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Comparision of the stress distribution between high-heeled and flat shoes on the first metatarsal bone

Topuklu ve topuksuz ayakkabı için birinci metatarsal kemik üzerindeki stress dağılımının karşılaştırılması

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Comparision of the Stress Distribution Between High-Heeled and Flat Shoes on the First Metatarsal Bone

Highlights

- *The stress distribution on the first metatarsal bone was examined depending on the heel height.*
- *Muscle forces that is affecting the bone were also included in the analysis. The unknown forces are calculated using a mathematical approach.*
- *It was determined that the stress distribution increased %54 on the bone due to the changing heel height of shoe.*

Graphical Abstract

In this study, the effects of increased heel height of the shoe were examined on the first metatarsal bone. The results were evaluated according to varying stress, strain and total deformation parameters.

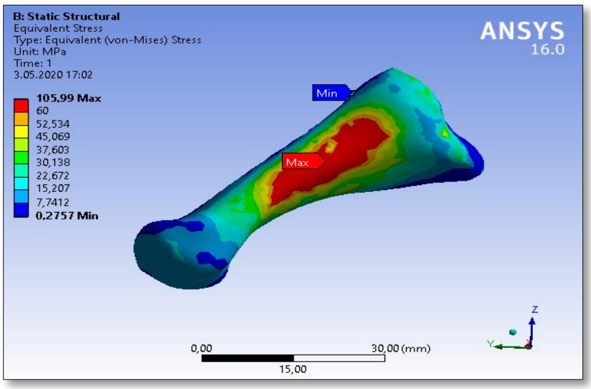

Figure. Stress distribution on the first metatarsal bone in the HHS

Aim

The aim of the study was to determine the changing stress distribution on the first metatarsal bone for two different heel heights.

Design & Methodology

The bone was modeled from the CT image in the DICOM format using the MIMICS program and analyzed with the ANSYS Workbench program.

Originality

In addition to the ground and joint force acting on bone, muscle forces are also included in the analysis.

Findings

It was determined that the stress distribution increased %54 on the bone due to the changing heel height of shoe.

Conclusion

It has been determined that is the increasing heel height increases the stress distribution and strain values on the bone.

Declaration of Ethical Standards

The authors of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

Topuklu ve Topuksuz Ayakkabı İçin Birinci Metatarsal Kemik Üzerindeki Stress Dağılımının Karşılaştırılması

Araştırma Makalesi/ Research Article

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ÖZ

Bu çalışmanın amacı topuklu ve topuksuz ayakkabı giyildiğinde birinci metatarsal kemik üzerinde oluşan stress dağılımı ve total deformasyondaki değişimi sonlu elemanlar metoduyla incelemektir. Birinci metatarsal kemik, bilgisayarlı tomografi (BT) görüntüsünden üç boyutlu olarak modellenmiş ve ANSYS Workbench yazılımına aktarılmıştır. Proximal bölgeden sınır şartlarına göre sabitlenen kemiğe vücut ağırlığı, kas kuvvetleri uygulanmıştır. Analiz sonucu stress, toplam deformasyon ve gerinim değerleri olmak üzere üç farklı kritere bakılarak değerlendirilmiştir. Değişen stress ve gerinim değerlerinin kemik hasarına neden olup olmadığı incelenmiş ayrıca stabilite açısından kemiğin deformasyonu değerlendirilmiştir. Sonuç olarak, yüksek topuklu ayakkabının , düz ayakkabılara nazaran birinci metatarsal kemik üzerindeki stress değerini % 54 arttırdığı sonucuna varılmıştır. Gerilme değerlerinin kemik çatlağı veya kırığına neden olmadığı sonucuna varılırken, yüksek topuklu ayakkabı giymenin birinci metatarsal kemik üzerinde oluşan deformasyonu artırdığı gözlemlenmiştir. Çalışmanın sonucu yüksek topuklu ayakkabı giymenin birinci metatarsal kemiği olumsuz etkilediği yönündedir. Bu nedenle günlük hayatta yüksek topuklu ayakkabı kullanım sıklığı azaltılmalı ve yüksek topuklu ayakkabı dizaynı kemikte oluşan gerilmeler dikkate alınarak yapılmalıdır.

