# FINITE ELEMENT ANALYZE OF THE FIRST METATARSAL VERTICAL ARCH OF THE FOOT IN THE HIGH-HEELED GAIT

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A two-dimensional numerical model of the foot, incorporating, for the first time in the literature, realistic geometric and material properties of both skeletal and soft tissue components of the foot, was developed for biomechanical analysis of its structural behavior during gait. Using a Finite Element solver, the stress distribution within the first metatarsal vertical arch of the foot (FMVA) structure was obtained and regions of elevated stresses for three subphases of the stance (heel-strike, push-off, and toe-off) were located. Validation of the pressure state was achieved by comparing model predictions of contact pressure distribution with Novel Pedar. The presently developed measurement and numerical analysis tools open new approaches for clinical applications, from simulation of the development mechanisms of common foot disorders to pre- and post-interventional evaluation of their treatment.

**KEY WORDS:** finite element analysis, numerical modeling, plantar pressure

**INTRODUCTION:** Research has been done to study the various long term effects of wearing high heels, but the outcomes have not reached our society, especially the youth of today. The newest trends are narrow toed and high round toed heels, and many young girls today do not realize what they are getting themselves into by embarking on the habit of wearing high heels. Surveys have found that 37%-69 % of women wear high heels everyday (Esenyel, 2003). Much of the female population seems to be more concerned with their image and appearance than the effects their beautification methods have on their bodies. The constant elevation of the heel causes a shortening of Achilles tendon. The shape of shoe can also cram the foot which may result in hammer toes, pointed toes, blisters, bunions or corns.
The latest quantitative models that have analyzed the human foot as a mechanical structure used various simplifying assumptions concerning its geometry, mechanical properties of its tissues, and muscle loading. Chu et al. (1995) presented an asymmetric FE foot model for analysis of ankle-foot orthosis effects. Linear elasticligaments and soft tissue were included in this model, yet, the complex articulated structure of the foot skeleton was treated as a single body. The recent two-dimensional FE model by Patil K. M., Braak, L. H., and Huson, A., (1996) used to study regions of high stress in normal and neuropathic feet during gait, was constructed according to the two-dimensional cross-sectional anatomy of the foot, obtained from a lateral X-ray image; although their work is an important step toward the ability to predict structural stress concentrations in normal and disordered feet. The models developed by Jacob and patil(1999) have been employed to investigate the biomechanical effects of soft tissue stiffeningin the diabetic feet. Their models predicted that the peak plantar pressure was found to increase with soft tissue stiffness but with minimal effect on the bony structures. Gefen (2003) further speculated that the development of diabeticfoot-related infection and injury was more likely initiated by micro-damage of tissue from intensified stress in the deeper subcutaneous layers rather than the skin surface.
The present study is therefore aimed to develop an integrated system of experimental and numerical tools, in order to analyze the FMVA structural behavior during high-heeled gait and to open new approaches to research biomechanics.

**METHODS:**

**The model:** The subject of this study was female college student. (23 years old, 160 cm, 48 kg) Her foot was healthy and no medical record. The height of the shoe which used in the experiment was 7cm. X-ray system was used to get the geometry of FMVA components in the high-heeled gait.
The foot bones were initially modeled as individual parts, which are interconnected by cartilaginous joints. Proximal, middle, and distal phalanges were unified in each toe for

simplification, due to computational limitations of the FE solver. This assumption is not expected to yield significant inaccuracies in the predicted stress distributions, since during normal gait, at a moderate velocity, the contact stresses applied to the forefoot do not flex the interphalangeal joints.

**Material properties:**The biological material properties according to the Gefen research date, and the basic parameter shows in Table 1.

**Table 1 The biologica material properties of the FMVA.**

| | Young's modulus | Poisson ratio |
|---|---|---|
| foot bones | 7300.0MPa | 0.3 |
| Metatarsus Joint cartilage | 20.0MPa | 0.4 |
| Other joint cartilage | 5.0MPa | 0.4 |
| Plantar muscle | 125.0MPa | 0.4 |

