Modeling the Non-Linear and Anisotropic Properties of *in-vivo* Human Skin

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Abstract— **A combination of multiaxial loading experiments and finite element modeling has been used to investigate the mechanical behavior of *in-vivo* human skin. A forward solve algorithem, incorporating natural residual skin tension, was developed in order to estimate values for the material parameters of a constitutive law. This law described the quasi-static stress-strain relationship in human skin as a non-linear anisotropic material using an exponential strain energy function. Differences in the stress-strain relationship were observed on a single body location, between comparable subjects.**

Keywords— **Finite element modeling, *in-vivo* human skin, multiaxial loading experiments,**

I. Introduction

Langer was the first to investigate the relation between structure and mechanical behavior in human skin [1]. From the observation that stab wounds caused by a circular object had an oval shape, he derived a set of lines indicating the directions in skin with the least amount of cross-sectional residual tension. Microscopic investigations showed that these lines coincided with the predominant collagen directions within the skin. Langer's lines are a map of the anisotropy in human skin, and define the coordinate system for a constitutive law based on the structural directions within the tissue. Human skin is in general anisotropic, non-linear and exhibits strong viscoelastic behavior [2]. The requirement for preconditioning of the sample, in order to achieve a repeatable stress-strain relationship between loading cycles, and loss of strain energy between loading and unloading cycles, has been reported [3]. To complicate matters, differences in mechanical behavior have been shown to be dependent on age and body location [4, 5]. In order to accurately describe the mechanical behavior of most types of soft tissue, a constitutive model has to account for the anisotropic and non-linear stress-strain properties. There are many constitutive laws presented in the literature that are capable of modeling this behavior in human skin [6-8]. None of these models does however incorporate viscoelastic properties, and the common practice in biaxial and multiaxial loading experiments has been to use quasi-static deformations to model the tissue behavior.

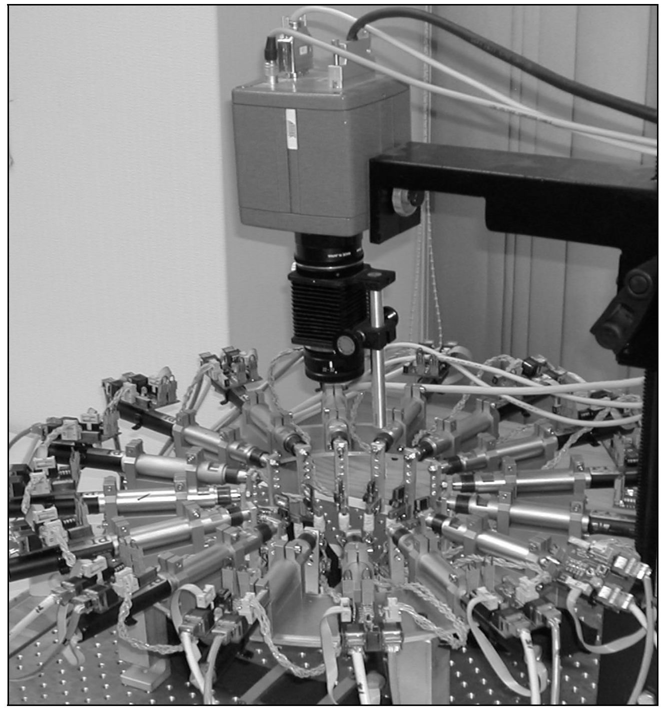

Figure 1: The multiaxial testing rig

II. Methodology

A multiaxial testing rig, Figure 1, was used in this study in order to investigate the stress-strain properties of in-vivo human skin. The rig was equipped with a circular array of sixteen displacement actuators (*Physike Instruments*), each with a travel range of 50 mm and a resolution of 0.1 µm. This arrangement allowed deformations to be imposed along eight separate axes of the sample simultaneously. Each actuator was equipped with a custom build 2-D force transducer, with a range of 2 N and a resolution of 1 mN. These transducers measure the force vectors associated with each of the sixteen attachment points of the tissue sample. The geometry of the sample and its deformations were recorded using a high resolution CCD camera (*Atmel*). The actuator control, data acquisition from the force transducers, and the image acquisition from the camera were all performed using an integrated software system developed with LabView (*National Instruments*). This software supported actuator control in either position or force feedback modes, allowing deformation states to be specified in terms of stress or strain.

