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3D FINITE ELEMENT MODEL OF THE DIABETIC NEUROPATHIC FOOT: A GAIT ANALYSIS DRIVEN APPROACH

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SUMMARY

Diabetic foot is an invalidating complication of diabetes that can lead to foot ulcers. Three-dimensional (3D) finite element (FE) analysis allows characterizing the loads developed in the different anatomical structures of the foot in dynamic conditions. The aim of this study was to develop a subject specific 3D FE model of both a diabetic neuropathic and a healthy subject's foot whose subject specificity can be found in term of foot geometry, in-vivo kinematics and kinetics measured data. The biomechanical analysis of the foot was carried out as in [Sawacha Z, 2012] on 10 healthy and 10 diabetic neuropathic subjects with a synchronized instrumentation setup. The FE models were developed segmenting bones, cartilage and skin from MRI and drawing a horizontal plate as ground support. Materials properties were adopted from previous literature. FE simulations were run with the kinematics and kinetics data of four different phases of the stance phase of gait (heel strike, loading response, midstance and push off). Validity of the models was assessed through the comparison between the experimental plantar pressures (PP) and the simulated ones. Results showed that when the gait data of the subjects in the two groups were adopted for the simulations, the healthy FE model underestimated the PP in each foot subarea, while the neuropathic FE model resulted in mean errors between experimental and simulated data below the 20% in the peak PP values. This knowledge is crucial in understanding the aetiology of diabetic foot.

INTRODUCTION

Diabetic foot is an invalidating complication of diabetes mellitus that can lead to foot ulceration and amputations. Three-dimensional (3D) patient specific finite element (FE) models of the foot allow to characterize and quantify the loads developed in the different anatomical structures of the foot and to understand how these affect foot tissue in dynamic conditions [1]. This knowledge is crucial in understanding the aetiology of diabetic foot and allows identifying the mechanisms priming ulceration. The aim of this study was to develop a subject specific 3D FE model of both a neuropathic and a healthy subject's foot whose subject specificity can be found in term of foot geometry (obtained from MRI), kinematics and kinetics experimentally measured data.

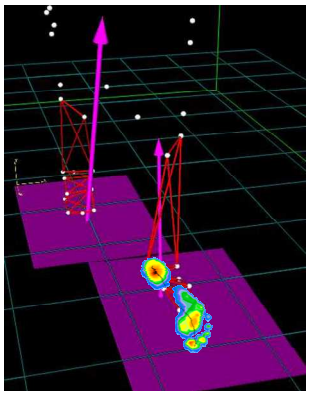

Figure 1: Experimental procedure: gait analysis.

METHODS

Experimental procedure

The biomechanical analysis of the foot was carried out as in [2] on 10 healthy (HS - age 58.7±10 years, BMI 24.5±2.6 kg/m2) and 10 diabetic neuropathic subjects (DNS - age 63.2±6.4 years, BMI 24.3±2.9 kg/m2). A 6 cameras motion capture system (60-120 Hz, BTS S.r.l, Padova), 2 force plates (FP4060-10, Bertec, USA), 2 plantar pressure (PP) systems (Imagortesi, Piacenza). The signals coming from all systems were synchronized (Figure 1). For each patient the hindfoot (HF), midfoot (MF), forefoot (FF) subsegments and tibia 3D kinematics, kinetics (ground reaction forces) and PP were calculated. The protocol was approved by the local ethic committee.

FE models

The foot MRI (Philips Achieva and Siemens Avanto, Spacing between slides: 0.6-0.7mm, Slice thickness: 1.2-1.5mm) of both a HS (HS1) and a DNS (DNS1) were acquired, and 3D subject specific FE models were created (Figure 2): a healthy FE model (HFE) and a neuropathic one (DNFE).

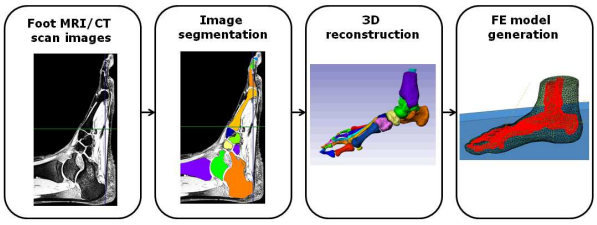

Figure 2: Workflow to obtain the 3D FE foot and ankle models.

MRI were segmented with Simpleware ScanIP-ScanFE (v.5.0) into 30 bones (grouped into hindfoot, midfoot, forefoot), cartilage (in the space between the bones) and the foot skin (as contour of the soft tissues) in order to get a 3D representation of the whole foot (WF) and ankle.

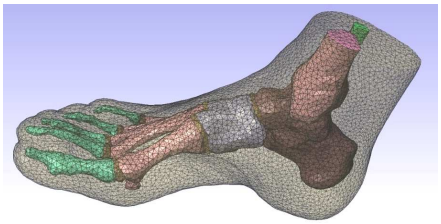

Figure 3: 3D mesh of the whole foot and ankle with bones grouped into segments.

