한국운동역학회지, 2009, 제19권 1호, pp. 13-25
Korean Journal of Sport Biomechanics
2009, Vol. 19, No. 1, pp. 13-25

REVIEW OF COMPUTATIONAL MODELS FOR FOOTWEAR DESIGN AND EVALUATION

신발 설계 및 평가를 위한 컴퓨터 모델

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ABSTRACT

CHEUNG, J. T., YU, J., and ZHANG, M., Review of Computational Models for Footwear Design and Evaluation. Korean Journal of Sport Biomechanics, Vol. 19, No. 1, pp. 13-25, 2009. Existing footwear biomechanics studies rely on simplified kinetics and kinematics, plantar pressure and muscle electromyography measurements. Because of the complexity of foot-shoe interface and individualized subject response with different footwear, consistent results regarding the biomechanical performance of footwear or footwear components can yet be achieved. The computational approach can be an efficient and economic alternative to study the biomechanical interactions of foot and footwear. Continuous advancement in numerical techniques as well as computer technology has made the finite element method a versatile and successful tool for biomechanics researchdue to its capability of modelling irregular geometrical structures, complex material properties, and complicated loading and boundary conditions. Finite element analysis offers asystematic and economic alternative in search of more in-depth biomechanical information such as the internal stress and strain distributions of foot and footwear structures. In this paper, the current establishments and applications of the computational approach for footwear design and evaluation are reviewed.

KEYWORDS : FINITE ELEMENT ANALYSIS, FOOT AND ANKLE BIOMECHANICS, SHOE, INSOLE, INSERT, ORTHOSIS, SOFT TISSUE, PLANTAR PRESSURE, STRESS, STRAIN, DEFORMATION

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Introduction

In spite of years of development in the fields of orthopaedics and sports biomechanics, the biomechanical rationales behind the design of different therapeutic andfunctional footwear have not been fully evaluated. Existing treatments and products are based on limited experimental evaluations or empirical knowledge of clinicians, biomechanists and engineers. Because of the complexity of the foot-shoe interface, large variations of prescribed footwear, and individualized subject response, consistent outcomes can yet be achieved and conflicting results are common in terms of the performance of different conventional treatments and functional sportswear.

Researchers have turned to the computational approach such as the finite element (FE) method, which offers a systematic and economic alternative in search of more in-depth biomechanical information such as the internal stress and strain distributions of foot and footwear. Continuous advancement in numerical techniques as well as computer technology has made the FE method a versatile and successful tool for biomechanical research due to its capability of modelling irregular geometrical structures,complex material properties, and complicated loading and boundary conditions in both static and dynamic analyses. In this paper, existing studies on the development of computational footwear models and their applications are reviewed. The limitations and future directions of the computational approach for the biomechanical research of footwear are discussed.

Finite Element Models of Footwear

A number of FE footwear models (Table 1) have been built for the design and evaluation of orthotic device, shoe sole and other shoe components. The development and applications of two-dimensional (2D) models were first presented, followed by studies using three-dimensional (3D) models.

1. Two-dimensional Models

The first known FE analysis of foot and support was reported by Nakamura et al. (1981), who developed a 2D FE foot model of a unified bony structure of the foot, plantar soft tissue and a shoe sole. A sensitivity analysis on the shoe sole material with varied Young's modulus (0.08 to 1000 MPa) suggested an optimum range of 0.1 to 1 MPa for stress reduction in the plantar soft tissue. A further simulation using a nonlinearly elastic foamed shoe sole showed similar responses in stress reduction as compared to the predictions with the optimized linearly elastic shoe material.

