Three-dimensional numerical foot model for running shoe designing

Tsuyoshi Nishiwaki, and Mai Nonogawa

ASICS Corporation, Institute of Sport Science

Abstract*: In the production process of running shoes, multiple requirement functions such as stability, cushioning, and comfort must be designed. Especially a lot of researchers have pointed out the importance of stability which means the management of excessive foot joint motions, because the long term running with poor stability shoes causes various lower extremity injuries. In this study, running shoe stability prediction method is proposed by using Abaqus. The numerical foot model constructed by stacking computed tomography images has 24 bones, cartilage, soft tissue, plantar fascia, and 3 ligaments. As loading conditions, the forces and torques at the ankle joint which can be obtained by the inverse dynamics of the 3-dimensional ground reaction forces during the contact phase in running were used. In order to check the validity of the numerical model, heel eversion angles on the polymer foams with 3 kinds of hardness were calculated and compared with the practical running motion analytical results. Therefore it was confirmed that the numerical model could predict heel eversion angle during the contact phase. This indicates that the proposed model is a powerful tool in the practical running shoe designing.*

Keywords*: Foot, Ankle joint, Motion analysis, Polymer foam, Running shoe sole, Shoe stability.*

1. Introduction

Nowadays lots of people play various sports in their lives. Running is one of the most popular sports because it is unconstrained by place and mate. Running shoes are very important gears, which have 2 absolutely necessary roles. One is injury prevention and the other is enhancement of runners' performance. Therefore running shoes have various requirement functions such as *cushioning*, *stability*, *fitting*, *breathability*, *grip* and so on. Especially the stability which control excessive foot joints' motions called as *pronation* during the contact phase in running is the most important functions in running shoes as shown in Figure 1. The pronation means a series of foot deformation behavior including *heel eversion*, *medial arch deformation* and *tibial internal rotation*. It has been said that the long term running with poor stability shoes which cannot manage the above excessive pronation may cause various lower extremity injuries. In the designing process of running shoes, designers and developers must consider the stability designing, how to prevent the excessive pronation. It has been reported that the heel eversion angle can be an important index to evaluate shoe stability. Many running shoe sole structures with the better stability have been provided by various shoe manufacturers. The most predominant structure is the sole with hard material insertion to the medial side. This sole structure is effective for controlling excessive heel eversion. On the other hand the best inserting position depends on the running motion and foot skeletal conformation. Moreover an establishment of the quantitative evaluation method of stability must be necessary in the running shoes designing. The evaluation method must be based on the runners' responses, i.e. heel eversion angle during contact phase. Many experimental methods based on the motion capture system have been reported. However the experimental results are sensitively affected by the running conditions, running velocity and volunteers' motivations. The establishment of the prediction method based on the numerical simulation can become a strong tool in the designing process because it can reduce the prototyping period and cost (Natali, 2010) (Pasquale, 2013). These reductions are also important from a viewpoint of sustainable manufacturing.

Figure 1. Heel eversion of right foot.

In this paper, a numerical foot model which can predict the heel eversion angle during the contact phase in running is proposed. The model is constructed by main components with accurate geometries. The validity is checked by the comparison with experimental results obtained from motion capture system. Moreover as a practical deigning example, the influence of sole hardness distribution upon the sole stability is systematically discussed.

2. Numerical foot model

The heel eversion angle which can be an index of shoe stability means the inward rotation angle of heel. It can be said that shoes produce the large eversion angle have poor stability, because the large eversion angle is the most common precipitating cause of running injury (Benno, 1980). In order to precisely predict the shoe stability, foot components should be independently modeled. A healthy female volunteer (weight: 45kg, height: 1.58m) with no history of a lower extremity injury participated in this study. Serial cross-sectional images of right foot under the supine condition were shot by X-ray computed tomography scanner with the pitch of 0.312mm. Through the skinning these images, geometry data of foot model was constructed by Simpleware (Simpleware Ltd.).

