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Identification of hyperelastic properties of passive thigh muscle under compression with an inverse method from a displacement field measurement

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A B S T R A C T

The mechanical behavior of muscle tissue is an important field of investigation with different applications in medicine, car crash and sport, for example. Currently, few *in vivo* imaging techniques are able to characterize the mechanical properties of muscle. Thus, this study presents an *in vivo* method to identify a hyperelatic behavior from a displacement field measured with ultrasound and Digital Image Correlation (DIC) techniques. This identification approach was composed of 3 inter-dependent steps.

The first step was to perform a 2D MRI acquisition of the thigh in order to obtain a manual segmentation of muscles (quadriceps, ischio, gracilis and sartorius) and fat tissue, and then develop a Finite Element model. In addition, a Neo-Hookean model was chosen to characterize the hyperelastic behavior (C_{10}, D) in order to simulate a displacement field. Secondly, an experimental compression device was developed in order to measure the *in vivo* displacement fields in several areas of the thigh. Finally, an inverse method was performed to identify the C_{10} and D parameters of each soft tissue.

The identification procedure was validated with a comparison with the literature. The relevance of this study was to identify the mechanical properties of each investigated soft tissues.

1. Introduction

A deep knowledge of *in vivo* human soft tissues is necessary (Payne et al., 2015) and has a significant field of investigation with different applications such as surgery where clinicians are more and more assisted by robotic devices and where they need a precise feedback of the mechanical response of tissues to ensure safety interventions.

Currently, several *in vivo* techniques, from Magnetic Resonance Imaging (MRI) or ultrasound, allow clinicians to assess the elastic behavior, such as Magnetic Resonance Elastography (MRE) (Bensamoun et al., 2006; Muthupillai et al., 1995), SuperSonic Imaging (SSI) or Transient Elastography (TE) (Gennisson et al., 2005; Bercoff et al., 2004; Sandrin et al., 2002a, 2002b). These elastography techniques are mainly limited by the dynamic excitation, that only allow us to characterize the viscoelastic behavior (Leclerc et al., 2013; Debernard et al., 2013; Gennisson et al., 2010). These behaviors do not describe correctly tissues at large strains and a hyperelastic behavior could be more appropriated.

Avril et al. (2010) and Tran et al. (2007), proposed to develop an inverse method from quasi-static solicitations, an indentation and a contention, to identify the Neo-Hookean behavior (C_{10}, D) of a group of muscle. In these studies, a Finite Element Model Updating (FEMU) approach was developed where the cost function was built in displacement between the subset outlines of a Finite Element (FE) simulation and of the muscle image under solicitation. It can be noted that a force term was added to the cost function used by Tran et al. (2007). The displacement cost function is built from a few measurement points and an identification of the isolated muscles would probably give results with high uncertainty. As a result, a measurement of displacement fields appears to be beneficial to identify the mechanical properties of muscles.

In comparison to Avril and Tran's studies, Affagard et al. (2014) has developed a FEMU leading to the displacement fields and the identification (C_{10}, D) of the *in vivo* isolated thigh muscle. In this study the cost function was also built on the displacement. Similar study had characterized the *in vivo* Neo-Hookean behavior of soft

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tissues from a surface displacement field obtained with stereo-correlation (3D DIC) [Moermann et al., 2009]. This approach enables the identification of surface tissues behavior but seems limited for the characterization of deep tissues such as muscles.

A way to measure the displacement and strain fields was developed in the 1990s (Ophir et al., 1991; Ponnekanti et al., 1992, 1994) and consisted in correlating the B-mode signal (Zhu and Hall, 2002; Hall et al., 2011). Tumors from breast tissue were discerned using the spatial distribution of the hyperelastic material properties, but a full slice member identification was not performed (Goenezen et al., 2011; Gokhale et al., 2008). Moreover, the displacement field measurement performed by coupling Digital Image Correlation and ultrasound techniques was described and validated in Affagard et al. (2015a, 2015b).

The literature presents a general lack of *in vivo* hyperelastic characterization of isolated muscle. The challenge of this study is to characterize isolated muscles with a hyperelastic behavior

2. Materials and methods

This section aims at presenting the FEMU approach developed for the identification of the hyperelastic properties of the thigh muscles. Fig. 1 presents the approach, consisting of three interconnected blocks:

- The experimental protocol (Fig. 1B),
- The modeling (Fig. 1A),
- The identification (Fig. 1C).

