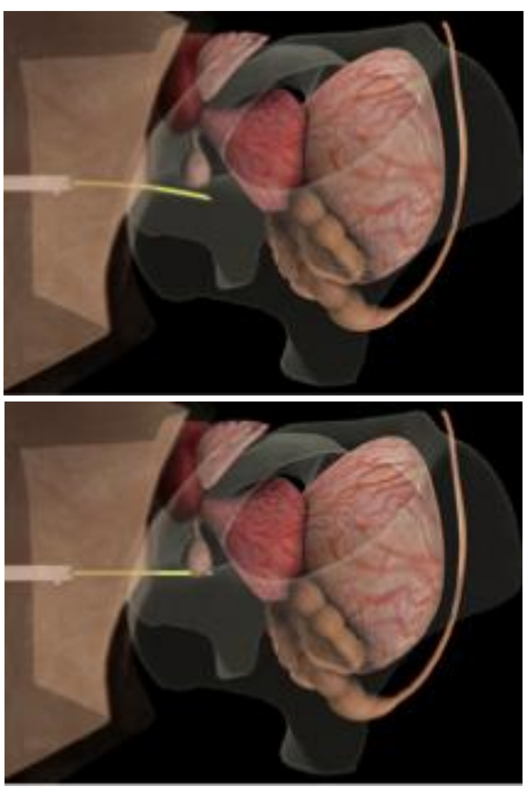
Physically-based Simulation of Medical Procedures for Training and Planning

Department of Computer Science University of North Carolina at Chapel Hill March 2010

The Challenge

Computer simulations of medical procedures enable physicians and other clinicians to train in a controlled environment that exposes them to both common and rare patient cases without risks to patient safety. Studies indicate that surgical skills learned using computational simulators directly improve operating room performance by significantly decreasing procedure time and reducing the frequency of medical errors by up to sixfold compared to traditional training. Surgical simulations also have uses for pre-operative planning.

We have focused on simulating and planning medical procedures involving needles. Numerous medical procedures, including brachytherapy cancer treatment, biopsies, and anesthesia drug injections, require inserting a needle tip to a specific target location inside the human body. This is difficult because inserting needles causes the surrounding soft tissues to deform. Ignoring these deformations can result in substantial placement error, resulting in failure of the procedure or increased side effects. To facilitate physician training and planning for needle-based medical procedures, we are developing an interactive simulation of needle insertion in soft tissues.



Screenshots from our prostate brachytherapy simulator. A needle is inserted from the left through the epidermis into the prostate gland. We simulate both bevel-tip flexible needles (top) and symmetric-tip stiff needles (bottom).

Highlights

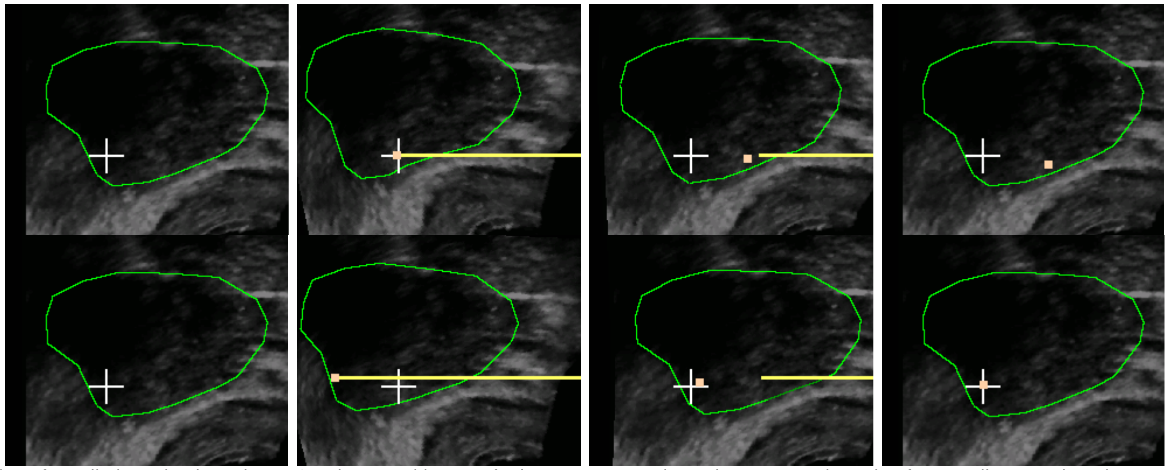
- **Simulating medical procedures enables pre-operative procedure planning and surgical training in virtual environments.**
- **Simulating medical procedures is challenging due to tissue deformations and complex tool/tissue interactions.**
- **We created a real-time, interactive simulation of needle insertion in deformable tissues.**
- **Simulation of needle insertion in deformable tissue can be used to anticipate and correct for needle placement errors due to tissue deformations.**

The Approach

Medical simulations are challenging to develop because they require both physical realism and real-time interactive performance. We are developing 2D and 3D simulations of needle insertion procedures by modeling tissue deformations using a finite element method, modeling needle frictional and cutting forces, and using novel re-meshing to ensure conformity of the mesh to the curvilinear needle path.