Figure 2 shows the finite element model created by HyperMesh (Altair Engineering, Inc.) from the geometry data. Bone, cartilage and soft issue are represented by tetrahedral solid elements. Plantar fascia and ligaments are represented by truss elements, T3D2. These material and physical properties are listed in Table1. The mechanical properties of soft tissue (Nakamura, 1981) (Lemmon, 1997), bones (Amit, 2002), cartilage (Athanasiou, 1998), ligaments (Siegler, 1988), and plantar fascia (Jason, 2004) were determined by reference to the previous literature. Only soft tissue is modeled by the Herrmann element C3D4H, and represented by hyper elastic material, whose mechanical property is shown in Figure 3.

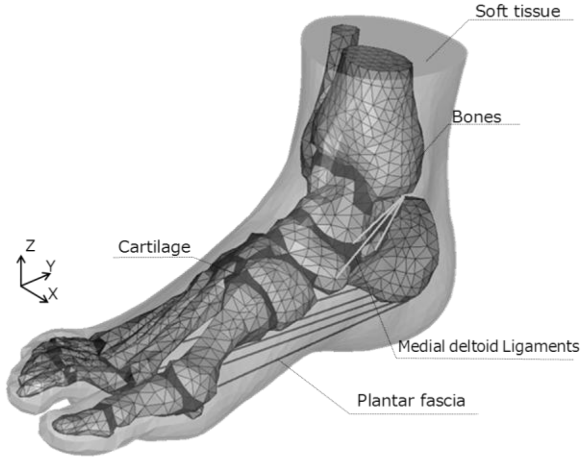


Figure 2. Finite element model of foot.

Table 1. List of model information.

	Young's modulus [MPa]	Poisson's ratio	Element type	Num of elements	Sectional area [mm^2]
Bone	7300	0.3	C3D4	9785	
Cartilage	1.0	0.4	C3D4	2468	
Soft tissue	Hyper elastic		C3D4H	25915	
Plantar fascia	700		T3D2	5	290.7
Ligament	260		T3D2	3	18.4

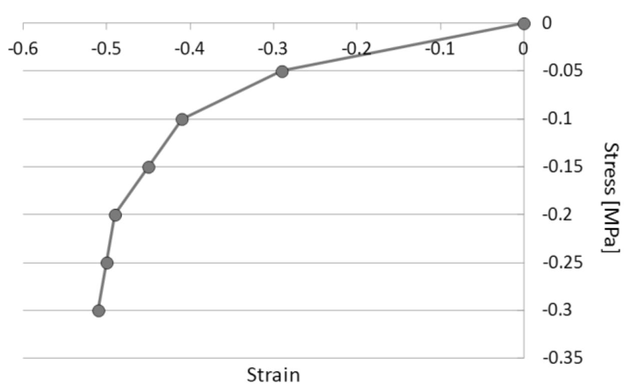


Figure 3. Stress-Strain curve used in the soft tissue part.

3. Analytical method

Motion analyses were carried out to set the analytical conditions. The healthy female volunteer mentioned in the previous chapter is used. The volunteer took a bearfoot running at the constant speed of the 2.8m/s on the 20mm thickness of polymer foam sheet with hardness of JIS-C 65 degrees. Three dimensional coordinates of markers on foot landmarks, plantar pressure distribution and ground reaction force (GRF) were measured by using VIOCN-MX system (Vicon motion systems, Ltd.), F-scan system (Tekscan Inc.) and force platform (Kistlar AG) as shown in Figure 4. At the same time, in order to check the validity of the foot model, barefoot running tests on polymer foam sheets of C-45 and 55 were also performed. For reference, most running shoes approximately have soles with hardness of C53.

(a) Reflective markers attached. **(b) Motion analysis with force plate and motion capture cameras.**

Figure 4. Experimental setup.

