Special issue: Computational Biomechanics for Patient-Specific Applications

Computational models of the foot and ankle for pathomechanics and clinical applications – A review

Yan Wang, Duo Wai-Chi Wong, Ming Zhang

Interdisciplinary Division of Biomedical Engineering, Faculty of Engineering, The Hong Kong Polytechnic University, Hong Kong SAR, China

Abbreviated title: Review of computational models

Corresponding author

Prof. Ming Zhang

Interdisciplinary Division of Biomedical Engineering, Faculty of Engineering,

The Hong Kong Polytechnic University, Hung Hom,

KLN, Hong Kong SAR, China

Tel: (852) 27664939

Fax: (852) 23342429

E-mail: ming.zhang@polyu.edu.hk

Abstract

Complementary to experimental studies, computational biomechanics has become useful tool for the understanding of human foot biomechanics and pathomechanics. Its findings have been widely used for the evaluation of the effectiveness of surgical interventions. These models, however, were developed with a wide range of variations in terms of simplifications and assumptions on the representation of geometrical structures and material properties, as well as boundary and loading conditions. These variations may create differences in prediction accuracy, and restrict practical and clinical applications. This paper reviews the state-of-the-art technologies and challenges in computational model development, focusing on foot problem-specific models for the assessment of the effectiveness and accessibility of clinical treatments. The computational models have provided valuable biomechanical information for clinical applications but further investigations come with many challenges in terms of detailed and patient-specific models, accurate representations of tissue properties, and boundary and loading conditions. Multi-scale computational models are expected to be an efficient platform to fully address the biomechanical and biological concerns.

Key words: Finite element; patient-specific; biomechanics, surgery, insole, stress and strain; computational orthopedics.

1. Introduction

The foot is vulnerable to injury, trauma and other ailments because it sustains complicated and high loads to support the body during locomotion and other activities. Surgical treatments are expected to restore the normal functions of the injured parts effectively. However, the foot and ankle complex is an intricate structure and each segment interacts with other segments interdependently. Clinical interventions may thus result in functional alterations such as joint motion and tissue deformation, not only at the modified site but also in the adjacent regions, and even over the entire foot. These abnormal biomechanical alterations contribute to iatrogenic complications such as joint arthritis, secondary fractures, and foot pain, which are the main complaints from patients postoperatively.

Evaluations of the potential biomechanical variations before and after surgeries could provide references for surgery planning and optimizations to minimize complications. Subjective methods such as observational and functional score systems and experimental evaluations can be used to obtain some information; however, the detailed biomechanics of the inner foot, like the stress distribution in the bones and soft tissue, and the contact pressure at the joints, are difficult to obtain due to the limitations of measurement techniques. Computational approaches such as finite element (FE) analysis have become complementary tools for the biomechanical investigations of human musculoskeletal structures.

Since FE analysis was introduced to human musculoskeletal biomechanics in the early 1970s, the capability to model irregular geometries and multi-bodies, complex material properties, and various loading and boundary conditions makes it notably valuable for the biomechanical assessment of the foot and ankle complex. The biomechanical assessment based on computational models of the foot and ankle has been applied for injury mechanism analyses, prosthetic designs, surgery predictions, shoe and insole designs and basic biomechanics knowledge understanding. The clinical applications of these models have significantly enhanced the foot biomechanical knowledge to surgeons, but these models were developed with a wide range of variations in terms of simplifications and assumptions on geometrical structures, interactions among components and material properties, as well as boundary and loading conditions. These variations produce differences in the accuracy of the predictions, and restrict the practical applications. This review aims to understand the state-of-the-art technologies and challenges in model development, focusing on foot problem-specific models for the effectiveness and accessibility of clinical applications.

2. *Overview of the finite element models for the foot and ankle*

FE models of the human foot and ankle were developed from two-dimensional (2D) to three-dimensional (3D), and from partial to anatomically detailed structures as reviewed[18]. Since the first 2D FE model first reported, a number of 2D models with partial structures, such as the toe, metatarsal, heel and entire foot, were developed mainly for foot support designs. 3D models with simplified and partial structures were reported to study the loading response of the foot to foot supports, such as ankle-foot- orthosis and footwear.

With the advancement of computational and modeling techniques, 3D FE models of the foot and ankle complex were developed with the representation of the majority of anatomical characteristics and complicated connection behaviors [15, 20, 41, 43, 49, 53] for a more delicate exploration of foot biomechanics. These models were reconstructed from computed tomography or magnetic resonance images and could replicate anatomical contours of foot segments, as shown in Figure 1. The geometries of bones could be constructed individually, and some could be fused together for simplification. Connective components such as ligaments and plantar fascia were commonly simplified as trusses rather than 3D physical geometries. The material properties were defined from rigid to deformable such as linear or non-linear elasticity[25, 59]. Viscoelasticity[52] has been taken into account for dynamic simulation[13, 54, 60].

