females and 32 males. Subjects of group 1 walked in the treadmill for 10 minutes. The subjects were imaged by using high resolution ultra sound with 12-MHz linear transducer probe immediately before and after walk session on treadmill. Subject of group 2 were conducted the same procedure but in different movement style. They were ran in the treadmill for 30 minutes. All participants were required to wear athletic footwear as a procedure for this study. The image of foot were taken in seated position with extended knee as well as rising up the toe. They found that there is a changed in mean of plantar fascia thickness where it is reduced about 0.03mm ± from its original thickness for group 1. The result for group 2 shows that the changed of 0.06mm ± of the plantar fascia thickness. The changes was slightly small in value because of certain limitation. The quantity of loading that toward the foot is not enough as well as the duration of walking and running on the treadmill is too short. The footwear that used by subjects during this study also influenced the result because the footwear itself has features in protection of foot during walking or running. The lack of these criteria will resulted only small changes in the thickness of plantar fascia. The method used in this study significantly different with the real condition of natural way where the plantar fascia works.

On the other hand, Clark et al. [4] investigated about the mechanical strain in the intact of plantar fascia. This study used frozen intact limb cadaveric as experimental subject as illustrated in Figure 4(a). The frozen intact limb was thawed before begin the experiment. Three-way rosette gauges were used to measure the strain in plantar fascia. The intact limb cadaveric was positioned supine on the metal dissection table and a pulley system was designed to placing a load toward the intact limb toe as shown in Figure 4(b). The foot of intact limb was dissected to attach six strain gauge. The limitation of using this strain gauge is the size of gauge itself may cause significant deformation of tissue where the gauges were attached. This could damage the collagen fibril as well as affecting the outcome result. A load of 98.1 N was applied to the foot through the pulley system and the reading of strain gauges were taken. The results showed that the mean of oscillation frequency of the limbs was similar to the data for live subject. It was found that the plasticity of plantar fascia was similar between live subject and cadaver intact limb. Also, the strain mapping of the plantar fascia shows that the majority of the strain is centrally longitudinal.

![Fig. 4](image_url)

(a) Supine position of intact limb cadaveric. (b) Attachment of six strain gauges (one gauge is not shown) on plantar fascia [21].

V. FINITE ELEMENT ANALYSIS ON PLANTAR FASCIA

One of the best method to analyze the mechanical responses of 3D solid model is using Finite Element Method (FEM). This method has been widely used because of the broad function in conducting an analysis. By using computer to perform the analysis of foot model, we are able to
manipulate certain parameters and other constant in order to achieve the expected result in precise manner. It is also easy to control and monitor the whole structure of analyzed model.

Finite element analysis (FEA) on plantar fascia has a wide range of variant in term of research and studies. Many studies related to plantar fascia have been conducted by using FEA because through this method, various analysis can be performed upon plantar fascia since it is not require any subject to accomplished the experiment. Only development of the foot model in three dimensional is required to perform the analysis.

5.1. Geometrical Modelling
Cheung et al. [4,15] developed the 3D geometrical of foot bone by reconstruction images obtained from CT scanner. The model comprises of 28 bony segment. A total of 72 ligaments and plantar fascia were included and defined as the attachment point between the bones. Similarly, Cheng et al. [13] generated the 3D model of foot bone from images. The DICOM image from CT scanner was taken and then reconstructed by using image processing. 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.

Gu and Li [15] developed the 3D foot bone model by reconstruction of a three dimensional CT image. Coronal CT images were taken and the images were then processed and segmented by using MI\_MICS 8.0 (Materialise, Leuven, Belgium) software. The processed image of foot bone then imported to Solidworks 2005 (Solidworks Corporation, Massachusetts, USA) to generate 3D solid models. Next, the 3D solid model from solidworks was imported into Geomagis Studio\_TM (Geomagic, INC., Research Triangle park USA) to smoothing the rough surface that caused by CT scan imaging process.

5.2. Meshing
Cheung et al. [4,15] 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 model is shown in Figure 5.

Similarly, Cheng et al. [13] created the mesh for the 3D solid foot bone model with total of 50,482 elements and 72,930 nodes. The bone and cartilage were set to tetrahedral solid element type while ligament was set to tension-only truss element type. All tissue were set as linearly elastic, homogeneous and isotropic except soft tissue and plantar fascia. Meanwhile, Guo et al. [18] assigned the bony structures cartilaginous as four-node tetrahedral elements type. The soft tissue and plantar fascia were set to 8-node hexahedron elements type and ligaments were defined as tension truss element type. All tissues were set as linearly elastic, homogeneous and isotropic except soft tissue and plantar fascia.

![Figure 5 Meshed 3D solid foot bone [9].](image-url)
5.3 Mechanical Properties of Foot

The mechanical properties of foot for FEA of plantar fascia for some authors are summarized in Table 1. Since most of the previous studies focused on linear elastic, only the elastic constants was assigned as material properties in the FE model. Furthermore, the investigation and studies are focused to the plantar fascia whereas the bone is just become the basic structure where the plantar fascia located.

Table 1 Summary of mechanical properties for foot model in previous studies.

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<th>Young’s modulus (MPa)</th>
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5.4 Findings

Research findings of the previous FE studies focused on the mechanical stress and strain responses that could lead to injury on plantar fascia. Cheung et al. [9] 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 resulted by the weight of the foot and Achilles tendon loading. In the previous study [17], there was significant increment of the long and short plantar and spring ligament when the value of Young’s modulus decreased. To simulate the plantar fascia release, zero Young’s Modulus has been chosen by the author. With no value of Young’s modulus, it results to the shifting in peak von Misses stresses from the third to the second metatarsal bones and also increased stresses at the plantar attachment area around the cuboid bone.

Fig. 6 Von Misses stress distribution pattern of plantar fascia in different stretch combinations. The highest point of stress located near to the medial calcaneal tubercle (marked with red circle) [13].

Moreover, Cheng et al. [13] found that the maximum stress was concentrated near to the medial calcaneal tubercle as shown in Fig. 6. The stresses of plantar fascia was increased when the dorsiflexion angle is increasing. Three dorsiflexion angle are selected in this study which is 15, 30, and 45 degree.
VI. CONCLUSION

Studies on the mechanical stress and strain of plantar fascia that could lead to injury are summarized in this paper. Due to concern on the injury risk such as plantar fasciitis, it is expected more research will be conducted in future to enhance the mechanism and progression on plantar fascia strain subject to load during daily life and sport activities.

REFERENCES