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Research Article

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Deep transverse metatarsal ligaments mechanical response during landing

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ABSTRACT

The deep transverse metatarsal ligaments play an important role in stabilizing the metatarsal bones and manipulating foot transverse arch deformation. However, the biomechanical research about transverse metatarsal ligaments in the foot maneuver is quite few. Due to the difficulties and lack of better measurement technology for these ligaments experimental monitor, the load transfer mechanism and internal stress state also hadn't been well addressed. The purpose of this study was to develop a detailing foot finite element model including transverse metatarsal ligaments tissues, to investigate the mechanical response of transverse metatarsal ligaments during the landing condition. The transverse metatarsal ligaments were considered as hyperelastic material model was used to represent the nonlinear and nearly incompressible nature of the ligament tissue. From the simulation results, it is clearly to find that the peak maiximal principal stress of transverse metatarsal ligaments was between the third and fourth metatarsals. Meanwhile, it seems the transverse metatarsal ligaments in the middle position experienced higher tension than the sides transverse metatarsal ligaments.

Keywords: Finite element analysis, Landing, Deep transverse metatarsal ligaments, Maximal principal stress.

INTRODUCTION

The deep transverse metatarsal ligaments (DTML), a series of four short ligamentous bands that span between the distal ends of adjacent metatarsal bones and intersect with the plantar ligaments of the metatarsophalangeal joint is a narrow band that runs across and connects together the heads of the metatarsal bones [1]. This ligament is very strong, as it above the plantar nerve, creating the ceiling of the nerve compartment. Every step, the ground reaction force pushes up on the enlarged nerve, but the DTML pushes down. Although it didn't contribute substantially to cause the foot deformity such as hallux valgus [2], it plays an important role in stabilizing the metatarsal bones and manipulating foot transverse arch deformation [3]. However, the biomechanical research about DTML in the foot maneuver is quite few.

Foot pain and injuries are common in the running community. The most common condition we treat is plantar fasciitis and heel pain syndrome. Less common injuries also appear in the foot and are often overlooked or misdiagnosed by most physicians. Pain under the 2nd -4th metatarsal can be metatarsalgia, stress fracture or a torn transverse metatarsal ligament [4]. Due to the difficulites and lack of better measurement technology for these ligaments experimental monitor, the load transfer mechanism and inernal stress state also hadn't been well addressed. The purpose of this study was to develop a detailing foot Finite element model including DTML tissues, to investigate the mechanical response of DTML during the landing condition.

EXPERIMENTAL SECTION

The foot model was developed through the reconstruction of 3D CT scan of the right foot of a normal male volunteer. This detailed foot model developing methods were illustrated in Gu et al. [5], in particularly, DTML were built through the Solidworks 2010 (Solidworks Corporation, Massachusetts, USA) to form solid models (Fig.1), defining by connecting the corresponding attachment position on the bones [6]. All the foot bones were considered as one layer material, and the mechanical properties of foot tissues were assigned according to the FE model developed by Gu et al.[5]. For DTML materials, the hyperelastic material model was used to represent the nonlinear and nearly incompressible nature of the ligament tissue. Mooney–Rivlin strain energy potential was adopted with the form

$$W = C_1 (I_1 - 3) + C_2(I_2 - 3), \tag{1}$$

Where W is the strain energy per unit of reference volume, C_1 and C_2 are material parameters , in which material constants C_1 and C_2 of 1.687 and 0.106 (kg/cm^2) were adopted from Hirokawa and Tsuruno [7] ligament experimental results.

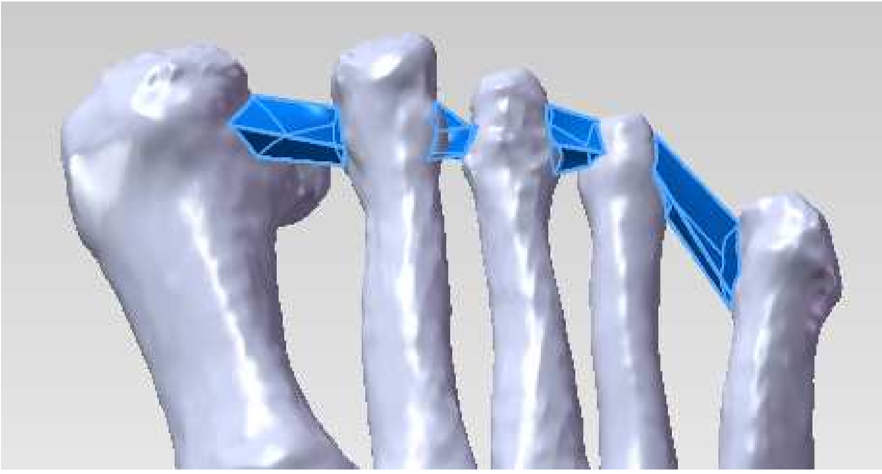
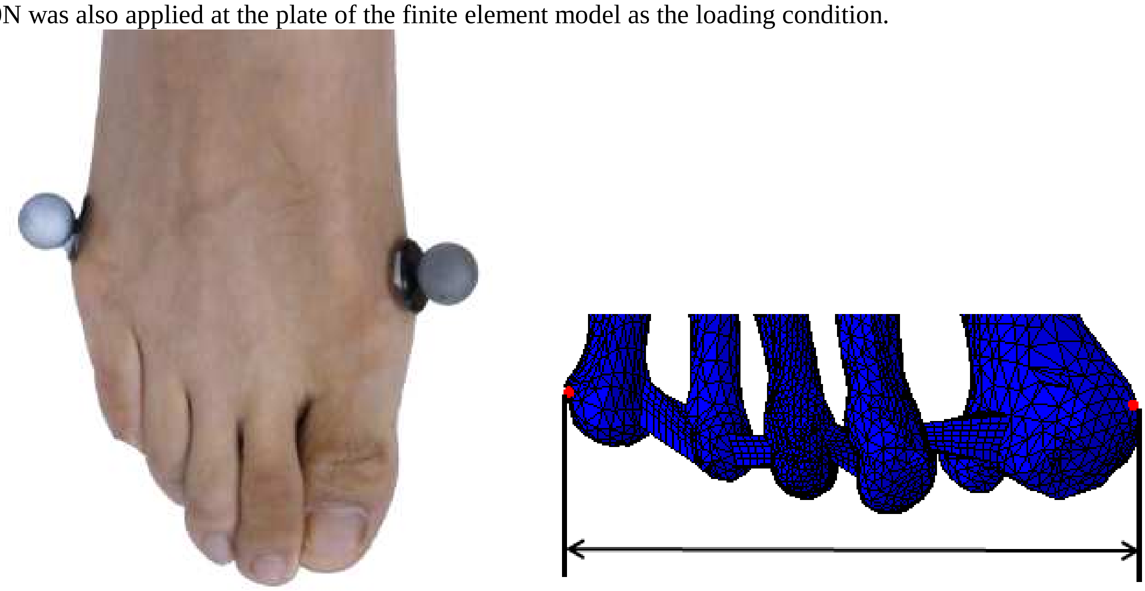