It was not until late nineties further development of foot and footwear became popular. Lemmon et al. (1997) developed a 2D model of the second metatarsal bone and encapsulated soft tissue to investigate the metatarsal head pressure as a function of sixinsole thicknesses and two tissue thicknesses. The plantar soft tissue, polyurethane insole, and cloud crepe foamed midsole were defined with hyperelasticand hyperform material models. Frictional contact between the foot and support was considered and a vertical load was applied at the metatarsal bone to simulate push off. Orthosis with relatively soft material was found to reduce peak plantar pressure, which also decreased with an increase in insole thickness. The pressure reduction for a given increase of insole thickness was greater when plantar tissue layer was thinner. A further study by the group (Erdemir et al., 2005) investigated 36 plug

designs of a Microcell Puff midsole including a combination of three materials (Microcell Puff Lite,

Table 1. Configurations and applications of finite element footwear models in the literature.

Years	Authors	Geometrical Properties	Material and Loading Conditions	Parameters of interest
1981	Nakamura et al.	2D, engineering sketch (unified foot bones, plantar soft tissue, shoe sole)	Bones (linearly elastic), plantar tissue (nonlinearly elastic) Shoe sole (linearly / nonlinearly elastic) Ankle joint & Achilles tendon forces to simulate midstance	Shoe sole stiffness on stress in plantar soft tissue
1995 1995	Chu et al. Chu & Reddy	3D, engineering sketch (unified ankle-foot bones, encapsulated soft tissue, ankle-foot orthosis)	Bones, ligaments, soft tissue, orthosis (linearly elastic) Ground reaction, Achilles, flexor, extensor tendons forces to simulate heelstrike & toe off	Drop foot, stiffness of orthosis & soft tissue on stress distribution in ankle-foot orthosis
1997 1998 2005	Lemmon et al. Shorten Erdemir et al.	2D, video image of specimen (metatarsal bone, encapsulated soft tissue, insole, midsole, soccer shoe sole & stud)	Bone, sole plate, thread & stud (linearly elastic), encapsulated tissue, insole, midsole, surface (hyperelastic / nonlinearly elastic) Contact simulation of foot-support interface Vertical load on metatarsal bone to simulate push off	6 insole thicknesses, 2 tissue thicknesses, 36 plug designs of midsole (3 materials, 6 geometries, 2 locations of placement), soccer shoe stud length & penetration, sole plate stiffness on plantar tissue stress & peak plantar pressure
1997	Shiang	3D, engineering sketch (insole, midsole)	Insole (linearly elastic), midsole (nonlinearly elastic) Vertical heel pressure & shear to simulate loading on heel	Different cushioning configurations of insole & midsole on plantar pressure relief
1999	Baroud et al.	3D, engineering sketch (shoe & surface)	Shoe sole & ground surface (hyperelastic) Ground reaction forces during running	Structural surface-shoe configurations on energy return
1999	Shorten	3D shell, engineering sketch (cushioning spring elements)	Compression load	Wall thickness and shape of spring element on stress & strain characteristics
2000	Syngellakis et al.	3D shell, engineering sketch (ankle-foot orthosis)	Ankle-foot orthosis (nonlinearly elastic) Uniform pressure at distal orthosis to simulate plantar & dorsiflexion	Thickness on stiffness characteristics of plastic ankle- foot orthosis
2003	Alemany et al	3D, engineering sketch (high heeled shoe insole)	High heeled shoe insole Spatial load field determined from plantar pressure of walking subject	Shankpiece design on overall sole deformation
2003	Chen et al.	3D, CT images of subject (ankle-foot bones, encapsulated soft tissue)	Bones, cartilages, ligaments, encapsulated tissue (linearly elastic) Insole, midsole (hyperform) Contact simulation of plantar support Displacement control of plantar foot & support to simulate midstance to push off	Flat & total-contact insoleswith different material combinations on plantar pressure distribution
2003	Lewis	2D, engineering sketch (rocker sole footwear)	Shoe surface, insole, midsole, outsole (linearly elastic) Fix contact between shoe & ground Vertical loads on insole surface to simulate loading on shoe	Material of midsole & outsole on stress & displacement of shoe
2003	Oda et al.	3D (bones, soft tissue, shoe sole)	Impact during heel contact	Shoe sole plate material and shape on stability & cushioning of ankle joint
2004	Verdejo & Mills	2D, engineering sketch (heel bone, heel pad, midsole)	Bone (linearly elastic), heel pad, midsole (hyperform) Contact simulation of heel-support interface Vertical deformation on plantar heel to simulate heelstrike	Stress distribution in heel pad with & without midsole support

Cont' Table 1.

