Experimental Characterization and Simulation of Layer Interaction in Facial Soft Tissues

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Abstract. Anatomically detailed modeling of soft tissue structures such as the forehead plays an important role in physics based simulations of facial expressions, for surgery planning, and implant design. We present ultrasound measurements of through-layer tissue deformation in different regions of the forehead. These data were used to determine the local dependence of tissue interaction properties in terms of variations in the relative deformation between individual layers. A physically based finite element model of the forehead is developed and simulations are compared with measurements in order to validate local tissue interaction properties. The model is used for simulation of forehead wrinkling during frontalis muscle contraction.

Keywords: tissue layer interaction, facial soft tissues, finite element modeling, ultrasound, wrinkles.

1 Introduction

Understanding the mechanical behavior of facial soft tissues is of great importance for many clinical applications. Physically-based deformation mechanisms describing the tissue response during muscle activation for facial expressions, wrinkle formation, and aging enhance the predictive capabilities of simulations for surgery planning, implant design, diagnosis, and for the animation industry. The experimental characterization of mechanical properties of individual tissues and their interactions, the development of corresponding constitutive model equations, and their implementation into a numerical framework for robust simulations represent key steps towards realistic simulations providing substantial insight into the complex nature of facial soft tissues.

The mechanical characterization of soft biological tissues aims at determining the highly nonlinear, anisotropic, time dependent, and often loading history

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dependent material response. Several different in- and ex-vivo measurement methods have been proposed in literature suitable for the assessment of individual tissues, tissue structures and the interaction of individual facial tissue layers. Barbarino *et al.* applied suction experiments to evaluate skin and deeper layers [2]. Hendriks *et al.* [6] present a combined suction based experimental and finite element (FE) modeling approach allowing to quantify the relative contribution of different skin layers (e.g. epidermis and dermis) to the overall tissue response. The specific method provides an estimation of material properties and a description of the connection between the epidermis and dermis layer of human skin. The related through-plane layer behavior of full-thickness skin tissue was investigated by Gerhardt *et al.* [5] in shear experiments. Real-time video recording captured skin layer deformations used to perform a displacement, strain, and stiffness analysis as well as the assessment of tissue layer interaction.

In-vivo quantitative visualization of tissue deformation provides essential information on the mechanical interaction between individual layers. Ultrasonography is a widely used measurement method due to its highly flexible applicability, the possibility of combining it with real-time mechanical testing, and good spatial resolution. Analysis of ultrasound images during mechanical tests provides displacement fields and corresponding strain mappings for the quantification of tissue properties as presented by Tang *et al.* [12] for porcine sclera; Vogt and Ermert [13] and Diridollou *et al.* [4] for skin tissue. Real-time ultrasound measurements allow to visualize tissue behavior due to voluntary muscle contraction in terms of tissue motion and relative tissue deformation. Such experiments are presented by Wu *et al.* [18] who investigated masseter muscle tissue motion and shape changes during active contraction as well as tissue interaction between muscle and neighboring tissues.

Our work aims at improving with respect to existing FE models [3,17,14] in terms of physical relevance of soft tissue geometry and mechanical response. In recent papers we have demonstrated the implementation of advanced active and passive constitutive models of face tissue [15,16], as well as the accurate representation of anatomical features, and realistic boundary conditions [3]. Our model allows to simulate facial expressions and wrinkling by incorporating experimentally quantified interaction properties of individual tissue layers. In contrast to the general assumption of tight contact between all tissue layers, there are distinct tissue interfaces that exhibit significant relative tissue movement upon shearing. The present paper describes the procedure applied to determine the mechanical properties of the interaction between specific tissue layers in different regions of the forehead by means of ultrasound-based visualization of the tissue displacement field during pull-experiments. The anatomy of the forehead displays a layered organization of tissues characterized by a distinct local variation in their interactions [8,9]. The forehead is easily accessible for ultrasound measurements and is clearly bound by skin surface and skull ensuring sufficient repeatability and high accuracy in measurement data. The experimentally observed through-layer tissue deformation and corresponding properties of layer interaction are projected onto an anatomically detailed finite element model of the forehead. This FE model serves as a benchmark for evaluating layer interaction properties in the simulation of the pull-experiments and the formation of forehead wrinkles upon muscle contraction.

2 Experimental Characterization of Tissue Interaction

The forehead is a layered tissue structure consisting of skin, subcutaneous fat, galea aponeurotica, loose areolar tissue, muscle, and periosteum. The two layers of skin and subcutaneous fat are present across the whole forehead and are rather constant in thickness. The distribution of the other tissues varies locally, and the temporal fusion line generally divides the medial and temporal zone; it consists of stiff connective tissue that inserts onto the skull, see ultrasound images in Figure 1 and work by [9].

