Geometric Nonlinearity: Is it Important for Real-time FEM Surgical Simulation?

Michael Wehner
ME Department
University of California, Berkeley
michael_w@berkeley.edu

Ron Alterovitz
IEOR Department
University of California, Berkeley
ron@ieor.berkeley.edu

Ken Goldberg
IEOR & EECS Departments
University of California, Berkeley
goldberg@ieor.berkeley.edu

1. Background/Problem

In real-time surgery simulation and planning, the Finite Element Method (FEM) is often used to simulate small and large deformation of human tissue for applications such as laparoscopy training [4], needle insertion planning [1], and image registration [2]. In using FEM, assumptions must be made about material properties and the scale of deformation of human tissues in and around the area of interest. Past work often relies on linear FEM, which assumes that tissues exhibit (1) linear elastic material behavior and (2) geometric linearity. Geometric linearity implies linear FEM is accurate only for relatively small deformations. It assumes material geometry will remain relatively constant both overall and locally and any change in geometry will not affect the distribution of applied forces. While these assumptions may be appropriate for historic applications of linear FEM, such as relatively stiff machine parts, human tissues may be subject to larger deformations making local forces and strains behave in a nonlinear manner. Past work has examined hyperelastic (large deformation) and viscoelastic (rate dependent) properties of structural tissues (tendon, rat tail) done in-vitro with various animals, and some research has examined internal organ tissue [3]. These cases are very specific to the tissue and organ type in question as well as the measurement method, thus these results vary greatly and cannot be assumed for other organs. Little information is available regarding a head-to-head comparison of linear to nonlinear geometry for the soft tissues often modeled in surgery simulation. For a case study of the prostate, we relax one assumption of linear FEM, geometric linearity, and quantify the difference in simulated tissue deformations.

2. Tools and Methods

We compare linear versus nonlinear geometry assumptions for a case study in the deformation of the prostate. In magnetic resonance spectroscopy imaging (MRSI), an inflatable endorectal balloon probe, which causes significant deformation of the prostate, is inserted to improve signal-to-noise ratio [2]. We simulate the deformation of surrounding soft tissues, including the prostate, using the commercially available software ABAQUS using a 2D analysis with a plane strain assumption (tissue does not deform normal to the plane of interest). We approximate tissues as incompressible and hyperelastic materials with a Poisson's ratio of 0.49 and a modulus of elasticity of 60 kPa. Bone is considered rigid. The mesh contains 980 elements and 566 nodes, each with 2 degrees of freedom. We perform two analyses: the first uses an assumption of geometric linearity, and the second allows successive recalculations to determine the nonlinear effects of large displacement.

3. Results

As a percent of the overall prostate diameter (4.58 cm), results indicate only a 3.7% average difference with a 6.7% maximum difference in simulated tissue deformations. Linear analysis, which assumes an initial and final state with no large-scale deformation, results in elements that overlap one another in areas of high distortion. Figure 1(c) shows an area with overlapping elements (negative area) along the balloon probe boundary. Nonlinear analysis computes successive smaller intervals thus eliminating this overlap, and is shown in figure 1(d).

4. Conclusions/Discussion

The results of our linear FEM problem with 566 nodes and 980 elements, which can be computed in real-time using previously developed linear FEM solvers for surgery simulation [1,4], differs from the results of the nonlinear geometry solver by less than 4% on average in our case study involving large tissue deformations caused by insertion of a probe larger than the prostate. Thus our experiment suggests that geometric non-linearity is helpful for avoiding degenerate (overlapping) elements, but for this application does not dramatically affect deformation modeling.

5. References

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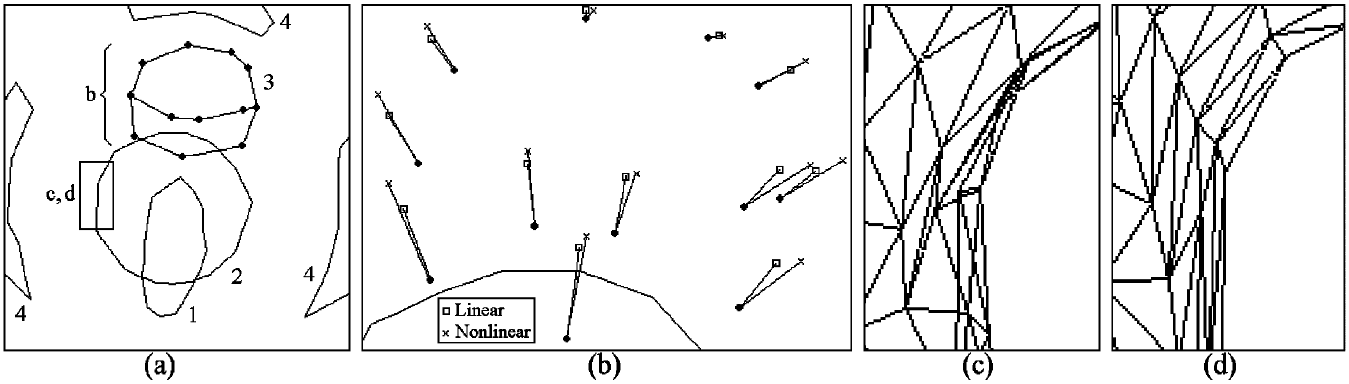

Fig 1. A probe is inserted and expands a rectum (a)[1] to the probe outline (a)[2], deforming the prostate (a)[3] and surrounding tissues relative to rigid bones (a)[4]. Linear and nonlinear geometry FEM analyses yield prostate deformations with a 3.7% average difference relative to the prostate diameter (b). Linear geometry FEM assumption results in overlapping elements (c), which is avoided with geometric nonlinear FEM (d).