Years	Authors	Geometrical Properties	Material and Loading Conditions	Parameters of Interest
2005	Barani et al.	3D, CT images of insole	Insole (hyperelastic) Vertical pressure on insole at 6 locations to simulate midstance	Insole material on stress distribution in insole
2005 2007 2008 2008	Cheung & Zhang Cheung et al. Cheung & Zhang Yu et al.	3D, MR images of male & female subjects (ankle-foot bones, encapsulated soft tissue, shoe upper & sole, high heeled support)	Bones, cartilages, ligaments, shoe upper, high heeled support (linearly elastic) Encapsulated tissue, shoe sole(linearly elastic / hyperelastic / hyperform) Contact simulation of most foot joints (except the toes) & plantar support Ground reaction & Achilles tendon or other extrinsic musclestendon forces to simulate balanced standing / midstance / shod walking	Flat & custom-molded foot orthosis with different combination of material stiffness, arch height & thickness, assembled shoe model, 2-inch high heeled support on plantar pressure & bone stress distribution,
2005	Sun et al.	3D, engineering sketch, (soil ground, outsole)	Outsole (rigid), soft soil ground (linearly elastic) Vertical compressive & transverse shear forces applied to ground	Five sole tread patterns on traction force & soil deformation
2006 2008	Actis et al.	2D, CT images from 6 subjects (foot bones, encapsulated soft tissue, insole, shoe sole)	Bones, cartilages, plantar fascia, flexor tendon (linearly elastic), encapsulated tissue, insole, shoe sole (nonlinearly elastic) Contact simulation of foot-support interface Vertical forces & moment on ground support to simulate push off	Modulus of elasticity of bone, cartilage, fascia, flexor tendon & the use of total contact insert & multi-plug insoles on peak metatarsal pressure in feet with diabetic neuropathy & forefoot pain
2006	Even-Tzur et al.	3D, engineering sketch (calcaneus bone, heel pad tissue, midsole)	Bone (linearly elastic), heel pad (nonlinear viscoelastic), EVA foam (uniform linear viscoelastic) Sinusoidal vertical load on heel bone to simulate dynamic heelstrike	Properties & wear of EVA sole on heel pad stress & strain
2006	Goske et al.	2D, MR image of subject (heel bone, heel pad tissue, heel counter, insole, midsole)	Bone (Rigid), heel counter (linearly elastic), Heel pad, insole, midsole (hyperelastic / hyperform) Contact simulation of foot-shoe interface Vertical load on heel bone to simulate heelstrike	3 insole conformity levels, 3 different materials, 3 insole thicknesses on heel pressure distribution
2007	Budhabhatti et al.	3D, MR images of subject (first ray bones, soft tissue, insole)	Bone (rigid), soft tissue (hyperelastic), Insole (hyperfoam) Forces on base of the first metatarsal to simulate late stance instances	5 different insole properties on plantar pressure distribution
2007	Spears et al.	2D, MR imagesof subject (heel bone, heel pad tissue, heel counter, insole, midsole)	Bone (Rigid), heel counter (rigid / linearly elastic), Skin, fat pad, insole, midsole (hyperelastic / hyperform) Contact simulation of foot-shoe interface Vertical load on heel bone to simulate standing	Heel counter on tissue stress distribution in skin & fat pad of heel
2008	Hsu et al.	3D, CT images of subject, (bones, encapsulated soft tissue, insole)	Bones, cartilages, ligaments, fascia, insole, encapsulated soft tissue (linearly elastic) Ground reaction & Achilles tendon forces to simulate balanced standing	Conformity of insole contour on plantar pressure reduction

Plastazote Medium, Poron), sixgeometries (straight or tapered with different sizes), and two locations of placement. Plugs that wereplaced according to the most pressurized area were more effective in plantar pressure reduction than those positioned based on the bony prominences. Large plugs (40mm width) made of Microcell Puff Lite or Plastazote Medium, placed at peak pressure sites, provided the largest peak pressure reductions of up to 28%.