Figure 1 A demonstration of current modeling technique of finite element model of foot and ankle.

The boundary and loading conditions were determined empirically for simplified partial foot models, since the muscle structures were seldom constructed and it was not practical to obtain physiological loadings of individual segments. For more geometrical detailed entire foot models, the boundary and loading conditions were commonly obtained from human motion analysis with inverse dynamics, more closely representing the loading conditions. The muscle forces were either estimated from electromyography (EMG) or obtained from multi-body musculoskeletal modeling. There are still challenges in the accuracy of muscle forces.

3. Foot problem-specific computational models

3.1 Flatfoot

Flatfoot (Pes Planus) is characterized by a lowering of the medial longitudinal foot arch, and could be a progressive deformity secondary to the posterior tibial tendon dysfunction, associated with ligament deficiency. Correction surgeries have been reported to change the interdependent action between the osseous alignment and dynamic stability within the foot. Computational analyses of surgeries have been adopted based on FE models[54] and multi-body musculoskeletal models[8, 34].

The stress distribution of the plantar foot is an essential contributor of normal function of the foot. It was investigated under a balanced standing state using an FE model consisting of simplified bony structures, some of the ligaments, tendons and plantar fascia [54]. Linear elasticity and viscoelasticity were used for tissue properties. This model was expected to mimic surgical operations.

Joint loads and foot deformation may be affected by surgeries and have been investigated using rigid-body models in deformity correction interventions such as subtalar arthroereisis[6], calcaneal osteotomy, the Evans procedure, and calcaneocuboid distraction arthrodesis[34]. For more accurate representation of foot deformity, 3D patient-specific musculoskeletal models of six flatfoot patients were developed [48] to supplement the 2D radiographs for diagnosis and staging of this disease. The unipedal stance was simulated with the application of body weight and muscle contraction vectors based on EMG measures. The model was validated through comparison between kinematic measurements in these models and photographs. Some of these measures showed strong correlations and demonstrated that computer modeling offers a promising alterative to 2D radiographs for non-invasive *in vivo* kinematic diagnosis.

The mentioned FE model provided the stress distribution of the plantar foot, but the biomechanical behavior of the inner foot, which is the advantage of the FE analysis, was lacking investigations. These musculoskeletal models can quantify the effect of surgeries on certain kinematics and kinetics of the entire foot, but are not capable of investigating rationale information, such as stress distribution in the bones and contact pressure at the joints.

3.2 Diabetic Foot

Nearly one-third of diabetic patients have pathological conditions in the feet and the forefoot region is reported as the most common affected site in an FE study which showed that the bony prominence at the sesamoids produce large internal stress concentration in the soft tissue [14].

The microvascular changes in diabetic patients, accompanied with repetitive micro-trauma give rise to tissue breakdown. This condition was resembled by altering the material properties of the encapsulated bulk tissue. Cheung et al.[21] conducted a sensitivity analysis on bulk tissue properties to investigate soft tissue stiffening associated with diabetic foot. Patient-specific tissue properties were acquired using ultrasound indentors[1, 2]. The role of the impaired tissue was investigated using a hierarchical approach[2].

The structural change and loading profile of diabetic patients were considered by a patient-specific model [31]. With this model an analysis with a patient-specific loading profile was conducted, followed by another analysis using the averaged gait data from 10 diabetic patients[31]. The findings were compared to that of a normal participant to examine the influence of diabetic foot on the plantar pressure.

Orthotic intervention aims to redistribute the localized plantar pressure that causes ulceration. The design factors of orthotics and therapeutic footwear have been investigated such as the material properties [7, 19, 24] and the geometrical designs [1, 2, 24]. Cheung et al. [19] implemented the Taguchi approach to reduce the simulation counts and study the insole and midsole thickness and hardness.

3.3 Hindfoot

Compared to the fore- and midfoot, the hindfoot structures are more flexible with a relatively large joint sliding and play a major role in transferring force between the body and the support. Computational analyses in this region have been increasingly adopted for the prediction of surgical outcomes.

Soft tissue reconstruction

Soft tissue reconstruction is commonly adopted for corrections of foot dysfunctions. To evaluate the effectiveness of a reconstruction operation, 3D FE models of the ankle joint complex were developed to simulate ligamentous deficient and reconstruction interventions[58, 61]. Forces in the ligaments and bone displacements were estimated, and the findings indicated that no reconstructions could completely restore the normality of the ankle joint but some procedures could be beneficial for restoring joint stability.

Ankle arthrodesis

Ankle arthrodesis constrains the relative motion between the talus and tibia, which may subsequently exert extra stress on the adjacent joints or segments and accelerate joint degeneration. FE models of the ankle joint have been developed to investigate effects of inferior tibiofibular syndesmosis injuries and screw fixation treatments on ankle functions[37, 38], to compare the effectiveness among different surgical protocols[4, 5], and subsequently to investigate the effect of bone quality on surgical outcomes[3]. Ankle instability, the stress distribution around the ankle joint and joint range of motion were investigated and found to be changed before and after ankle joint fixation. The stress in the screws, which is a factor related to screw fractures, was evaluated[23] with the application of approximate loads mimicking normal gait. In these simulations, linear elastic, isotropic and homogeneous properties were applied to structures for simplification.

