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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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## ► To cite this version:

Jean-Sébastien Affagard, Pierre Feissel, Sabine F Bensamoun. Identification of hyperelastic properties of passive thigh muscle under compression with an inverse method from a displacement field measurement. *Journal of Biomechanics*, 2015, 48 (15), pp.4081-4086. 10.1016/j.jbiomech.2015.10.007 . hal-03807683

**HAL Id: hal-03807683**

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Submitted on 21 Nov 2022

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1 **ABSTRACT**

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

8 The first step was to perform a 2D MRI acquisition of the thigh in order to obtain a manual  
9 segmentation of muscles (quadriceps, ischio, gracilis and sartorius) and fat tissue, and then  
10 develop a Finite Element model. In addition, a Neo-Hookean model was chosen to  
11 characterize the hyperelastic behavior (C10, D) in order to simulate a displacement field.  
12 Secondly, an experimental compression device was developed in order to measure the in vivo  
13 displacement fields in several areas of the thigh. Finally, an inverse method was performed to  
14 identify the C10 and D parameters of each soft tissue.

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

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19 **Keywords:** In vivo mechanical properties Thigh muscles, Digital Image Correlation (DIC),  
20 Medical imaging, Inverse method

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## 1 I. INTRODUCTION

2

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

7

8 Currently, several *in vivo* techniques, from MRI (Magnetic Resonance Imaging) or ultrasound, allow  
9 clinicians to assess the elastic behavior, such as Magnetic Resonance Elastography (MRE)  
10 (Bensamoun et al., 2006; Mutupillai et al., 1995), SuperSonic Imaging (SSI) or Transient Elastography  
11 (TE) (Gennisson et al., 2005; Bercoff et al., 2004; Sandrin et al., 2002a; Sandrin et al., 2002b). These  
12 elastography techniques are mainly limited by the dynamic excitation, that only allow us to  
13 characterize the viscoelastic behavior (Leclerc et al., 2013; Debernard et al., 2013; Gennisson et al.,  
14 2013). These behaviors do not describe correctly tissues at large strains and a hyperelastic behavior  
15 could be more appropriated.

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

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

1 (3D-DIC) [Moermann et al. 2009]. This approach enables the identification of surface tissues behavior  
2 but seems limited for the characterization of deep tissues such as muscles.

3  
4 A way to measure the displacement and strain fields was developed in the nineties (Ophir et al., 1991;  
5 Ponnekanti et al., 1992; Ponnekanti et al., 1994) and consisted in correlating the B-mode signal (Zhu  
6 and Hall, 2002, Hall et al., 2011). Tumors from breast tissue were discerned using the spatial  
7 distribution of the hyperelastic material properties, but a full slice member identification was not  
8 performed (Goenezen et al., 2011; Gokhale et al., 2008). Moreover, the displacement field  
9 measurement performed by coupling Digital Image Correlation and ultrasound techniques was  
10 described and validated in (Affagard et al., 2015a; Affagard et al., 2015b).

11  
12 The literature presents a general lack of *in vivo* hyperelastic characterization of isolated muscle. The  
13 challenge of this study is to characterize isolated muscles with a hyperelastic behavior

## 14 15 **II. MATERIALS AND METHODS**

16  
17 This section aims at presenting the FEMU approach developed for the identification of the hyper-  
18 elastic properties of the thigh muscles. Figure 1 presents the approach, consisting of three  
19 interconnected blocks:

- 20 - The experimental protocol (Figure 1B),
- 21 - The modeling (Figure 1A),
- 22 - The identification (Figure 1C).