Using a similar 2D toe model, Shorten (1998) incorporated a soccer shoe sole to study the effect of stud length, surface penetration and sole plate stiffness on induced tissue stress. Stud length and surface penetration of the stud had only minimal influence onplantar stress distribution. A partially penetrated stud caused only a 5% increase in peak plantar stress in spite of relatively high stresses concentration in the stud andshoe sole. A parametric study on sole plate stiffness suggested that a stiff sole plate is important in protecting tissue above the stud position from high plantar stress with partial stud penetration. The peak plantar stress induced by a rubber sole plate was about30% higher than the ordinary nylon plate. Above all, a double-studded condition was able to redistributemore evenly the plantar stress and reduce about 30% the peak stress.

Recently, Actis et al. (2006) developed six subject-specific 2D FE models of the second and third metatarsal rays from CT images to study the plantar pressure distribution in diabetic feet during push off. The FE model considered a unified rearfoot and midfoot structures, one metatarsal and three phalangeal bones connected by cartilaginous structures, flexor tendon, fascia, and encapsulated soft tissue. A total-contact plastazote insert with a rubber shoe sole was incorporated to study its effect on forefoot pressure. Subject-specific bulk soft tissue material properties were obtained and vertical loadand moment were applied at the ground support. Frictionless contact interface between the foot-sole and shoe-ground surfaces was assumed. The sensitivity analysis on bone Young's modulus showed a minimal effect on pressure distribution while the corresponding effect of cartilage has a stronger influence. An increase in fascia and flexor tendon Young's modulus produced minimal effects on pressure distribution. Peak metatarsal pressure was reduced by about 46% with the use of a total-contact insert. The authors suggested that incorporating the bony segments of the rearfoot, metatarsal, and toes, tendon and fascia with linear material properties, and surrounding bulk soft tissue with nonlinear material properties, are plausible simplified configurations for determining metatarsal head pressure distribution during push off. A further study by Actis et al. (2008) investigated the effect of Poron multi-plug in a total-contact plastazote insole on forefoot plantar pressure distribution of subject with either forefoot pain or diabetic neuropathy. Experimentally measured and FE predicted plantar pressure distributions during push off with different total-contact insoleconfigurations (no plug, multi-cylindrical plugs, box plug and inlay) were examined. Comparing to total-contact insole alone, addition of localized plugs was able to reduce peak plantar pressure of up to 14% and 7% in experiments and FE predictions, respectively.

Several studies used 2D models to study the loading response of the plantar heel pad. Verdejo and Mills (2004) developed a 2D hyperelastic FE model of theheel to study the stress distribution in the heel pad during barefoot running and with ethylene vinyl acetate (EVA) foamed midsole. The heel pad had a higher order of nonlinearity but a lower initial stiffness than the foam material. The predicted peak bareheel plantar pressure was about two times the pressure during shod.

Goske et al. (2006) incorporated a shoe counter and sole into a hyperelastic heel model to investigate the effect of three insole conformity levels (flat, half conforming, full conforming), three insole thickness values (6.3, 9.5, 12.7mm), and threeinsole materials (Poron Cushioning, Microcel Puff Lite and Microcel Puff) onpressure distribution during heelstrike. Conformity of insole was a more important design factor than insole material in terms of peak pressure reduction. Themodel predicted a 24% reduction in peak plantar pressure compared to the barefoot condition using flat insoles while the pressure reduced up to 44% for full conforming insoles. Increasing the insole thickness provided further pressure reduction.

