DOCTORAL (PhD) THESIS BOOKLET

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Morphological and biomechanical effects of high heel shoes on the lower limbs during gait

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1 Summary in Hungarian Language

A legtöbb nő számára elkerülhetetlen, hogy mindennapi életében ne hordjon magassarkú cipőt társasági eseményeken, annak ellenére, hogy a nemzetközi orvosi szövetségek széles körben figyelmeztetnek a magassarkú cipők viselésének káros egészségügyi hatásaira. Számos tanulmányt végeztek a magassarkú cipők által kiváltott mozgásszervi változások feltárására, hogy egyrészt kapcsolatot teremtsenek a magassarkú cipők viselése és a sérülés/betegség között, másrészt javaslatokat tegyenek a magassarkú cipőkhöz kapcsolódó patológiás kezelésekre. Néhány probléma azonban még megoldatlan. Ezek közül egyik, a magassarkú cipők hatása a lábfej szegmenseinek kinematikai jellemzőire járás közben, illetve a magassarkú cipők hatása a talpi bőnye megnyúlásása különböző sarokmagasságok esetén. A disszertáció célja ezeknek a kérdéseknek a megválaszolása átfogó komplex módszerrel.

Először, a magassarkú cipők hatását vizsgáltam a hallux, az elülső és a hátsó láb szegmenseinek biomechanikai jellemzőire egy Oxford lábmodell segítségével. A főbb eredmények szignifikánsan nagyobb dorsiflexiós mozgást mutattak ki a halluxban és nagyobb addukciós mozgást a láb elülső szegmensében magassarkú cipőben történő járás során, mint mezítlábas járás során. A kombinált hatás miatt a hallux, hosszú távon, kifelé csavarodik, míg az elülső lábfej befelé csavarodik. Ez a mechanizmus hosszú távú traumát hozhat létre, amely végül hallux valgus-ban vagyis „bütyökben” végződik.

Továbbá, egy 3D lábmodell készítettem, ahol különböző sarokmagasságot vizsgáltam (0 cm, 3 cm, 5 cm és 7 cm). A lábfej morfológiáját 8 fő paraméterrel írtam le. Ezek a mérések átfogó megértést biztosítottak a magassarkú cipők által okozott láb morfológiai változásairól. A főbb eredmények azt mutatták, hogy a calcaneus szegmens viszonylag stabil maradt, amikor a sarokmagasság 0 cm-ről 7 cm-re nőtt, a hosszanti ív magassága jelentősen megnőtt, és a hallux szegmens fokozatosan emelkedett a sarokmagasság emelkedésével 0 cm-ről 7 cm-re.

Végül, numerikus úton (VEM) vizsgáltam a talpi bőnye megnyúlását három különböző sarokmagasság mellett (3 cm, 5 cm, 7 cm). A főbb eredmények azt mutatták, hogy azonos sarokmagasság esetén a disztális és a középső rész között 20%-os feszültségváltozást tapasztaltunk az első és a középső állásban. Az 5 cm-nél nagyobb sarokmagasság jelentősen megnöveli a plantáris fascia feszültséget, ami növelheti a plantar fasciitis kialakulásának vagy a sarokfájdalom tünetének gyakoriságát a magassarkú cipők viselőinek körében. Ezek az eredmények átfogó biomechanikai részleteket és referencia információkat nyújthatnak a klinikusok és orvosok számára a magassarkú cipőkhöz kapcsolódó lábsérülések vagy -betegségek hatékony rehabilitációs programjának kidolgozásához.