## 1 **1. Experimental protocol**

2

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

9

### 10 *1.1. MRI and US acquisitions*

11 The experiment was performed on the lower third part of the thigh of a 33 year old male without any  
12 venous pathology. The muscle tissues were thus easy to strain because this section is slim with few fat  
13 tissues. The subject will have two imaging tests: MRI (1.5T, GE) and ultrasound (9  
14 MHz, LOGIQ E9, GE). The MRI acquisition was realized to perform the finite element (FE) modeling  
15 and the ultrasound acquisitions were made within the anterior, posterior, lateral and medial areas  
16 (Affagard et al., 2015a; Affagard et al., 2015b). In order to match the same MRI and US sections of  
17 the thigh, a US fusion process was performed using anatomical landmarks.

18

### 19 *1.2. Custom made mechanical device*

20 The thigh was placed in a purposely designed compression device (Figure 2) composed of three plates  
21 (300 x 200 mm<sup>2</sup>). The lower plate was used as a support for the leg. The upper ones can be moved up  
22 and down (along the Y axis), parallel to the lower plate, to compress the muscle and have a specific  
23 design to fit the ultrasound probe (9MHz). This parallelism ensures the planarity of the upper plate and  
24 the alignment of the thigh compared to the lower plate, and the normality of the US beam. Moreover,  
25 sensors (I-scan, Tekscan, 5027) can be placed between the two upper plates in order to quantify the  
26 distribution of pressure applied with the screws.

27

28

### 1.3. Displacement field measurement

The displacement field measurement was obtained from ultrasound acquisitions performed between unloaded and 60N loaded applied on the upper plates. This loading rate was chosen to obtain large strains. Figure 3 shows the different ultrasound acquisitions where a DIC (correli\_Q4 (Hild and Roux, 2006; Hild and Roux, 2008)) was performed to obtain the horizontal and vertical displacement fields around the thigh. This algorithm presents the particularity to regularize the displacement field as a decomposition of shape function. Subsequently, the leg was rotated to measure the displacement fields within the anterior, posterior, medial and lateral areas (Affagard et al., 2015a Affagard et al., 2015b). These US images were acquired with previously optimized ultrasound parameters (Affagard et al., 2014). In addition intermediate US images, with a step of 15N, have been added to facilitate the convergence (Affagard et al., 2014).

## 2. Computational modeling

The numerical modeling was already described in Affagard et al., 2014. The numerical modeling consisted in developing a 2D plane strain Finite Element (FE) model. A MRI acquisition of the thigh (1.5T, GE) was performed, allowing a manual contour detection of four muscles and fat tissue (Figure 4). Although the muscle tissues are known to be heterogeneous, each region was described with a compressible, homogeneous and Neo-Hookean behavior. The incompressibility was not enforced due to the presence of volumetric variation during the experimental test. The energy density was defined as:

$$W = C_{10}(\bar{I}_1 - 3) + \frac{1}{D}(J - 1)^2 \quad (1)$$

where  $C_{10}$  is related to the shear modulus and  $D$  is related to the volumetric variations.  $D = 2/K$  with  $K$  the bulk modulus.  $J = \det(\underline{\underline{F}})$ ,  $\bar{I}_1 = J^{-2/3}I_1$  and  $I_1 = tr(\underline{\underline{F}}^t \cdot \underline{\underline{F}})$ , with  $\underline{\underline{F}}$  is the deformation gradient tensor.

1 Then, the geometry was meshed with 25392 4-node linear elements, hybrid with constant pressure  
2 (CPE4H), corresponding to 40776 nodes and the integration was performed on 4 gauss points.

3 The four compression tests (anterior, posterior, medial and lateral areas) were simulated using two  
4 parallel rigid bodies on each side of the thigh. As performed during the experimental test, a loading  
5 was imposed (60 N on a surface of 300 x 200 mm<sup>2</sup>). The bone tissue was considered as a rigid body  
6 and therefore was not modeled. Thus, Neumann conditions where all the degrees of freedom are equal  
7 to 0, were applied between the bone and muscle tissues.