A similar 2D heel model was developed by Spears et al. (2007) to study the influence of heel counter on the stress distribution during standing. Considering a distinction between the material properties of fat pad and skinrather than a unified bulk soft tissue provided a better match with the measured barefoot plantar pressure. The predicted stresses in the skin were higher and predominantly tensile in nature, whereas the stress state in the fat pad was hydrostatic. Inclusion of a heel counter to the shod model resulted in an increase in compressive stress of up to 50% and a reduction in skin tension and shear of up to 34% and 28%, respectively. The compressive and shear stresses in the fat pad reduced up to 40% and 80%, respectively, while minimal changes were found in tension. A properly fitted heel counter was suggested to be beneficial in terms of heel pad stress relief.

There wereonly a limited number of 2D full-length shoe models reported in the literature. Lewis (2003) used a 2D FE model to perform a sensitive study of the effect of the materials used for the midsole and outsole of a solid rocker bottom design of a therapeutic shoe on the stress and displacement of a model of the shoe. Linear elasticity was considered for all structures and concentrated loadings were applied on the insole surface. There were noticeable differences in the displacement and distribution of the von Mises stress at the interface between the bottom of the foot and the top of the top layer of the insole in the therapeutic shoe, as a consequence of a change in the material selected for the two layers of the midsole and outsole.The von Mises stress at the heel region was 62% higher with a relatively rigid midsole to the outsole.

2. Three-dimensional Models

A number of 3D FE models, considering partial, simplified or geometrically detailed foot structures were reported. In 1995, Chu and colleagues developed a linearly elastic model with simplified geometrical features of the foot and ankle to study the loading response of ankle-foot orthosis. During heelstrike and toe off, peak compressive and tensile stresses concentrated at the heel and neck regions of the ankle-foot orthosis, respectively. The highly stressed neck region reflected the common site of orthoses break down. The peak compressive stress in the orthosis increased with increasing Achilles tendon force whereas the peak tensile stress decreased with increasing stiffness of the ankle ligaments. The stress distribution in the orthosis was more sensitive to the stiffness of orthosis than that of the soft tissue. A 3D shell model of plastic ankle foot orthosis was developed by Syngellakis et al. (2000) to study its stiffness characteristics. Nonlinear elasticity was considered along with geometrical nonlinearity. It was found that thickness of ankle foot orthoses have a pronounced effect on the deflection of the ankle-foot orthosis. Both the material and geometrical nonlinearity were found to be essential in obtaining a realistic simulation of the stress distribution of the ankle foot orthosis.

Shiang (1997) introduced a 3D FE model of the shoe heel, composing of the insole and midsole with measured heel pressure applied as the loading condition at the heel region. Nonlinear elasticity was defined for the soft tissue and insole/midsole properties. The mean peak plantar pressure of the running situation was found to be higher than that of the walking situation as predicted and that the present of an insole provided better cushioning effect. The results showed that nonlinear stress/strain curve and compressibility offered by the nonlinear hyperfoam approach provided a better approximation of the behaviour of footwear material because of large deflections of structures.Addition of an insole layer especially with a contoured surface on top of the midsole was found to provide better cushioning performance for plantar pressure relief.

Even-Tzur et al. (2006) employed 3D nonlinear viscoelastic FE model of the shoe-heel interaction to study EVA midsole viscous damping to heel pad stress and strain attenuation during heelstrike in running. Wear of EVA was defined by three different parameters separately: reducing 50% or 90% the original thickness increasing the elastic modulus by 25% or 50% decreasing the relaxation time constants by 50%. The decrease in EVA midsole thickness was found to be the most sensitive factor for heel pad stress, which increased up to 36%. Increasing the elastic modulus and decreasing relaxation timeresulted in up to 6% increase and 3% decrease of heel pad stress. The induced heel pad strains were affected only by up to 13% only among all conditions.

A 3D hyperelastic FE model of a full-length insole was developed by Barani et al. (2005) to study the effect of different insole materials including silicon gel, plastazote, polyfoam, and EVA. Discrete pressures were applied at the forefoot and heel regions to simulate the loading on the insole surface during midstance. They concluded from the stress analysis of the insole that most of the materials especially Silicon Gel could be effective in plantar stress reduction.