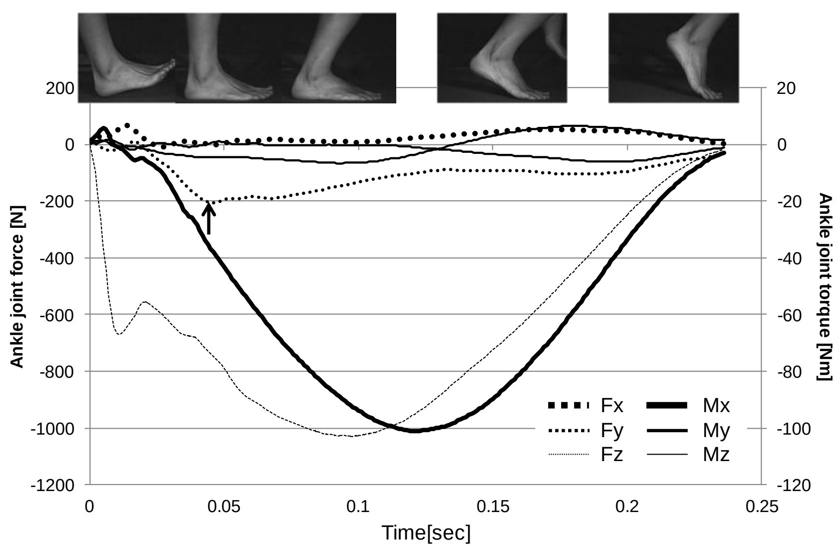


Figure 5. Reaction force and torque histories generated at the ankle joint during the contact phase.

Figure 5 shows the reaction force and torque histories generated at ankle joint during contact phase on polymer foam sheet with hardness of JIS-C65. Here, x, y and z denote lateral, forward and vertical directions, respectively. A series of photos are approximately corresponding to foot behaviors. The forces and the torques at the ankle joint can be obtained from the GRF and markers' trajetories by the application of the inverse dynamics problem (David, 2004). In this paper, the time of minimum Fy as indicated by a bold arrow in this graph is focused. It is well known that maximum angle of heel eversion appears at the time. Force components Fx, Fy, Fz, torques Mx, My and Mz at the time of minimum Fy used as the loading condition are -9.2N, -138.7N, -1028.9N, 92.0Nm, -6.4Nm and -0.1Nm, respectively. A friction coefficient of 0.1 is set between foot plantar surface and polymer foam sheet. These loading values are subjected to the top surface of talus (ankle bone) as shown in Figure 6. Polymer foams with 3 kinds of hardness, C45, C55 and C65 were modeled by elastic hexagonal brick elements, C3D8I and the elastic moduli are 3.69, 5.78 and 7.90MPa, respectively. Poisson's ratio is constantly 0.2. The thickness is also constant, 20mm. As a solver Abaqus v.6.14-2 is used.

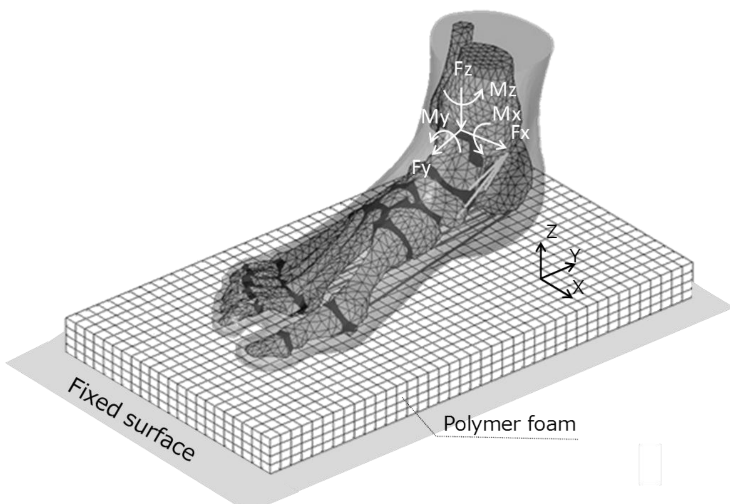
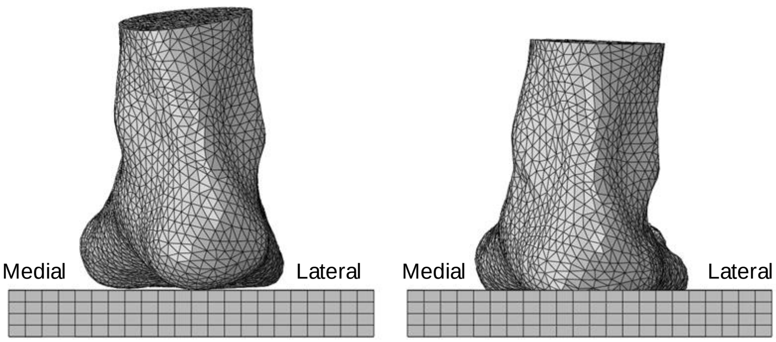


Figure 6. Loading conditions.