The frontalis muscle is the main active tissue in the forehead and it is primarily responsible for lifting the eyebrows during facial expressions and the resulting formation of forehead wrinkles. The muscle fibers insert into the dermis in the lower forehead enabling a maximum tissue lift upon contraction. Movement of the eyebrow is enhanced by loose areolar tissue and galea fat pads surrounding the frontalis muscle which form a glide plane allowing for reversible relative movement between superficial skin and subcutaneous tissue and the deeper tissues [8,7,11].

The locally varying tissue interactions are characterized by means of ultrasound-based visualization of the through-layer displacement field upon application of external skin displacement. The experimental setup is based on work presented by [1] and consists of a chin rest as used in ophthalmology which was modified to include a clamping device for the ultrasound probe. The experimental setup was optimized for (i) reproducible alignment of the subject's forehead and the ultrasound probe for multiple consecutive measurements, (ii) an adjustable orientation of the transducer with respect to the curvature of the forehead for optimal image quality, (iii) minimal movement between subject and transducer during individual measurement sequences, and (iv) flexibility in measurement site and displacement magnitude. Measurements were performed on a 29 year old subject using a *GE Logiq E9* ultrasound machine with a *L8-18i-D* broad-spectrum linear transducer operating at 15 MHz with a field of view of 25mm. 6 seconds video sequences (33 fps) were recorded to capture a full loading and unloading cycle consisting of a horizontal displacement of a tape attached to the skin. Location dependence of tissue response was assessed by measuring in the medial and temporal forehead including the temporal fusion line.

The image sequences were analyzed in order to extract the deformation field within the soft tissue structure. Based on the optical flow tracking algorithm introduced by Lucas and Kanade [10], multiple regular grids were aligned tangentially to the surface of the skin in order to visualize the gradient of deformation through the individual tissue layers. Densely connected tissue layers show a rather homogeneous displacement field across the layer boundary, while loosely connected tissues experience a pronounced gradient. Moreover, the deformation

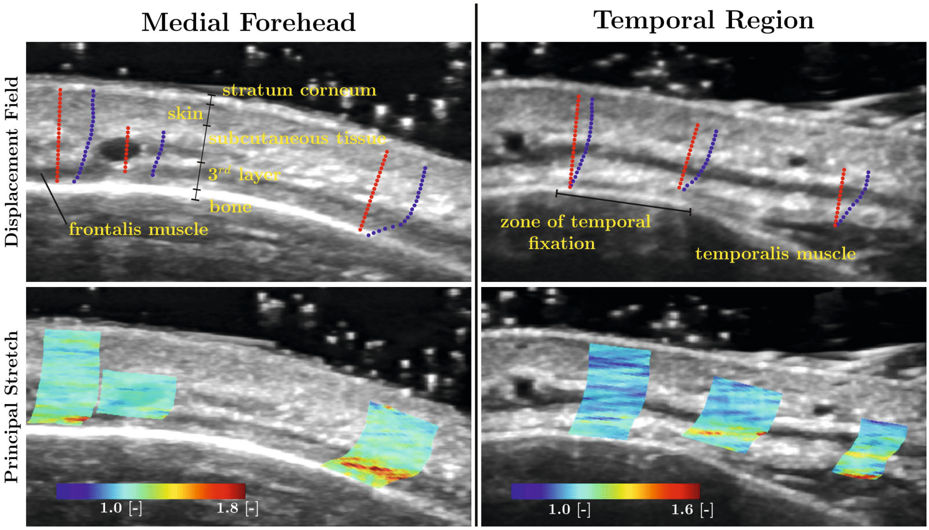

Fig. 1. Ultrasound measurements in the medial and temporal forehead. Tissue layer interaction is quantified through the evaluation of the displacement field and principal stretch in the measurement plane.

distribution provides an indirect measure of the stiffness of individual layers. The difference in the gradient between two neighboring layers depends on the stiffness ratio between both tissues. Figure 1 shows the displacement field and maximum principal stretch for a representative measurement in the medial and the temporal forehead region.

The measurement results are found to provide significant quantitative and qualitative information on the mechanical properties between individual layers and comprehensively visualize the effects of the highly differentiated forehead anatomy on the tissue response. The image resolution allows to distinguish between three characteristic main tissue layers (see Figure 1): (i) skin as the most superficial layer including the stratum corneum which appears very bright due to reflections at the boundary between gel and skin surface; (ii) SMAS or the subcutaneous tissue layer; (iii) the third layer consists of muscle fibers that are embedded in loose areolar tissue. The structure of the third layer varies significantly when moving across the forehead, i.e. the temporalis muscle lies on top of the temporal bone, the frontalis muscle covers the medial forehead, and the temporal fusion line represents the transition zone between medial and temporal forehead. The temporal fusion line is characterized by a strong interaction between all layers and provides substantial support to the whole forehead.

