ISB 2013 BRAZIL
XXIV CONGRESS OF THE INTERNATIONAL SOCIETY OF BIOMECHANICS
XV BRAZILIAN CONGRESS OF BIOMECHANICS

GAIT ANALYSIS DRIVEN 2D FINITE ELEMENT MODEL OF THE NEUROPATHIC HINDFOOT

Alessandra Scarton, MsEng(1), Annamaria Guiotto, MsEng(1), Zimi Sawacha, PhD(1), Gabriella Guarneri, MD(2), Angelo Avogaro, MD, PhD(2), Claudio Cobelli, PhD(1)

(1) *Department of Information Engineering, University of Padova, Padova, Italy.* email: scartona@dei.unipd.it
(2) *Department of Clinical Medicine and Metabolic Disease, University of Padova, Padova, Italy*

SUMMARY

Foot ulcerations are one of the most common and invalidating complication that affect the diabetic patients [1]. In order to understand what are the causes and to decrease their progress, several finite element (FE) models of the foot have been developed in the last decades [2-7].
The aim of this work was to create two 2 dimensional FE models of a healthy (HS) and of a diabetic neuropathic subject (NS) integrating kinematic, kinetic and pressure data and to validate them by means of a comparison between experimental and simulated peak pressure values. Root Mean Square Error in percentage of the experimental peak value (RMSE%) was also evaluated.

INTRODUCTION

The diabetic foot is determined by the simultaneous presence of both peripheral neuropathy and vasculopathy that alter the biomechanics of the foot with the formation of callosity and ulcerations. The social and economic burden of the diabetic foot can be reduced through a prompt diagnosis and treatment. FE analysis allows to characterise and quantify the loads developed in the different anatomical structures and to understand how these affect foot tissue in dynamic conditions [2]. In this study two experimentally kinematics-kinetics based FE models of the hindfoot of a healthy and of a diabetic neuropathic subject were developed in order to define more efficient subject specific computational model of the hindfoot that accounts for in-vivo kinematics, kinetics and plantar pressure data together with foot magnetic resonance images (MRI) data.

METHODS

Experimental procedure

The biomechanical analysis of the foot was carried out as in [8-10] on 10 healthy (HS) (age 58.7±10 years, BMI 24.5±2.6 kg/m^2) and 10 diabetic subjects with neuropathy (NS) (age 63.2±6.4 years, BMI 24.3±2.9 kg/m^2). The experimental setup included a 6 cameras stereophotogrammetric system (60-120 Hz BTS S.r.l, Padova), 2 force plates (FP4060-10, Bertec Corporation, USA) and 2 plantar pressure systems (Imagortesi, Piacenza). The signals coming from all systems were synchronized in post processing as in [10]. For each patient's foot the hindfoot, midfoot, forefoot and tibia subsegments 3-dimensional (3D) kinematic was calculated together with hindfoot, midfoot, forefoot 3D ground reaction forces and plantar pressure.

Finite element models

The MRI of the foot of a healthy subject and of a diabetic neuropathic subject was acquired with 1.5T devices (Philips Achieva and Siemens Avanto, Spacing between slides: 0.6-0.7mm, Slice thickness: 1.2-1.5mm). MRI images were then segmented with Simpleware ScanIP-ScanFE (v.5.0) in order to get a slice of the hindfoot passing through the malleoli. Finally the slice was imported into ABAQUS (Simulia, v.6.12) and meshed with quadrilateral elements according to the literature [7]. For each subject this reconstruction procedure of foot geometry was performed (see Figure 1).

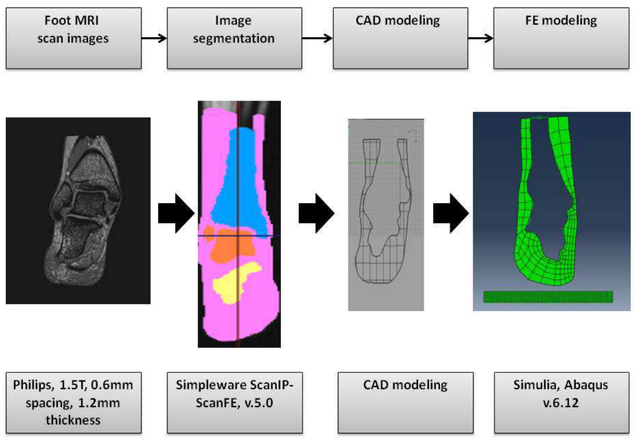

Figure 1: The figure shows the workflows of the development of a FE model of the hindfoot.

An horizontal rectangular element was drawn in ABAQUS under the heel slice to simulate the ground support (see Figure 2). It was meshed with 8 mm side quadratic elements with the aim to obtain contact pressures values comparable with the experimental ones (according to plantar pressure system sensors dimension). The heel pad was represented by a homogeneous isotropic soft tissue model with an hyperelastic material formulation in first order Ogden form and coefficients from [3]. Both the floor and the bones were modelled as homogeneous isotropic linear elastic materials [5,6].