These models exclusively include the ankle joint, based on which valuable knowledge at the ankle joint, related bones and implants was provided. No muscle structures being represented for muscle force application, loadings were therefore applied with assumption and approximations.

Ankle arthroplasty

Ankle arthroplasty is becoming more popular as an alternative to ankle arthrodesis. It reserves ankle motion, but improper design of implants and surgical protocols can cause complications such as surgical failure, subsidence of implants and arthritis. To improve the design of the prosthesis and the effectiveness of the surgery, FE analyses using more comprehensive foot and ankle models were conducted [11, 22, 41, 51].

Replaced ankle joint could alter the load distribution of the entire foot in considering that the design cannot accurately replicate the nature joint geometries. The effect of ankle arthroplasty on bone distribution and plantar pressure have been estimated using a comprehensive FE model of the foot and ankle consisting of major anatomical structures and components of ankle prosthesis[41]. FE models consisting of ankle joint bones and prosthesis[22, 45] instead of the entire foot have been constructed for the investigation of biomechanical behaviors of the ankle prosthesis. In both the models of the entire foot and the ankle joint, muscle structures were not represented resulting in the impossibility of muscle force applications. The interfacial biomechanics of the bone and implants was also investigated in a more microscopic level through the simulation of strain-adaptive bone remodeling processes[11]. A model of the ankle-implant assembly was developed and bone density distribution and compression force were applied.

Because of the complexity of ankle joints, a full understanding of the effects of arthrodesis and arthroplasty needs more comprehensive FE models involving the entire foot, ankle, and implants, proper representation of connective tissues and muscles.

Calcaneus bone fixation

The calcaneal fracture accounts for more than 60% of the entire tarsal bone fractures [47]. Improper treatments might lead to symptoms and dysfunctions of joints and muscles. Partial FE models mimicking calcaneus fracture were used to explore the necessity and function of sustentaculum tali screw placement [42] and the effectiveness of bone fixation methods [32], based on the investigation of maximum principal stress and fracture displacement. A FE model consisting of 28 bones of the foot was developed to investigate the effect of progressive bone removal from the calcaneus on the mechanical stress redistribution of the foot [8]. Elastic and isotropic properties were assigned to bones, cartilage, ligament, and plantar fascia. Concentrated forces were applied as the loading condition. Stress distribution in the calcaneus bone was investigated and was found to be significantly different from the intact condition indicating an increase in fracture risk.

Subtalar

Several treatment strategies including leg cast, internal fixation and external fixation have been used to address subtalar dislocation. To assess the optimal configuration of screw fixation for subtalar arthrodesis, an FE model of the talus and calcaneus was constructed[36]. Rotational torque was applied to mimic the loading condition of subtalar external and internal rotation. The divergence angle and contact length were recorded to evaluate the rotational stability, and suggested an optimal surgical choice among different screw configurations. External fixation of subtalar has been evaluated in a simplified foot model[44] under axial loading through the tibia bone. The displacement was investigated to explore the stability and indicate a more effective treatment.

The current FE models for the simulation of calcaneus fracture treatments are partial foot models focusing on the involved bones or implants with simple elastic material properties. The loadings are implemented using torque or concentrated forces.

3.4 Midfoot

The midfoot is a relatively stable structure with less motion during locomotion compared with the hindfoot and forefoot. Contusion, sprain, subtle acute fracture and osteoarthropathy are associated with instability and malalignment. Surgical protocols were proposed and evaluated using computational simulations[17, 40, 53] to explore detailed knowledge for evidence-based treatments.

An accurate representation of the foot and ankle in an FE model was used to simulate the surgery of the first and second tarsometatarsal joint fusion[17, 53]. Linear- and hyper-elasticity were assigned to the bones and soft tissues. Physiological boundary and loading conditions obtained from gait analysis were applied to the simulation. Joint contact pressure, bone stress and plantar pressure of the entire foot were investigated and compared between the normal foot model and the surgery-interfered foot model. The results indicated that the surgery resulted in a high risk of arthritis in adjacent joints and stress fracture in the second metatarsal bone. Improvement in surgical protocol such as fusion with wedge osteotomy at involved joints was proposed, but requires further verifications. In an investigation of midfoot biomechanics, the mid-stance event of the gait was simulated in an FE model of a normal foot [40], which similarly consists of major bony and soft tissue structures. The stresses in the bones of the midfoot were investigated, and the navicular bone was found to be more susceptible to stress fracture than other bones in the midfoot because of the tensile stress in the transverse direction.

