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A Preliminary Inverse Optimization Method for the Identification of Muscle and Adipose Material Properties in the Context of Pressure Ulcers

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1. Introduction

A current issue in healthcare is the prevention of pressure ulcers: chronic wounds developed from the long-term repetitive loading of soft tissue. Finite element models have been proposed to investigate the internal stresses and strains induced by external loading to better understand the damage occurring within the soft tissue (Linder-Ganz et al. 2008). However, many models do not use personalized material properties despite the reported modifications of soft tissue between healthy and at-risk individuals, and the reported sensitivity of these models to input material properties (Luboz et al. 2014).

Inverse optimization has emerged as a method for identifying personalized material properties, and typically compares the force-displacement curves between the numerical and experimental data results. However, it was demonstrated that this simple comparison is not sufficient to identify a unique set of material properties which characterizes the soft tissue accurately, and the addition of tissue deformation field comparisons in the cost function was proposed (Oddes et al. 2023). Unfortunately, extracting deformation fields experimentally remains an ongoing challenge in research. Thus, the authors propose an inverse optimization method for the identification of Ogden material properties of muscle and adipose tissue which

considers both the force-displacement curves and tissue kinematics parameterization through variables to describe the change in morphology of the tissue.

2. Methods

2.1 Experimental Protocol

The force-displacement data of one individual (male, age: 25) was collected using an improved version of the protocol proposed in (Fougeron et al. 2020). The participant was lying down with his knees beyond the edge of the table for ~90-degree knee flexion to maintain a passive stretching position of the rectus femoris. Mechanical testing was performed by manually indenting the anterior thigh using a handheld linear ultrasound probe (L 18-5) and force sensor. The tracking of points A-C (Figure 1 in red), selected at the highest point of the femur (C) and directly above at the muscle-adipose interface (B) and skin (A), were used to calculate the vertical compression of the tissue. Points D and E (Figure 1 blue) were selected ~1 cm laterally, such that points A-E characterized the change of curvature of the skin and muscle-adipose interface.

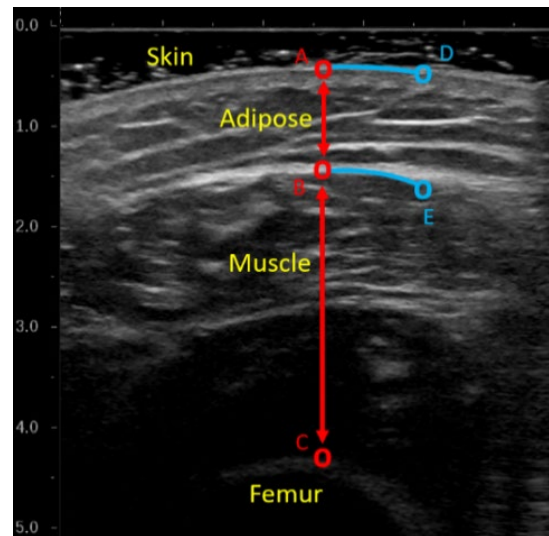


Figure 1. Tissue tracking of skin, muscle-adipose interface, and bone from ultrasound data.

2.2 Finite Element Model

Inverse optimization was performed using a modified version of Fougeron's model which includes the separation between muscle and adipose soft tissue (Fougeron et al. 2020). Both were modeled separately using the standard Ogden hyperelastic constitutive model as shown, where α and μ are the parameters of interest.

$$\Psi = \frac{2\mu}{\alpha^2} (\bar{\lambda}_1^\alpha + \bar{\lambda}_2^\alpha + \bar{\lambda}_3^\alpha - 3) + \frac{1}{D} (J^{el} - 1)$$

Table 1. Optimized material properties from partial (P) and full (F) cost function procedures and their initial starting points (I).

Property	I1	P1	F1	I2	P2	F2	I3	P3	F3
μ_{muscle} (kPa)	0.172	0.396	1.183	1.675	0.395	2.982	1.675	1.665	1.887
α_{muscle}	29	28.3	1.2	27	29.0	14.3	16	15.5	17.7
μ_{fat} (kPa)	1.675	0.356	0.797	0.304	0.186	0.357	0.537	0.196	0.739
α_{fat}	29	29.0	9.8	37	34.3	39.01	32	31.9	29.64

The incompressibility parameter D was calculated using the following relation, where ν is equal to 0.49.

$$D = \frac{3(1 - 2\nu)}{\mu(1 + \nu)}$$

2.3 Inverse Optimization

Previously, the material parameters were optimized using the `fmincon` built-in function in MATLAB and the cost function was defined as the RMSE between the experimental (see Figure 1 in red) and modeled force-displacement curves. An additional term was added which calculated the error in position of all points (in red and blue from Figure 1).

To identify the impact of the new term on the cost function and resulting material properties, two optimizations were launched, where one considered only the force-displacement term (partial) and the second considered the full cost function (full). Both were initialized with 3 different starting points to test whether the additional term of the cost function helps for the identification of a unique set of material points. These results are summarized in Table 1.

3. Results and discussion

The measured change in tissue thickness of the participant was 52% in compression and the hyperelasticity of the tissue was noted in both the force-displacement and stress-strain curves for both tissue types. Table 1 reports the Ogden material properties obtained by different initial starting points and both optimization methods. For the first set of starting points, the optimization procedures calculated markedly different properties for both the muscle and adipose tissue. This difference can be observed for both tissue types with the second set of initial properties, and for the adipose tissue in the third set of initial properties. Thus, the cost function directly impacts the optimized properties, and the addition of the lateral position of the tissue brings valuable information of the tissue deformation to the determination of its material characterization.

However, the initialization of the optimization procedure with different starting points does not result

in the same determined material properties. Additionally, for the third set of initial parameters, both procedures return similar material sets for the muscle. This suggests that the optimizations are falling into local minimums, and the current descent algorithm should be modified or changed to acquire a convergence towards a unique set of parameters.

4. Conclusions

The authors present a new optimization approach which combines the use of force-displacement and points of position for the identification of Ogden material properties of muscle and adipose tissue. The addition of a new term in the cost function is shown to impact the optimized properties. However, as shown with the different starting points, the current descent approach limits the convergence towards a unique set of material properties. This study is an ongoing work towards determining a method which accurately achieves personalized material properties for the characterization of soft tissue.

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Conflict of Interest

The authors report no conflict of interest.

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