8

9

### 10 **3. Identification**

11

12 The identification of the Neo-Hookean parameters was performed by the minimization of a cost  
13 function with a BFGS algorithm. The cost function,  $\Pi$ , was defined as the quadratic discrepancy  
14 between the measured,  $\tilde{U}$ , and simulated,  $\bar{U}$ , displacements as:

$$\Pi = \frac{1}{2}(\bar{U} - \tilde{U})^t(\bar{U} - \tilde{U}) \quad (2)$$

15 In this study, two identifications with different hypotheses were performed:

16 The first identification consisted in identifying the parameters of the fat and grouped muscle tissues. In  
17 terms of properties, each muscle was assumed to contribute to the average hyperelastic behavior.  
18 Therefore, four parameters ( $C_{10}^{\text{muscle}}$ ,  $C_{10}^{\text{fat}}$ ,  $D^{\text{muscle}}$ ,  $D^{\text{fat}}$ ) were characterized.

19 For the second identification, the muscles were considered independently and 7 parameters were  
20 identified:  $C_{10}^{\text{quadriceps}}$ ,  $C_{10}^{\text{ischios}}$ ,  $C_{10}^{\text{grouped}}$ ,  $C_{10}^{\text{fat}}$ ,  $D^{\text{quadriceps}}$ ,  $D^{\text{grouped}}$ ,  $D^{\text{fat}}$  Based on our previous  
21 methodology (Affagard et al., 2014), the D parameters of the gracilis, sartorius and ischio muscles, as  
22 well as the  $C_{10}$  parameters of sartorius and gracilis, were grouped to decrease the identification error.

23 The presented data are the absolute values obtained from the identification results of the lowest cost  
24 function performed with different initializations.

25

26



### 1 **III. RESULTS**

2

#### 3 **1. Materials properties for undifferentiated muscles**

4

5 Table 1 presents the Neo-Hookean parameters identified for the undifferentiated muscles. The  $C_{10}$  and  
6 D parameters for muscle tissue are respectively 11.6 kPa and  $11.9 \text{ MPa}^{-1}$ . For the fat tissue, the  $C_{10}$  and  
7 D parameters are respectively 0.64 kPa and  $29.4 \text{ MPa}^{-1}$ .

8

9 Comparing with the Avril et al., 2010 study, all the parameters are in the same range (relative  
10 discrepancy  $< 14.4 \%$ ) except the fat tissue D parameters (relative discrepancy  $< 126.4 \%$ ). In  
11 comparison with the Tran et al., 2007 study, which aimed at characterizing the skin layers behavior,  
12 the errors on muscle parameters are high for the  $C_{10}$  muscle parameter (relative discrepancy  $< 217.8$   
13  $\%$ ) and low for the D parameter (relative discrepancy  $< 16.4 \%$ ). This comparison is summarized in  
14 Table 1. The error could be explained by the low spatial resolution link to the different number of  
15 measured points in each muscle and the different applied mechanical tests. Indeed, Affagard et al.,  
16 2014 have performed a sensitivity analysis three tests (compression, indentation and contention) to  
17 illustrate the identification accuracy for each parameter. In the present study, a compression was  
18 performed on the thigh muscle, whereas Avril et al., 2010 performed a contention on the leg and an  
19 indentation on the arm was carried out in Tran et al., 2007. In addition, the identification error could  
20 be due to involuntary contractions and inter-individual differences in muscle physiology.  
21 Electromyography tests could be applied to ensure and quantify the passive state of muscles.

22

23

#### 24 **2. Materials properties for isolated muscles**

25

26 Table 2 shows the Neo-Hookean parameters identified for the isolated muscles. The identified  $C_{10}$  and  
27 D parameters are respectively 0.52 kPa and  $30.5 \text{ MPa}^{-1}$  for the fat tissue, 11.7 kPa and  $16.3 \text{ MPa}^{-1}$  for

1 the quadriceps, 17.3 kPa and 12.9 MPa<sup>-1</sup> for the ischio and 21.3 kPa and 12.9 MPa<sup>-1</sup> for the sartorius  
2 and gracilis complex.