Clinical biomechanics of the midfoot was investigated using a comprehensive FE model of the entire foot and ankle complex under physiological loading conditions, which were obtained from 3D human motion analysis. The results could be more persuasive and reliable than that from over simplified models for clinical reference.

3.5 Forefoot

Hallux

Hallux valgus is one of the most common foot disorders affecting more than one-third of elderly. It is associated with ligamentous laxity and hypermobility which exacerbate the load balance of the forefoot and is thought to be related to certain extrinsic factors such as high-heeled shoes and constricted footwear.

The forefoot transverse deformation entails the spread and collapse of the transverse arch presented in hallux valgus and was investigated during landing[30] and gait[55]. A whole stance phase was simulated with stiffness reduction on the ligaments to mimic first ray hypermobility[55]. The hypermobile first ray was found to increase the load at the metatarsocuneiform joint in the medial-lateral direction. The mediolateral joint force would shift the first metatarsal out of normal alignment, leading to metatarsus primus varus and subsequent hallux abducto valgus. A computational analysis using a patient-specific first ray model[56] showed that the joint force direction and deformity angle would be exacerbated extensively under load compared to the normal foot. Yu et al. [59] studied the interaction between the foot and a high-heeled shoe. The first metatarsophalangeal joint was found to experience higher stress with high-heeled shoes, which may contribute to the progression of hallux valgus.

Computational models have been applied for the estimation of hallux valgus corrections. Chevron osteotomy was investigated using a 2D first metatarsal model and compared the compressive and shearing stress of the bone under a surgical protocol of 60- and 90-degree incision angles[39]. The modified 90-degree Chevron osteotomy could produce better union loading conditions. A load-to-failure scenario was simulated using 3D metatarsal models that were drilled with holes according to the surgical protocol of hallux valgus correction[52]. Inhomogeneous and isotropic material properties were applied. The sensitivity of position and dimension of the drilled holes on the principal strain was evaluated aiming to optimize the outcome of hallux valgus surgery.

FE studies have also been adopted to investigate biomechanics of hallux rigidus[26] and clawed hallux surgeries[35]. A 3D FE model of the first metatarsophalangeal joint was developed and used to simulate suggested causes of hallux rigidus[26] including tendon and fascia tightness and bone geometry mismatch. The analysis showed that fascia tightness produced high stress on the articular cartilage which was demonstrated as a possible cause of hallux rigidus. Two correction surgeries of claw hallux including muscle transecting and interphalangeal joint fusion were simulated and compared using FE models[35]. The surgeries were demonstrated to restore hallux alignment, nevertheless, in some cases resulted in high pressure in metatarsal region.

Lesser Toe

Lesser toe deformities are related to an imbalance of muscle forces. Flexor digitorum longus (FDL) transfer, flexor digitorum brevis (FDB) transfer, and proximal interphalangeal (PIP) joint fusion, which are common corrections for the hammer/mallet toe deformity, were investigated by 3D models from a normal participant [9, 10, 28]. The tendon transfer surgeries were performed by moving the insertion of the tendon. These procedures were claimed to reduce the dorsal displacement of the proximal phalanx[10, 28]. Moreover, FDL and FDB transfer was found to reduce the stress of the proximal phalanx, whereas PIP fusion had a distinct stress profile [10]. Notwithstanding, all procedures increased the stress of the second metatarsal, particularly PIP fusion [9].

Metatarsal

The configuration of the metatarsal is crucial in maintaining the transverse arch[27]. The load transfer mechanism under different metatarsal configurations were analyzed using FE method[27]. This study discovered that abnormal metatarsal head arrangement reduced the load sharing of the first ray, which may contribute to metatarsalgia.

The shape of the fifth metatarsal is associated with risk of stress fracture. Researchers have investigated the principal stresses along the site of the Jones fracture to postulate the vulnerable region for fracture initiation[46]. Furthermore, Brilakis et al. [12] investigated the influence of standing posture on the healing of the fifth metatarsal fracture at different healing stages. Their findings suggested that the everted and dorsiflexed standing posture produced higher strain compared with balanced standing, especially for a metaphyseal-diaphyseal junction fracture. However, there was a lack of FE analysis with regard to metatarsal trauma and its surgical interventions.

3.6 Plantar Fascia

Plantar fasciitis is one of the most common foot complaints associated with heel pain. The high incidence rate in runners suggests that plantar fasciitis could be caused by repetitive micro-injury. Despite simulations of plantar fasciitis being rare, various studies have investigated the stress and pressure alleviation by orthotic insoles.

The shapes and materials of orthotic insoles are frequently studied based on 2D and 3D FE models. A 2D cross-section FE model along the frontal plane of the heel was constructed[29] consisting of the insole, midsole, heel pad and bone to estimate the conformity. A 3D FE model of the foot and ankle[33] was developed for the optimization of insole designs aiming to reduce the junctions stress between the fascia and calcaneus. The optimized insole could reduce the peak plantar pressure, the plantar fascia stress and strain.