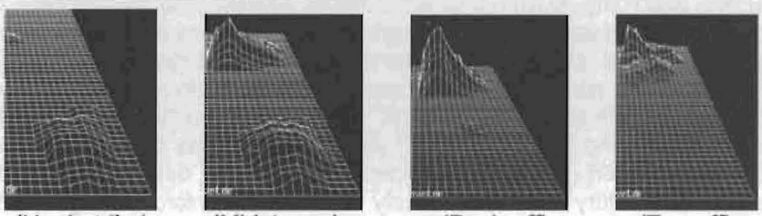
The ligaments, plantar fascia, and soft tissue fat pad were considered nonlinear. The typical experimental load-deflection relationship used to model the ligaments was obtained by Race and Amis through Instron uniaxial tensile tests on healthy, normal lower-limb ligaments. The following expression was fitted to the experimental data for the computational procedure:

$$P_l = a_l\delta^3 + b_l\delta^2 + c_l\delta + d_l \qquad (1)$$

with a correlation coefficient of $R^2 = 0.995$, whereas $P_l$ is the ligament load in kN, $\delta = \Delta l / l$ is the elongation in percent and the constants are $a_l = -4.09$, $b_l = 5.388$, $c_l = 0.287$, $d_l = 0.0017$. The stiffness curve of the plantar fascia was taken as 70 percent of the ligament stiffness.

**Contact Pressure Method:** We used the Pedar system, manufactured by Novel (Munich, Germany), measure the plantar pressure. This is an in-shoe measuring system consisting of two shoe insoles, wired to a computer recording and evaluating static and dynamic pressure distribution under the plantar surface. Each insert consists of 99 pressure sensors. Each sensor has a measuring range from 1 to 120 N/cm$^2$. Each pressure sensor only registers force vectors perpendicular to its surface. The resulting force exerted through the brace-pad was calculated from the force values of the separate pressure sensors. Before each measurement, the inserts were calibrated.

The reaction forces generated during the foot-ground interaction and their evolution during gait are some of the most important biomechanical gait parameters. Vertical reaction forces on the plantar area of the foot model for the heel-strike, midstance, push –off and toe-off four characteristic positions are shown in Figure 1.

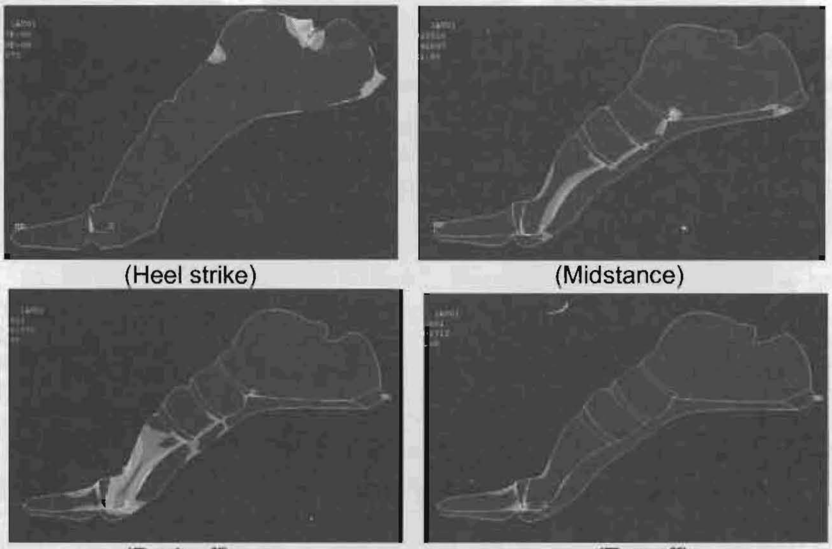


(Heel-strike) (Midstance) (Push-off) (Toe-off)

**Figure 1 The plantar pressure distribution of high-heeled gait in one period.**

**RESULTS:** The FE method was selected for numerical analysis of the model due to its unique capability to analyze structures of complex shape, loading, and material behavior. The model was elaborated using the ANSYS 7.0 software package. This powerful version enables generation of up to 4,083 nodes. Automatic division was used to generate an optimal mesh of 1381 solid structural elements that described the curved geometry of bones, cartilage, and soft tissue, as well as 98 rod elements building the ligaments. This mesh was determined by a converging process in which the mesh density was gradually increased, until the deviation in the produced stress values did not exceed 5 percent. Considering to the result application and stress distribution in character postions (Figure 2), Results of the FE analysis are presented in terms of von Mises equivalent stresses (σv.M.)which weight the effect of all principal stresses ($\sigma_1$, $\sigma_2$, $\sigma_3$) according to the relation:

$$\sigma_{v.m} = \{ \tfrac{1}{2}\left[ (\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 \right] \}^{\frac{1}{2}} \quad (2)$$

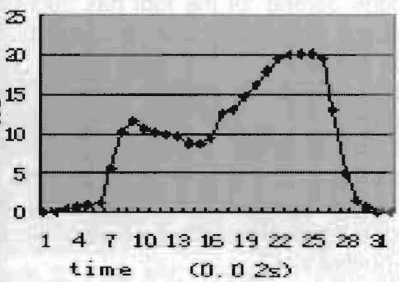


(Heel strike) (Midstance)