Several computational shoe sole models were built to study the performance of different structural design for sports surface, shoe soles and components. Shorten (1999) demonstrated the use of FE analysis for determining the stress-strain characteristics of hemispherical and hemiellipsoidal spring elements of shoe sole with respect to wall thickness and shape. Inhomogeneous and distinct cushioning characteristics can be configured with varying material and geometrical properties of individual spring element. Baroud et al. (1999) developed hyperelastic FE models of sport surfaces and shoes and demonstrated that an oblique surface-shoe structural configuration could enhance the energy return of more than 14 times that of conventional horizontal shoe-surface system. Alemany et al. (2003) developed an FE model of 6 cm high heel shoe sole to optimize shankpiece design in terms of deformation levels. The orientation angle between the shankpiece and the insole's rear axis, the shankpiece transverse position and the longitudinal position of a joint that divides the shankpiece into two parts were optimized such that the maximum insole deformation was reduced and gradient smoothed. Sun et al. (2005) developed 3D models of shoe sole of five different sole tread patterns to study their performance of slip resistant on soft soil ground. Traction forces, evaluated by shoe-ground reaction were able to identify the best slip resistant capability among different sole designs. The predicted soil deformations were comparable to the experimental measurements of soil tray test.

A number of anatomical detailed 3D FE foot-shoe models targeted for footwear design were reported in early 2000. Oda et al. (2003) developed 3D model of foot bones, soft tissue and shoe sole to study the effect of shape and material of a sole plate on the stability andcushioning ability of shoe sole. Heel impact during running was simulated and modified shoe sole resulted in better cushioning from reduced shank acceleration but reduced stability with increased calcaneal pronation. A 3D linearly elastic ankle-foot model, consisting of the bony, encapsulated soft tissue and major plantar ligamentous structures, was developed by Chen et al. (2003) using CT images to estimate the plantar foot pressure and bone stresses. The joint spaces of the metatarsophalangeal joints and ankle joint were connected with cartilaginous structures while the rest of the bony structures were merged. Frictional contact between the plantar foot and a rigid support was considered. The peak stress region was found to shift from the second metatarsal to the adjacent metatarsals from midstance to push off. They studied the efficiency for stress and plantar pressure reduction and redistribution using flat and total-contact insoles with different material combinations. Nonlinear elasticity for the insoles and the frictional contact interaction between the foot and support were considered. The predicted peak and average normal stresses were reduced in most plantar regions except the midfoot and hallux regions with total-contact insole. The percentage of pressure reduction by total-contact insole with different combination of material varied with plantar foot regionsand the difference was minimal.

Cheung and Zhang (2005) developed a linearly elastic FE ankle-foot model from MR images, which took into consideration large deformations and interfacial slip/friction conditions, consisted of 28 bony structures, 72 ligaments and the plantar fascia embedded in a volume of encapsulated soft tissue, to study the interactions between the foot and orthosis. Custom-moulded shape was found to be a more important design factor in reducing peak plantar pressure than the stiffness of orthotic material.A further study considering the hyperelastic material properties of the encapsulated soft tissue and shoe sole was conducted to identify the sensitivity of five design factors (arch type, insole and midsole thickness, insole and midsole stiffness) of foot orthosis assigned with four different levels on peak plantar pressure relief (Cheung and Zhang, 2008). The Taguchi experimental design method, which utilizes a fractional factorial design approach to assess the sensitivity of each design factor of a system and to determine its optimal quality level, was used. The custom-moulded shape was the most important design factor in reducing peak plantar pressure while the insole stiffness ranked the second most important factor. Other design factors, such as insole thickness, midsole stiffness and midsole thickness, contributed to less importantroles in peak pressure reduction in the given order. The FE predictions suggested that custom pressure-relieving foot orthosis providing total-contact fit of the plantar foot is important in the prevention of diabetic foot ulceration. The cushioning insole layer of an orthosis should contribute to the majority of the thickness of the foot orthosis to maximize peak pressure reduction.