As part of a multi-institution collaboration between UNC-Chapel Hill, UC Berkeley, and Johns Hopkins University, we are developing a new simulator that models tissue deformation, needle elasticity, and their interaction. It allows us to realistically simulate the deflections that occur as thin needles travel through inhomogeneous tissues. A motivation for modeling needle elasticity is a new class of steerable needles that have a flexible shaft that curves as it penetrates soft tissue due to asymmetric forces exerted at the needle's bevel tip. By twisting the needle as it is inserted, a physician can steer its tip around obstacles to reach clinical targets in soft tissues. It is not easy to learn how to control steerable needles, and realistic training simulations will accelerate their deployment in clinical practice.

Several impediments make it difficult to simulate the interaction between a needle and soft tissues: a static spatial discretization (e.g. a fixed finite element mesh) does not easily support the accurate computation of contact forces and needle steering; the mismatch between needle stiffness and tissue stiffness hinders numerical stability; and the simulation must run at interactive rates. To address these challenges, we have introduced (1) a novel algorithm for local remeshing, (2) an efficient algorithm for coupling a 3D finite element simulation and



Simulation of needle insertion based on a 2D ultrasound image of a human prostate (green) to a target (cross). After needle retraction, the placement error, the distance between the target and implanted seed location, is 26% of the diameter of the prostate when no planning is used. Preoperative planning can anticipate and correct for the effects of tissue deformations, significantly reducing placement error, which improves treatment quality and reduces side effects.

a 1D elastic rod simulation with stick-slip friction, and (3) several generally applicable optimizations for reducing computation time for physically based simulations. Our remeshing algorithm efficiently relocates and creates nodes so they lie along a curvilinear needle path in a volumetric mesh, enabling the simulation to apply cutting and frictional forces along the needle shaft at mesh nodes while maintaining a high quality tetrahedral mesh for computing tissue deformations. Our optimizations fully exploit parallelization and the sparseness of finite element method meshes.

Our algorithms and enhancements enable us to realistically simulate needle insertion into deformable tissue at interactive frame rates. We achieve frame rates of 25 Hz on an 8-core 3.0 GHz Intel Xeon PC for a prostate mesh of 13,375 tetrahedra and 2,763 vertices. We use realistic material properties for human tissue, making it more challenging than the more compliant materials for which real-time performance is usually reported. As shown on the previous page, we applied our simulators to prostate brachytherapy with needles of different stiffness.

We are also developing a planning system for prostate brachytherapy cancer treatment. In this procedure, physicians use needles to implant radioactive seeds in the prostate. We combine our simulation of needle insertion with numerical optimization to compute needle insertion offsets that compensate for tissue deformations. We applied the method using 2D simulation to seed implantation during prostate brachytherapy to minimize seed placement error in simulation.

Current Project Members

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Research Sponsors

National Science Foundation (NSF) under grant #IIS-0905344 on "Robust Intelligent Manipulation and Apprenticeship Learning for Robotic Surgical Assistants."

Selected Publications

N. Chentanez, R. Alterovitz, D. Ritchie, J. Cho, K. Hauser, K. Goldberg, J. R. Shewchuk, and J. F. O'Brien, "Interactive simulation of surgical needle insertion and steering," *ACM Transactions on Graphics (Proc. SIGGRAPH)*, vol. 28, pp. 88:1–88:10, Aug. 2009.

R. Alterovitz, K. Y. Goldberg, J. Pouliot, and I.-C. Hsu, "Sensorless motion planning for medical needle insertion in deformable tissues," *IEEE Trans. Information Technology in Biomedicine*, vol. 13, pp. 217–225, Mar. 2009.

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K. Hauser, R. Alterovitz, N. Chentanez, A. Okamura, and K. Goldberg, "Feedback control for steering needles through 3D deformable tissue using helical paths," in *Proc. Robotics: Science and Systems*, June 2009.

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M. Torabi, K. Hauser, R. Alterovitz, V. Duindam, and K. Goldberg, "Guiding medical needles using single-point tissue manipulation," in *Proc. IEEE Int. Conf. Robotics and Automation (ICRA)*, pp. 2705–2710, May 2009. ***Best Medical Robotics Paper Award Finalist***

Keywords

Physically-based simulation; surgery simulation; virtual reality; steerable needles; medical robotics; motion planning; path planning; minimally invasive surgery; training; procedure planning

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