

# A sensitivity analysis method and its application in physics-based nonrigid motion modeling<sup>☆</sup>

Yong Zhang<sup>a,\*</sup>, Dmitry B. Goldgof<sup>b,1</sup>, Sudeep Sarkar<sup>b</sup>, Leonid V. Tsap<sup>c</sup>

<sup>a</sup> Department of Computer Science and Information Systems, Youngstown State University, Youngstown, OH 44555, USA

<sup>b</sup> Department of Computer Science and Engineering, University of South Florida, 4202 East Fowler Avenue, Tampa, FL 33620, USA

<sup>c</sup> Advanced Communications and Signal Processing Group, Electronics Engineering Department, University of California Lawrence Livermore National Laboratory, Livermore, CA 94551, USA

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## Abstract

Parameters used in physical models for nonrigid and articulated motion analysis are often not known with high precision. It has been recognized that commonly used assumptions about the parameters may have adverse effect on modeling quality. In this paper, we present an efficient sensitivity analysis method to assess the impact of those assumptions by examining the model's spatial response to parameter perturbation. Numerical experiments with a synthetic model and skin tissues show that: (1) normalized sensitivity distribution can help determine the relative importance of different parameters; (2) dimensional sensitivity is useful in the assessment of a particular parameter assumption; and (3) models are more sensitive at the locations of property discontinuity (heterogeneity). The formulation of the proposed sensitivity analysis method is general and can be applied to assessment of other types of assumptions, such as those related to nonlinearity and anisotropy.

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## 1. Introduction

During the past two decades, physics-based modeling has emerged as one of the most important techniques for nonrigid and articulated motion analysis [18]. Its popularity is evidenced by the increasing number of publications each year as well as the diversity of the fields in which the papers appeared. For example, physical model has found applications in: nonrigid and articulated motion tracking [21,22,15,34], realistic facial animation [19,17], surgery simulation and operation planning [6,3,7], elastic medical image registration [4,36,14], dynamic cloud simulation using satellite images [33], as well as shape representation and recognition [25,24], to name a few. More

comprehensive survey and in-depth discussions on physics-based nonrigid motion analysis can be found in [1,20].

In comparison to geometrical and mass-spring models, physical models that are based on continuum mechanics have high computational complexity. As a result, various assumptions are often made to simplify the model and its parameters. For example, a commonly used assumption is that the material properties of an object are isotropic and homogeneous. However, results from large amount of biomechanical tests [12] indicate that the mechanical behavior of many biological materials, especially soft tissues, cannot be accurately described by such a simplified model. Certain types of muscles (such as skeletal muscle) are characterized by strong anisotropic behaviors. More importantly, the property heterogeneity of several orders of magnitude is also common in human organs [9]. Recently, measuring elastic property of abnormalities caused by the pathological processes has been utilized for early cancer detection [11,10].

Recognizing the inadequacy of simplified physical models, researchers have started to investigate to what degree the various assumptions, especially those about the material properties and the boundary conditions, may affect the model's performance by means of sensitivity analysis. For example, Alterovitz et al. [2] studied the influence of both the physician-controlled

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\* Corresponding author. Tel.: +1 330 941 1786; fax: +1 330 941 2284.

E-mail addresses: [yzhang@cis.yzu.edu](mailto:yzhang@cis.yzu.edu) (Y. Zhang), [goldgof@cse.usf.edu](mailto:goldgof@cse.usf.edu) (D.B. Goldgof), [sarkar@cse.usf.edu](mailto:sarkar@cse.usf.edu) (S. Sarkar), [tsap@llnl.gov](mailto:tsap@llnl.gov) (L.V. Tsap).

<sup>1</sup> Tel.: +1 974 4055/974 2113; fax: +1 813 974 4055/2113.

parameters and the intrinsic material parameters on the accuracy of needle insertion simulation. In the study of model-based breast cancer diagnosis, Tanner et al. [28] compared the results of biomechanical models with different settings of boundary condition and material properties. However, those studies were done on the case-by-case basis using ad hoc comparison methods, and therefore the conclusions cannot be readily generalized to other domains. Moreover, the experiments were performed based on the assumption that the model has homogeneous material properties, which implies that the solution of a Dirichlet type problem could be independent of the internal property variation, and hence the subsequent sensitivity analysis results may not be valid. Another limitation of their methods is that the sensitivity data is incapable of providing a complete picture of the model’s spatial response to the parameter variation on each individual point of the model.