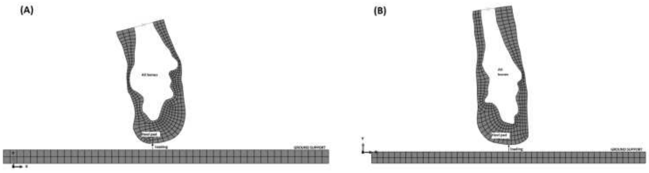

Figure 2 : Plane strain finite element models of the heel. (A) Model of the hindfoot of the healthy subject. (B) Model of the hindfoot of the neuropathic subject.

The foot-floor interface was modelled using contact surfaces with a coefficient of friction of 0.6 [4]. The bones were tied to the soft tissues.

During the simulation, the superior surfaces of the bones and soft-tissues were fully fixed to simulate the effects of constraints from superior-lying tissues [3].

Also the position of the foot with respect to the floor was considered matching the FE model angle between the floor and the mediolateral axis of the ankle (the axis passing through the prominences of malleoli) to the experimental one obtained from the kinematic data in the corresponding instant of the stance phase of gait. The loading conditions were set according to the ground reaction force registered with the force plate during gait.

Three instants of the stance phase of gait were chosen to perform the simulations [6]: the initial contact of the heel (1% of the stance), the loading response (first peak of the hindfoot vertical force) and midstance (minimum height of the markers of the foot from the floor). Simulations of the phases were run using the heel vertical force and the whole foot vertical force. Furthermore also FE simulations with the generic static force (half of the body weight) and one with the specific static force (% of the body weight calculated from the pressure map) were performed. FE simulations were run with the kinematics and kinetics data of 10 HS and of 10 NS included the 2 subjects whose MRIs were used for defining the FE models geometry.

RESULTS AND DISCUSSION

The validity of the models was assessed through the comparison between the experimental and the simulated peak plantar pressures data and by means of evaluating the Root Mean Square Error in percentage of the experimental peak value (RMSE%) in order to consider the spatial information.

Results showed that using the hindfoot ground reaction vertical component as input together with the subject specific kinematics there was a better agreement between the experimental and the simulated data then by applying the whole ground reaction vertical component (mean RMSE% changes from 13% to 25% of the peak experimental value). Best agreement was obtained when considering the subjects specific kinematics and kinetics data of the same subject used to develop the model in term of foot geometry (RMSE% changes from 15.8% to 7.7%) (Figure 3).

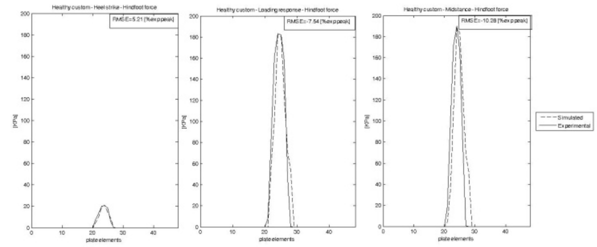

Figure 3. Healthy FE model of the same subject used for generating the model geometry: simulated over experimental pressure line on the three instants of the stance phase of gait using the specific force registered at the hindfoot.

The utility of running FE simulations with subject specific FE model of the neuropathic foot has been demonstrated together with the importance of foot positioning which has a great influence on the simulated stress distributions: there was a better agreement between the predicted pressures and the experimental one if the angles between the foot and the floor were set before applying the loads.

Furthermore the majority of the FE models of the foot reported in literature simulated the static loading condition, the midstance or only one critical instant of the stance phase of gait. This is limiting because it has been demonstrated that foot biomechanics alterations occur over the entire stance phase of gait [10]. Thus showing the importance of testing the model validity on several instants of the heel contact.

CONCLUSIONS

In general, model predicted plantar pressures were in good agreement with those measured during the considered sub-phases of the stance phase of gait, in particular for the healthy foot subject specific model.

Even under the restrictive assumptions of 2D representation, which is clearly inadequate for a complete model of the complex mechanics of the foot and of the foot-floor interaction, it is possible to run simulations that provide useful information towards a better understanding of the mechanism of plantar ulcer formation. This information may provide new insight into planning preventive treatment by including pressure relief insoles in the simulation. Moreover the bi-dimensional model developed herein serve to guide the development of a three-dimensional diabetic foot model.

In conclusion, our research indicated that using the subject specific in-vivo measured biomechanical data for the simulation of the FE foot model can provide more realistic results on the soft tissue plantar pad pressure distributions and deformations.

REFERENCES

1. Boulton AJM, et al. *Lancet* 366:1719–**24**, 2005**.**
2. Cavanagh et al, *J Foot Ankle Res*. **(Suppl 1)**: K4, 2008.
3. Chen W-M, et al. *Med Eng Phys*. **32(4)**:324-331, 2010.
4. Cheung JT, et al. *Arch Phys Med Rehabil.* **86(2)**:353-8, 2005.
5. Erdemir A, et al. *J Biomech*. **38(9)**:1798–1806, 2005**.**
6. Gefen A, et al. *J Biomech Eng.* **122(6)**:630-9, 2000.
7. Goske S, et al. *J Biomech*. **39(13)**:2363-70 2006.
8. Sawacha Z, et al. *Clin Biomech.* **24(9)**:722–8, 2009.
9. Sawacha Z, et al. *J NeuroEng Rehabil.* **6**:37, 2009.
10. Sawacha Z, et al. *Gait & Posture*. **6(1)**:20-6. 2012.