Plantar fasciotomy is a common procedure to treat chronic heel pain, while compromising midfoot stability. Total and partial fascia release were performed by dissecting the long plantar medially on a 3D FE model of the foot and ankle[16]. A pronounced change was found in plantar pressure distribution after 40% fascia release. Plantar ligamentous structure failures was simulated in a FE study[57] and the failures were found to increase the stress of the bones and plantar ligaments, accompanied by an increased passive tension on intrinsic muscles. Likewise, the contribution of individual plantar ligamentous structures was demonstrated by releasing the plantar fascia, spring ligament, and short and long plantar ligaments in succession[50]. Ligament release would impose additional tension on the rest ligamentous structures and lead to bone rotation and increased stress in the metatarsals.

4. Remarks

There is an increasing trend towards using computational modeling and simulations in medical advancement. The FE approach would be a versatile platform for the understanding of biomechanics and pathomechanics of the musculoskeletal system. Significant contributions are expected to address foot and ankle problems effectively for surgical protocols and the design of orthopedic implants and orthosis with adequate accuracy.

Many FE models of the foot and ankle have been developed and these developments have no doubt helped to lay important groundwork. However, we must realize the complexity of foot and ankle problems and strong challenges confronted in the further development of accurate models for clinical applications.

First, comprehensive FE models representing major anatomical structures of the entire foot and ankle are necessary for the evaluation of interventions. The foot and ankle complex is a synergic structure and any local change may alter not only at the modified site but also in the adjacent regions, even over the entire foot. A geometrically detailed model may involve bones, muscles, ligaments, plantar fascia, other soft tissues and foot support. Attention should be paid to balance between accurate details and proper simplifications.

Second, patient-specific FE models are strongly needed to involve individual features particularly with pathological conditions. Currently, it is not practical to create individual FE models involving all details since model establishment is time consuming. Most studies made use of normal participants to construct the model, or created a pathological model from the normal one. For foot problems with distinct structural deformity such as hallux valgus, using a normal foot as the representative model will inordinately lose the “abnormality”.

Third, it is necessary to properly describe the tissue material properties, particularly under large deformations and dynamic situations. Linear elasticity and hyperelasticity was used while viscoelasticity or poroelasticity can be used for biphasic materials under dynamic situations. Patient-specific material properties such as for the diabetic foot play an important role in the design of orthotics and are expected to be detailed in future.

Finally, the boundary and loading conditions are direct factors contributing to model accuracy. Currently, boundary and loading conditions can be acquired from human motion analysis; however, prescribing the appropriate muscle forces remains a challenge. Muscle forces are currently estimated from EMG or musculoskeletal models. The accuracy of the estimation under different conditions requires verifications. Patient-specific loading profiles are lacking, especially before and after surgical treatment.

Further attempts should aim towards applying multiscale modeling approaches to a comprehensive understanding of the biomechanical and biological issues of the foot and ankle complex with surgical treatment. For example, estimating the segment loading conditions can provide further information for down-scale investigations on the mechanism of bone fracture and remodeling. Computational models at single scales are provided from the body down to the microstructure, and the effects on all levels should be addressed.

Conflict of Interest

None of the authors will be benefited from any commercial group with this work, nor was there any financial support received or will be received by any of the authors for publication of this article.

Acknowledgements

This project was supported by Hong Kong Research Grant Council GRF (PolyU5326/11E, PolyU152216/14E) and NSFC (11272273, 11120101001).

References

1. Actis R. L., L. B. Ventura, D. J. Lott, K. E. Smith, P. K. Commean, M. K. Hastings and M. J. Mueller. Multi-plug insole design to reduce peak plantar pressure on the diabetic foot during walking. *Med Biol Eng Comput* 46: 363-371, 2008.

2. Actis R. L., L. B. Ventura, K. E. Smith, P. K. Commean, D. J. Lott, T. K. Pilgram and M. J. Mueller. Numerical simulation of the plantar pressure distribution in the diabetic foot during the push-off stance. *Med Biol Eng Comput* 44: 653-663, 2006.

3. Alonso-Vazquez A., H. Lauge-Pedersen, L. Lidgren and M. Taylor. The effect of bone quality on the stability of ankle arthrodesis. A finite element study. *Foot & Ankle International* 25: 840-850, 2004.

4. Alonso-Vazquez A., H. Lauge-Pedersen, L. Lidgren and M. Taylor. Finite element analysis of the initial stability of ankle arthrodesis with internal fixation: flat cut versus intact joint contours. *Clin Biomech* 18: 244-253, 2003.

5. Alonso-Vazquez A., H. Lauge-Pedersen, L. Lidgren and M. Taylor. Initial stability of ankle arthrodesis with three-screw fixation. A finite element analysis. *Clin Biomech* 19: 751-759, 2004.