2 Antecedents of the Research

The potential impact of high heel shoes (HHS) on women’s health has been concerned over 50 years in medical circles. Despite widespread warnings from public health institutions and international medical societies [1], there is still a large proportion of the population wearing HHS in their daily life. Regarding why women choose to wear HHS, Broega et al. surveyed 574 females, between the age of 24 to 45, who indicated that beauty and femininity were the key drivers of women's behavior [2]. However, the pursuit of beauty also comes with the risk of injury. According to the latest reported data on injury related to HHS wearing among the women in America from 2016-to 2020, it was recorded 6,290 HHS related emergency cases in 2020 involving ages from 15 to 69 years old [3]. More interestingly, the number of cases in 2020 was significantly lower than the 16,000 cases per year in 2016-2019, and the 2020 decline began after implement of the Coronavirus disease 2019 (COVID-19) shutdowns and quarantine regulations, which caused a restriction on mobility and socializing and more work from home, leading to women wearing HHS less, then decreased HHS related injury. There is a directly associated between HHS wearing and the prevalence of injury.

From the biomechanics perspective, it demonstrated that HHS leads to slower self-selected walking speed, shorter step length, and smaller stance phase duration, while it increases ankle plantar flexion, knee plantar flexion, anterior pelvic tilt, and trunk extension [4-10]. Redistributing the plantar pressure, higher ground reaction forces (GRF), larger loading rate, higher peak knee external adduction moments, and higher peak patellofemoral joint stress have been detected during walking in HHS [5, 9-11]. It is worthy to note that substantial bodily adjustments have been observed due to wearing HHS, e.g.: change in the neuromuscular activation pattern, shortening of the gastrocnemius muscle fascicle muscles, increase in the Achilles tendon stiffness, and higher muscle activity of the soleus, tibialis anterior, medial gastrocnemius [12-14]. These disturbances have been identified as negative implications for the human body. It is presumed that they contribute to several pathologies including metatarsalgia, hallux valgus, Achilles’ tendon tightness knee osteoarthritis (OA), plantar fasciitis, and lower back pain, not to mention elevated instability and imbalance, which can result in a greater risk of falling and slipping [3, 15-18].

As described, biomechanics characteristic of lower limbs during HHS gait has been widely investigated, mainly including kinematics and kinetics analysis of lower limbs' joints (ankle joint, knee joint, and hip joint), and muscle activation pattern during HHS gait cycle. However, the foot as a multi-segment structure plays a paramount important role in human movement, receiving little concern. For example, there is limited information on how foot multi-segments move in HHS gait. Especially, for hallux motion which could provide valuable details for understanding the potential mechanism of hallux valgus development related to HHS wearing. Moreover, morphological changes in the foot in HHS are still blank, which could provide an important clue for exploring functional adaptation and pathology of the foot. Furthermore, traditional approaches are limited to investigating the in vivo structure of the foot under HHS conditions. The finite element model (FEM) and musculoskeletal modeling (MSM) analysis could provide an efficient and fidelity way to simulate the internal variation of the foot in HHS. However, the workflow of combination analysis between FEM and MSM is needed. Therefore, this thesis is mainly focused on these undressed questions.

3 Objectives

The first objective: To reveal the mechanism of hallux valgus development related to HHS wearing during gait. This aim is to be accomplished by investigating the biomechanical characteristics of the hallux, forefoot, and hindfoot segments under HHS conditions by using a multi-segment model (Oxford foot model).

The second objective: To determine how the foot morphology is modified by HHS wearing as a function of different heel heights. This aim is to be accomplished by investigating the angular variation of the multi-bone structure of the foot, where a three-dimensional model reconstruction method will be adapted to create the high-fidelity 3D foot model in four different heel heights (0cm, 3cm, 5cm, 7cm) respectively.

The third objective: To reveal the plantar fascia biomechanics response in HHS gait. This aim is to be accomplished by investigating the strain distribution on the plantar fascia in HHS gait, where a methodology workflow of FEM combined with MSM derived force will be used to predict the internal strain distribution of the plantar fascia strain variation in three different heel height (3cm, 5cm, 7cm) respectively.