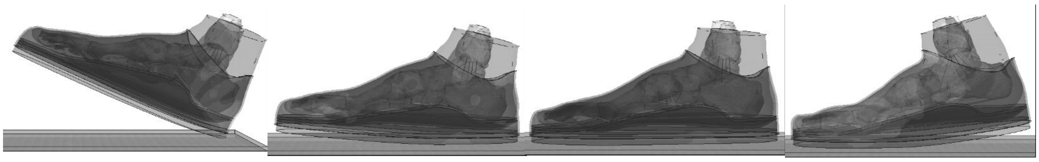

Figure 1. Finite element simulation of foot-shoe interface during walking

In the latest development by Cheung et al. (2007), the capability of the FE model was extended to 3D FE simulation of foot-shoe interfaceduring walking (Figure 1) by incorporating assembled footwear consisting of insole, midsole, outsole, upper cover.

Using similar model development techniques, Yu et al. (2008) developed a female FE model from MR images, which incorporated with high-heeled support to investigate the biomechanical effect of heel elevations on foot. Comparing the FE predictions of static standing on flat and high heeled supports, no noticeable rotation movement in transverse plane of the first metatarsophalangeal segment was found. The results implicated that heel elevation was not found to be a direct biomechanical risk factor but might contribute to progressivehallux valgus deformity.Development of 3D foot-sole models is becoming more and more popular in the field of biomechanics in recent years. Budhabhatti et al. (2007) developed a 3D hyperelastic FE model of the first ray from MR images. The orientation of the model and joint configuration were manipulated to simulate late stance instances from push off to toe off. A flat insole support of five different materials (Puff, Firm Plastazote, Puff Lite, Medium Plastazote, Poron) was modeledto investigate its effect on plantar pressure distribution. The posterior edge of the insole layer was tied to the metatarsal base to simulate the bending and movement of the insole with the foot.Among all the insole material, pressure reduction of 18% and 43% could be achieved underneath the metatarsal head and hallux, respectively. Poron insole provided the highest pressure reduction by 69%. Hsu et al. (2008) developed an anatomically detailed linear 3D foot FE model from CT images to investigate the effect of insole contour on the tensile stress in plantar fascia. An optimization procedure was performed with insole shape to indentify the optimal insole configuration for plantar fascia stress relief. The valuesof 15 geometrical references on the insole surface were optimised to improve the conformity of insole to the plantar foot. Comparing to a flat insole, the optimal insole could decrease the plantar fascia stress and peak plantar pressure by 14% and 39%, respectively.

Limitations of Existing Finite Element Models for Footwear Biomechanics

The biomechanical interface of foot and footwear has been receiving more and more attention in recent computational studies. However, many FE foot models are developed under certain simplifications and assumptions including a simplified or partial foot shape, assumptions of linear material properties, and linear boundary conditions without considering friction and slip. Because of the high demanding accuracy for simulation of geometry, material behaviour, loading and boundary conditions for realistic biomechanical simulation of the human foot and ankle, improvements on certain categories are needed for the existing FE models in order to provide a reliable computational system for realistic simulation of foot-shoe biomechanics. In this section, the major drawbacks of existing FE models and potential advancements of the modelling techniques are discussed.

In many of the 3D foot models, only the major ligaments were considered and the whole encapsulated soft tissue was not included. The ignorance of these structures may affect the representation of accurate structural integrity and stiffness of the ankle-foot complex. In addition to geometrical simplification, many of the FE models for footwear or insole design incorporated only parts, symmetric or even did not include the foot structures. A number of FE models were built on a simplified or partial foot shape. For instance, some models are 2D in nature and incorporated only parts, symmetric structure of the foot in which the out of plane loading and joint movement cannot be accounted. Several 3D models considered only simplified foot bone structures representing the medial and lateral arch without differentiation of individual metatarsal bones in the medial-lateral directions. Meanwhile, fused tarsal and toes bones were often considered without allowing relative bone movements. Many foot modelsconsidered only the major ligaments and the plantar soft tissue, resulting in an inaccurate representation of thestructural integrity and stiffness of the ankle-foot complex.