6. Arangio G. A., K. L. Reinert and E. P. Salathe. A biomechanical model of the effect of subtalar arthroereisis on the adult flexible flat foot. *Clin Biomech* 19: 847-852, 2004.

7. Barani Z., M. Haghpanahi and H. Katoozian. Three dimensional stress analysis of diabetic insole: a finite element approach. *Technol Health Care* 13: 185-192, 2005.

8. Bayod J., R. Becerro-de-Bengoa-Vallejo, M. E. Losa-Iglesias and M. Doblare. Mechanical stress redistribution in the calcaneus after autologous bone harvesting. *Journal of Biomechanics* 45: 1219-1226, 2012.

9. Bayod J., R. B. de Bengoa Vallejo, M. E. L. Iglesias and M. Doblaré. Stress at the Second Metatarsal Bone After Correction of Hammertoe and Claw Toe Deformity: A Finite Element Analysis Using an Anatomical Model. *Journal of the American Podiatric Medical Association* 103: 260-273, 2013.

10. Bayod J., M. Losa-Iglesias, R. Becerro de Bengoa-Vallejo, J. C. Prados-Frutos, K. T. Jules and M. Doblare. Advantages and drawbacks of proximal interphalangeal joint fusion versus flexor tendon transfer in the correction of hammer and claw toe deformity. A finite-element study. *J Biomech Eng* 132: 051002, 2010.

11. Bouguecha A., N. Weigel, B. A. Behrens, C. Stukenborg-Colsman and H. Waizy. Numerical simulation of strain-adaptive bone remodelling in the ankle joint. *Biomedical Engineering Online* 10:58: 2011.

12. Brilakis E., E. Kaselouris, F. Xypnitos, C. G. Provatidis and N. Efstathopoulos. Effects of Foot Posture on Fifth Metatarsal Fracture Healing: A Finite Element Study. *Journal of Foot & Ankle Surgery* 51: 720-728, 2012.

13. Chen W. M. and P. V. S. Lee. Explicit finite element modelling of heel pad mechanics in running: inclusion of body dynamics and application of physiological impact loads. *Computer Methods in Biomechanics and Biomedical Engineering* 18: 1582-1595, 2015.

14. Chen W. M., T. Lee, P. V. S. Lee, J. W. Lee and S. J. Lee. Effects of internal stress concentrations in plantar soft-tissue—A preliminary three-dimensional finite element analysis. *Medical engineering & physics* 32: 324-331, 2010.

15. Chen W. M., J. Park, S. B. Park, V. P. W. Shim and T. Lee. Role of gastrocnemius-soleus muscle in forefoot force transmission at heel rise - A 3D finite element analysis. *Journal of Biomechanics* 45: 1783-1789, 2012.

16. Cheung J. T. M., K. N. An and M. Zhang. Consequences of partial and total plantar fascia release: A finite element study. *Foot & Ankle International* 27: 125-132, 2006.

17. Cheung J. T. M. and B. M. Nigg. Clinical applications of computational simulation of foot and ankle. *Sport-Orthopädie-Sport-Traumatologie-Sports Orthopaedics and Traumatology* 23: 264-271, 2008.

18. Cheung J. T. M., J. Yu, D. W.-C. Wong and M. Zhang. Current methods in computer-aided engineering for footwear design. *Footwear science* 1: 31-46, 2009.

19. Cheung J. T. M. and M. Zhang. Parametric design of pressure-relieving foot

orthosis using statistics-based finite element method. *Medical engineering & physics* 30: 269-277, 2008.

20. Cheung J. T. M., M. Zhang and K. N. An. Effects of plantar fascia stiffness on the biomechanical responses of the ankle-foot complex. *Clin Biomech* 19: 839-846, 2004.

21. Cheung J. T. M., M. Zhang, A. K. Leung and Y. B. Fan. Three-dimensional finite element analysis of the foot during standing--a material sensitivity study. *Journal of Biomechanics* 38: 1045-1054, 2005.

22. Elliot B. J., D. Gundapaneni and T. Goswami. Finite element analysis of stress and wear characterization in total ankle replacements. *Journal of the Mechanical Behavior of Biomedical Materials* 34: 134-145, 2014.

23. Er M. S., O. Verim, L. Altinel and S. Tasgetiren. Three-Dimensional Finite Element Analysis Used to Compare Six Different Methods of Syndesmosis Fixation with 3.5-or 4.5-mm Titanium Screws A Biomechanical Study. *Journal of the American Podiatric Medical Association* 103: 174-180, 2013.

24. Erdemir A., J. J. Saucerman, D. Lemmon, B. Loppnow, B. Turso, J. S. Ulbrecht and P. R. Cavanagh. Local plantar pressure relief in therapeutic footwear: design guidelines from finite element models. *Journal of Biomechanics* 38: 1798-1806, 2005.