4. Analytical results

Deformation modes on polymer foam sheets with 3 kinds of hardness were calculated. The heel eversion angles were calculated by the following simple method. 2 planes were defined by arbitrary 3 nodes at the leg and heel as shown in Figure 8. These nodes are located on the surface of soft tissue. From the relationship between 2 planes, rotation angle of heel along y-axis (foot longitudinal direction) was calculated. This method is also used in the conventional experimental method (Nakabe, 2002). In the experiment, heel eversion angle can be also calculated by using the trajectories of attached markers in Figure 4(a). Figure 7 shows comparison of backward views between before and after loadings on C65 EVA foam sheet. In Figure 7(b) the heel eversion can be checked as shown in Figure 1. Table 2 shows the contact pressure distributions on 3 polymer sheets. Experimental results are obtained at the time of minimum Fy in Figure 5. With decreasing the polymer foam hardness, the contact area obtained from barefoot running is spreading. It is also confirmed that the simulation results have same tendency.



(a) Before loading **(b) After loading**

Figure 7. Deformation mode on HC65 EVA foam sheet.

Table 2. Comparison of contact pressure distributions.

	C45	C55	C65	
Simulation				0.5  Contact stress[MPa] 0.001
Experiment				0.2  Plantar pressure [Mpa] 0.001

Figure 8 shows the dependency of surface hardness on heel eversion angle. With increasing the hardness, heel eversion angle decreases. These results indicate that the soft sole which can produce the better shock attenuation has poor stability. Both the simulation and experimental results have the same tendency, however there are large gaps between both the values. The difference may be mainly derived from material properties of the numerical model. The proposed model can consider the passive behavior, however it cannot consider the active behavior which is unique to human body. Considering that the large eversion angle indicates the poor stability, it is confirmed that the numerical model can predict the sole stability.

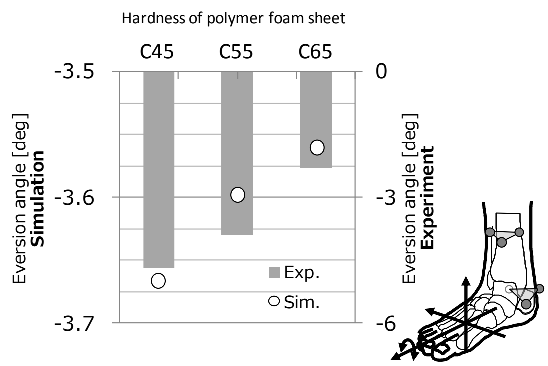


Figure 8. Comparison of heel eversion angles between experiment and simulation on polymer foam sheets with 3 kinds of hardness, JIS-C45, C55 and C65.

5. Discussions

5.1 Influence of hardness distribution on sole stability

In order to apply the above simulation technique, some case studies were carried out. As already mentioned, the harder material insertion is effective for improving shoe stability. On the other hand, the harder material insertion may make bad influence on shock attenuation. Shock attenuation can be derived from the sole deformation. The hard material insertion may block the conversion of impact energy in running to sole strain energy. Accordingly it is so important to systematically clarify the relationship between sole stability and sole hardness distribution. Figure 9 shows the simulation results obtained from sole structures with different hardness distributions. The dark and light colors denote the harder and softer polymer foams, C65 and C55. As a reference, result of one hardness sole is also shown on the extreme left. Judging from this bar chart, it is not effective to insert the harder material to forefoot area, however insertion to mid-foot area can improve the sole stability. It is clarified that, the heel eversion angle is decreasing with increasing the width of hard foam in mid-foot area. In other words, reinforcement of mid-foot area in medial side is effective for improvement sole stability. Judging from Figure 10, in case that the harder material is inserted to the longer and wider area in medial side, the sole stability can be drastically improved. The above results can be an important guideline for stability designing. Figure 11 shows the practical product examples. For stability improvement, harder materials are inserted as shown in hatched areas into the medial side.