Anahtar Kelimeler: Birinci metatarsal kemik, topuklu ayakkabı, topuksuz ayakkabı, stress dağılımı.

Comparision of the Stress Distribution Between High-Heeled and Flat Shoes on The First Metatarsal Bone

ABSTRACT

The aim of this study is to examine the effects of the wearing high-heeled shoes (HHS) by comparing the wearing the flat shoes on the first metatarsal bone using the finite element method. The first metatarsal bone is modeled from computerized tomography (CT) image as 3D and imported to ANSYS Workbench Software. Body weight (BW) and muscle forces were applied to the first metatarsal bone. The bone was fixed at the proximal region of the bone for the boundary conditions. Three evaluation criteria were examined for the results as the stresses, the total deformations and the strain values on the bone. The stress and strain distributions of the bone were evaluated for the bone failure. The deformation of the bone were evaluated for the bone stabilitiy. As a result, the wearing HHS increases the stress values on the first metatarsal bone approximately %54 compared to the flat shoes. The strain values showed that the bone crack or failure was not occured. The deformation of the bone was increased when wearing the HHS shoes. The conclusion of the study is that the wearing HHS negatively affects the first metatarsal bone. Hence, the frequency of the wearing HHS in daily life should be reduced and heeled shoe designs should be made taking into account the stresses occured on the bone.

Keywords: First netatarsal bone, high-heeled shoes, flat shoes, stress distribution.

1. INTRODUCTION

High-heeled shoes (HHS) use frequently in daily life with the trend of the fashion in the process of time. Changes in the way choosing clothes of people over time, also have become effective in the choosing shoes. Choosing of the shoes is very important for the foot the walking.

The walking functions change when wearing HHS like the walking with slower and shorter steps [1, 2]. The person spend more energy while walking for these reasons [3, 4]. Produced shoes in the various heel heights with the direction of the fashion causes some health problems besides the nice and attractive appearance. The design of the HHS affects the force distribution differently on the foot [5]. HHS are usually designed to taper towards the toe. This structure forces the toes and metatarsal bones to squeeze [6]. The painful sensation and the degenerative results occur on the bones and the lower extremity when the compression factor is added to the pressure increase caused by increased heel height. Degenerative disorders may start to become permanent if the preference for wearing HHS is repeated continuously. The comfortless effects caused by wearing HHS is not limited only to the foot and the lower limbs. It also causes various back and the lower back pain because the location of the center of mass of the body changes [7,8]. When the center of mass of the body changes forward or backward, the activity of the lower limb muscles increase