(Push off) (Toe off)

**Figure 2 The von Mises stress distributions in the FMVA at the four characteristic subphases of stance.**

At heel strike position,the max stress concentrate in the rearward of the talus. The talus-navicular joint、cuneiform、and metatarsus come forth biggish stress in the midstance,and the talus-navicular joint's maxσv.M is 5.53 MPa,the plantar aponeurosis σv.M is 2.13MPa.At push-off position, the max stress concentrate in the first metatarsus,in which the max σv.M is 20.12 MPa, and the plantar aponeurosis σv.M is 11.58 MPa.The max σv.M concentrates in the end of the phalange. We have analyzed the stress variety in the first metatarsus (Figure 3) and plantar aponeurosis (Figure 4) which is the largest stress appeared in the parenchyma.



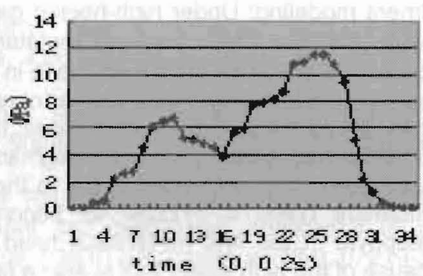




**Figure 3 The σv.M stress variety in the first metatarsus in one cycle of the high-heeled gait.**

**Figure 4 The σv.M stress variety in the plantar aponeurosis in one cycle of the high-heeled gait.**

For understanding these stress value better, we analysis the flat-shoe gait as well. It can help us to discover the high stress value in the specific part of the high-heeled gait through comparing. Figure 5 show us the FMVA von Mises distribution in the flat-shoe gait.

(Heel-strike) (Push-off) (Toe-off)

**Figure 5 The von Mises stress distributions in the FMVA at flat-shoe gait.**

Peak value of the first metatarsus and plantar aponeurosis appear in the push-off subphases of stance. But the first metatarsus' max$\sigma$v.M is 9.06 MPa and the plantar aponeurosis' max $\sigma$v.M is 7.26 MPa. We've compared these parts peak value (Figure 6) for knowing the high stress value more vividly.

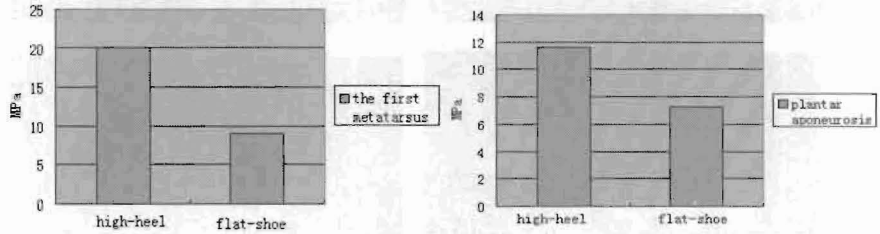



**Figure 6 Peak value comparing of high-heeld gait and flat-shoe gait.**

**CONCLUSION:** The structure of the human foot is extremely complex, development of reliable experimental methods and realistic computational simulations describing its mechanical behavior during gait, is highly complicated. In order to overcome the technical difficulties related with the computational limitations of the currently available commercial FE software packages, some simplifying assumptions were still required and should be kept in mind while interpreting the results. It is possible that introduction of a more realistic approach, not only for the cartilage but also for the plantar tissue pad, will decrease the foot-ground reaction forces and thereby, impose use of larger muscle forces to obtain successful validation with experimental data. Therefore, the model still lacks input of the relative motion between bones in the transverse plane during the subphases of stance.

These findings demonstrate that stress distribution within the FMVA structure during high-heeled gait can be obtained using a realistic two dimensional model, by combining two powerful techniques: integrative X-ray system/Novel Pedar measurements and Finite Element modeling. Under high-heeled gait, "arch bridge defend" of the foot has decreased greatly, and the stress value of metatarsus、cuneiform、talus-navicular joint and plantar aponeurosis are more large than these in the flat-shoe gait. Almost 85% of women list one or more of the above pains as a regular occurrence with the use of high-heeled shoes. If young female always wear high-heeled shoes, the inside ligament of the first metatarsus-phalange joint will be elongated and outside ligmament will be shrinked,When the pollex is pushed to the outside,extension tendon come to the outside too.The pollex is unbalance, and the first metatarsus come to outside so become pollex valgus position. Moreover,it will form osteophyte in the first metatarsus head.Plantar aponeurosis often bring on aponeurositis because of the high stress that is also a familiar high-heeled sick.

Finally,the presently developed finite element analyze open new approaches for sports biomechanics, from simulation of the development mechanisms of human movement to pre-and post interventional evaluation.

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