Finite Element Simulation of Shear Wave Propagation within Human Skeletal Muscle

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Resume — Human skeletal muscle is a living tissue with multi-scale architecture and complex mechanical function. The understanding of mechanical behaviors of the human skeletal muscle plays important role in the diagnosis and treatment evaluation of musculoskeletal diseases. The objective of this present study was to simulate a magnetic resonance elastography experiment. MRI images were used to develop a subject specific finite element model of the thigh of a healthy subject. Skeletal muscle was modeled using a linear viscoelastic law and its implementation was performed using Abaqus UMAT. Other tissues such as skin, adipose and bone tissues were also accounted into the model. A transient modal dynamics analysis was applied. Simulation results were presented and discussed. Our findings could be of great value to assist the experimenters in the set-up of MRE protocols.

Key words — shear wave propagation, human skeletal muscle, rheological viscoelastic model, finite element simulation

1. Introduction

Human skeletal muscle is the force-generating component of the musculoskeletal system. The understanding of the mechanical function of the human skeletal muscle may provide objective indicators for the diagnosis and treatment evaluation of the musculoskeletal disorders. Magnetic resonance elastography (MRE) has been commonly used to measure the skeletal muscle stiffness and viscosity [1]. However, the development of MRE protocol for the human skeletal muscle covers a large range of difficulties due to its multi-scale architecture and complex mechanical function. Thus, protocol parameters needs to be optimized to reduce the set up time and efforts as well as to produce reliable results. Recently, we proposed to use a finite element model as a computer-aided design tool to achieve such challenging issue [2].

Finite element modeling has become a common tool to study the interaction between biological tissues and their functional relationships. Moreover, medical imaging techniques (magnetic resonance imaging (MRI) or computed tomography) allow accurate tissue geometries to be acquired. However, the challenge of the finite element modeling remains in the modeling of tissue constitutive laws. Hard tissue like bone has been commonly modeled as linear elastic material. Soft tissues like skin or fat tissues have been modeled as hyperelastic material. The most challenging topic is how to accurately reproduce the skeletal muscle behaviors. Skeletal muscle has passive and active behaviors. Many research studies tried to model the skeletal passive muscle as a hyperelastic material [2], [3]. Active behavior of the skeletal muscle was usually integrated into transversely isotropic hyperelastic material [4]. According to the MRE experiment, skeletal muscle has been considered as viscoelastic material. However, according to our knowledge, the viscoelastic behavior of the skeletal muscle is still not well studied in numerical modeling. Thus, the objective of this present study was to develop and implement a linear viscoelastic law to model the skeletal muscle within the MRE experiment. Then, the shear wave propagation within the skeletal muscle tissue was performed. Note that we focused only on the vastus medialis.

2. Materials and Methods

2.1. Image-based geometries and respective meshed models

The model used in this present study was reported elsewhere [2]. The development process was briefly summarized here. MRI images of the thigh of a healthy subject (male, 33 year old) were acquired and segmented to provide geometrical models of different tissues of interest (skin, the femoral bone, the vastus medialis muscle and the ten remaining muscles grouped with the adipose tissue) (Fig. 1). The mesh was generated using a "home-made" process [5]. The mesh is composed of 4-node linear tetrahedron, hybrid, linear pressure elements (3D-tetrahedra C3D4H) and the element size was 5 x 5 x 5 mm^3. The skin model had 6111 nodes and 17914 elements. The vastus medialis muscle model had 5184 nodes and 24802 elements. The femoral bone model had 2049 nodes and 9224 elements. The group of adipose tissue and other muscles was obtained with 20847 nodes and 105031 elements (Fig. 2).

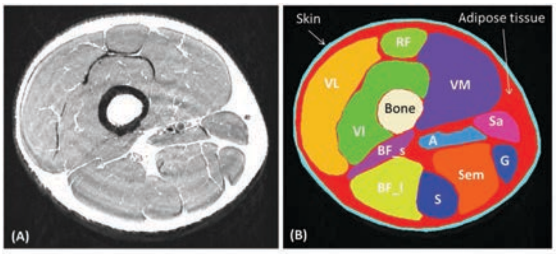

Figure 1 – MRI anatomical (A) and segmented (B) images including 14 regions of the thigh.

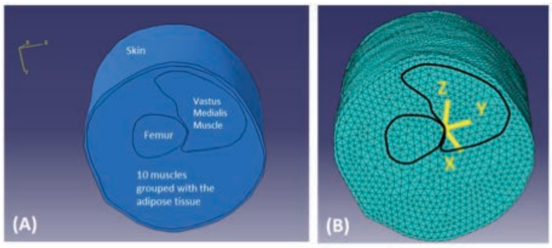

Figure 2 – Solid (A) and meshed (B) models of the thigh structures.

2.2. Materials constitutive laws

Femoral bone was modeled with a linear elastic and isotropic behavior while the adipose tissue was represented by a nonlinear hyperelastic Mooney-Rivlin law. The skin was modeled with Neo-Hookean behavior. Concerning the vastus medialis muscle, the Zener model was used. Constitutive equations of this viscoelastic rheological model were implemented using an Abaqus UMAT. The general equation of 1D rheological model is in the form:

$$\sigma + p_1\dot{\sigma} = q_0\varepsilon + q_1\dot{\varepsilon} \tag{1}$$

(1) can be generalized to small straining 3D case for an isotropic solid:

$$\sigma_{xy} + \tilde{\nu}\dot{\sigma}_{xy} = \mu\gamma_{xy} + \tilde{\mu}\dot{\gamma}_{xy} \tag{2}$$

$$\sigma_{xx} + \tilde{\nu}\dot{\sigma}_{xx} = \lambda\varepsilon_V + 2\mu\varepsilon_{xx} + \tilde{\lambda}\dot{\varepsilon}_V + 2\tilde{\mu}\dot{\varepsilon}_{xx} \quad (\varepsilon_V = \varepsilon_{xx} + \varepsilon_{yy} + \varepsilon_{zz}) \tag{3}$$

The five parameters $(\tilde{\nu}, \lambda, \mu, \tilde{\lambda}, \tilde{\mu})$ are inputs of UMAT codes. Appropriate values of these rheological parameters are derived from literature [1].