Recent efforts have been directed to the development of geometricallydetailed ligamentous joint contact model of the foot and ankle. However, realistic structural modelling of the hyaline cartilages, joint capsules, muscles, tendons, and ligaments as well as differentiation of the skin and fat tissue layer are potential rooms for improvement of existing computational models. Inclusion of comprehensive assembled footwear model consisting of upper shoe structure will also be one important step forward for realistic biomechanical simulations of foot-shoe interface. Above all, musculoskeletal computational model of the hip-knee-ankle-foot can further be developed to study the coupling mechanism among the joints of the lower limb.

For the material properties, a large number of existing models assumed homogeneous, isotropic and linearly elasticity for foot and footwear structures. This is surely an approximated situation of the biological tissues, which exhibit non-homogeneous, anisotropic, nonlinear, and viscoelastic behaviour. In addition, the justification of some of the parameter selection was not provided and the values assumed were deviated from experimental observations. Several foot models have considered the use of nonlinear elasticity, hyperelasticity, and viscoelasticity in modelling the material behaviour of ligaments, plantar soft tissue, bony structures and various orthotic materials. However, anatomically detailed FE models rarely considered the viscoelastic properties of foot and shoe structures and thus were restricted to static analyses. For advanced material modelling, comprehensive site, direction, and tissue dependent material models of the human ankle-foot structures should be obtained via experimental measurements on cadavers and human subjects.

In terms of loading and boundary conditions, a certain number of FE foot-shoe models considered only the ground reaction forces or vertical compression forces, with the stabilizing muscular forces ignored or lumped as a resulting ankle moment. Only a limited number of FE analysis of the foot and footwear considered the physiological loadings involving musculotendon forces. In these models, muscles forces were approximated by normalized electromyographic data by assuming a constant muscle gain and cross-sectional area relationship and by force equilibrium consideration. Except some vertical impact analyses, most models ignored the dynamic or inertia effects of ankle-foot motion. The quasi-static simulations may hinder the dynamic biomechanical behaviour of the foot whenever acceleration of the lower limb such as during heelstrike and push off is significant. Further FE simulations should include anatomically detailed structural models of musculotendon structures to allow realistic simulations of active and passive muscle characteristics as well as gliding response of tendon-bone interfaces. In addition, 3D ligament-bone interfaces can also be implemented to simulate more accurately the stabilizing mechanism of these soft tissues for the joints.

Finite joint and bone movements have not been accounted in many FE models. The adjacent articulating surfaces were usually fused by connective tissue without considering the relative joint movement. Although relative articulating surfaces movements were allowed in some models, these models consisted of only reduced number of distinct bony segments. Consequently, many of the existing models were limited in predictions of relatively small ankle-foot motions and should have resulted in a representation of an overly-stiffened ankle-foot structure. To enable a more realistic simulation of the foot and footwear, a contact modelling approach should be considered among all the bony segments, foot-ground and foot-shoe interfaces.

Conclusion

Existing computational models of footwear have shown their contributions to the understanding of footand footwear biomechanics. The ability of the FE model to identify vulnerable skeletal and soft tissue components of the foot can serve as a tool for development of novel clinical decision making and foot treatment approaches. In terms of orthotics or footwear design, it can allow efficient parametric evaluations for the outcomes of the shape modifications and other design parameters of the orthosis without the prerequisite of fabricated orthosis and replicating subject trials. The use ofcomputational models is expected to become an integrated partfor modern footwear research and development. Footwear design can be optimized to enhance its functional performance for the general public or individualised requirements. Despite tremendous potentials for the existing computational models, more realistic geometry and material properties of foot and footwear structures in addition to realistic physiological loadings are required to provide a better representation of the foot-shoe interface as well as accurate predictions of ankle-foot biomechanics.

Acknowledgment

Hong Kong Research Gran Council, GRF (No : PolyU 5331/07E and PolyU 5352/08E).

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투 고 일 : 01월 30일
심 사 일 : 02월 17일
심사완료일 : 03월 13일