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[8]. The load distribution on the foot bones changes asymmetrically as the heel height increases [9]. The load on the fifth metatarsal bone decreases as opposed to the increase in the load on the first metatarsal bone when the height of the heel increases [10]. There is a positive correlation between increased heel height and hallux valgus deformity, which is the widespread health problem caused by thumb bone protrusion [4]. There are varying height of the heel from 1-2 to 9-10 cm and the load on the first metatarsal bone increased as the heel height increased [11]. The forces on the bones and muscles change depending on the type and hight of the heel. There are various studies examining the changes that occur on the lower limbs when wearing HHS [4,9]. There are two ways to examine the changes that have occurred; change of force or change of pressure distribution. When the considering the difficulty in finding live tissue or cadaveric samples, the in-vitro methods are more preferred than the in-vivo methods. The plantar pressure distribution that is occurring under the foot could be determined by the transducer [12], dynamometer [11] or the various pressure sensors which is placed on the sole of the foot. One of the easiest ways to analyze the stress and the pressure distribution is Finite Element Analysis (FEA) [13-16]. The walking takes place in the three stages [17]. The sole of the foot is divided into the three separate areas as forefoot, rearfoot and midfoot. The pressure distribution under the foot is observed in the forefoot region in the push-off stage [16]. This stage is also important in the evaluating the force and the pressure distribution, since there is a 'second force peak' during the push-off stage [13, 18]. While the pressure center and the force distribution changes during the gait phases, the maximum plantar pressure under the foot observe in the push-off stage. Furthermore this stage is taken into consideration in pre&post operative process follow-up of the first metatarsal bone. The pressure under the foot concentrates more on the first metatarsophalangeal (MTP) joint as the height of heel rise [11, 18]. Consequence of changing the pressure center, the stress distribution varies on the first metatarsal bone. The percentage of the body weight (BW) that is affecting the metatarsal bones in flat shoes and HHS is %40 and %64, respectively [18]. Therefore, it is important to examine the changes caused by wearing HHS in lower limb joint kinetics [3]. The acting percentage of the BW increases when the height of heel increases, so the pressure increases under the foot [11]. The changing response of the foot in anterior and posterior directions at the different heel heights creates different kinetic and kinematic effects on the foot and the metatarsal bones [3, 19]. Electromyography (EMG) signals are more useful for the kinetic analysis to determine the effects of wearing HHS [11, 19]. The various methods are available to reduce the increased pressure distribution and the comfortless of this to the foot such as heel cup, metatarsal pad [20, 21]. There are many studies that is investigating the pressure distribution under the foot [13, 14, 16, 18] and the percentage change in the BW that is affecting the foot bones [11,22] when wearing HHS. However, the effects of wearing HHS on the first metatarsal bone were not fully known due to the lack of the study concentrating on the first metatarsal bone. In order to compare the change that will occur, it is necessary to reference the force distribution that occurs during normal walking [22, 23]. %40 of the BW affects the metatarsal bones during normal walking and the vast majority of this affects the first metatarsal bone [23]. The main loads affecting the first metatarsal bone are the ground reaction force, joint force and the muscle forces [22, 23]. The plantar and dorsiflexion angles of the first metatarsal bone change depending on the height of the heel [24]. Due to the increased angle of the first metatarsal bone with the ground, all forces increase compared to the flat shoes [10, 15]. It is important to know the force distribution that is acting on the first metatarsal bone before and after the operation of foot bone deformities such as hallux valgus. As the heel height increases, the average BW increases in the MTP joint [10,11]. When the heel height is gradually increased, the maximum increasement in the percentage of the BW that is affecting the bone is experienced for 5 cm height of the heels. In HHS with heels higher than 5 cm, the increase in BW ratio is relatively less than the increase up to 5 cm [11]. For this reason, the height of the heel to be referenced in this study was chosen as 5 cm. The change in forces at second, thirth and other metatarsal bones when wearing HHS is considerably less than the change in the first metatarsal bone [14]. The effect of the different heel heights is usually examined on the first metatarsal bone. It is difficult to examine the force distribution and the effects in metatarsal bones during walking as in vivo. The FEA method was chosen for numerical analysis due to its unique analysis capability for structural feature behaviors of the model. Therefore, FEA has been used in most of the studies so far. The percentage of the body weight that is affecting the first metatarsal bone is known when wearing HHS [14, 23]. The force change in the MTP joint was also calculated for two different types of shoes [10]. However, there is no biomechanical study that is investigating stress variation on the first metatarsal bone between two different shoe types. It is important to know the stress distribution on the bone as higher stress values cause bone cracks and less values cause weakness in the bone. The high stress values also creates a musculoskeletal fatigue.

The aim of this study to examine the effects of possible damages of HHS on the first metatarsal bone. The bone was modeled using computerized tomography (CT) image. The forces were applied to the distal region of the bone and the proximal region of the bone was fixed. The forces on the metatarsal bone change with the wearing the HHS and flat shoes. Because of this, the values of the different forces were applied to the bone. The total deformation, stress, and strain distribution on first metatarsal bone were examined for when wearing HHS and flat shoes.

