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A MATERIAL SENSITIVITY ANALYSIS OF PLANTAR FASCIA USING A THREE DIMENSIONAL FINITE ELEMENT MUSCULOSKELETAL MODEL OF HUMAN FOOT COMPLEX

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INTRODUCTION

As a common musculoskeletal disorder characterized by pain in the inferior heel, plantar fasciitis has been reported to account for from 11 to 15 percent of all foot symptoms requiring professional care [1]. Among various therapies, fasciotomy has been considered for patients who have persistent and severe symptoms, though some nonsurgical interventions were used for a long time [2]. Although favorable outcomes were reported in some case series, the effect of this surgical treatment on foot biomechanics has not been fully investigated.

In this study, a three-dimensional finite element (FE) musculoskeletal model of the human foot complex with detailed subject-specific representation of all major anatomical structures was constructed. Dedicated FE analyses in the mid-stance during normal walking were conducted to investigate the mechanical responses of the foot musculoskeletal structure subjected to varying elastic modulus of plantar fascia as simulated results of fasciotomy. The effects on the foot plantar fascia and deep transverse metatarsal ligament extensions, the plantar pressure, the bone stress distribution and also the total strain energy stored in the foot structure were calculated.

METHODS

The skeletal geometry of the FE foot model was reconstructed based on medical CT images (Lightspeed16, General Electric Company, Fairfield, U.S.A), which were obtained by scanning the right foot of a healthy male subject (age: 27 yrs, weight: 75kg; no history of lower limb injury or foot abnormalities) with a 1.5 mm slice interval. To accurately locate the origins of ankle plantiflexor and dorsiflexor muscles, femur, tibia and fibula bones are also constructed. Based on the constructed foot skeletal geometry, a total number of 85 foot ligaments including plantar fascia were integrated into the model. In this study, twelve major muscle groups around talocrural, subtalar and metatarsal-phanlangeal joints were constructed (see Figure 1). The musculoskeletal geometry of these muscle groups was determined according to the MRI images and also the 3D human anatomy software (Primal Picture Ltd., U.K). The muscles were constructed by considering the mechanical properties of the skeletal muscles, which include both contractibility (ability to contract) and extensibility (the ability to stretch). The muscle forces can not only be transmitted via linear path, but can also be transferred through curved path in 3D.

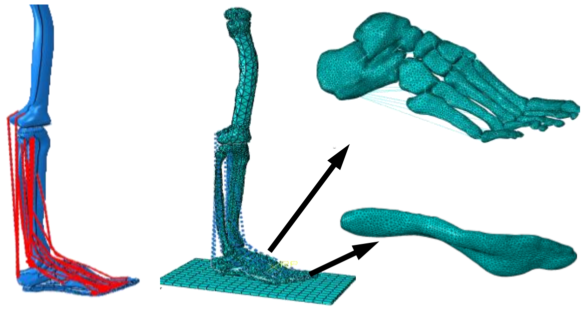

Figure 1: The FE foot model (consisting of 29 bones, 85 ligaments, 12 muscle groups and the plantar soft tissue)

The constructed subject-specific FE foot musculoskeletal model was then used to predict the mechanical behaviors of the foot musculoskeletal components in the mid-stance of normal walking by varying the material property of plantar fascia to simulate the effect of fasciotomy. This included eight different cases in which the Young's modulus of the plantar fascia has been changed gradually from the baseline value (350MPa) to 300MPa, 250 MPa, 200 MPa, 150 MPa, 100 MPa, 50 MPa and 1MPa, respectively. In the simulations, the muscle forces and ankle joint forces acting on the talus bone, estimated based on a subject-specific multi-segment musculoskeletal model were used as inputs. The simulations were conducted using ABAQUS/Explicit module based on the ABAQUS software (Simulia, Providence, U.S.A). A rigid fixed plate was used to simulate the ground support, and the foot-ground interface was defined as contact surfaces with a frictional coefficient of 0.6 [5, 6], while joint surfaces and the interactions between bones and foot plantar were all defined as frictionless contacts. The meshes of bones, soft tissues and ligaments were all determined using a converging analysis. The material properties of all structure components in the model were taken from previous studies [3-5, 7, 8].

RESULTS AND DISCUSSION

In our FE foot model, there are four deep transverse metatarsal ligament groups (each group consisting of three truss elements) around five metatarsal heads. Figure 2 shows the calculated extensions of the four ligament groups in the eight simulation cases. The extensions of 1st and 4th groups increased with the decreased elastic modulus of the plantar fascia. However, the trend is opposite for the 2nd group, and no obvious difference was observed for the 3rd group. This suggests that plantar fascia release may cause transverse splaying of the metatarsals, which was reported by previous cadaveric studies [9].