25. Erdemir A., M. L. Viveiros, J. S. Ulbrecht and P. R. Cavanagh. An inverse finite-element model of heel-pad indentation. *Journal of Biomechanics* 39:

1279-1286, 2006.

26. Flavin R., T. Halpin, R. O'Sullivan, D. FitzPatrick, A. Ivankovic and M. Stephens. A finite-element analysis study of the metatarsophalangeal joint of the hallux rigidus. *Journal of Bone & Joint Surgery, British Volume* 90: 1334-1340, 2008.

27. GarcÃa-Aznar J., J. Bayod, A. Rosas, R. Larrainzar, R. GarcÃa-BÃǵgalo, M. DoblarÃÐ and L. Llanos. Load transfer mechanism for different metatarsal geometries: a finite element study. *Journal of biomechanical engineering* 131: 021011, 2009.

28. García-González A., J. Bayod, J. C. Prados-Frutos, M. Losa-Iglesias, K. T. Jules, R. B. de Bengoa-Vallejo and M. Doblaré. Finite-element simulation of flexor digitorum longus or flexor digitorum brevis tendon transfer for the treatment of claw toe deformity. *Journal of Biomechanics* 42: 1697-1704, 2009.

29. Goske S., A. Erdemir, M. Petre, S. Budhabhatti and P. R. Cavanagh. Reduction of plantar heel pressures: Insole design using finite element analysis. *Journal of Biomechanics* 39: 2363-2370, 2006.

30. Gu Y., M. Rong, Z. Li, M. Lake and G. Ruan. Finite Element Analysis of Deep Transverse Metatarsal Ligaments Mechanical Response during Landing. In: *Advanced Materials Research* Trans Tech Publ, 2012, p. 2558-2561.

31. Guiotto A., Z. Sawacha, G. Guarneri, A. Avogaro and C. Cobelli. 3D finite element model of the diabetic neuropathic foot: A gait analysis driven approach. *Journal of*

Biomechanics 47: 3064-3071, 2014.

32. He K., S. Fu, S. Liu, Z. F. Wang and D. Jin. Comparisons in finite element analysis of minimally invasive, locking, and non-locking plates systems used in treating calcaneal fractures of Sanders type II and type III. *Chinese Medical Journal* 127: 3894-3901, 2014.

33. Hsu Y.-C., Y.-W. Gung, S.-L. Shih, C.-K. Feng, S.-H. Wei, C.-h. Yu and C.-S. Chen. Using an optimization approach to design an insole for lowering plantar fascia stress—a finite element study. *Annals of biomedical engineering* 36: 1345-1352, 2008.

34. Iaquinto J. M. and J. S. Wayne. Effects of Surgical Correction for the Treatment of Adult Acquired Flatfoot Deformity: A Computational Investigation. *Journal of Orthopaedic Research* 29: 1047-1054, 2011.

35. Isvilanonda V., E. Dengler, J. M. Iaquinto, B. J. Sangeorzan and W. R. Ledoux. Finite element analysis of the foot: Model validation and comparison between two common treatments of the clawed hallux deformity. *Clin Biomech* 27: 837-844, 2012.

36. Lee J. Y. and Y. S. Lee. Optimal double screw configuration for subtalar arthrodesis: a finite element analysis. *Knee Surg Sports Traumatol Arthrosc* 19: 842-849, 2011.

37. Liu Q., G. Zhao, B. Yu, J. Ma, Z. Li and K. Zhang. Effects of inferior tibiofibular

syndesmosis injury and screw stabilization on motion of the ankle: a finite element study. *Knee Surg Sports Traumatol Arthrosc* 2014.

38. Liu Q. H., K. Zhang, Y. Zhuang, Z. Li, B. Yu and G. X. Pei. Analysis of the Stress and Displacement Distribution of Inferior Tibiofibular Syndesmosis Injuries Repaired with Screw Fixation: A Finite Element Study. *Plos One* 8: e80236, 2013.

39. Matzaroglou C., P. Bougas, E. Panagiotopoulos, A. Saridis, M. Karanikolas and D. Kouzoudis. Ninety-degree chevron osteotomy for correction of hallux valgus deformity: clinical data and finite element analysis. *The open orthopaedics journal* 4: 152-156, 2010.

40. Niu W., T. Tang, M. Zhang, C. Jiang and Y. Fan. An in vitro and finite element study of load redistribution in the midfoot. *Sci China Life Sci* 57: 1191-1196, 2014.

41. Ozen M., O. Sayman and H. Havitcioglu. Modeling and stress analyses of a normal foot-ankle and a prosthetic foot-ankle complex. *Acta Bioeng Biomech* 15: 19-27, 2013.

42. Pang Q. J., X. Yu and Z. H. Guo. The sustentaculum tali screw fixation for the treatment of Sanders type II calcaneal fracture: A finite element analysis. *Pakistan Journal of Medical Sciences* 30: 1099-1103, 2014.