2. MATERIAL and METHOD

2.1. Model Development

The first metatarsal bone was modeled as 3D using CT images obtained from a voluntary female (aged 39, weight 70 kg, height 167 cm) taken from a Toshiba Aquilion CT scanner in the Department of Radiology, School of Medicine at Kocaeli University. CT images consist the paralel layers having a pixel-size 0.774x0.774 mm and Digital Imaging Communications in Medicine (DICOM) format. The images were segmented using MIMICS 12 (Materialise, Leuven, Belgium) 3D İmage Processing Software and the material properties were assigned as seen as Table 1 (length of bone 60 mm), [26, 27] by the contrast of [10], which accepts the modulus of elasticity of the first metatarsal bone as 20 GPa. The surface defects in the modeled were corrected using Geomagic Studio 10 software (Raindrop Inc. , USA). 3D bone model was imported into ANSYS Workbench (ANSYS Inc. Canonsburg, PA) in cdb format. The material properties obtained from MIMICS 12 were transferred to ANSYS Workbench in txt format.

the MTP joint head. The small angle between C and D is ignored to simplify the model and the total forces of the muscles were assumed as C+D. The first metatarsal bone relative to the ground was risen by about 12° [13] when wearing about 5 cm HHS [11]. BW increases about %20 [11], B also increases compared to the flat shoes and becomes 158% of BW [10].The triangle of forces given in Figure. 2 was constituted using available force and angle information.

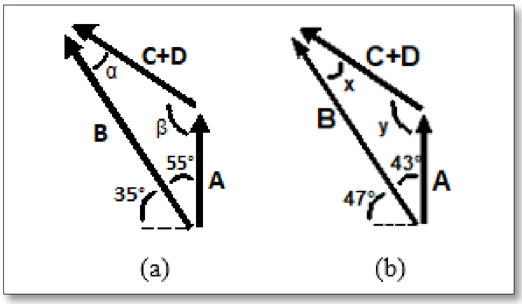

Figure 2. The forces on the first metatarsal bone in push-off stage (a) wearing flat-shoes (b) wearing HHS

Table 1. The material properties[28]

Density[g/cm^3]	Young's Modulus [MPa]	Poisson Rate
ρ= 1.067 × HU + 131	0.004 × $\rho^{2.01}$	0.3

2.2. Mesh Assignment

Mesh convergence was tested by increased the element size from 0.2 to 3.0 at 0.2 mm interval on the first metatarsal bone. The most suitable element sizes for the optimum results were determined 1.4 mm. Tetrahedron element was used in the whole finite element model and the number of the elements is 6602.

2.3. The Forces and Boundary Condition

The force distribution on the first metatarsal bone is as seen in Figure 1. according to literature [22,23]. Unknown forces are calculated from the triangle of the forces formed on the bone (Figure 2.).

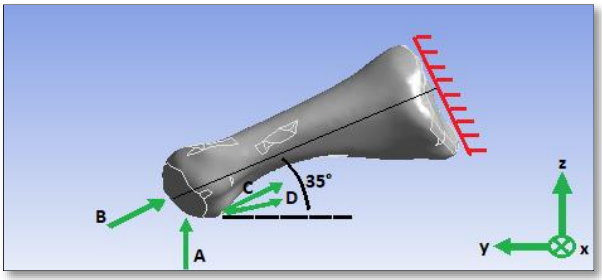

Figure 1. Boundary conditions of the first metatarsal bone in push-off stage wearing flat shoes

force. Contrary to what is stated in [23], flexor hallucis longus (C) and flexor hallucis brevis (D) having a certain angle to A, not perpendicular to it. The first metatarsal bone having a 35° between ground in push-off stage when wearing flat shoes [15]. A is the perpendicular to

The average peak forces for the flat shoes were C: %52, D: %36 and A: %29 times BW [22]. B, and were found using equation 1 (theorem of the sine).

$$\frac{\mathrm{C+D}}{\sin 55} = \frac{\mathrm{A}}{\sin\alpha} = \frac{\mathrm{B}}{\sin\beta} \tag{1}$$

$$\frac{615.81\ \mathrm{N}}{\sin 55} = \frac{203.7\ \mathrm{N}}{\sin\alpha} = \frac{\beta}{\sin\beta}\ , \qquad \alpha + \beta = 125°$$

The average peak forces for the HHS were A: %35, B: %158 times BW [16, 22]. Forces of muscles (C+D), x and y were found using equation 2 (theorem of the cosine).

