



HAL
open science

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

Jean-Sébastien Affagard, Pierre Feissel, Sabine F Bensamoun

► 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

<https://utc.hal.science/hal-03807683v1>

Submitted on 21 Nov 2022

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

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.

18

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

21

22

23

24

25

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).

23
24
25
26
27
28

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 mm²). 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 mm²). 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, Π , 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}^{muscle} , C_{10}^{fat} , D^{muscle} , D^{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}^{ischios} , C_{10}^{grouped} , C_{10}^{fat} , $D^{\text{quadriceps}}$, D^{grouped} , D^{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 MPa^{-1} . For the fat tissue, the C_{10} and
7 D parameters are respectively 0.64 kPa and 29.4 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 MPa^{-1} for the fat tissue, 11.7 kPa and 16.3 MPa^{-1} for

1 the quadriceps, 17.3 kPa and 12.9 MPa⁻¹ for the ischio and 21.3 kPa and 12.9 MPa⁻¹ 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.

20
21
22
23
24
25
26
27
28

1 **IV. DISCUSSION**

2

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).

24

25

26

27

1 **REFERENCES**

2

3 Affagard, J.S., Bensamoun, S.F., Feissel, P., 2014. Development of an inverse approach for the
4 characterization of in vivo mechanical properties of the lower limb muscles, *ASME J Biomech*
5 *Eng*, 136 (11), 111012-1–111012-8.

6 Affagard, J.S., Feissel, P., Bensamoun, S.F, 2015a. Measurement of the quadriceps muscle
7 displacement and strain fields with ultrasound and Digital Image Correlation (DIC)
8 techniques. *IRBM*, 36(3), 170-177.

9 Affagard, J.S., Feissel, P., Bensamoun, S., 2015b, Use of digital image correlation and ultrasound:
10 analysis of thigh muscle displacement fields, Conference: 37th Annual International Conference of
11 the IEEE Engineering in Medicine and Biology Society.

12 Avril, S., Bouten, L., Dubuis, L., Drapier, S., Pouget, J.F., 2010. Mixed experimental and numerical
13 approach for characterizing the biomechanical response of the human leg under elastic
14 compression. *J.biomech.eng.*, 132(3).

15 Bensamoun, S.F., Ringleb, S.I., Littrell, L., Chen, Q., Brennan, M., Ehman, R.L., An, K.N, 2006.
16 Determination of thigh muscle stiffness using magnetic resonance elastography. *J. Magn. Reson.*
17 *Imaging*, 23(2), 242-247.

18 Bercoff, J., Tanter, M., Fink, M., 2004. Supersonic shear imaging: a new technique for soft tissue
19 elasticity mapping. *Ultrasonics, Ferroelectrics and Frequency Control, IEEE Transactions*
20 *on*, 51(4), 396-409.

21 Debernard, L., Leclerc, G.E., Robert, L., Charleux, F., Bensamoun, S.F., 2013. In Vivo
22 Characterization of the Muscle Viscoelasticity in Passive and Active Conditions Using
23 Multifrequency MR Elastography, *J. Musculoskeletal Res.*, 16(2), pp. 397–401.

24 Gennisson, J.L., Cornu, C., Catheline, S., Fink, M., Portero, P., 2005. Human muscle hardness
25 assessment during incremental isometric contraction using transient elastography. *J.*
26 *biomech.*, 38(7), 1543-1550.

1 Gennisson, J. L., Deffieux, T., Macé, E., Montaldo, G., Fink, M., & Tanter, M., 2010. Viscoelastic and
2 anisotropic mechanical properties of in vivo muscle tissue assessed by supersonic shear imaging.
3 *Ultrasound in medicine & biology*, 36(5), 789-801.

4 Goenezen, S., Barbone, P., Oberai, A.A., 2011. Solution of the nonlinear elasticity imaging inverse
5 problem: The incompressible case. *Computer methods in applied mechanics and*
6 *engineering*, 200(13), 1406-1420.