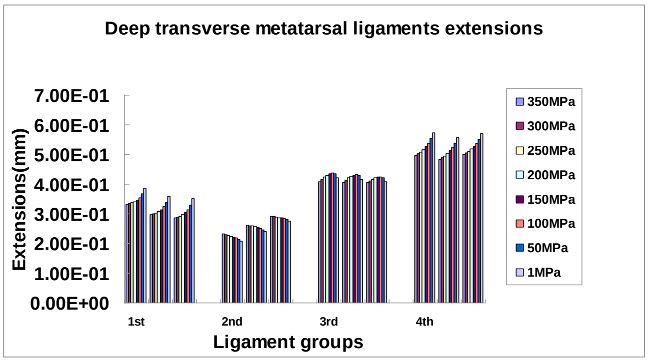

Figure 2: Deep transverse metatarsal ligament extensions for four groups (each group consisting of three sub-branches)

The calculated extensions of the plantar fascia in all the simulated cases are shown in Figure 3. As the foot arch tends to flatten in the mid-stance phase, the plantar fascia was stretched to transmit a tensile force between calcaneus and metatarsal heads. From our results, it seems that all the branches of the plantar fascia generate more extensions with decreased stiffness except the 1st branch, which may be due to the loading transfer condition.

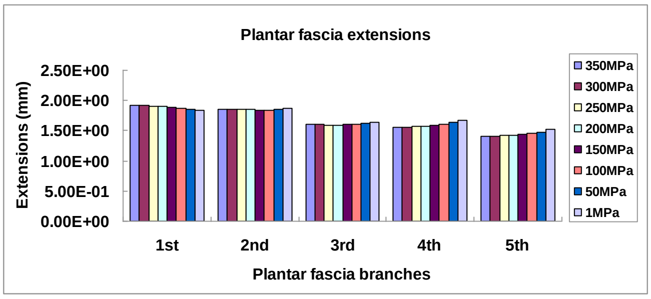

Figure 3: Plantar fascia extensions for five branches

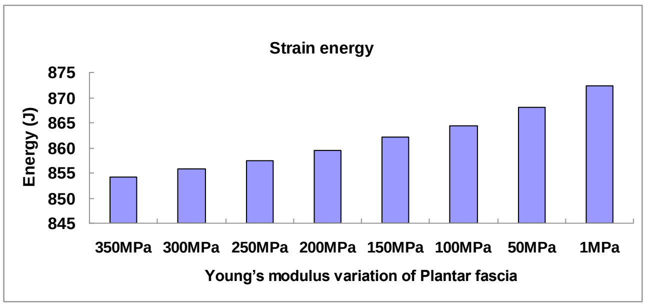

Figure 4: The strain energy variation in foot skeletal system

As seen from Figure 4, the strain energy of the whole foot musculoskeletal structure increased with the decrease of Young's modulus of plantar fascia, which implies the fasciotomy may reduce the gross structural stiffness of the foot complex to some extent.

Figure 5 shows the calculated peak plantar pressures in heel, metatarsal medial and metatarsal lateral regions, respectively. It can be seen that the peak pressure in both metatarsal medial and lateral regions increase with the decreased Young's modulus of plantar fascia. However, the peak pressure decreased at heel region. This suggests that the plantar fascia release may change the forefoot to rear foot force transfer in the mid-stance phase and hence moderate the load at heel region.

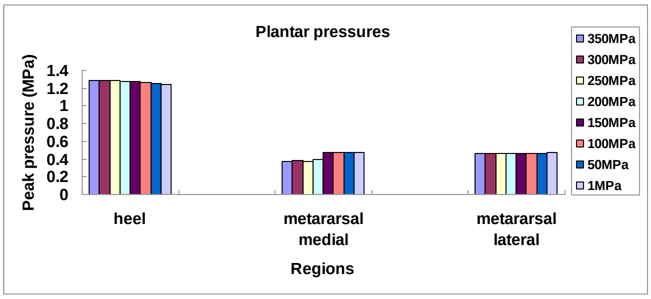

Figure 5: Peak plantar pressure in heel, metatarsal medial and metatarsal lateral regions.

The stress distribution on foot bones was also calculated. The maximal stresses in five metatarsals all increased, of which the 4th and 5th metatarsals show higher stress magnitudes and change rates than the other bones. This further supports that the plantar fascia release may change the load transfer between forefoot and rear foot.

CONCLUSIONS

A three-dimensional FE musculoskeletal model of the human foot complex with detailed subject-specific representation of all major anatomical structures was constructed and used to simulate the biomechanical responses of foot musculoskeletal components with varying stiffness of the plantar fascia. Our preliminary results, including foot plantar fascia and deep transverse metatarsal ligament extensions, peak plantar pressure, bone stress distribution and total strain energy, were showed and discussed.

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