Fig.1 The illustration of DTML solid models

The subject who experienced CT scan, also completed a biomechanical testing to measure the forefoot transverse deformation during initial landing. A Qualisys Motion Capture System (Qualisys, Gothenburg, Sweden), collected digital data from reflective markers on the first and the fifth metatarsal head (Fig.2). The initial landing force around 100N was also applied at the plate of the finite element model as the loading condition.



a **b**

Fig.2 The experimental measurement (a) and simulation prediction (b) methods of the forefoot transverse deformation

RESULTS

The forefoot transverse deformation, which measured the distance through the first and the fifth metatarsal, was showed in Fig.3. In the initial landing stage, simulated forefoot transverse deformation is in good accordance with the measured values.

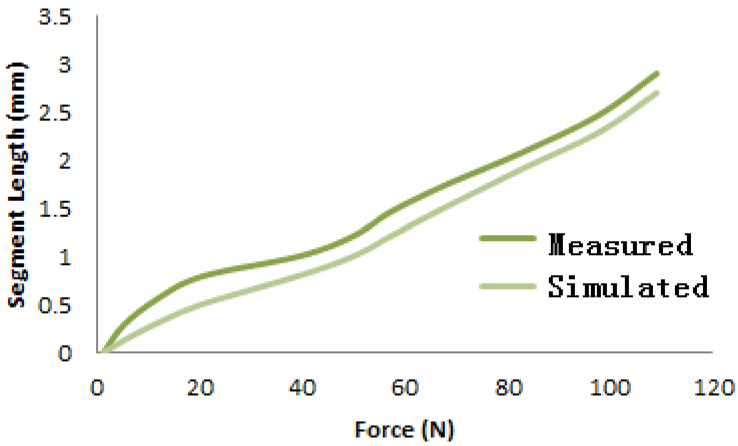


Fig.3 The forefoot transverse deformation during initial landing

Fig.4 shows the maximal principal stress distribution of DTML in the initial landing condition. It is clearly to find that the peak maiximal principal stress of DTML was between the third and fourth metatarsals. Meanwhile, it seems the DTML in the middle position experienced higher tension than the lateral and medial sides of DTML.

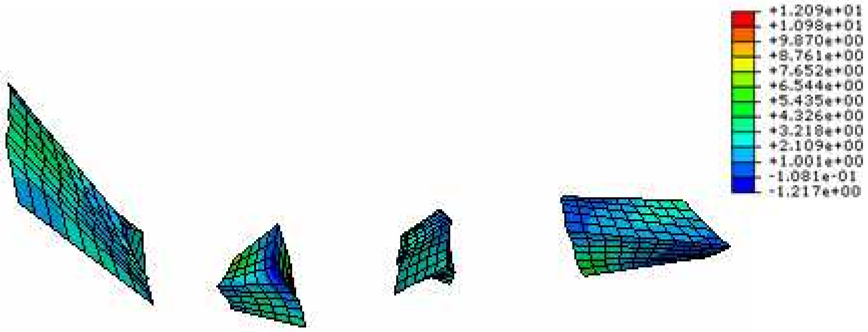


Fig.4 The maximal principal stress distribution of DTML during landing(From left to right view is foot lateral side to medial side)

DISCUSSION

Under forefoot initial landing condition, the finite element model predicted a similar profile of forefoot transverse deformation. The foot motion analysis could be one of effectively methods to evaluate the accuracy of finite element model. Most foot computational analysis in the literatures [8, 9] usually looking into the long arch deformation, in this case, the forefoot transverse arch deformation always been neglected. This study not only investigated the forefoot deformation trend during landing, but also found that the middle DTML playing more important role to restrict the forefoot expand than the two side parts. But it must point out that the landing force applied in the simulation was just in initial contact stage, therefore, the DTML mechanical response under high loading force shall be investigated in the further analysis.

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