2.1. Experimental protocol

The experimental protocol aimed at measuring the displacement field of the thigh muscle tissues between uncompressed and compressed states. The first step consisted in acquiring ultrasound images at different loading levels applied with a custom made compression device. Then, using a Digital Images Correlation (DIC) technique (Hild and Roux, 2006, 2008), 2D displacement fields were measured normal to the direction of the ultrasound probe. This measurement was the first entry of the identification process.

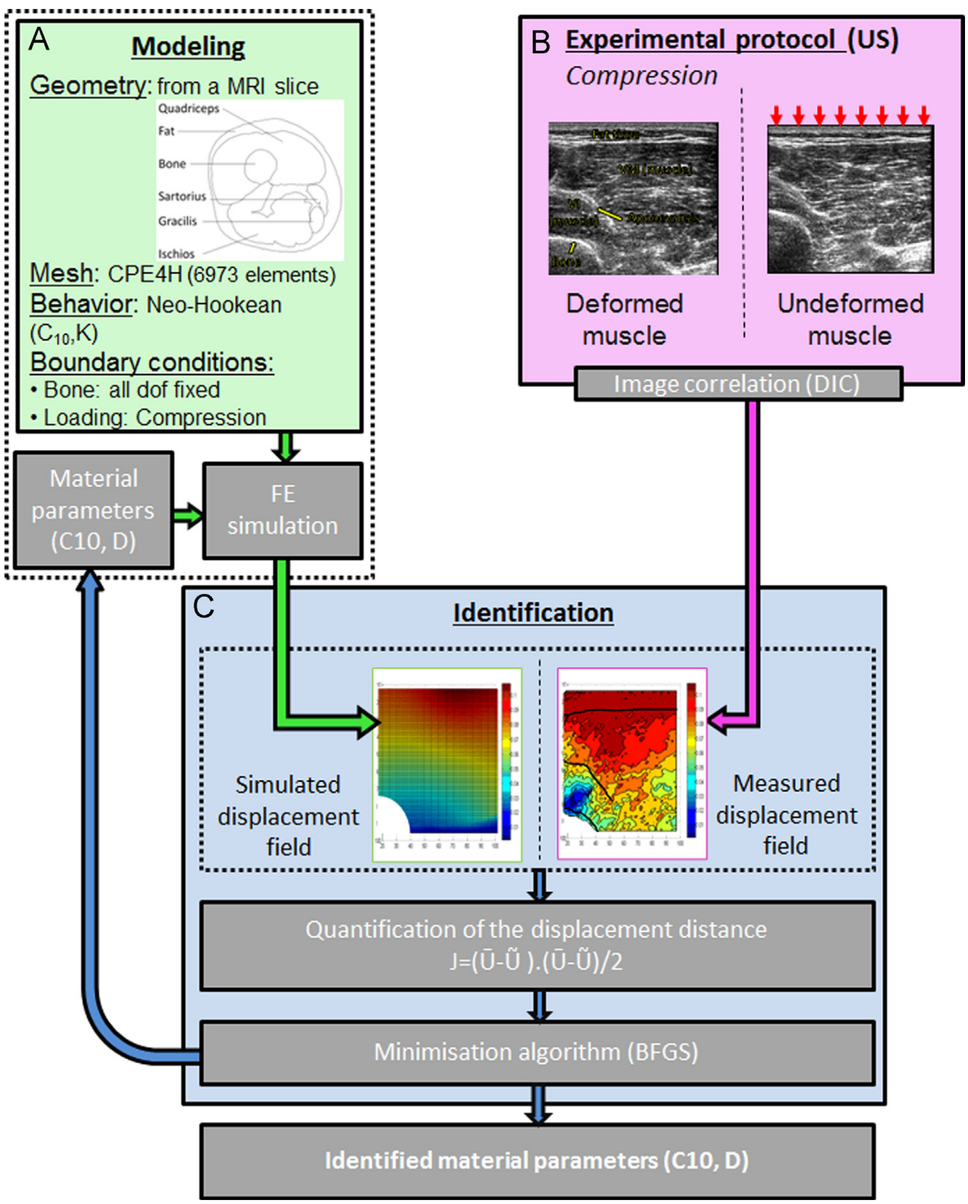

Fig. 1. Developed FEMU Identification approach: (A) modeling, (B) experimental protocol and (C) identification.