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A 3-dimensional finite element model of a newly designed adjustable high-heeled shoe

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ABSTRACT

Footwear plays a crucial role in several activities to realize aesthetic and cultural needs of urban society. The increasing popularity of high-heeled shoes (HHS) can be attributed to modern fashion, job requirement, and common belief in enhancing aesthetic appeal. Although most women like wearing HHS, it has been reported to be associated with foot problems, i.e., changing the body alignment and muscle activities, knee joint osteoarthritis, lower back pains, redistribute the plantar pressure and ground reaction forces as well as forefoot diseases, which finally can trigger clinical problems of lower extremity. However, wearing a flat-heeled shoe (FHS) would not be accompanied with such problems in the foot. This is why women would be pleased if they could have an adjustable HHS with fast, easy switching ability to a FHS one according to their needs. Therefore, this study was aimed at proposing a newly designed adjustable HHS/FHS to be worn by women for the sake of comfort. To do that, a 3-dimensional computational finite element (FE) model of our own proposed adjustable HHS/FHS was established and the amounts of stress and deformation in the foot and footwear during a simple standing were calculated and compared. The results revealed a lower von Mises stress in the soft tissue and bony structures of the foot when wearing a FHS compared to that of the HHS. The results have implication not only for proposing a newly designed adjustable HHS/FHS to the market, but also for deep understanding of foot and footwear biomechanics and proving women with an innovative flexible design which both keeps their fashion and comfort.

1. Introduction

Shoes are not only designed to protect the foot from the rough terrain, abrasion or any other external incursion during movement, but they also intended to meet the needs in the variety of disciplines, i.e., sports as well as aesthetic and cultural desires of urban society (Smith and Helms, 1999). Among women, high-heeled shoes (HHS) due to the benefit of modern fashion, job requirement as well as common belief in augmenting the aesthetic appeal from anthropological view are in high demands (De Lateur et al., 1991; Esenyel et al., 2003; Gefen et al., 2002). However, shoe discomfort and foot problems, such as knee joint osteoarthritis, lower back pains, forefoot diseases (Cronin, 2014; McBride et al., 1991; Yung-Hui and Wei-Hsien, 2005), ingrown nail, hammertoe, metatarsal stress fracture, and ankle sprain (Thompson and Coughlin, 1994; Goud et al., 2011) are accompanied with HHS. Meanwhile, it is reported that the heel height has a remarkable role in the rate of the biomechanical injuries as well as discomfort in the HHS (Ebbeling et al., 1994; Hong et al., 2005).

In the other words, wearing a flat-heeled shoe (FHS) provides more comfort during a long patency of walking. Therefore, it would be an interesting idea if we could provide an adjustable shoe which helps to both keep their fashion, pleasure according to their needs, and also provide a sense of comfort during a usual walking, etc. Although experimental techniques have been developed to quantify the biomechanical interactions of foot and footwear, such as in-shoe pressure, motion analysis, and muscle electromyography; numerical analyses, i.e., finite element (FE) method would allow us to perform a parametric study with a wider range of variables. So far, different studies have shown that wearing a HHS increases ankle plantarflexion angle (Stefanyshyn et al., 2000), changes muscle activity (Cronin et al., 2012; Simonsen et al., 2012), reduces gait stability (Ebbeling et al., 1994; Bendix et al., 1984), changes lower limb posture (Henderson and Piazza, 2004), increases forefoot pressure and shear in general (Broch et al., 2004; Cong et al., 2011), and possibly increases the risk of knee injuries (Simonsen et al., 2012; Kerrigan et al., 2005). However, the amount of stress and deformation as a consequence of an adjustable

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HHS/FHS wearing have not been computed or compared. Understanding the internal mechanical response of the human foot through the computational models help us in enhancing our knowledge of the internal stresses and strains for the aim of proper footwear designing (Tao et al., 2009).

Yu et al. (2013), established a computational FE model of a coupled foot-ankle-shoe complex to investigate the mechanical performance of a HHS during the gait. The impact of HHS on ankle complex during walking in young women were investigated experimentally (Wang et al., 2016). The effect of heel height on in-shoe localized triaxial stresses were investigated due the common problems among the women as a result of HHS wearing (Cong et al., 2011). Effects of sole design on the plantar pressure and bony stress by developing a foot-sole FE model were investigated (Chen et al., 2003; Cheung and Zhang, 2008). Nonetheless, so far the studies have only been focused on the foot model for HHS and there is a paucity of knowledge on how an adjustable HHS/FHS can minimize the complexities of a HHS and provide a sense of comfort for women. Thus, this study was aimed at proposing a newly designed adjustable HHS/FHS model to be used in women shoe fashion industry. To do that, a 3-dimensional FE model of a shoe was established and the induced stresses and deformations in the foot and shoe as a consequence of simple standing were calculated and compared.

2. Methods

2.1. Foot model

This study adopted a simplified version of a previously developed 3D anatomically detailed FE foot model (Tao et al., 2009; Yu et al., 2008). In addition, we also benefitted from a set of magnetic resonance images (MRI) of the foot in neutral position to adapt the foot structure to that of the footwear design.

