# Physically Valid Surgical Simulators: Linear Versus Nonlinear Tissue Models

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**Abstract.** Realistic modeling of the interaction between surgical instruments and organs has been recognized as a key requirement in the development of high-fidelity surgical simulators. For a nonlinear model, the well-known Poynting effect developed during shearing of the tissue results in normal forces not seen in a linear elastic model. It is demonstrated that the difference in force magnitude for myocardial tissue is larger than the just noticeable difference for contact force discrimination thresholds published in the psychophysics literature. This work also proposes the validation of simulators by careful examination of relevant simulator design parameters that relate to final simulator behaviors affecting clinical outcomes.

**Keywords.** elasticity, force feedback, poynting effect, surgical simulation, tissues

## 1. Introduction

The development of a high-fidelity surgical simulator involves many steps, including: determining the constitutive law that describes an organ's response to applied loads, building a computational model that simulates tool-tissue interaction behavior in real time, generating visual and haptic displays that present the user with the tool-tissue interaction responses, and creating a curriculum and/or feedback mechanisms that aim to improve operator performance. Validation of surgical simulators is essential to motivate their application as a method for training and pre- or intra-operative planning. Validation techniques can be subjective (e.g. face and content validation) or objective (e.g. construct, concurrent, and predictive validation) [1].

In this work we propose that each stage of the surgical simulator development process acts as a "filter" in which information about force-motion relationships are lost or transformed (Figure 1). For example, the filter may be a result of (1) the resolution of the measurement devices used for gathering experimental data, (2) limitations in the tissue model based on the constitutive law derived from experimental data, (3) simplification of the model required to perform real-time graphic and haptic rendering, or (4) the force resolution of the haptic device.

[1] This research was supported by NSF Grant No. EIA-0312551 and NIH Grant No. R01-EB002004. The authors would also like to acknowledge help from Matthew Moses with the experimental setup.

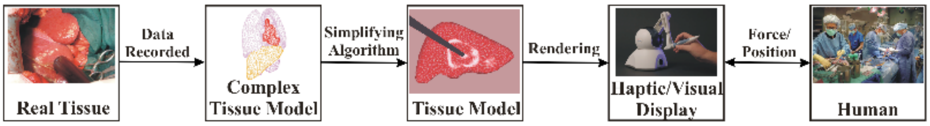



**Figure 1.** Modeling the information flow in simulator development and application. Each stage acts as a "filter" in which information about force-motion relationships are lost or transformed. Images from [6,7,8,9,10].

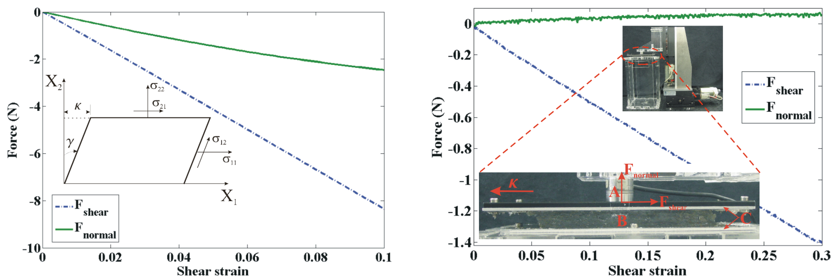
## 2. Methods and Results

Primarily due to computational considerations, most simulators have assumed non-physical or linear elasticity-based models for tissues, even though human soft tissues generally possess nonlinear viscoelastic properties. Using the principles of continuum mechanics and hyperelasticity, we demonstrate here that, for a nonlinear model, palpation of tissue may result in normal forces not seen in a linear elastic model. Shear is considered because it is common practice for clinicians to palpate and perform a shearing motion on the organ either by hand or with an instrument. We considered bovine myocardial tissue and Sylgard 527 gel samples, which are often used as models for human heart and brain tissue, respectively.

We used data both from prior work (for myocardial tissue) and new experiments (for Sylgard gel). The material properties were obtained for myocardial tissue using biaxial test data [2], and for Sylgard gel using the Rheometrics Solids Analyzer (RSA) II for compression and shear experiments. Analytical nonlinear stress-strain expressions for the palpation task were derived for both materials. Figure 2(a) provides the shear and normal forces that would be developed on the shear plane for palpation of myocardial tissue. The presence of stress in the normal direction, $\sigma_{22}$, and the inequality, $\sigma_{11} \neq \sigma_{22}$, is due to the nonlinearity of the material; linear models report zero stress in these directions. The stress-strain relationship is derived using an exponential strain energy function that accounts for anisotropy in myocardial tissue fibers [2]. A normal force of $2.46$ N is generated by a $10\%$ shear of bovine myocardial tissue, which is significantly larger than the absolute human perception threshold for force discrimination [4]. In contrast, the only stress developed for the commonly implemented linear elastic tissue model is $\sigma_{12} = G\kappa$, where $G$ is the shear modulus, $\kappa$ is shear strain, and all normal forces are masked by the linear elasticity assumption. In addition to the evaluation of material parameters of Sylgard gel (using RSA II), large gel samples that are representative of actual organ sizes, of dimensions $100$ mm $\times$ $50$ mm, and $5$ mm, $7.5$ mm and $10$ mm thick were sheared ($30\%$, $50\%$, and $80\%$) using a robot (Figure 2(b)). The robot experimental setup is designed to replicate palpation of Sylgard gel. In this case, the normal forces generated are less than the absolute human perception threshold for force discrimination.

## 3. Discussion

The presence of normal forces during shearing of tissue is a consequence of the nonlinearity of the material, which is not observed in linear elastic or non-physical models. For isotropic materials, this phenomenon is known as the Poynting effect. Though linear elastic models are computationally simple and easy to implement, such models do not exhibit the Poynting effect. Depending on the type of tissue (e.g. myocardial tissue




(a) (b)

**Figure 2.** (a) Shear and normal forces developed on the shear plane of area 100 mm $\times$ 50 mm, during palpation (10% shear) of bovine myocardial tissue. Inset: The palpation task is simplified to be the simple shear problem; the shear strain is $\kappa$ in the $X_1$ direction. (b) Shear and normal forces developed on the Sylgard 527 gel sample of dimensions 100 mm $\times$ 50 mm $\times$ 10 mm (thick). Inset: Robot shearing the Sylgard gel samples, where A, B, and C are the Nano17 force sensor, Sylgard gel sample, and metal plates used for shearing, respectively.

versus Sylgard gel) being sheared, the normal forces generated could significantly affect tissue deformation, as well as the magnitude and direction of force feedback provided during surgical simulation. Further, tissue models solely based on one set of experiments, e.g. compression or indentation tests, are not sufficient to describe tissue deformation characteristics accurately [4].

This study provides a concrete example of how tissue modeling techniques relate to haptic feedback in surgical simulators. Rendering of haptic and/or visual feedback in real time, in conjunction with nonlinear tissue models, is possible but computationally intensive, as demonstrated in [5]. Considering physical phenomena such as the Poynting effect, which is significant for some organs but may not be for others, will allow researchers to make justified simplifications to enable realistic, real-time simulation of realistic tool-tissue interactions. One area of future work is to analyze each source of information loss in the modeling procedure (Figure 1), and link them to metrics related to simulator realism, human perception, and clinical outcomes.

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