4 Research Methods and Challenges

Methods: In this doctoral work, the complex method is used to address problems involving experimental measurement, 3D model reconstruction, and numerical methods. Firstly, the thesis begins with the experimental measurement to describe the kinematics characteristic of the foot multi-segments in HHS gait. A Vicon motion system with 8 cameras (Oxford Metrics Ltd., Oxford, UK) was used to capture kinematic data, the oxford foot model (OFM) was utilized in this measurement to estimate the hallux, midfoot, and hindfoot movement variation in HHS gait.

Secondly, the reconstruction technique is used to establish a high-fidelity 3D foot model under HHS conditions with different heel heights. The reconstruction of the foot model is based on computed tomography (CT), the subject's foot morphology can be scanned under HHS wearing. Therefore, creating a high and reliable fidelity foot model conducts a foot morphology measurement using various angular descriptions in different heel heights (0cm, 3cm, 5cm, 7cm). Also provides a foot model for FEM analysis.

Thirdly, the MSM analysis is used to estimate the major muscle force in HHS gait with different heel heights and is conducted in Opensim software, which could create a subject-specific model, to provide an optimal loading condition for FEM analysis. Fourthly, the FEM is used to evaluate the biomechanical response of the plantar fascia under HHS condition with different heel height, simultaneously, the major muscle forces obtained from MSM analysis as loading condition is combined. In this part, the workflow of FEM and MSM analysis on HHS gait is established.

Challenges: Firstly, in terms of the kinematic study of foot multi-segment under HHS condition. Considering the foot structure is commonly characterized by the complex alignment of the foot segment, varies significantly between individuals, and directly affected by the shoe's construction, it is difficult to reveal the movement of each foot segment during gait under HHS condition. Although OFM as a multi-segment kinematic model with high repeatability and reliability has been widely used to investigate the inter-segment angle of foot through the gait cycle in the range of populations, it has not been applied to HHS population. Therefore, the kinematic results of multi-segment foot during HHS gait need to be validated.

Secondly, in terms of foot model reconstruction. In this research, 3D foot morphology reconstruction is based on computed tomography scanning (CT) technology. Undoubtedly, an accurate skeletal morphology should be established under weight-bearing conditions when it comes to its biomechanical value. However, the weight-bearing CT equipment is limited, the conventional CT scanning way has been utilized, the subject is supine on the CT scanning bed, and the ankle joint is fixed in a neutral position by a foot orthodontic bracket. On the other hand, numerous times need to be spent to reconstruct each bone separately.

Thirdly, in terms of FEM combined with MSM derived force in the plantar fascia biomechanical characteristic in HHS gait. There is no integrated foot modeling that could be directly applied and considerable progress is still needed, such as foot structure reconstruction more than 50 components need to be established and assembled (soft skin, bone, cartilage, plantar fascia, and ligament), mesh sensitive testing is required for each component to find the appropriate mesh size based on the material properties and size of the different components, and many simulations are required to get a convergent result.

5 New Scientific Results

1st thesis point: Based on my experimental results, significantly higher dorsiflexed movement occurred on the hallux and higher adduction movement occurred on the forefoot segment during HHS gait compared to barefoot gait. I derived the following conclusions:

- The HHS wearing does not affect the add/abduction of the hindfoot as is seen in Figure 5.1. Only the last 10% of the movement shows some deviation.
- The hindfoot internal rotation becomes significantly higher during HHS gait, in the stance phase (between 0% and 50% of the complete gait cycle). Higher movement of the hindfoot in the transverse plane leads to an unstable posture during the stance phase that could increase the risk of ankle sprain.
- If Figure 2.2 is considered, it is obvious to see that the hallux dorsiflexion becomes significantly higher during HHS gait, in the majority of the motion (between 17% and 85% of the complete gait cycle). This result has particular physical effects as well. First, the higher hallux dorsiflexion leads also to greater change in forefoot adduction, as it is seen in the first 50% of the gait cycle (see Figure 2.2). Second, the

higher peak, which is visible in the dorsiflexion function (see Figure 2.2, between 50 and 70% of the gait cycle), will cause an inflexion in the forefoot adduction in the “toe-off phase”. The rapid change, with an approximately 11° of amplitude creates cyclic bending stress in the forefoot. The combined effect of cyclic bending and the high rate of change will result that the hallux will be twisting outwardly, while the forefoot will be twisting inwardly. This mechanism will create a propagating, long term trauma that eventually ends in hallux valgus or “bunion”.