7 Gokhale, N.H., Barbone, P.E., Oberai, A.A., 2008. Solution of the nonlinear elasticity imaging inverse
8 problem: the compressible case. *Inverse Problems*, 24(4).

9 Hall, T.J., Barbone, P., Oberai, A.A., Jiang, J., Dord, J.F., Goenezen, S., Fisher, T.G., 2011. Recent
10 results in nonlinear strain and modulus imaging. *Current medical imaging reviews*, 7(4), 313.

11 Hild, F., Roux, S., 2006. Digital image correlation: from displacement measurement to identification
12 of elastic properties—a review. *Strain*, 42(2), 69-80.

13 Hild, F., Roux, S., 2008. Correli Q4: A software for-finite-element-displacement field measurements
14 by digital image correlation. *Rapport interne LMT Cachan*, 269.

15 Leclerc, G.E., Charleux, F., Robert, L., Ho-Ba-Tho, M.C., Rhein, C., Latrive, J.P., Bensamoun, S.F.,
16 2013. Analysis of Liver Viscosity Behavior as a Function of Multifrequency Magnetic Resonance
17 Elastography (MMRE) Postprocessing, *J. Magn. Reson. Imaging*, 38(2), pp. 952–957.

18 Moerman, K. M., Holt, C. A., Evans, S. L., Simms, C. K., 2009. Digital image correlation and finite
19 element modelling as a method to determine mechanical properties of human soft tissue in vivo.
20 *Journal of Biomechanics*, 42 (8), 1150 – 1153.

21 Muthupillai, R., Lomas, D.J., Rossman, P.J., Greenleaf, J.F., Manduca, A., Ehman, R.L., 1995.
22 Magnetic resonance elastography by direct visualization of propagating acoustic strain
23 waves. *Science*, 269(5232), 1854-1857.

24 Ophir, J., Cespedes, I., Ponnekanti, H., Yazdi, Y., Li, X., 1991. Elastography: a quantitative method
25 for imaging the elasticity of biological tissues. *Ultrasonic imaging*, 13(2), 111-134.

26 Payne, T., Mitchell, S., Bibb, R., Waters, M., 2015, The evaluation of new multi-material human soft
27 tissue simulants for sports impact surrogates, *Journal of the Mechanical Behavior of Biomedical*
28 *Materials*, 41, 336-356.

1 Ponnekanti, H., Ophir, J., Cespedes, I., 1992. Axial stress distributions between coaxial compressors
2 in elastography: an analytical model. *Ultrasound in medicine & biology*, 18(8), 667-673.

3 Ponnekanti, H., Ophir, J., Cespedes, I., 1994. Ultrasonic imaging of the stress distribution in elastic
4 media due to an external compressor. *Ultrasound in medicine & biology*, 20(1), 27-33.

5 Sandrin, L., Tanter, M., Gennisson, J.L., Catheline, S., Fink, M., 2002a. Shear elasticity probe for soft
6 tissues with 1-D transient elastography. *Ultrasonics, Ferroelectrics and Frequency Control, IEEE*
7 *Transactions on Ultrasonics*, 49(4), 436-446.