The deformations in the tissue were traced between different deformation states by performing a two-dimensional cross-correlation on subsets of the images [9]. This technique traced the displacements of small regions, typically 64x64 pixels, with an accuracy of up to one twentieth of a pixel. The accuracy of the cross-correlation relies on high-contrast high-frequency information within the images, which was provided by staining the tissue sample with fine-grain carbon powder before each experiment.

Data from experiments were combined in a finite element model to analyze the sample deformations. The geometry of the samples was represented with a circular mesh of 192 elements, using bi-cubic hermite basis functions, and the skin modeled in two-dimensions as an incompressible material using plane-stress theory. The displacements of the nodal positions in a deformed state are, in Figure 2, used to illustrate the deformation of the geometry upon applying loading at the sixteen attachment nodes. An additional 800 internal data points were traced using the cross-correlation technique. The displacements of these were used for geometrical fitting when estimating the material parameters of a constitutive law.

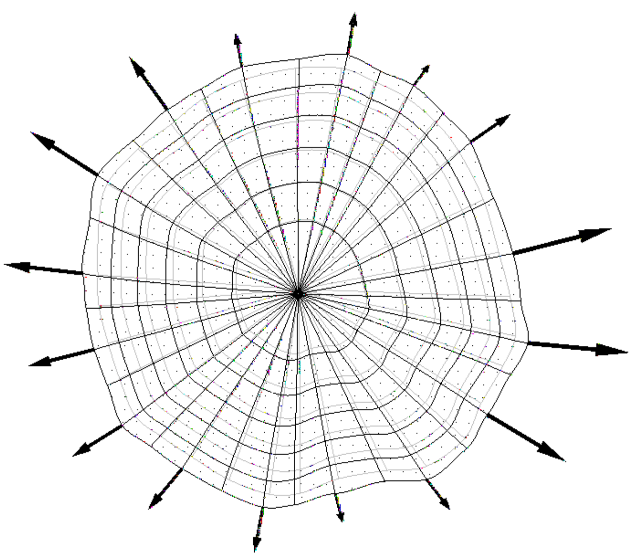

Figure 2: The finite element model of a test sample containing all data from a single deformed state of an experiment on *in-vivo* human skin. The light grey mesh represents the undeformed geometry. The deformations occurring when the sample is subject to loading, indicated by the force vector arrows, are represented by the black mesh. The dots indicate the data points used to evaluate geometrical residuals during estimations of the constitutive stress-strain relationship.

A technique was developed to estimate material parameters of constitutive laws using a forward solve algorithm. A typical experiment had multiple loading cycles, where each consisted of up to fifteen deformation states with associated boundary forces. With an initial estimate of the material parameters, the constitutive model initially solved the forward problem for each deformed state of a loading cycle by applying the recorded boundary forces to the undeformed geometry. The algorithm then proceeded by applying small changes to each of the material parameters, and for each change solving the forward problem for all of the deformed states. For each solution, geometric residuals were evaluated between the simulated deformations and the experimentally determined displacements at each of the data point. As comparisons were made between the displacements at each deformed state of a loading cycle, a total of ~10,000 residuals were used for the optimization. Once all the geometric residuals were obtained, a non-linear, least square, optimization algorithm evaluated new estimates of the material parameters in the constitutive law. The complete forward solve procedure was repeated until the parameter estimates satisfied a specified optimizer criterion, which indicated that an optimal solution had been found.