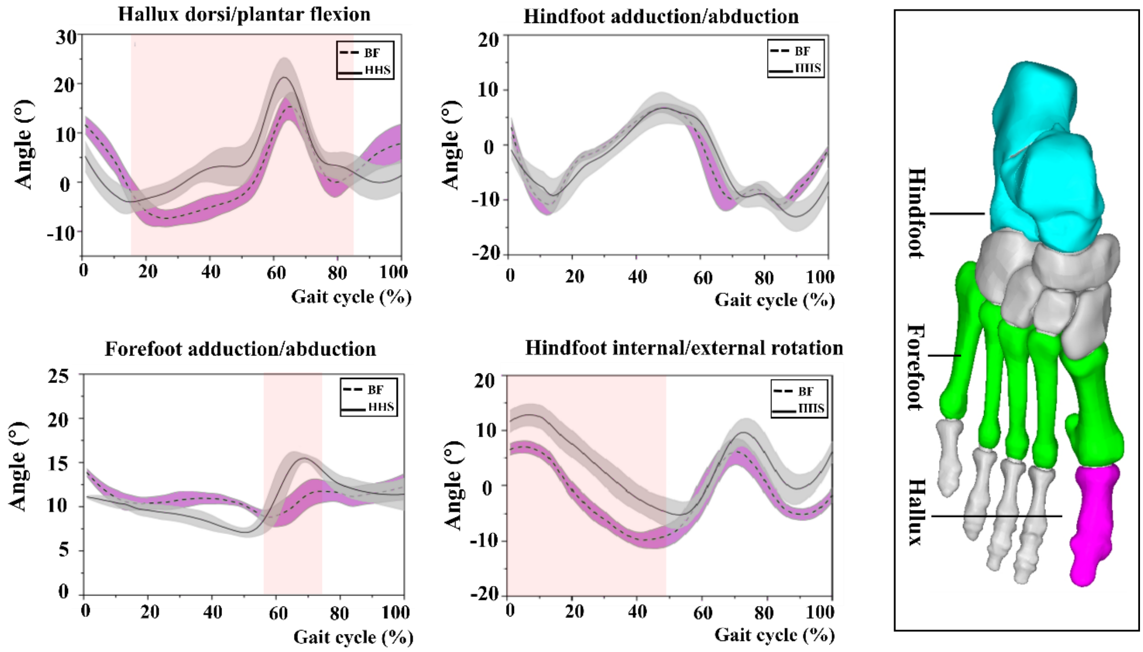

Fig 5.1. The comparison of foot kinematics in three different planes between the HHS and BF. The red region indicated the significant differences between HHS and BF.

2st thesis point: Based on 3D model reconstruction method, a high-fidelity 3D foot model, with four different heel height (0 cm, 3 cm, 5 cm, and 7 cm), has been built respectively, to provide a new perspective on foot morphological details under HHS condition. As a result, I provided a complete characterization, by the use of 8 parameters, about the forefoot segment (HV, FIM, MB, 1MD), the longitudinal arch height (TFM, C1M) and the calcaneus segment (Böhler, Gissane), the detail of the angle variation is shown in the Fig.5.2. I deduced the following scientific morphological trends:

- In case of the calcaneus segment, there a slight change is observed while the Böhler angle and the Gissane angle slowly progress as heel height increased. It is indicated that the position of the calcaneus segment remains relatively stable within the height range of 7cm.
- In the case of the longitudinal arch height, the talus-first metatarsal (TFM) angle shows a strongly progressive increasing trend (increased by 89.71% in 0-7 cm), while the calcaneus 1st metatarsal (C1M) angle shows a strongly progressive decreasing trend (decreased by 18.56% in 0-7 cm). It is indicated that the longitudinal arch height significantly increased as heel height elevation from 0 cm to 7cm, which could result in a loss of the arch shock absorption ability.
- In the case of the forefoot segment, the hallux valgus (HV) angle and 1st metatarsal declination (1MD) angle show a strongly progressive increasing trend (increased by 71.50% and 63.13% in 0-7 cm, respectively). In addition, the first intermetatarsal (FIM) angle shows a slow progressing trend (increased 36.28% in 0-7cm), while the metatarsal break (MB) angle shows a slight decreasing trend (increased 4.1% in 0-7 cm). Those progressively increased values of the angles indicate that the prevalence of the hallux valgus increased as heel height elevation.

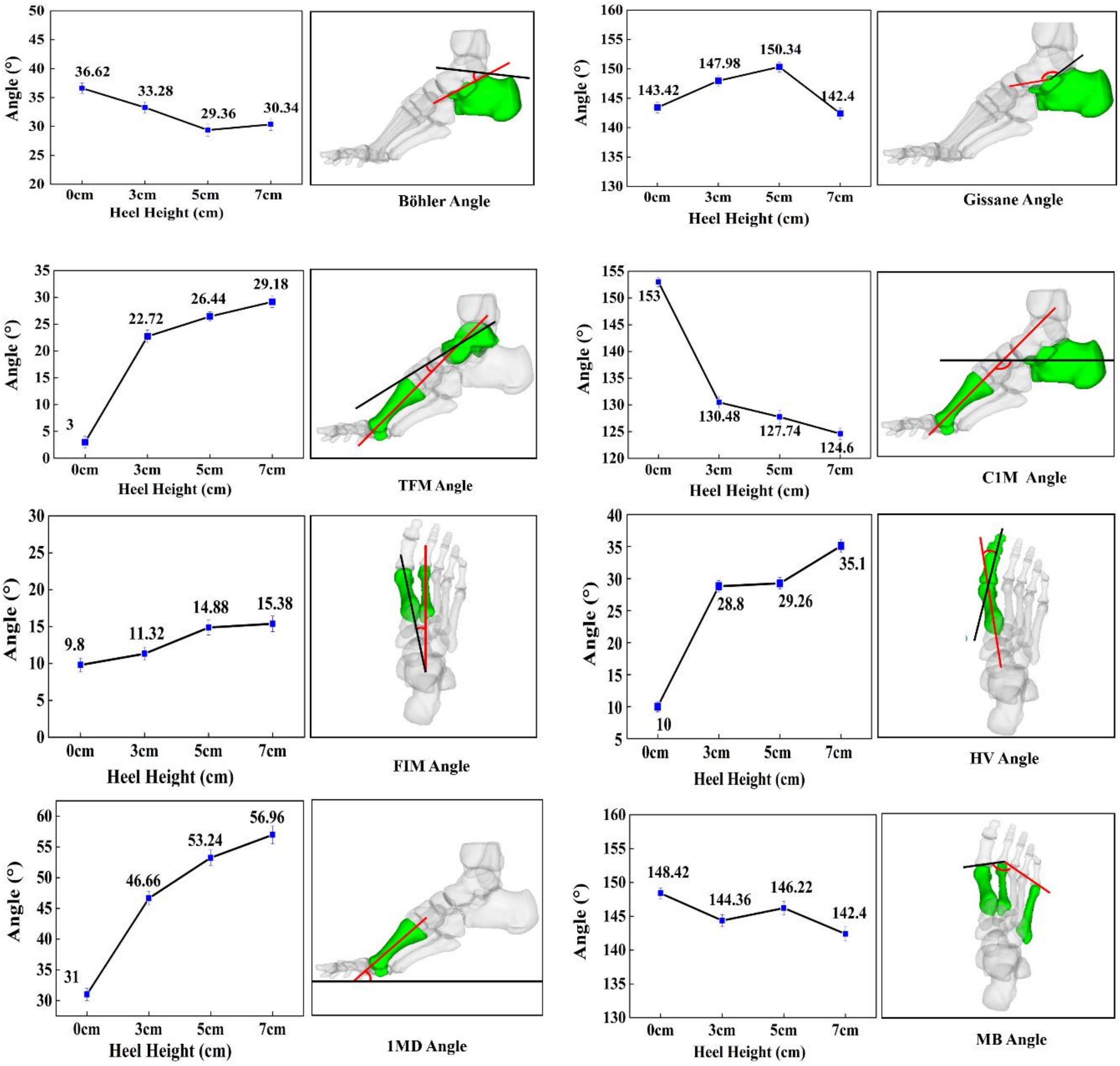

Fig 5.2. 8 specific types of angular change among four heel heights.

3^{rd} thesis point: I deduced the strain distribution of the plantar fascia during HHS gait at different heel heights by combining FEM, MSM, and motion capture techniques. My scientific results are summarized in four points:

- I calculated an average change of strain (ACS) of 20% between the distal and the middle part when identical heel height was considered during the first and mid-standing phases. The ACS has been deduced for each phase between the 3-5 and 5-7 cm (see Table 5.1), a heel height over 5cm significantly increases the plantar fascia strain, which could increase the prevalence of plantar fasciitis development or heel pain symptom in the HHS population.

Table 5.1. The average change of strain at different heel heights in three gait phases.

Phases	**ACS at 3-5 cm [%]**	**ACS at 5-7 cm [%]**
First peak phase	12.1	9.2