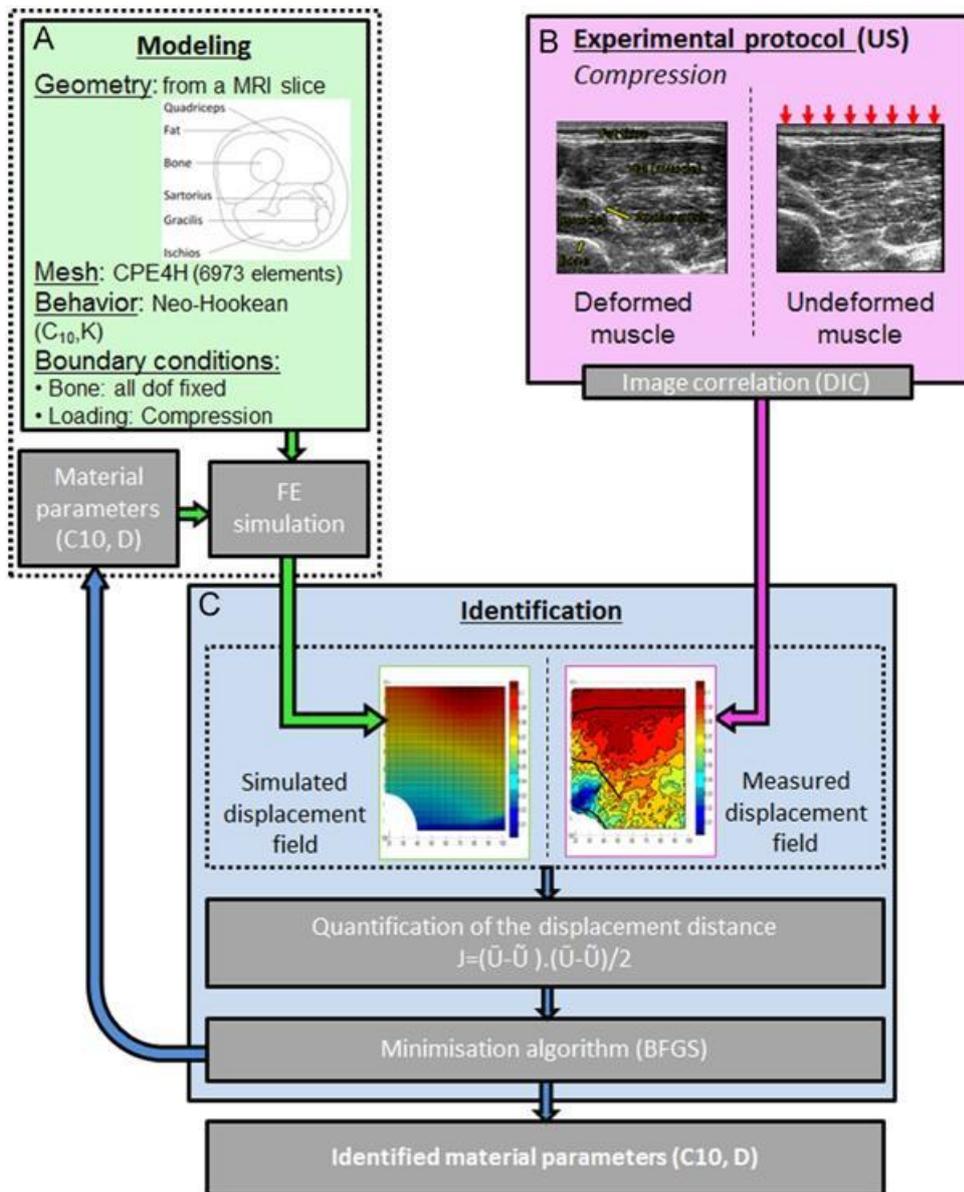
8 Sandrin, L., Tanter, M., Catheline, S., Fink, M., 2002b. Shear modulus imaging with 2-D transient
9 elastography. *Ultrasonics, Ferroelectrics and Frequency Control, IEEE Transactions on*
10 *Ultrasonics*, 49(4), 426-435.

11 Tran, H.V., Charleux, F., Rachik, M., Ehrlacher, A., Ho Ba Tho, M.C., 2007. In vivo characterization
12 of the mechanical properties of human skin derived from MRI and indentation
13 techniques. *Computer methods in biomechanics and biomedical engineering*, 10(6), 401-407.

14 Zhu, Y., Hall, T.J., 2002. A modified block matching method for real-time freehand strain
15 imaging. *Ultrasonic Imaging*, 24(3), 161-176.

16
17
18
19
20
21
22
23
24
25
26
27
28

1 FIGURES



2

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

4 identification.