3  
4 For each muscle, the D parameter value is higher than the previously identified D value for all  
5 undifferentiated muscles. The low sensitivity for the D parameters could explain this variation and the  
6 convergence difficulties (Affagard et al., 2014). Moreover, the identified D parameter for the  
7 quadriceps is the closest from the D identified for undifferentiated muscles. This result appears logical  
8 because the quadriceps is the largest muscle of this thigh section and has therefore the highest spatial  
9 resolution.

10  
11 Moreover, comparing with the Bensamoun et al. 2006 study, where the parameters were identified by  
12 MRE, the relative discrepancy of the fat tissue is less than 23.1 %. The muscle comparison reveals a  
13 larger discrepancy (more than 184 %). This difference can be explained by the fact that Bensamoun et  
14 al., 2006 characterize the muscle in the longitudinal direction, while the transverse properties are  
15 characterized here. The discrepancy for the fat tissues is lower (32.9 %). This result could be explained  
16 because fat tissues are expected to be homogeneous.

17  
18 To conclude, the identified parameters generated results of comparable magnitude with literature and  
19 therefore verified the capabilities of the technique to produce meaningful results.

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## 1 **IV. DISCUSSION**

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### 3 **1. Experimental protocol**

4

5 During the experimental mechanical solicitation, a compressive force was imposed. This force was  
6 measured by sensors that enable us to characterize the spatial distribution of pressure. In the present  
7 study, this force was considered exactly known. Some questions can be raised about the accuracy of  
8 the measurements. A way to take into account the force measurement error could be to change the FE  
9 modeling and the cost function shape to take into account both the displacement and the force. In  
10 addition, the plates were assumed to be parallel during the compression to meet the 2D modeling  
11 requirement. In fact, thighs having a conical shape, the plates were not always parallel. This  
12 hypothesis could induce mismatches with the 2D modeling.

13

### 14 **2. Finite element model assumptions**

15

16 The assumption of plane strain was adopted. The out of plane strains were equal to 0, as presented in  
17 Avril et al., 2010 and Tran et al., 2007. The longitudinal strains are therefore neglected, which can  
18 induce modeling errors. In Avril et al., 2010 study, a comparison between 2D and 3D assumptions was  
19 done and few differences were observed. Nevertheless, the main advantage of a 2D model is that the  
20 computation time is drastically reduced, because of the model nonlinearities (behavior and geometry).

21

22 Moreover, the various differentiated tissues were considered isotropic and homogeneous. Indeed, the  
23 vascular system was not taken into account and was considered as included in the average of the  
24 surrounding tissues. This can also lead to errors in the simulated displacement.

25

26 Finally, during the acquisition of ultrasound images, some sliding between the different muscles and  
27 the bone were observed (Affagard et al., 2015a; Affagard et al., 2015b). For modeling, a perfect

1 adhesion was imposed on these interfaces. It would be interesting, thereafter, to model this sliding to  
2 obtain a more realistic simulation but this characterization remains a challenge.

3

### 4 **3. Identification**

5

6 The cost function is based on the quadratic difference between measured and simulated displacements.  
7 In Tran et al., 2007 study, the displacement of the indenter was imposed and the cost function was  
8 optimized from both forces and displacement borders. The cost function could also be improved by  
9 visual observations. For example, in our study, the visual contact surface between the compression  
10 plates and the skin could be added. Finally, it is also possible to add regularization terms. Gokhale et  
11 al., 2008 and Goenezen et al., 2011 added regularization terms based on **estimated** material parameters  
12 to characterize the local spatial distribution of hyperelastic properties. The choice to add regularization  
13 terms was not done in this present study, because of the lack of reliable data in the literature regarding  
14 mechanical properties of *in vivo* thigh muscles.