In this paper, we propose a local gradient based computation method that can be used to conduct a systematic and comprehensive sensitivity analysis of any motion model. Specifically, physics-based nonrigid motion modeling will benefit from such a sensitivity analysis in the following aspects:

1. The proposed method allows us to compare the relative importance of different parameters using the normalized sensitivity data and quantify the impact of various assumptions on model’s performance using the dimensional sensitivity data;
2. The algorithm is designed based on the adjoint state method, which significantly reduces the computational cost and is suited for handling large scale finite element models;
3. The sensitivity contour map enables us to identify the vulnerable areas of a model that are most affected by a poor assumption, so that further improvement can be made;
4. The parameter value can be obtained by either the direct measurement [12] or the indirect inference [23]. But those acquisition procedures are time-consuming and expensive. It would be economic to first conduct a sensitivity analysis to identify the primary parameters and then to concentrate our effort on the acquisition of those parameters.

## 2. Sensitivity analysis

Sensitivity analysis is closely related to optimization problems often encountered in the traditional model calibration tasks, such as optimal shape design, boundary condition specification, discretization strategy investigation, as well as material property assignment [16]. In this study, we focus on assessing the impact of two elastic parameters (the Young’s modulus and the Poisson’s ratio) on model’s performance, based on the computed sensitivity information. Without loss of generality, we will discuss the deformation of a linear elastic body and its response to parameter perturbation. However, the methodology developed here can be readily applied to nonlinear systems. We will give a brief review of the primary

problem [37,12], and then discuss the derivation of the adjoint state equation and related computational issues.

### 2.1. Primary problem

The deformation of an elastic body can be described by the following partial differential equations and the boundary conditions (primary problem)

$$\rho \frac{\partial^2 u}{\partial t^2} = \nabla \cdot \sigma^T + B, \quad \text{in } \Omega = \Gamma_1 + \Gamma_2, \tag{1}$$

$$\sigma = \lambda(\text{tr}\varepsilon)I + 2\mu\varepsilon = \lambda(\nabla \cdot u)I + \mu\nabla u + \mu(\nabla u)^T, \tag{2}$$

$$\varepsilon = \frac{1}{2}[\nabla u + (\nabla u)^T], \tag{3}$$

$$u = \bar{u}, \text{ on } \Gamma_1, \tag{4}$$

$$\frac{\partial u}{\partial n} = \bar{g}, \text{ on } \Gamma_2, \tag{5}$$

where  $u$  denotes the displacement vector,  $\rho$  is the mass density,  $t$  denotes the time,  $\sigma$  is the stress tensor,  $T$  denotes the transpose operator,  $B$  is the body force,  $\nabla \cdot$  is the divergence operator with respect to a tensor,  $\varepsilon$  is the strain tensor,  $\text{tr}$  denotes trace,  $I$  is the identity matrix,  $\lambda$  and  $\mu$  are the Lamé constants,  $\nabla$  is the gradient operator defined with respect to a vector,  $(\bar{u}, \bar{g})$  are the Dirichlet and Neumann data on the boundary  $(\Gamma_1, \Gamma_2)$  that define the modeling domain  $\Omega$ , and  $n$  is the outward unit normal on the boundary (see Fig. 1).

Eqs. (1)–(3) are also known in continuum mechanics as the motion equation, the constitutive equation and the strain-displacement equation, respectively. Material properties commonly used in the engineering literature such as the Young’s modulus ( $E$ ) and the Poisson’s ratio ( $\nu$ ) are related to the Lamé constants by:

$$\mu = \frac{E}{2(1 + \nu)}, \tag{6}$$

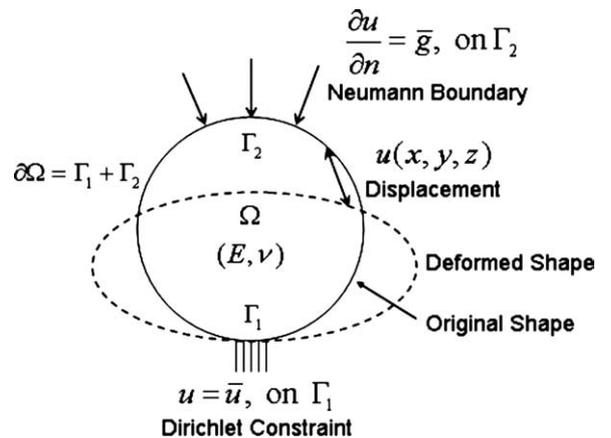


Fig. 1. Illustration of the primary problem.

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