Mid-standing phase	5	27.2
Second peak phase	13	42

- By my new method, I proved that the middle and proximal segments of the plantar fascia behave completely the same way in the first and mid-standing phase when identical heel height is considered.
- Based on my calculation, the highest and lowest peak plantar fascia strain occurred on the proximal region and the middle part respectively, in the second peak stance phase when identical heel height is considered.
- I identified a controversial part of my model, which is the simulation of the second-peak phase. The highest average change of strain (ACS) values was found here, but no visible trend could be established.

6 Possibility to utilize the Results

The results from this thesis are mainly concerned pathology of foot injury or disease caused by high heel shoe wearing, explored the biomechanical mechanism of hallux valgus development, foot structure deformation, and plantar fasciitis development during HHS gait with different heel height. Those findings can provide comprehensive biomechanical details and reference information for clinicians and physicians to develop an efficient rehabilitation program for HHS-related foot injuries or diseases.

7 References

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8 Publications

8.1 Scientific Publications related to the Thesis Points

1. **Wang, M.,** Jiang, C., Fekete, G., Teo, E. C., Gu, Y. (2021). Health view to decrease negative effect of high heels wearing: a systemic review. Applied bionics and biomechanics, 2021, 1-12. **IF: 1.781, Q2**
2. **Wang, M.,** Li, S., Teo, E. C., Fekete, G., Gu, Y. (2021). The influence of heel height on strain variation of plantar fascia during high heel shoes walking-combined musculoskeletal modeling and finite element analysis. Frontiers in Bioengineering and Biotechnology, 9, 1-10. **IF: 5.48, Q1**
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8.2 Additional Scientific Publications (optional)

1. **Wang, M.,** Ying, J., Ugbolue, U. C., Buchan, D. S., Gu, Y., Baker, J. S. (2021). Cardio-Metabolic Risk Factors in Scottish South Asian and Caucasian Youth. International Journal of Environmental Research and Public Health, 18, 1-10. **IF: 4.614, Q2**
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