15

16 Finally, the results illustrate the feasibility of the material parameters identification of *in vivo* thigh.  
17 The parameters were nevertheless identified for a single subject with no venous pathology. Therefore,  
18 in order to validate the methodology, a repeatability test should be performed and thus the inter-  
19 individual variability could be assessed. Finally, this approach could be applied to other muscle areas.

20

### 21 **4. Potential study applications**

22

23 During the last years, techniques for characterizing the mechanical properties have been evolved  
24 considerably in clinical routine (MRE, SSI ...). These techniques aim at describing the elastic  
25 behavior of the tissue to facilitate and supplement non invasive medical diagnostics. The present study  
26 is another approach that can be applied to all soft biological tissues for several applications. For  
27 instance, in car crash, skin and muscle tissues are often neglected although they have an essential role  
28 in the maintaining of the body and in the shock absorption. The knowledge of their mechanical

1 properties will dramatically improve the numerical prediction and will enable to reduce the number of  
2 experimental tests. Moreover, in ergonomic field, the design of prostheses, wheelchair, etc ... could be  
3 optimized from the functional behavior of human tissues.

4

## 5 **V. CONCLUSION**

6

7 The purpose of this study is to propose a technique for characterizing hyperelastic properties of  
8 muscles to increment the in vivo mechanical properties databases of muscle. The originality of this  
9 study was to couple imaging techniques (Ultrasound, MRI) with numerical methods (DIC, FEMU).

10 This methodology could have an impact in the scientific (sport, ergonomic ...) and medical (robotic  
11 devices ...) fields and will enable a better understanding of diseases and muscle injuries (tear, tensile  
12 ...).

13

14

## 15 **CONFLICT OF INTEREST STATEMENT**

16

17 All authors do not have conflict of interest.

18

19

## 20 **ACKNOWLEDGEMENT**

21

22 This project is co-financed by the European Union engaged in Picardie with the European Regional  
23 Development Fund and CNRS (grant Collegium UTC CNRS INSIS).

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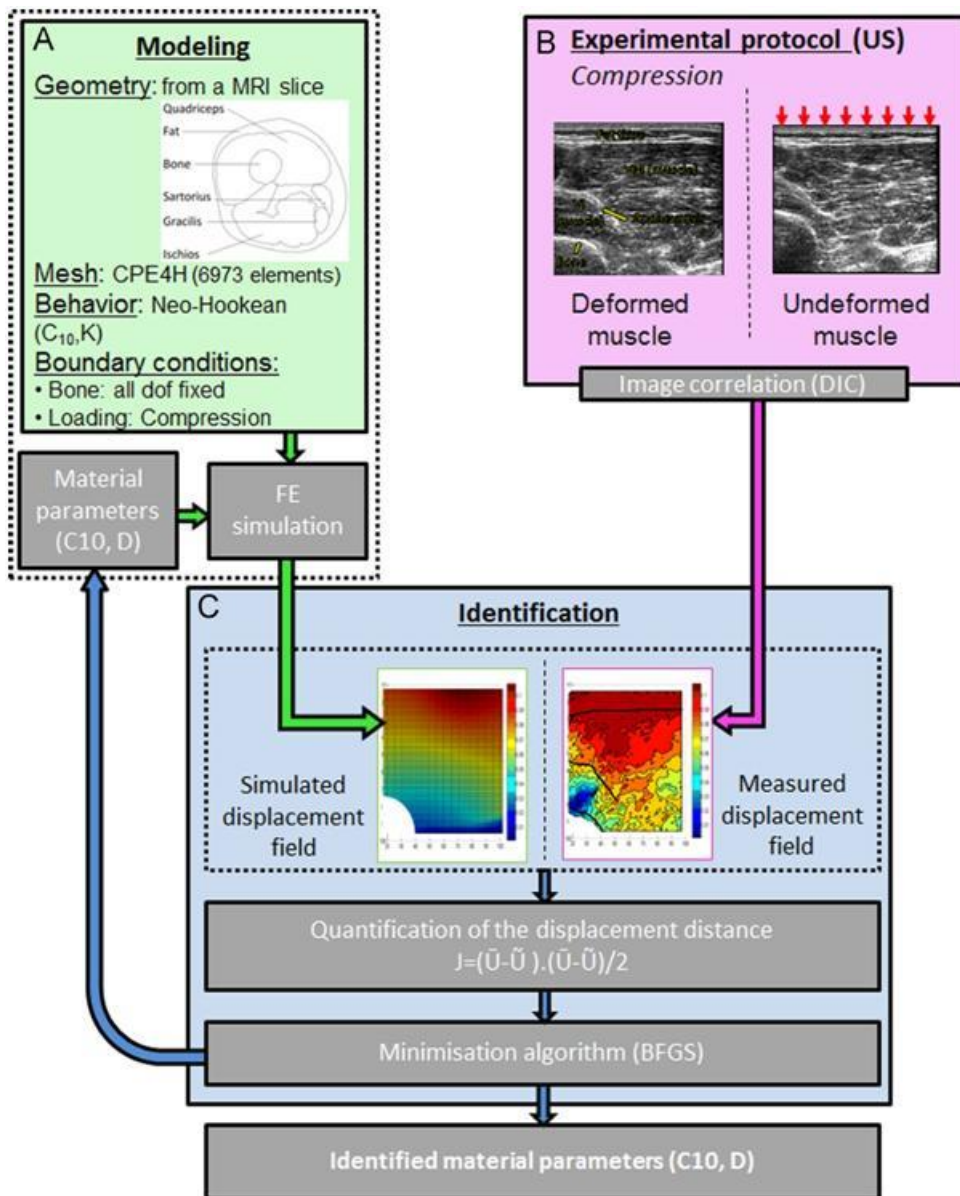
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1 FIGURES