$$(\mathrm{C+D})^2 = \mathrm{B}^2 + \mathrm{A}^2 - \mathrm{BAcos}43 \tag{2}$$

$$(\mathrm{C+D})^2 = (1105.9)^2 + (243.51)^2 - (1105.9)(243.51)\cos 43$$

Table 2. The forces applied to the first metatarsal bone for 700 N weight person

Forces[N]	F_x	F_y	F_z	$F_{resultant}$
Flat-Shoes Push-Off Stage				
Ground Force (A)	0	60	194	203.7
MTP Joint (B)	0	-503	503	711.35
Forces of Muscles(C+D)	0	-551	275	615.81
HHS Push-Off stage				
Ground Force (A)	0	60	236	243.51
MTP Joint (B)	0	-782	782	1105.9
Forces of Muscles(C+D)	0	-902	275	942.99

5. RESULTS AND DISCUSSION

The 3D FE model for the first metatarsal bone used to simulate the biomechanical response during push-off stage wearing the flat-shoe and HHS. Three different criteria were selected to evaluate the results from the FEA. First, the peak von Mises stress distribution on the bone. Second, the total deformation were investigated between the flat shoe and HHS. Finally, the strain distributions of the bone to evaluate the bone crack risk. As can be seen Table 3 and in Figure 3., the peak von Mises stress value, the total deformation and the strain distribution on the first metatarsal bone increased from 68.203 MPa to 105.99 MPa, from 2.54 mm to 4.3954 mm and from 0.0266 mm to 0.0472, respectively. This shows that the load on the front of the foot increases when the heel height of the shoe increases.

These increasing values in all these results during high-heeled gait can be interpreted as extra load on the bone and soft tissue. The bone is living tissue and the stresses on the bone affect the bone growth. The high stress values on the bone increase the risk of the bone fracture. On the other hand, the higher stress values can create the bone cracks, while the less values causes weakness in the bone. In addition, the overloading and the cyclic loading creates a musculoskeletal fatigue that affects structural sustainability in the absence of adequate rest and recovery [28]. HHS are often preferred by women in daily life. The stress, strain and deformation change depending on the forces on the foot bones when wearing HHS. The majority of the BW affects the first metatarsal

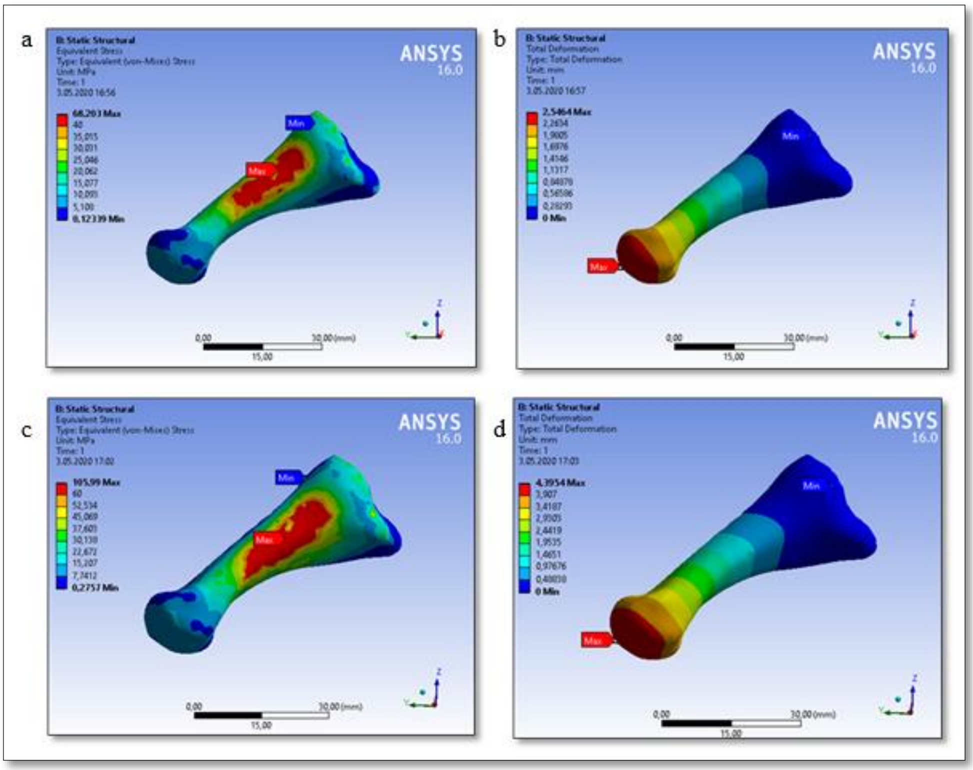

Figure 3. PVMS distribution in the flat shoe (a), in the HHS (c), total deformation in the flat shoe (b), in the HHS (d)

