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MATERIAL PROPERTIES CHARACTERIZATION OF THE HUMAN ABDOMINAL MUSCULAR ZONES IN RELAXED AND CONTRACTED STATES: AN APPROACH COMBINING *IN VIVO* EXPERIMENTS AND NUMERICAL SIMULATIONS

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SUMMARY

A methodology was developed to characterize the material properties of the muscular zones of the human abdominal wall (AW) in relaxed and contracted states. It combined *in vivo* experiments and numerical simulations. The material properties of the rectus muscle zone (RMZ) were identified by reverse engineering and the material properties of the lateral muscles zone (LMZ) were coupled with them. The influence of the intra-abdominal pressure (IAP) on the identification was evaluated.

INTRODUCTION

The human AW biomechanics is driven by the characteristics of the AW components (geometry and material properties) and the IAP. There is a large variability of these characteristics in the population and the understanding of their influence is required to optimize ventral hernia repair.

In vivo characterization of the AW geometry is provided by medical imaging. Cobb *et al.* measured *in vivo* the IAP for different activities [1]. However, little is known about *in vivo* material properties of the AW muscles for different activities.

In the present study, the material properties of the abdominal muscular zones were characterized in relaxed and contracted states using an inverse approach. *In vivo* experiments were simulated with biomechanical finite element (FE) models of the AW [2] and the RMZ material properties were identified by reverse engineering [3]. The LMZ material properties were assumed to be coupled with the RMZ material properties.

METHODS

The subject was in a sitting position. AW investigations were carried out first in a relaxed state and then in a contracted state corresponding to the Valsalva maneuver (high IAP).

An indentation experiment was conducted on the AW external surface at the RMZ location. The displacements of the probe and makers fixed on the AW were recorded by 4 cameras. Images were analyzed by the Vic3D software.

The FE model geometry consisted of a posterior layer, shown in Figure 1, covered by an anterior layer composed of the fat and the skin.

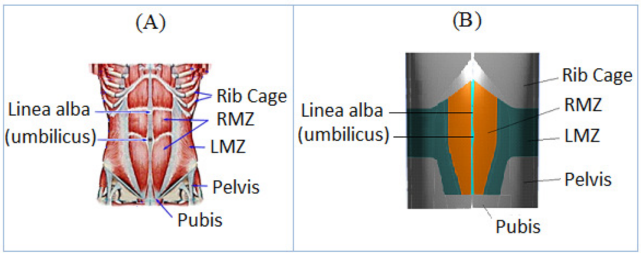

Figure 1: (A): Schematic of the anterior-lateral muscular structures of the human AW and (B): geometry of the FE model posterior layer.

The geometrical subject-specific characteristics were evaluated separately in the two considered states using the positions of the markers fixed on the AW and echographic images.

For the relaxed state, the geometrical parameters of the FE model were fixed at the initial state, with the IAP assumed to be zero (no differential pressure between outside and inside the abdomen). For the contracted state, they were fixed to fit the geometrical characteristics at Valsalva IAP.

The soft tissues were modeled by a neo-Hookean model. The bony structures (the rib cage, the pelvis and the pubis) were assumed as an isotropic linear elastic material.

The RMZ indentation was simulated. Simulations were run using the FE code ANSYS®. For the contracted state, the model was first pressurized to 8.6kPa (mean IAP value for the Valsalva maneuver [1]. The RMZ shear modulus μ_{RMZ} was identified by reverse engineering to fit the reaction force measured by the probe. The LMZ thickness e_{LMZ} and shear modulus μ_{LMZ} were related to the RMZ thickness e_{RMZ} and shear modulus μ_{RMZ} as follows:

$$\begin{cases} e_{LMZ} = e_{RMZ} & \text{Equation 1} \\ \mu_{LMZ} = \alpha \mu_{RMZ} & \text{Equation 2} \end{cases}$$

In the equation 2, α is the ratio between the rectus muscle thickness and the sum of the three lateral muscle thicknesses measured in the experiments. The material properties of the other AW components (linea alba, skin, fat and bony structures) were defined according to the literature [4,5].

RESULTS AND DISCUSSION

Figure 2 illustrates the RMZ indentation: the experiment and the numerical simulation. Figure 3 shows a good fit provided by the neo-Hookean material law.

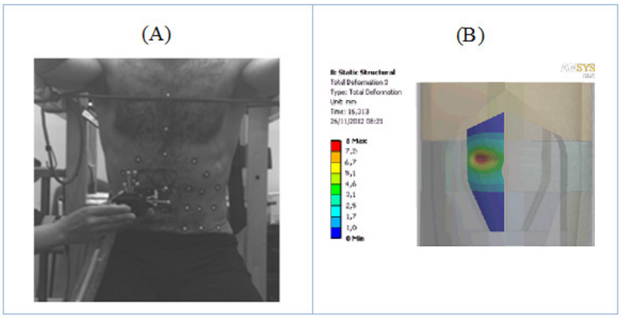

Figure 2: The RMZ indentation in contracted state. (A): a photograph taken during the Valsalva maneuver (B): numerical simulation.

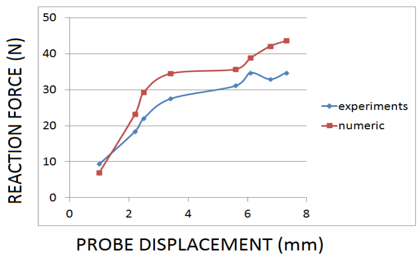

Figure 3: Reaction force measured by the probe during the indentation in the contracted state.

The resulting RMZ and LMZ shear moduli in relaxed and contracted states are given in Table 1.

Since the subject-specific IAP was not measured in the experiment, it was based on the ranges provided in [1]. The influence of the IAP variation on the RMZ shear modulus was evaluated in the ranges corresponding to the considered states. For the contracted state, 80% increase of the IAP (15.5kPa) resulted in approximately 23% decrease of the RMZ shear modulus. For the relax state, if the IAP was set to 2.6kPa instead of 0mmHg, the RMZ shear modulus decreased in approximately 8%.

Table 1: Shear moduli of the abdominal muscular zones.

	Relax state	**Contracted state**
RMZ	0.43 MPa	3.12 MPa
LMZ	0.65 MPa	4.7 MPa

CONCLUSIONS

In vivo human experiments were simulated with FE models exhibiting a subject-specific geometry. The shear modulus of the abdominal rectus zone was identified by an inverse method.

The shear moduli of the AW passive components (linea alba, skin and fat) were not subject-specific. The influence of their variations on the results should be studied in a future work and the relationship between the RMZ and the LMZ shear modulus (Equation 2) should be validated.

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