Metatarsal stress distribution and joint contact pressure of hallux valgus: A finite element analysis

Y. ZHANG[1], J. AWREJCEWICZ[2]

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1. Introduction

Studies have suggested that the peak pressure increased significantly under the first and second metatarsals in hallux valgus (HV) feet [1]. The finite element (FE) model is capable of predicting the internal stress in the foot complex and eventually interpreting potential risks associated with foot deformities. Information on stress distribution of the internal structures is useful in enhancing the understanding of podiatric biomechanics and may contribute to surgical treatments. In this study, FE foot models of a normal subject and a severe HV patient were developed to evaluate the metatarsal stress and the MTP joint contact pressure under a balanced standing condition.

2. Methods

2.1. Finite element model

The two-dimensional CT images were segmented using MIMICS 16.0 to obtain the three-dimensional model of the bone tissue and the encapsulated soft tissue. Each surface component was imported into Solidworks 2016 individually to form a solid part. A solid volume was created between the adjacent surfaces of two bones, and the bones were then subtracted from the solid volume to create cartilage. The ligaments and plantar fascia were defined by connecting attaching points on corresponding bones with straight line structures. Bones, cartilages and the encapsulated soft tissue were assigned hexahedral elements. ANSYS Workbench 17.0 was used for subsequent analysis. The contact between bone and cartilaginous surfaces was assumed as frictionless.

2.2. Materials properties

The bones are defined as a linear elastic isotropic material (Young's Modulus = 7300 MPa, Poisson's ratio = 0.3). The stiffness of the Cartilage, Plantar Fascia and Ligament is set at 1, 350 and 260 MPa, respectively; the Poisson's ratio is set as 0.4. The encapsulated soft tissue was set as nonlinear hyperelastic material which was defined as a Moonley-Rivlin model.

2.3. Loading and boundary conditions

A balanced standing condition was considered for the FE analysis. The superior surfaces of the encapsulated soft tissue, distal tibia, and distal fibula were fixed. A plate was created assigned with an elastic property to model the ground support. A vertical ground reaction force of a half-body weight (255 N for normal foot; 260 N for HV foot) was applied at the inferior surface of the plate. The interaction between the foot and the plate was simulated as contact surface with a coefficient of friction of 0.6 [2]. The force of the Achilles tendon (128 N for normal foot; 130 N for HV foot) was estimated as 50% of the load applied on the foot [2].

2.4. Model validation

The numerical model was validated by comparing plantar pressure from computational simulation in FE software and experimental measurement by a Novel emed pressure platform (Novel, Munich, Germany).

[1]Yan, Zhang, 90-924 Łódź, ul. Stefanowskiego 1/15, e-mail: champagne0906@hotmail.com

[2]Jan, Awrejcewicz, 90-924 Łódź, ul. Stefanowskiego 1/15, e-mail: jan.awrejcewicz@p.lodz.pl

3. Results and discussion

3.1. Metatarsal von Mises stress

Pressure distribution from the FE result was generally consistent with the experimental result. Also, a good match between peak pressure value and location were found for both models. For the normal foot model, the peak pressure from prediction and measurement was 0.141 MPa and 0.135 MPa, respectively, and for the HV foot the values were 0.144 MPa and 0.137 MPa, respectively.

The von Mises stress in metatarsals generally increased due to HV deformity, as shown in Fig. 1. Compared to the normal foot, medial and lateral forefoot sustained a larger percentage of von Mises stress in the HV foot, indicating an increasing risk of stress or fatigue failure. As balanced standing is the most common and basic behaviour in daily life, it can be speculated that the increased metatarsal stress may cause metatarsalgia while sustaining weight bearing. The most obvious increasing of von Mises stress at the fifth metatarsal indicates that the fifth metatarsal is more susceptible to injury for patients with severe HV. However, the stress concentration at the second metatarsal decreased (less than 3%) in the severe HV foot.

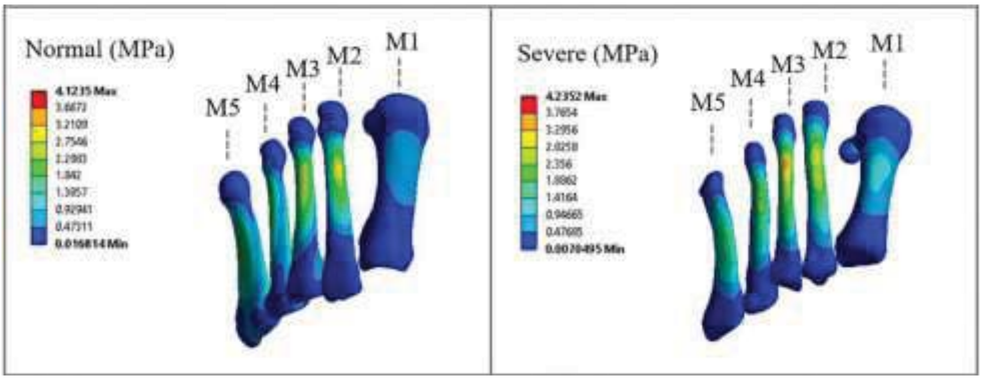

Fig. 1. Metatarsal stress distribution

3.2. MTP joint contact pressure

The HV foot showed lower MTP joint contact pressure, especially at the second to fifth MTP joints. The decreased joint loading may imply the impairment of load bearing and transfer function of MTP joint in gait. For the normal foot, the maximum pressure is located at central bottom of the contact surface, while for the severe HV foot, it transfers medially so that it is located at medial bottom of the contact surface.

References

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