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FINITE ELEMENT MODELING OF SOFT TISSUES FOR PRESSURE ULCERS PREVENTION

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INTRODUCTION

Pressure ulcers are localized injuries that affect the skin and underlying tissues, usually over a bony prominence. It is the result of too much pressure over a short period of time or less force applied over a longer period of time (see www.epuap.org and/or www.npuap.org). Specific forms of pressure ulcers, termed Deep Tissue Injuries (DTI), are defined as pressure-related injury to subcutaneous tissues such as skeletal muscle [1]. DTI are particularly dangerous since they may not be visible to the naked eye and are therefore difficult to detect. They start in deep tissues underneath an intact skin and progress outward rapidly, causing substantial subcutaneous damages. While surface pressure measurements are believed to be effective in alerting users against focal pressures that may cause skin injury [2], these measurements cannot predict dangerous internal tissue loading [3]. For example, a similar pressure map may be observed under the buttocks of a heavy paraplegic person with sharp ischial tuberosity (IT) and a thin person with blunt ITs; however, their susceptibility to DTI depends on the IT curvature as well as the thickness of the soft tissues [4]. The only way to take into account these anatomical differences and to quantitatively estimate the internal stresses from the measured external pressures is (1) to build a patient-specific biomechanical model of the soft tissues/bony prominence and (2) to use this numerical model to compute the internal strains and stresses [5].

This paper introduces patient-specific Finite Element (FE) models of the foot and buttocks area, with the objective to address preventions against pressure sores and deep foot ulcers, respectively for paraplegic persons and diabetic patients.

METHODS

Our foot and buttocks models have been developed using the 3D biomechanical simulation platform, Artisynth [6]. The models are composed of soft tissues and bones, including ligaments and joints for the foot model. The soft tissues are divided into skin, muscles and fat. They are modeled as FE meshes. The outer surfaces of these meshes are inspired by the skin surface from the zygote database (www.zygote.com). Using an automatic FE mesh generator [7], the skin surfaces of both were filled with finite elements based on a hexahedral grid, completed with wedges and tetrahedrons to maximize the surface representation accuracy. The mesh generator does not create elements at the bone locations (also given by the zygote database). Figures 1 and 2 plot the corresponding FE meshes.

As concerns the foot model, the resulting FE mesh (Fig. 1, left panel) is composed of 36,894 elements and 22,774 nodes. The skin, muscles and fat are modeled as four different Neo Hookean materials with Young moduli set to 6 GPa for the plantar skin, 200 kPa for the rest of the skin, 50 kPa for the muscles and 4 kPa for the fat. All materials have a Poisson ratio value set to 0.495. The 26 foot bones are modeled as rigid body surfaces coupled to the nearby finite element nodes (Fig. 1, right panel). 33 foot joints are simulated by cylindrical or spherical pivots connecting each bone with its neighbors. Their angle of rotation varies from 45 degrees for the phalanx pivots to 5 degrees for the back of the foot. Six main ligaments constrain the foot model: the plantar fascia, the transversal metatarsal head ligament, the Achilles tendon, the triangular ligament between the navicular, calcaneus and cuboid bones, and two internal ligaments between the calcaneus and navicular bones, and between the talus and navicular bones. These ligaments are simulated as cables with an extension stiffness of 200 MPa and a compression stiffness of 0 kPa.

The buttocks FE mesh (Figure 2, left panel) is composed of 7,590

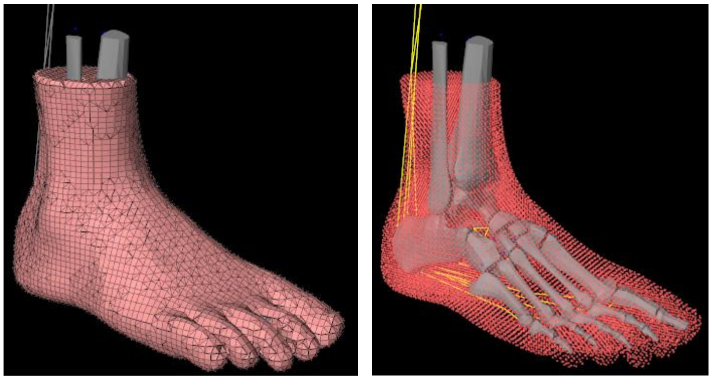

Figure 1: Finite Element model (left) and bones and ligaments (right) of the biomechanical foot model

