A MULTI-DOMAIN EMG-DRIVEN 3D FINITE ELEMENT OF THE FOOT FOR DYNAMIC ACTIVITIES

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INTRODUCTION

Estimating the internal tissue loading while the body is moving is of great interest for clinicians as well as for sport industry. Internal tissue behavior mainly depends on its material properties (stiffness and viscosity to name a few) and the forces acting on it, either muscular or external (i.e., ground reaction force). In order to merge both the material properties and the forces, one needs to develop a multidomain biomechanical model of the human body coupling both finite element (FE) and musculoskeletal modeling. A multidomain foot model has recently been published [1] and provides valuable information on how to merge both domains (FE and musculoskeletal modeling). However, the proposed representation of the foot is bi-dimensional and the muscle forces are not taken into account when estimating the bone loadings.

The aim of the present work is to develop a multidomain finite element model of the foot driven by realistic muscle forces estimated using an EMG-driven model of the lower limb to study the internal tissue loading during dynamic activities such as running and walking.

METHODS

A framework of the different steps involved in the development of the model is presented in Table 1.

A 3D finite element model of the foot was developed based on medical imaging data. MRI and CT scan data were obtained from one adult male subject (30 years, 1.80 m, 72 kg). For each acquisition, the ankle joint was kept in neutral position by using an anatomical cast of the lower limb. CT scans were imported in Mimics© software to extract the surfaces of the bones, tendons, ligaments, and plantar fascia. MRI data were used every time the CT scan data weren't sufficiently accurate to determine the paths of the tendons, ligaments, and fascia. Mechanical properties of the tissues (bones, ligaments, skin, fascia, flesh) were taken from the literature [2], except for the tendons where specific data collection was undertaken to estimate the in-vivo force strain relationship.

In-vivo force-strain relationship of the Medial Gastrocnemius muscle (MG) was obtained using Ultrasonography (US) to track the displacement of the muscle-tendon junction and a custom ergometer to record synchronously the muscle torque developed around the ankle joint. The subjects were asked to develop ramp-up contractions from rest to their maximal force. 2 ramp-up times were studied: 1.5sec and the minimal time the subjects can achieve. After processing of the US images and torque data, the MG tendon force-strain relationship was modeled using a second order Ogden hyperelastic model.

To simulate the HAT complex (not included in the FE model) and its influence on the foot loading, a 70kg mass-equivalent element located approximately around the subject center of mass was added and connected to the top of the shin.

The boundary conditions of the FE model (initial velocity of the foot before ground contact, initial velocity of the center of mass element, foot angle at contact) together with the estimation of the muscle forces necessary to drive the FE model were deduced from experimental data of a walking and running subject.

The subject performed five walking and running trials at controlled speed (preferred speed for walking and 12 km/h for running).

Kinematic of the lower limb, ground reaction, and electromyographic data of the four major muscles crossing the ankle joint (i.e., Tibialis Anterior, Gastrocnemius Medialis and Lateralis, Soleus) were recorded synchronously. An EMG-driven Hill-type model was used to estimate the muscle forces of the four muscles during the dynamic activities [3].

The FE solver Abaqus© was used to simulate the impact and stance phases of each activity. Once the boundary conditions were set, the model was driven by muscle forces only.

From this EMG-driven FE model, the stress and strain of the different structures can be obtained, as well as the ground reaction force computed using the FE model (Table 1 & Figure 1).

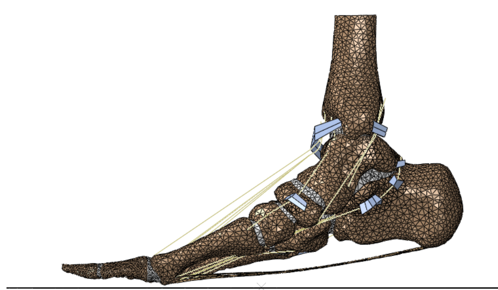

Figure 1: Lateral view of the EMG-driven 3D finite element model of the foot. Note the presence of the bones, retinaculum, cartilage, plantar fascia, and tendons. The geometry of each structure was obtained from CT scans data and the FE model is driven by realistic muscle forces.

RESULTS AND DISCUSSION

The EMG-driven 3D finite element model of the foot was driven solely by the initial foot angle relative to the ground, the velocity of the foot and the center of mass element as boundary conditions and the muscle forces throughout the gait cycle.

The vertical component of the ground reaction force is a key parameter in identifying abnormal gait patterns. This parameter also represents an output of the FE model of the foot and has been used to validate the model. The general shape and timing of the vertical component of the ground reaction force computed by the EMG-driven FE model are in broad agreement with the experimental data (Figure 2).

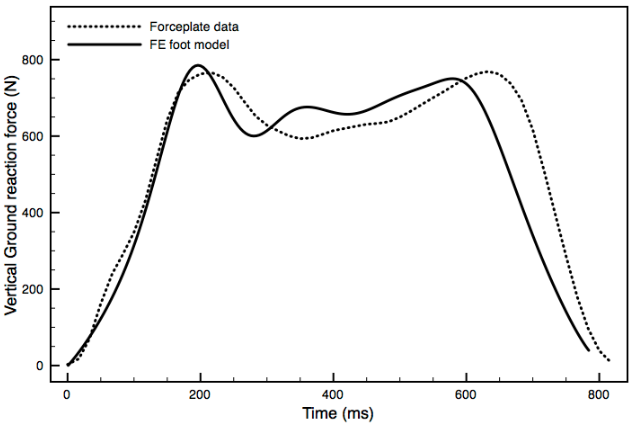

Figure 2: Vertical ground reaction force during gait computed by the EMG-driven 3D Finite Element model of the foot. Experimental data of the corresponding trial are also presented for comparison. Note the really good correspondence between both curves.

We are currently investigating the difference in tissue loading between walking and running. More specifically, the location and the magnitude of the higher stress regions are compared. The internal stress regions of the foot will also been investigated with regards to the walking and running speeds.

In its current form, only the muscle forces from the four major muscles that cross the ankle joint (TA, GM, GL, Sol) are used to set the FE model in motion. While this simple assumption gave promising results both in terms of ground reaction force and kinematics (Figure 2), more muscles are involved in the real gait motion. Several others tendons had been included in the model (Tibialis Posterior, Peroneus Brevis, Peroneus Longus, Extensor Hallucis Longus, Extensor Digitorum Longus, Flexor Hallucis Longus, Flexor Digitorum Longus) and the next step will be to develop an EMG-driven model that includes theses muscles to finely drive the FE foot model and simulate pathologies.

CONCLUSIONS

The present work aimed at investigating the differences in internal tissue loading between walking and running by means of a multidomain EMG-driven 3D finite element model of the foot. First results showed a really good agreement between simulated and experimental data, thus giving credit to the multidomain approach. This type of approach is recent and very promising as all the parameters that can influence the tissue loading (i.e., geometry of the structure, material properties, external forces, muscles forces) are taken into account in an integrated way.

REFERENCES

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Table 1: Summary of the different steps necessary to develop the multidomain EMG-driven 3D finite element of the foot. Grey boxes correspond to data obtained experimentally.