2

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

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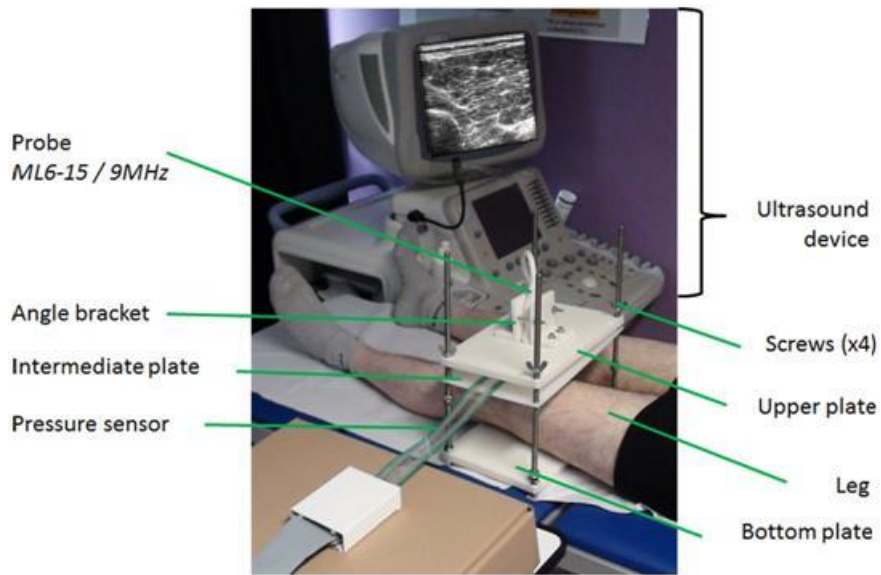
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2 **Fig. 2.** Home-made compression device.