5

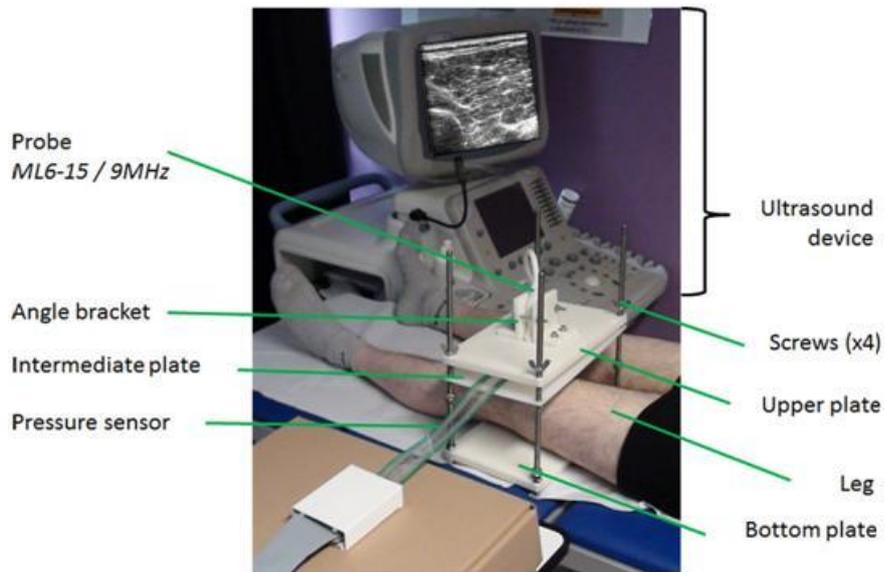
6

7

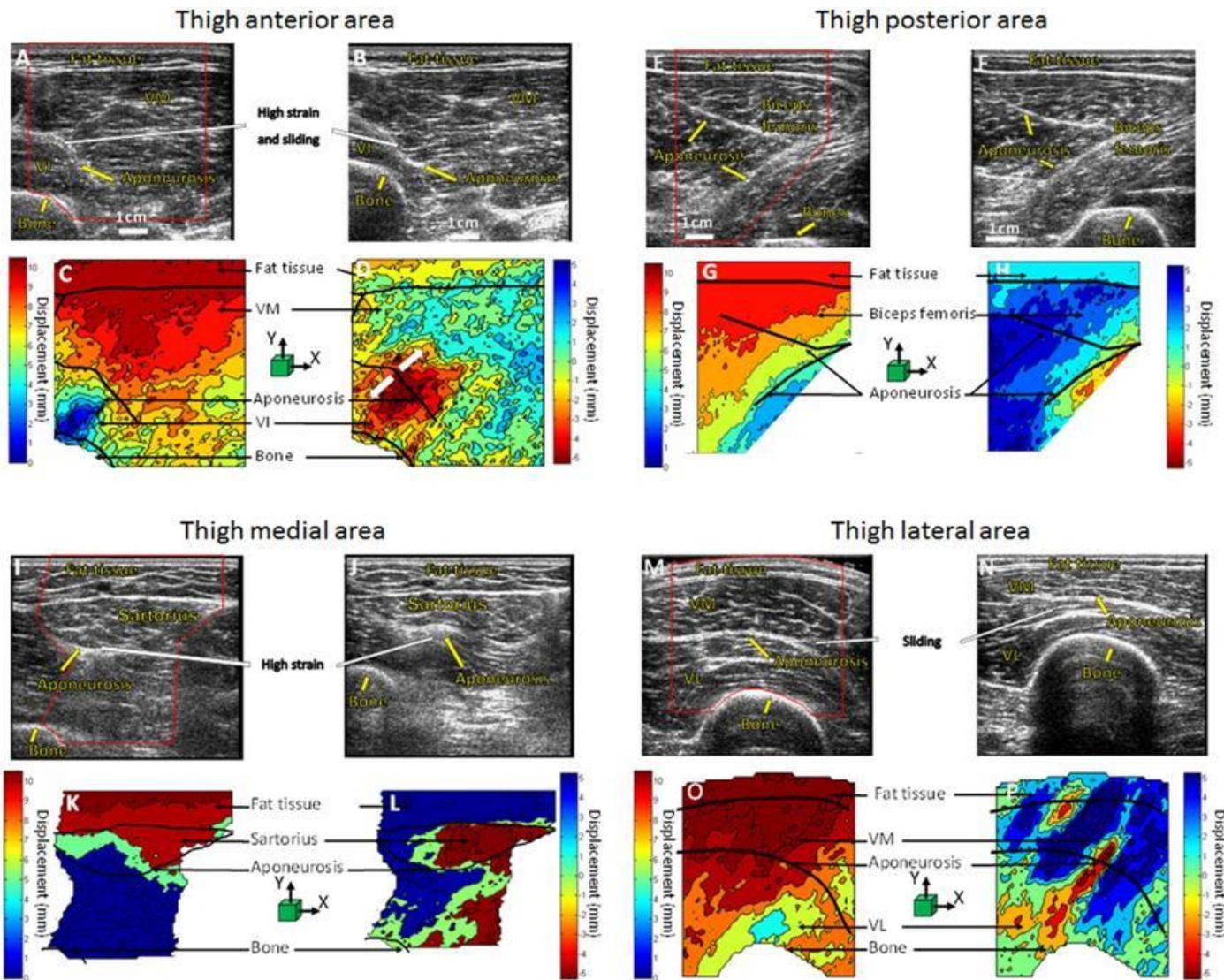
8

9

10

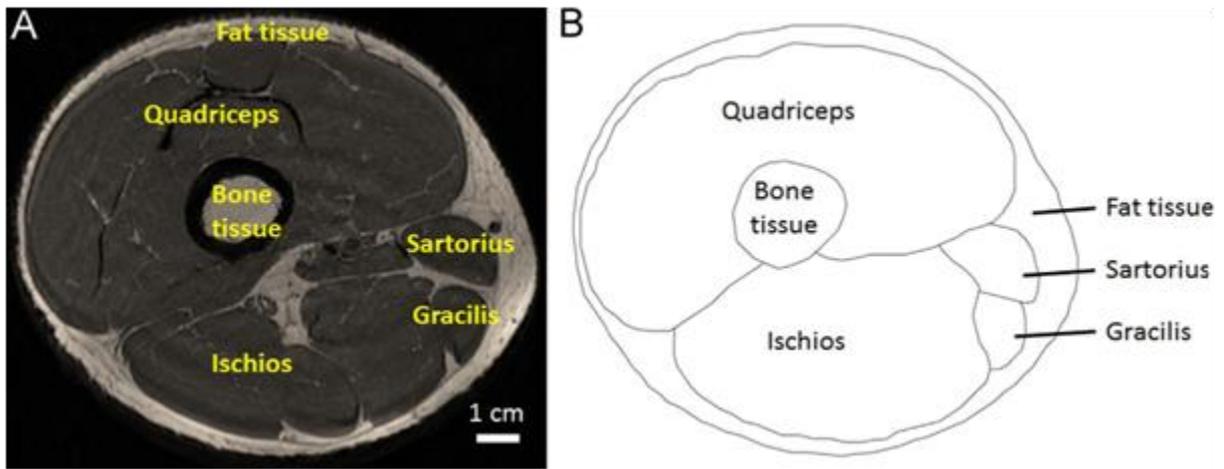


1
2 **Fig. 2.** Home-made compression device.
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20



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 ⁻¹)	C_{10} (kPa)	D (MPa ⁻¹)
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 ⁻¹)	C_{10} (kPa)	D (MPa ⁻¹)	C_{10} (kPa)	D (MPa ⁻¹)	C_{10} (kPa)	D (MPa ⁻¹)
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	-

7