The experimental data was fitted to an exponential strain energy function, originally derived by Tong and Fung [6] to describe the behavior of rabbit skin subject to biaxial loading [3]. This constitutive law models quasi-static stress-strain properties of skin as an anisotropic, non-linear material, and is given by:

$$W = \frac{1}{2}\left(\alpha_1 e_1^2 + \alpha_2 e_2^2 + \alpha_3 e_{12}^2 + 2\alpha_4 e_1 e_2\right)$$
$$+ \frac{1}{2} c \exp\left(a_1 e_1^2 + a_2 e_2^2 + a_3 e_{12}^2 + 2a_4 e_1 e_2 + \gamma_1 e_1^3 + \gamma_2 e_2^3 + \gamma_4 e_1^2 e_2 + \gamma_5 e_1 e_2^2\right)$$

where e_1, e_2, and e_{12} are the strain components. The equation has a total of thirteen material parameters (α, c, a and γ) that need to be estimated from experimental data.

III. Results

The stress-strain curves generated from Tong and Fung's strain energy function, using material parameters obtained from four experiments, are shown in Figure 3. These experiments were performed on the skin of the inner part of the forearm, on three different age and gender matched subjects. Differences between the subjects were observed, while the two experiments performed on the same subject only showed minor differences. Dependencies on body location and age in the mechanical behavior of human skin have previously been shown [4, 5]. The result from the current study further shows that variations must also be expected for a single location on comparable subjects. This indicates that accurate simulations of the stress-strain behavior in human skin, in a clinical contest, can only be achieved if these simulations are based on experimental data obtained from the specific sample in question.

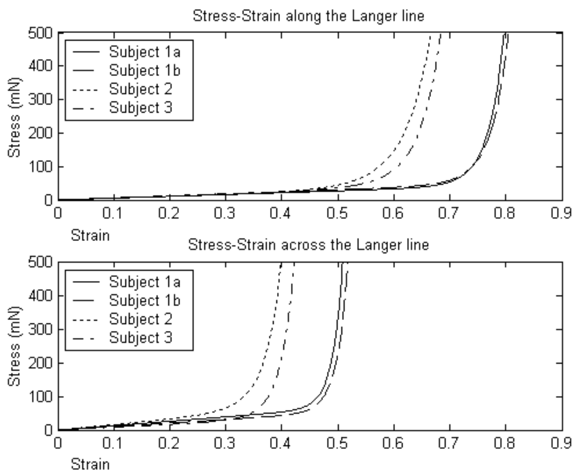

Figure 3: The stress-strain relationship generated from a constitutive model using material parameter values estimated from *in-vivo* experiments on human skin, of three individuals. The two experiments on the same subject were conducted on the same body location two weeks apart.

IV. Discussion

The combination of multiaxial loading experiments and finite element analysis was successfully used to investigate the mechanical properties of *in-vivo* human skin. Estimates of material parameter values for a constitutive law describing the anisotropic and non-linear stress-strain properties of human skin was obtained from multiple experiments. The variations between the estimated parameter values indicate that differences of mechanical properties exist between similar individuals.

In order to describe accurately the mechanical behavior of most types of soft tissue, a constitutive model has to account for the anisotropic and non-linear stress-strain properties. There are many constitutive laws presented in the literature that are capable of modeling these properties in different soft tissue types [6-8]. Most soft tissues does, however, also exhibit strong viscoelastic behavior showing stress relaxation and creep, and a constitutive law will not be complete without incorporating these time dependent effects. The multiaxial testing rig was successfully used to obtain viscoelastic measurements. However, only quasi-static deformation data was modeled, due to a lack of constitutive laws capable of modeling this behavior.

One limitation of the multiaxial testing rig was that it could only obtain data in 2-D. The finite element analysis thus correspondingly modeled the tissue as a 2-D membrane using plain stress theory. In order to improve the model accuracy further, more detailed information of the tissue microstructure in the third dimension would be required. We are currently investigating combining multiaxial loading with optical coherence tomography as a method for determining this information.

Acknowledgment

The authors would like to thank Sharif Malak, Rob Kirton, Martyn Nash, Kevin Augenstein, Duane Malcolm, Poul Charette, Peter Hunter, and David Budgett for help and contributions to the development and testing of the multiaxial rig and the finite element analysis techniques.

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