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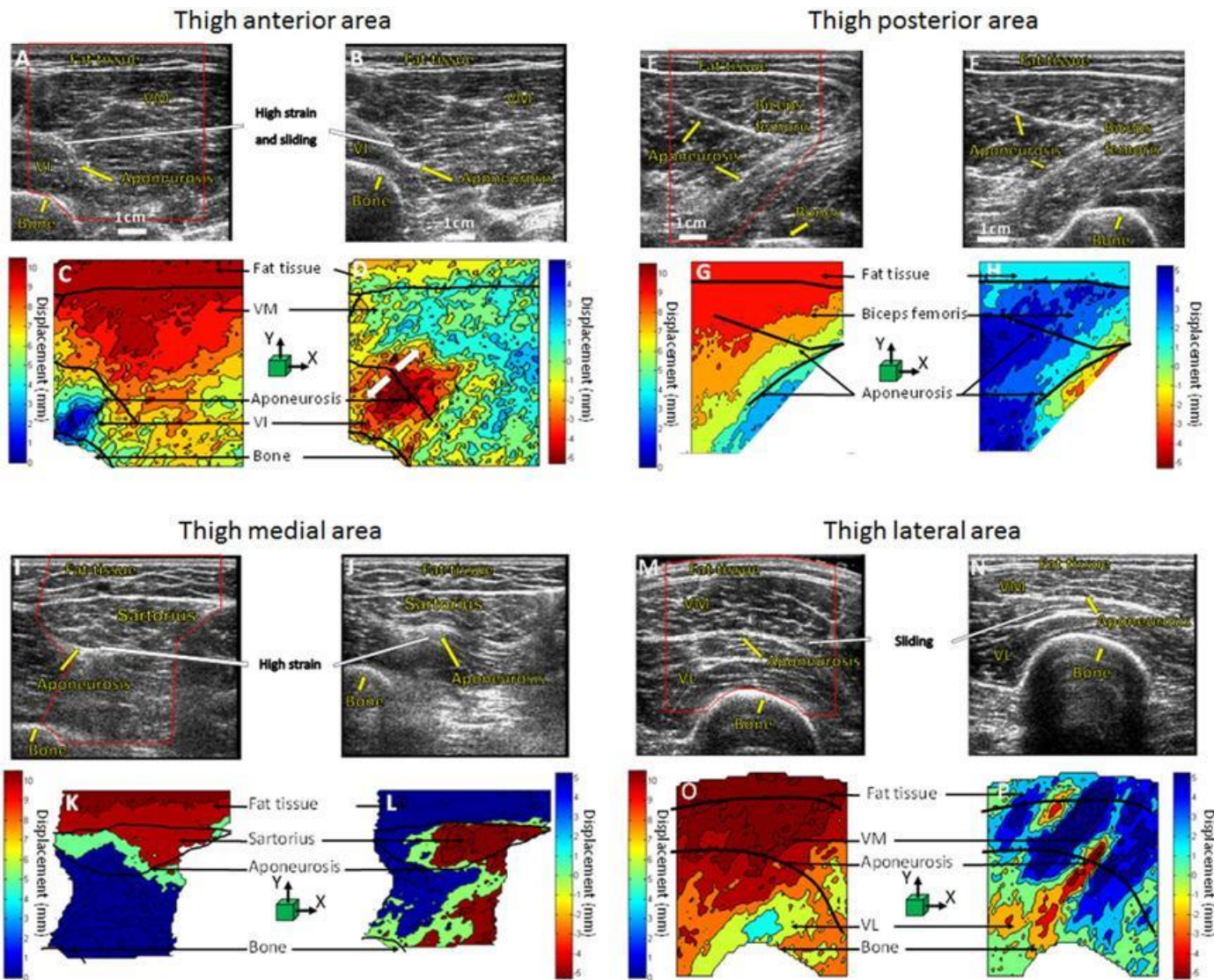
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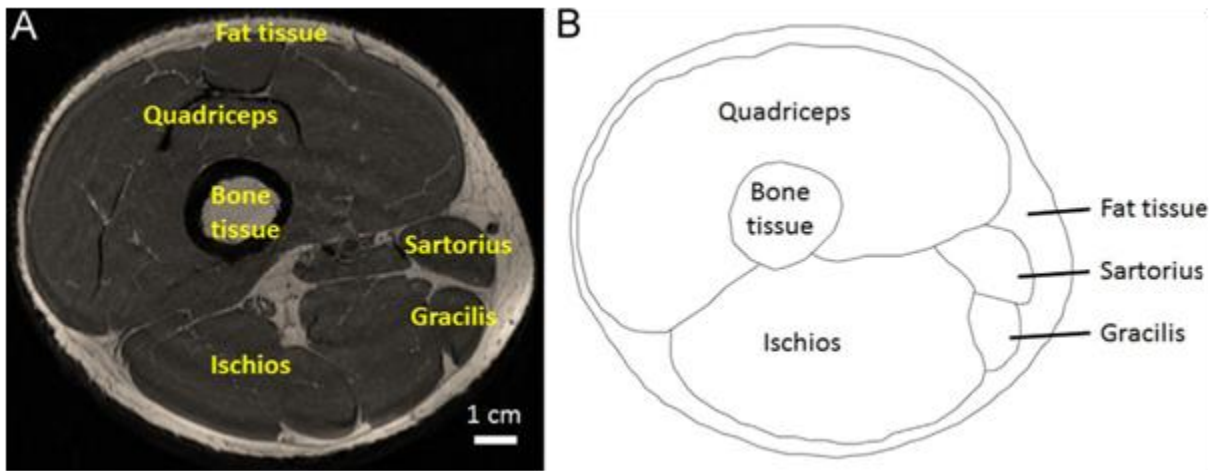
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1  
 2 **Fig. 3.** Ultrasound acquisitions on different areas of the thigh (A, E, I, M) in the unloaded state and (B,  
 3 F, J, N) under a load of 60 N. Associated maps of the vertical (C, G, K, O) and horizontal (D, H, L, P)  
 4 displacement fields. Explored areas are respectively the anterior thigh regions (A–D), posterior (E–H),  
 5 medial (I–L) and lateral (M–P).