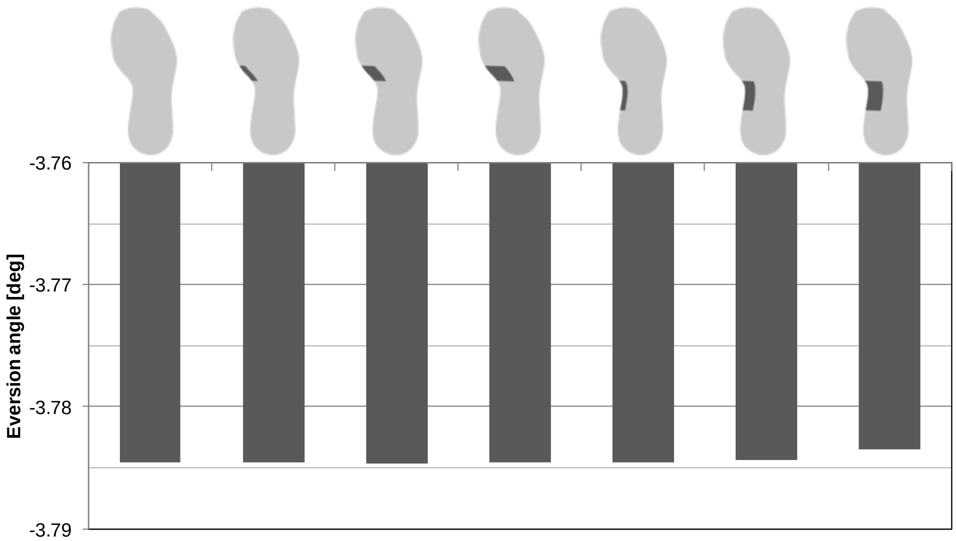


Figure 9. Hard material insertion effect to forefoot and mid-foot areas.

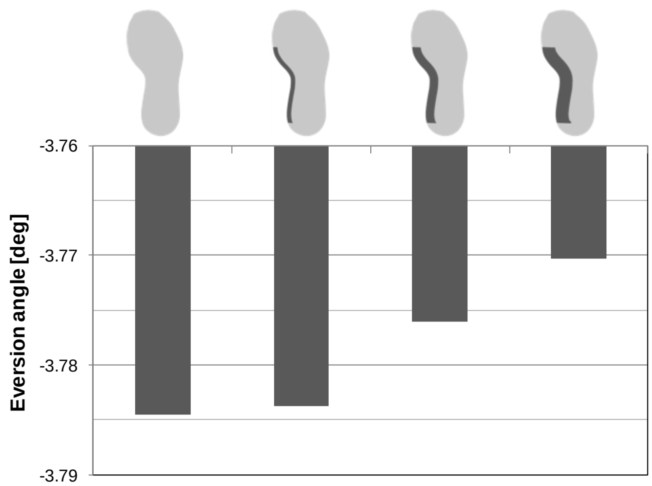


Figure 10. Hard material insertion effect to the whole medial side.

Figure 11. Product examples with hard sole material insertion.

6. Conclusions

The numerical simulation technique based on Abaqus for stability designing of running shoe sole was introduced. The foot model was constructed by bones, ligaments, soft issue and plantar fascia, the loading condition was obtained from the practical running motion analyses and the inverse dynamics problem. As a index of stability, the heel eversion angles were predicted by using the foot model and compared with experimental results. Therefore it was confirmed that the model was a powerful tool for shoe stability designing. Moreover the products were introduced as practical designing examples.

The simulation technique can reduce the prototyping cost and time. In addition, it can skip the practical prototyping in the development process. This is so-called sustainable designing and the important key in the future manufacturing.

7. References

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