The model was meshed in Simpleware-scanFE with tetrahedral elements according to the literature [3] (Figure 3) and imported into ABAQUS (Simulia,v.6.12).
An horizontal rectangular element was drawn in ABAQUS under the foot to simulate the ground support. It was meshed with 8 mm side quadratic elements with the aim of obtaining contact pressures values comparable with the experimental ones (according to plantar pressure system sensors dimension). Materials properties were adopted from previous literature [4-5]. The plantar soft-tissue was represented as a continuum and its nonlinear material behavior was modelled as an isotropic, incompressible, hyperelastic second-order polynomial formulation with parameters provided by [5]. For the DNFE the increased stiffness values of the parameters were adopted in order to take into account the diabetic tissues stiffening.

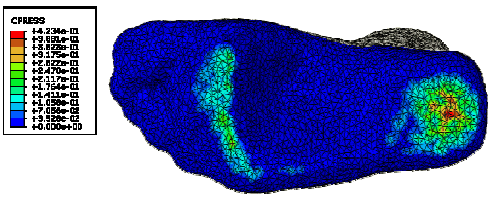

Figure 4: Simulated PP in DNFE during midstance.

Both the floor and the bones were modelled as homogeneous isotropic linear elastic materials [4]. 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. Four different loading conditions and foot positions with respect to the ground were applied considering different phases of the stance phase of gait (heel strike, loading response, midstance and push off) when critical loads occurred [4]. FE simulations were run with the kinematics and kinetics data of the HS as input to HFE and of the DNS to DNFE. Validity of the models was assessed through the comparison between the experimental PP and the simulated ones (peak and mean values in the 3 foot subareas and in the whole foot). Von Mises internal stresses were also obtained from the simulations.

RESULTS AND DISCUSSION

Results showed that there was a good agreement in the overall pattern between predicted and measured PP distribution (figure 5) when the kinematic-kinetic data of HS1 and DNS1 were used. However, when the gait data of the subjects in the two groups were adopted for the simulations, the HFE underestimated the PP in each foot subarea, while it overestimated the contact surfaces everywhere (Figure 6). For what regards the neuropathic subjects' group, the results found better agreement. For instance in the peak pressure values the mean errors of the simulations with respect to the experimental data were below the 20% with the exception of the hindfoot (Figure 7). The von Mises values were in good agreement with the ones reported in literature. These results confirmed that better prediction are obtained with subject specific models.

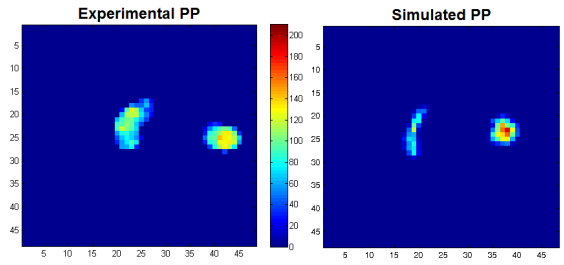

Figure 5: Experimental PP of the DNS1 and simulated PP with DNFE and kinematic-kinetic data of the DNS1.

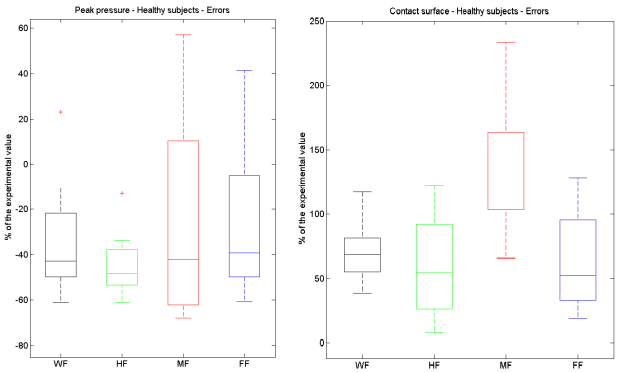

Figure 6: HFE with HS data: differences between the simulated and the experimental peak PP (left) and contact surfaces (right) in percentage of the experimental datum.

Furthermore results demonstrated that by combining gait analysis and FE modeling, realistic PP and internal stresses during gait can be obtained either in the case of the healthy foot or the diabetic neuropathic one.

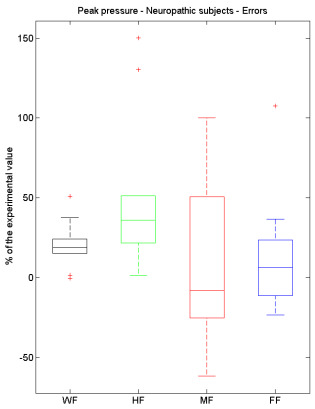

Figure 7: DNFE with DNS data: differences between the simulated and the experimental peak PP in percentage of the experimental peak PP.

CONCLUSIONS

Reliable PP during gait were obtained by means of a healthy and a neuropathic subject's 3D FE model. This knowledge is crucial in understanding the aetiology of diabetic foot.

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