6



1  
2 **Fig. 4.** (A) MRI acquisition and (B) finite element geometry of the thigh obtained by a manual  
3 segmentation.

1 **TABLES**

2 Table 1

3 Neo-Hookean parameters identified for the undifferentiated thigh muscles.

	Fat tissue		Muscle tissue	
	$C_{10}$ (kPa)	$D$ (MPa <sup>-1</sup> )	$C_{10}$ (kPa)	$D$ (MPa <sup>-1</sup> )
Identified parameters	0.64	29.4	11.6	11.9
Mean identified parameters (Avril et al., 2010)	0.65	25.7	11.3	27.1
Relative discrepancy (%)	1.4	14.4	1.9	126.4
Mean identified parameters (Tran et al., 2007)	–	–	3.6	13.9
Relative discrepancy (%)	–	–	217.8	16.4

4

5 Table 2

6 Neo-Hookean parameters identified for the isolated thigh muscles.

	Fat tissue		Quadriceps		Ischios		Sartorius and gracilis	
	$C_{10}$ (kPa)	$D$ (MPa <sup>-1</sup> )	$C_{10}$ (kPa)	$D$ (MPa <sup>-1</sup> )	$C_{10}$ (kPa)	$D$ (MPa <sup>-1</sup> )	$C_{10}$ (kPa)	$D$ (MPa <sup>-1</sup> )
Identified parameters	0.52	30.5	11.7	11.9	17.3	12.9	21.3	12.9
Mean identified parameters	0.64	29.4	11.6	11.9	-	-	-	-
Relative discrepancy (%)	23.1	19	-	-				
Mean identified parameters [Bensamoun et al., 2006]	1.6	–	3.5	-	-	-	7.5 and 4.4	-
Relative discrepancy (%)	32.9	–	234.8	-			184 and 384.1	-

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