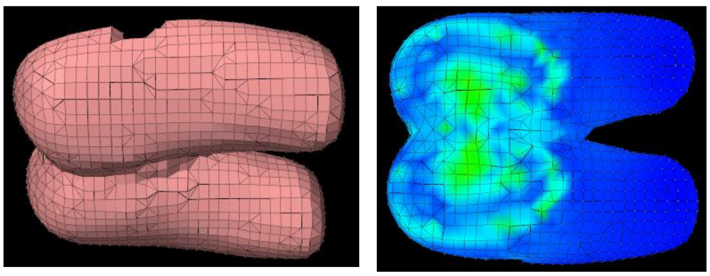

Figure 2: Finite Element mesh of the biomechanical buttocks model (left) deformed under the action of external pressures (right)

elements and 5,278 nodes. This mesh models the soft tissues representing the skin, muscles and fat and combines them using the incompressible hyperelastic Mooney Rivlin material proposed by [8]. The bones are simulated as fixed nodes at the FE mesh interface.

RESULTS

Models can be used to simulate the deformations due to an external pattern of pressures applied at the skin surface. For example, the right panel of figure 2 plots the buttocks' tissues external deformations due to pressures measured at the seat/skin interface. On the other hand, models can be used to compute the internal strains and stresses in the subcutaneous tissues. As an example, figure 3 shows the influence of a given foot position on internal strains, with a set of pressures simulating the patient's foot in standing stance applied as boundary conditions to our FE foot model. This position was modeled by fixing the tibia and fibula bones and letting the rest of the foot loose under the influence of gravity. The applied plantar pressures were measured using a pressure sensor under the foot while standing and ranged from 0 to 10.5 $N.cm^{-2}$. Figure 3 shows the internal Von Mises strains corresponding to the simulation with the maximum pressures. Strains of 2% and 137% were observed at the heel skin surface and near the calcaneus bone respectively. Similarly strains of 3% and 33% were simulated under the second toe at the skin surface and near the metatarsal head. The same differences between surface and internal strains are simulated with the buttocks model.

DISCUSSION

Our biomechanical models allow simulating the foot and buttocks with a realistic behavior in terms of surface and internal pressures. These constraint analyses resulting from a prescribed load could consequently determine if ulcers may appear. Future works aim at coupling interactively these models with pressure data provided by the "TexiSense Smart Sock" (www.texisense.com).

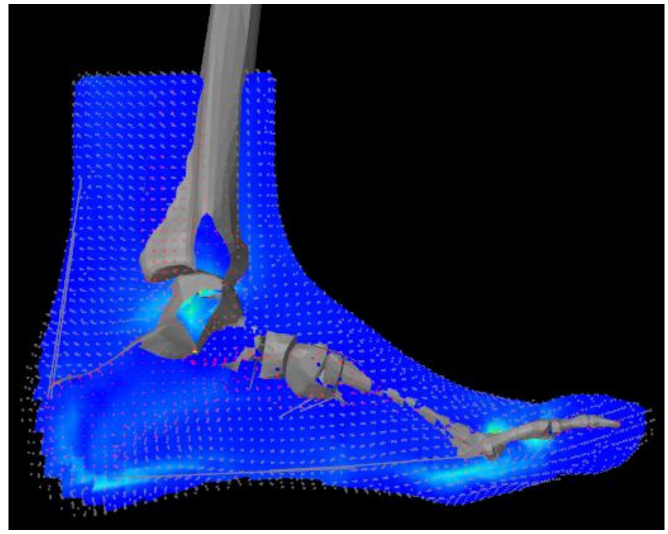

Figure 3: Cross section at the second toe showing the internal Von Mises strains resulting from the pressures applied to the foot sole and simulating a static position

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