43. Qian Z. H., L. Ren, L. Q. Ren and A. Boonpratatong. A Three-Dimensional Finite Element Musculoskeletal Model of the Human Foot Complex. *6th World Congress of*

Biomechanics (Wcb 2010), Pts 1-3 31: 297-300, 2010.

44. Ramlee M. H., M. R. A. Kadir, M. R. Murali and T. Kamarul. Biomechanical evaluation of two commonly used external fixators in the treatment of open subtalar dislocation-A finite element analysis. *Medical engineering & physics* 36: 1358-1366, 2014.

45. Reggiani B., A. Leardini, F. Corazza and M. Taylor. Finite element analysis of a total ankle replacement during the stance phase of gait. *Journal of Biomechanics* 39: 1435-1443, 2006.

46. Rohr E. S., J. E. Johnson, L. Zhao and G. F. Harris. Three-dimensional finite element analysis of the fifth metatarsal Jone fracture. In: *Foot and Ankle Motion Analysis*, edited by G. F. Harris, P. A. Smith and R. M. Marks CRC Press, 2008, pp. 347-362.

47. Sanders R., P. Fortin, T. DiPasquale and A. Walling. Operative Treatment in 120 Displaced Intraarticular Calcaneal Fractures Results Using a Prognostic Computed Tomography Scan Classification. *Clinical orthopaedics and related research* 290: 87-95, 1993.

48. Spratley E. M., E. A. Matheis, C. W. Hayes, R. S. Adelaar and J. S. Wayne. Validation of a Population of Patient-Specific Adult Acquired Flatfoot Deformity Models. *Journal of Orthopaedic Research* 31: 1861-1868, 2013.

49. Spyrou L. A. and N. Aravas. Muscle-driven finite element simulation of human foot movements. *Computer Methods in Biomechanics and Biomedical Engineering* 15: 925-934, 2012.

50. Tao K., W.-T. Ji, D.-M. Wang, C.-T. Wang and X. Wang. Relative contributions of plantar fascia and ligaments on the arch static stability: a finite element study. *Biomedizinische Technik/Biomedical Engineering* 55: 265-271, 2010.

51. Terrier A., X. Larrea, J. Guerdat and X. Crevoisier. Development and experimental validation of a finite element model of total ankle replacement. *Journal of Biomechanics* 47: 742-745, 2014.

52. Trabelsi N., C. Milgrom and Z. Yosibash. Patient-specific FE analyses of metatarsal bones with inhomogeneous isotropic material properties. *Journal of the Mechanical Behavior of Biomedical Materials* 29: 177-189, 2014.

53. Wang Y., Z. Y. Li and M. Zhang. Biomechanical study of tarsometatarsal joint fusion using finite element analysis. *Med Eng Phys* 36: 1394-1400, 2014.

54. Wang Z., K. Imai, M. Kido, K. Ikoma and S. Hirai. A finite element model of flatfoot (Pes Planus) for improving surgical plan. IEEE, 2014, p. 844-847.

55. Wong D., M. Zhang, J. Yu and A. Leung. Biomechanics of first ray hypermobility: An investigation on joint force during walking using finite element analysis. *Medical engineering & physics* 36: 1388-1393, 2014.

56. Wong D. W.-C., M. Zhang and A. K.-L. Leung. First ray model comparing normal and hallux valgus feet. In: *Computational biomechanics of musculoskeletal system*CRC Press, 2014, pp. 49-60.

57. Wu L. Nonlinear finite element analysis for musculoskeletal biomechanics of medial and lateral plantar longitudinal arch of Virtual Chinese Human after plantar ligamentous structure failures. *Clin Biomech* 22: 221-229, 2007.

58. Xu C., M. Y. Zhang, G. H. Lei, C. Zhang, S. G. Gao, W. Ting and K. H. Li. Biomechanical evaluation of tenodesis reconstruction in ankle with deltoid ligament deficiency: a finite element analysis. *Knee Surgery Sports Traumatology Arthroscopy* 20: 1854-1862, 2012.

59. Yu J., J. T. M. Cheung, Y. B. Fan, Y. Zhang, A. K. L. Leung and M. Zhang. Development of a finite element model of female foot for high-heeled shoe design. *Clin Biomech* 23: S31-S38, 2008.

60. Yu J., D. W.-C. Wong and M. Zhang. Dynamic Foot Model for Impact Investigation. In: *Computational Biomechanics of the Musculoskeletal System*2014, pp. 61-71.

61. Zhang M. Y., C. Xu and K. H. Li. Finite Element Analysis of Nonanatomic Tenodesis Reconstruction Methods of Combined Anterior Talofibular Ligament and Calcaneofibular Ligament Deficiency. *Foot & Ankle International* 32: 1000-1008, 2011.

Figure legends

Figure 1. A demonstration of current modeling technique of finite element model of foot and ankle.