In general, both measurement sites show a similar behavior in terms of the deformation gradient in the two most superficial layers. Skin and subcutaneous tissue exhibit a homogeneous displacement field and a similar and almost constant deformation gradient across both layers. The difference in stiffness between skin and underlying tissue is indicated by a minor change in the slope of the displacement gradient as visible in Figure 1 at the transition from the most superficial to the second tissue layer. The third layer, however, shows a locally dependent but consistently pronounced drop in the displacement magnitude. The externally applied displacement of skin propagates through the rather stiff superficial layers all the way to the third layer. The much softer third layer of loose areolar and fat tissue exhibits significant shearing to compensate for the propagated displacement. The significant shear response of the loose areolar tissue, expressed in a large relative movement between the second layer and bone, is often associated with a gliding response of individual layers [8]. This relative movement is fully reversible upon unloading (e.g. relaxation of the muscle after a facial expression) and is apparent in the full recovery of the initial tissue state. This interaction property is evident in both, medial and temporal region. However, the measurements strongly indicate that specifically in the zone of fixation (i.e. temporal fusion line) this relative motion is fully inhibited by the strong connectivity between all layers. This is most visible in the plots of the temporal region which are characterized by a homogeneous deformation field and a very smooth gradient in comparison to the medial forehead. Finally, the principal stretch provides an additional measure to quantify the individual tissue properties.

3 Simulation of Tissue Response

An anatomically detailed finite element model of the forehead was reconstructed from MR images and consists of a multi-layered tissue structure including skin, subcutaneous tissue, a third layer with locally dependent material properties, periosteum, and temporalis muscle. The frontalis muscle is embedded in the soft areolar tissue of the third layer and inserts into subcutaneous tissue and skin close to the region of the eyebrows enabling the lift of surrounding tissue during facial expressions and wrinkle formation due to muscle contraction and tissue compression. The lower part of the face is included in this model for visualization purposes. The forehead model introduced here was generated similar to the procedure presented in [3].

Skin, subcutaneous tissue, and the third layer are tied at their individual layer surfaces to form a densely connected tissue structure. Based on the experimental observations shown in Figure 1, the interaction between the lower surface of the third layer and periosteum varies locally. In the medial forehead and superficial to the temporalis muscle, the third layer is free to slide on top of the periosteum. In proximity of the temporal fusion line, these two tissue layers are tied together, to accurately represent the dense connectivity between all tissues in the transition zone from medial to temporal forehead as described by [8]. The mechanical behavior of the active muscle and passive soft tissue layers is based on the implementation of constitutive material models as presented in [15,16]. The corresponding material parameters for facial skin were determined from suction-based in-vivo experiments on the same subject.