2.2. High-heeled shoe/flat-heeled shoe model

The shoe model was designed by our group at Heel of Scene Ltd, Fukuoka, Japan. The 3D structure of the model along with all its assembly details are indicated in Supplementary movie files 1 and 2. The FE models of the HHS and FHS were made according to the shape and structure of our newly designed shoe as presented in Fig. 1. The 3D geometrical model of a HHS was established according to the volunteer's shoe size (7.5 US size). A 10.50 cm heel height for the HHS was chosen for the sake of high popularity and sustainability for wearers in Japan. The HHS model consisted of a 3.70 mm thick sole and a 2 mm thick shankpiece and a homogenous regularly shaped HHS upper. Insole and midsole layers were not separated from the sole because of their minimal construction and for the sake of simplification. The material properties of each component of the HHS/FHS and foot tissues were selected from the literature and listed in Table 1. The elastic modulus of the sole was divided into four different categories, including a very soft, soft, firmer, and rigid for simulation of open-cell polyurethane foams, such as Professional Protective Technology's or PPT, high-density ethylene vinyl acetate, and polypropylene materials. A very rigid, 1 mm thick bottom layer was used to simulate the ground support and to facilitate the application of concentrated ground reaction forces.

2.3. Numerical simulation

A balanced standing position was simulated by applying a vertical ground reaction force (half body weight (Cheung and Zhang, 2005), 300 N as displayed in Fig. 1) underneath a flat horizontal support which was used to establish the frictional contact with the HHS support using a coefficient friction of 0.5 (Hanson et al., 1999). Regarding the contact between the shoes and the ground, it was considered to be automated surface-to-surface with automatic update as provided in LS-DYNA 970 (LSTC, Livermore, CA, United States) (Karimi et al., 2014; Razaghi et al., 2018). The mathematical equations of the present study were solved by the dynamic FE package of LS-DYNA. The solid elements were assigned to the model as 8-nodes hexagonal to provide an in-plane mechanical properties for the shear modulus. The suitable number of elements were also defined through a mesh density analysis as listed in Table 2. Once the error of the FE solver in respect to its previous stage was found to be lower than 5%, the mesh density analysis stopped and the present ones considered as the most suitable number of elements. In here, the 2nd try was selected for the modeling process. The suitable number of mesh can help to provide appropriate results at low cost and apt time span. That is, for finding the right number of elements, four different mesh densities (one as a primary try considered to be coarse) were chosen and the amount of von Mises stress in the components was compared. Afterward, by comparing the resultant stresses if a lower difference among the stresses was observed at each row, that number of elements was chosen as the most suitable one among three tested mesh sizes.

The von Mises stress in each region of the foot and footwear were calculated by the post-processing software (LS-PREPOST of LS-DYNA). According to the von Mises stress theory, failure will happen in a material once the stress meets the yield stress at elastic limit in a simple tension/compression.

3. Results and discussions

A survey conducted by the APMA in 2003 (APMA, 2003) showed that 72% of women wore HHS and 40% wore on a daily basis. However, the problems which pop up occur by wearing a HHS in a long-term, including knee joint osteoarthritis, lower back pains, forefoot diseases, ingrown nail, hammertoe, metatarsal stress fracture, and ankle sprain are inevitable and should be minimized or removed. Wearing a FHS at least to some levels can lessen these foot problems. This is why the concurrent study was aimed at proposing a newly designed adjustable HHS/FHS to provide women with a sense of comfort and good fashion. In addition, in order to investigate the stress and deformation distribution in the foot and shoe as a result of wearing our newly proposed shoe, the 3D FE models of the foot (MRI data) as well as HHS/FHS were established, assembled, and subjected to a normal vertical force which induced as a consequent of a simple standing (Fig. 1). The developed FE model can serve as a systematic tool to help understand foot and footwear biomechanics. This preliminary model can assistance to observe gross loading response of foot under HHS/FHS support condition, although the point-to-point correspondence in pressure distribution was not achieved.

The contour of von Mises stress distribution in the soft tissue when wearing a HHS and FHS under various sole elastic modulus, i.e., 0.1, 1, 10, 100 MPa, are indicated in Figs. 2 and 3, respectively. The stresses as it is obvious are concentrated in the applied area (standing area) which was in contact with the ground, namely calcaneus bone (this bone was not modeled separately in our simulation). This is the area where the vertical standing load was applied in our simulation. The stresses were found to be 0.89, 0.92, 0.95, and 1.51 MPa in the soft tissue as a result of wearing a HHS under the sole elastic modulus, i.e., 0.1, 1, 10, 100 MPa, respectively (Fig. 2). Similarly, the amounts of stresses in the soft tissue of the foot as a result of wearing a FHS were found to be 0.65, 0.66, 0.68, and 0.74 MPa, under the sole elastic modulus, i.e., 0.1, 1, 10, 100 MPa, respectively (Fig. 3). The results revealed a higher stress in the soft tissue by increasing the sole elastic modulus regardless of wearing a HHS or FHS. For example, under the sole elastic modulus of 0.10, 1, 10, 100 MPa, the stresses in the soft tissue when wearing a HHS were 36.92%, 39.39%, 39.70%, and 104.05%, respectively, higher than that of when wearing a FHS. The von Mises stress when wearing a FHS is more distributed as when wearing a HHS. This shows well that it would be more comfortable for women to switch their HHS to FHS