Back

8th World Congress of Biomechanics

O1146

A multi-scale framework for the prevention of plantar ulcers in diabetic subjects: a multidisciplinary approach combining gait analysis, musculoskeletal and finite element foot modeling.

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Abstract

Introduction

Lifetime prevalence estimations of foot ulceration in diabetic subjects are as high as 25%, hence lower-extremity complications constitute a substantial burden [1]. Recent literature on multi-segment foot and finite element modeling (FEM) indicates that diabetic subjects display altered dynamic foot function and excessive stresses [2]. This study aims to evaluate the accuracy of a multiscale workflow applicable in clinical practice aiming to prevent ulceration by detecting excessive external and internal stresses preceding overloading and breakdown in diabetic subjects.

Methods

Gait analysis, musculoskeletal dynamic simulations (Opensim) and FEM (Abaqus) were combined and muscles forces, internal stresses and plantar pressure distribution (external stresses) were estimated. Two subjects (healthy: age 39, BMI 23.9 kg/m^2, diabetic: age 72, BMI 37.2 kg/m^2) were analyzed [2-3]. Each subject received a foot MRI scan. A stereophotogrammetric system (BTS) synchronized with 2 plantar pressure (Imagortesi), 2 force plates (Bertec), and 12 channels surface electromyography system (BTS) were used [3]. An extended marker set for 3D multi-segment foot and whole body kinematics was applied [3]. For the foot MSM, 3 different models were generated: a generic 2DOF model (OpenSim GaitModel 2392, MOD1), a 6DOF foot model (MOD2) and a 6DOF model with intrinsic foot muscles (MOD3) [3]. The extrinsic muscle activation was validated against experimental surface electromyography. Two FEMs containing subject-specific structure and tissues properties, were defined and subject-specific kinematics, muscle and ground reaction forces were applied as boundary conditions. For each subject, three FEMs were created using different sets of boundary conditions: extrinsic muscle forces calculated by MOD1, extrinsic muscle forces calculated using (MOD2), extrinsic and intrinsic muscle forces calculated using (MOD3). Four phases of the gait cycle were simulated [2-3]. External stresses on the foot sole were validated against the experimental plantar pressure [2-3].

Results

Overall, the diabetic subject presented higher external and internal stresses than the control subject (Fig1) and obtained best correspondence between simulated and experimental plantar pressure. Best correspondence was found for the diabetic patient on the forefoot at pushoff and for the control subject on the hindfoot at initial

contact. The models that performed best were: MOD1 for the initial contact and the loading response; MOD2 for the midstance and the pushoff 3.

Discussion: Inclusion of subject-specific, multi-scale information in FEM enhances estimation of internal and external stresses on the foot of diabetic subjects. This methodology could be integrated in clinical practice and supplement current guidelines targeting ulcers' prevention.

References:

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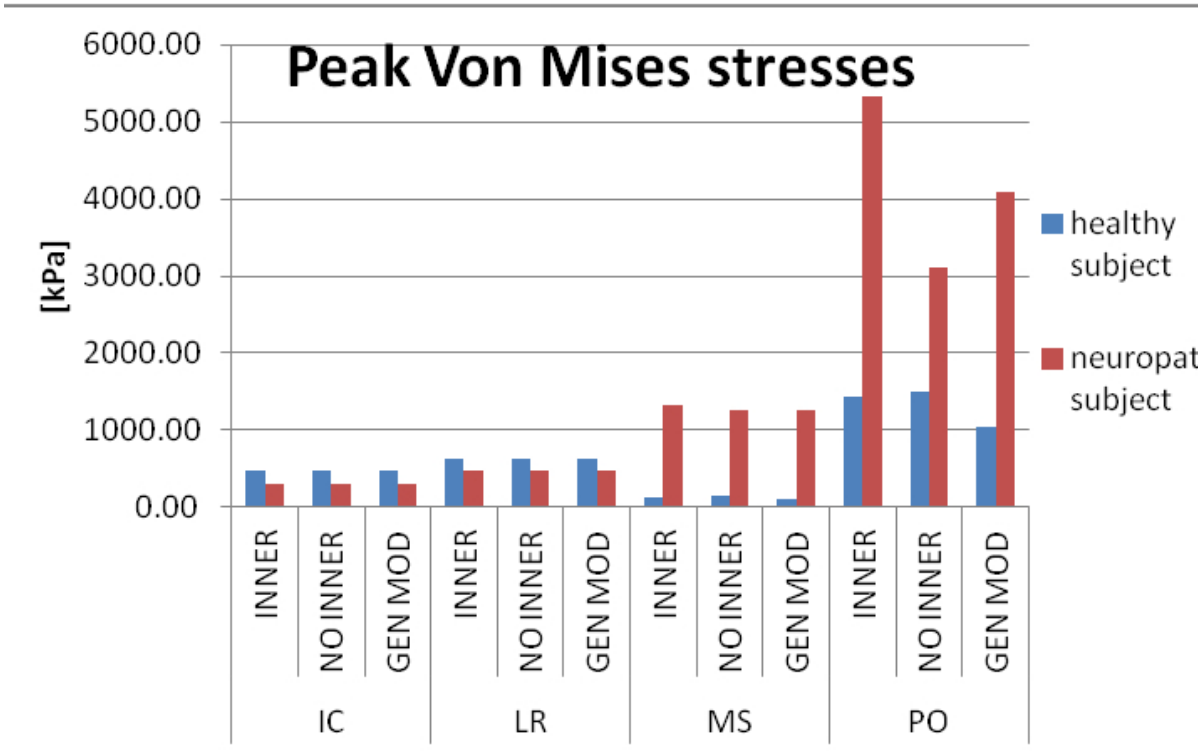

Fig. 1. Peak of Von Mises stresses for both subjects.