Table 3. The results of the FEA

Types of Shoes	PVMS on the bone (MPa)	Total Deformation(mm)	Equivalent strain(mm)
Flat Shoes	68.203	2.5464	0.0266
HHS	105.99	4.3954	0.0472

PVMS peak von Mises stress

bone [23]. Because of all these reasons, it is essential to analyze the stress distribution that occur on the first metatarsal bone. The biomechanical comparision response of the first metatarsal bone between HHS and flat shoes were investigated in this study by using FEA. In the studies carried out so far, the force distribution [10, 22, 23] and the pressure distribution [13, 14, 18] were examined in order to investigate the effect of the HHS on the foot and the metatarsal bones. There is no biomechanical study about the change of the stress and the strain distribution on the first metatarsal bone. Therefore, the change in the stress and the strain distribution was evaluated between the HHS and the flat shoe. In addition to the given [18], the forces of muscles was included to investigate the mechanical response on the bone. There is no information about the some changing forces while information about the percentage of the BW and the changing angle may be accessed in literature [10, 15, 16, 22]. Such the unknown forces is calculated using a geometric approach as seen in Figure. 2. The load on the bone increased as the heel height increased. As a expected, the stress, strain and total deformation increased on the first metatarsal bone. Tension increased by 54% when wearing 5 cm HHS, the most preferred heel height. The obtained results from this study are also similar to the studies given in the literature [13]. If a female wear HHS from an early age, size of MTP joint flaments will change because of the tip of the shoe forces the foot to squeeze.

The increased load and the squeezing on the bone causes various health problem such as hallux valgus, ballerina syndrome, degenerative joint disease, deformity of shape of the metatarsals, calcification in joints. Therefore, regularly wearing the HHS can create the bone cracks or fractures in the first metatarsal bone. The HHS manufacturers should design shoes considering the effects of the high heel on the first metatarsal bone and the entire lower limb. The strain values must exceed 1500 microstrain to generate microdamage on the bone [28]. In this study, the strain values in the flat shoes and HHS were, 26.6 and 47.2 microstrain, respectively. Therefore, the wearing 5 cm HHS do not produce micro damage or fracture on the first metatarsal bone. Experimental studies have not been conducted in this study to determine the stress and the strain distribution on the first metatarsal bone. The reason for this is that it is difficult to calculate the stress and the strain values in this specified region in the experimental studies. Therefore, FEA method was used for investigate the biomechanical response of the first metatarsal bone. Although, the 5 cm heel height shoes are the most preferred option in daily life, the shoes higher than 5 cm heel height are also often used. There is no study about the force distribution acting on the first metatarsal bone for the shoes with the different heel heights. Further research should be conducted to determine joint and muscle forces on the first metatarsal bone for the several heel heights and the examine the effects of these changing forces on the stress distribution and the foot health. Additionally, the future study about the effects of the age, height and weight may be examined.

6. CONCLUSION

This article provides a research of the effect of wearing HHS on the first metatarsal bone. The result of this study, which examined the stress and strain distribution on the first metatarsal bone between flat and HHS, is that the height of the heel increased the tension on the bone. In addition, this study calculated the forces acting on the first metatarsal bone in detail when wearing HHS. It is can provide reference for assesment the effect of wearing HHS on the first metatarsal bone.

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DECLARATION OF ETHICAL STANDARDS

This article does not contain any studies with human participants or animals performed by any of the authors.

AUTHORS' CONTRIBUTIONS

Zeliha COŞKUN : Performed the experiments, analyse the results and wrote manuscript.

Talip ÇELİK: Performed the experiments and analyse the results.

Yasin KİŞİOĞLU: Analyse the results.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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