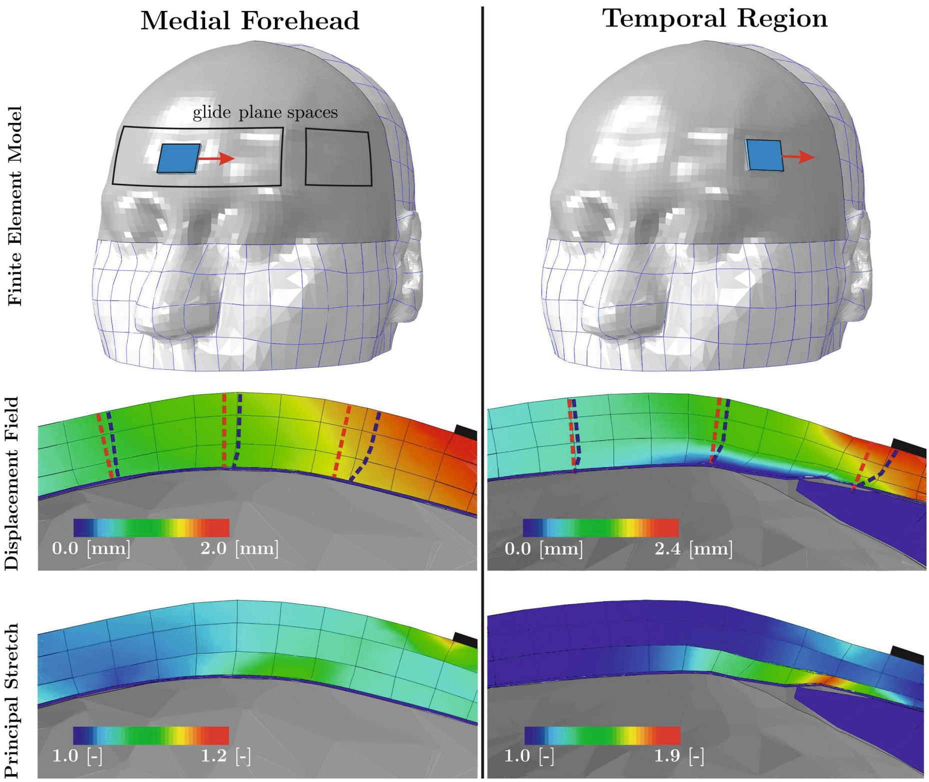

Fig. 2. FE model of pull-experiments (tape in experiments modeled by the rigid element in blue; black squares indicate regions of frictionless contact). Through-layer deformation and principal stretch fields for a sagittal cut close to the loading point.

The forehead model is used to investigate the experimentally observed tissue behavior and to validate the proposed interaction properties. The results from the numerical evaluation of the pull-experiments are shown in Figure 2 in terms of the through-layer displacement field and the corresponding principal stretch in a sagittal cut close to the loading point. A comparison of displacement magnitudes from simulation and experiment for selected points revealed an error of less than 20% which shows the significant predictive capability of the model with respect to location dependent tissue deformation and pronounced shearing. The displacement fields represent same material points at their initial position and at maximum displacement. The sliding of the third layer over periosteum causes enhanced mobility of all superficial layers which is clearly visible in the large displacement of material points across the entire thickness. Modeling the pronounced intergrowth of tissues in the zone of fixation as tightly connected layers attached to the layer of periosteum yields good agreement with the experiments showing limited displacement close to the bone and a small displacement gradient across subcutaneous tissue and skin. The connection between tissue

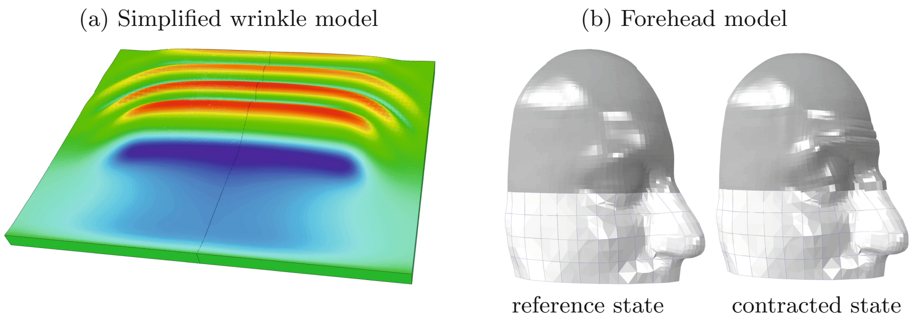

Fig. 3. (a) Deformation pattern of a simplified forehead wrinkling model (b) Simulation of frontalis muscle contraction (as in facial expressions) using the full benchmark forehead model

layers corresponds to contact conditions for which tight contact and free sliding represent limiting cases. The proposed configurations simplify the anatomical features of (i) connective collagen fibers between individual tissue layers, (ii) the embedment of frontalis muscle fibers in surrounding tissue, and (iii) the observable shearing behavior of loose areolar tissue in the forehead. However, given the predictive capabilities of the model with respect to the experimental observations, the proposed interaction properties are well justified.

A simulation of wrinkle formation is numerically challenging and requires a sophisticated numerical framework with respect to robust numerical implementations of material models and a suitable geometric discretization of the individual structures. Figure 3 shows a simplified FE model to investigate typical forehead wrinkle patterns and the simulation results based on the forehead model for the case of active frontalis muscle contraction and the resulting wrinkle formation. The model including the proposed layer interaction properties provides a suitable representation of forehead wrinkles.

4 Conclusions

An experimental setup for the visualization of full-thickness facial tissue deformation during external skin displacement and facial expressions was developed and allowed to determine location dependent properties of layer interaction in terms of inter-tissue displacement gradients. Our measurements suggest to differentiate between two different configurations: (i) a strong connection between two layers (i.e. for skin and subcutaneous tissue or for all tissues close to the temporal fusion line) and (ii) a very loose connection as in free sliding (i.e. for tissues above the eyebrow in order to enable maximum lift upon frontalis muscle contraction during facial expression).

An anatomically detailed forehead model was reconstructed from MR images and used in the simulation of pull-experiments to validate the proposed interaction properties between specific tissue layers. The physically based representation of tissue interaction properties made it possible to simulate the formation of wrinkles.

In future work, the experimental method will be employed to quantify age- and health-related changes in the observed tissue response. These measurements could form part of a diagnostic tool to quantify the impact of dermatological diseases such as fibrosis. Additionally, our experimental findings will be incorporated in the finite element model of the face [3] to simulate the tissue response during facial expression and mastication.

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