2.3. Simulation of Shear Wave Propagation

The contacts between the tissues were considered as « tie » constraints. To simulate the propagation of the shear waves within the thigh segment, sinusoidal motions were prescribed to the nodes located at the surface of the skin using applied loadings in the y direction. Then, the shear wave propagation in the thigh tissues was analyzed using a two-steps process: 1) natural frequency extraction for the first 30 frequencies and 2) transient modal dynamics analysis with prescribed frequency and load during four motion cycles (0.1 ms time step) [2].

3. Results

The pattern of the shear wave propagation within a 3D finite element model of the vastus medialis muscle is represented in Fig. 3. The shear wave is propagated and attenuated along the vastus medialis muscle. The shear wave displacement was depicted in Fig. 4.

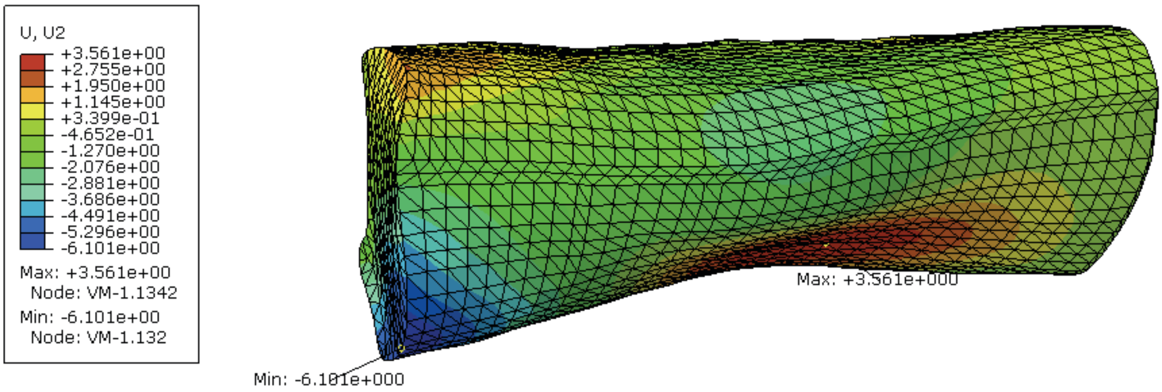

Figure 3 – Pattern of the shear wave displacement within the vastus medialis muscle.

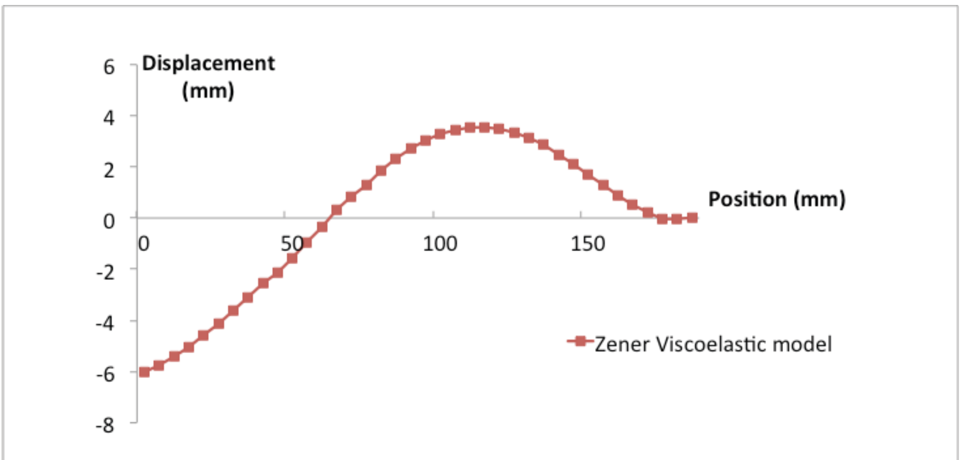

Figure 4 –Shear wave displacement over the vastus medialis muscle.

4. Discussion and Conclusions

This present study is the first to study the *in vivo* displacement of the shear wave within the vastus medialis muscle using a viscoelastic behavior to mimic accurately the MRE experiment. According to our previous study based on hyperelastic behavior of the skeletal muscle [2], the modeling of skeletal muscle as a linear viscoelastic material leads to reduce the amplitude of shear wave displacement. Thus, this finding has demonstrated that the response of the shear wave displacement is linked to the material laws (hyperelastic or viscoelastic) of the tissue of interest. Thanks to the present numerical approach, these different laws could be analyzed in a straightforward manner. The next step will be the identification of constitutive parameters using experimental data [1].

In conclusions, finite element modeling may be used as a potential tool to optimize the set-up of MRE protocols to inaccessible tissues, such as deep muscles (i.e vastus intermedius or adductor) where the wave displacement is difficult to generate. Moreover, when validated using experimental data, the developed methodology may be extrapolated to compute the tissue stiffness and viscoelasticity of other skeletal muscles in an *in vivo* and non-invasive manner.

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