Measurement of Surgical Instrument Force-Trajectories and Cartilage Stiffness for Simulation of Arthroscopic Knee Surgery

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The Problem: Surgical simulation incorporating haptics and computer graphics holds great promise for the initial training, continuing education and skill assessment of surgeons. However, current surgical simulation systems lack patient-specific tissue material properties—models of soft tissue in current simulators typically employ "literature values" for material parameters such as tissue stiffness. Furthermore, little quantitative information exists regarding the forces and gestures surgeons employ when probing or otherwise manipulating tissue such as cartilage. Finally, in the particular case of arthroscopic surgery, it would also be quite valuable clinically to have a means of noninvasively assessing the stiffness of cartilage as an aid to diagnosis and surgical planning. This project was undertaken to address each of these issues.

Motivation: Injury and arthritic degeneration of the knee are common pathologies, and arthroscopic knee surgery is one of the most frequent surgical procedures, with an estimated 1.9 million performed in 1997 in the U.S. alone. Compared to open techniques, arthroscopic surgery provides many benefits to patients, but it is technically demanding, with challenging psychomotor skills requirements and a steep learning curve. Effective surgical simulation requires perceptually realistic tissue behavior. In particular for arthroscopic surgery, the realistic "feel" of the cartilage surfaces is crucial for simulating the evaluation and treatment of joint pathologies. Our current work aims to enhance the realism of arthroscopic surgery simulation by (1) developing a noninvasive means to map cartilage stiffness, providing data which can help build more realistic computer models of the joint surfaces and (2) measuring the forces and gestures surgeons employ when probing real cartilage surfaces.

Previous Work: The current research grew out of work on an arthroscopic knee surgery simulation system developed over the past three years in a collaboration between MERL (A Mitsubishi Electric Research Laboratory), MIT, CMU and the Brigham and Women's Hospital [1]. Previous research in cartilage imaging and biomechanics providing the foundation for the current MR imaging work is described in [2] and [3].

Approach: Cartilage and the underlying bone are harvested from the tibial surface of either bovine or human knee joints. Currently, human knee tissue is being obtained during total knee replacement or limb amputation surgery. Each specimen is first mounted on a rigid polycarbonate calibration/registration frame and then undergoes three experimental procedures:

1. **Gadolinium-enhanced MR imaging** The compressive stiffness of cartilage is principally determined by the macromolecule glycosaminoglycan (GAG). It has been shown that the dynamic compressive stiffness of cartilage is directly and linearly dependent on GAG concentration [3]. Our approach is to image and map the GAG concentration in the cartilage using gadolinium-enhanced magnetic resonance imaging [2], thereby allowing us to noninvasively infer the stiffness of the tissue.

2. **Surface probing** Each sample is then examined by a surgeon using a specially instrumented arthroscopic probe. Strain gages are affixed to the shaft of the probe, permitting measurement of the force applied at the probe's tip. The handle of the probe is mounted to a PHANToM haptic device, which in this application is used for sensing 6 degrees of freedom of position and orientation of the probe. As the surgeon examines the cartilage surface, we continuously record the tip force, probe position, and the subjective clinical impressions of the surgeon regarding the health or pathology of the sample.

3. **Indentation testing** The cartilage is indented at selected locations using a precision compression testing apparatus (Fig.1 *right*). Testing is performed at a variety of locations on the sample, in particular at any locations found to be soft or degenerated by the surgeon. We apply computer-controlled displacements to the indenter (which is machined to match the geometry and dimensions of the arthroscopic probe tip) and measure the resulting load. These force-displacement relations provide a measure of the relative stiffness at points on the cartilage surface.

The MR-derived stiffness maps, validated by the indentation testing, will be used in the creation of 3D renderings of the cartilage surface and models for the surgical simulator.

Difficulty: A major challenge of this work is the accurate registration of points in a 3D MR image with physically measured coordinates on the surface of a sample. This has been addressed by the development of a novel registration frame with markers, positioned at precise locations in three dimensions around the sample, which can be touched by the indenter and also seen on the MR scans.

Impact: The ability to incorporate noninvasively-acquired, patient-specific cartilage stiffness data into a knee (or other joint) surgery simulation system offers the potential to significantly increase the realism of the system. For example, we hope to be able to simulate a variety of naturally occurring pathologies which can provide varied, clinically relevant goals for training. In addition, the 3D maps of cartilage stiffness are potentially useful on their own: they can be displayed as a color-coded, three-dimensional rendering of the joint surface. These images can provide surgeons, before and during an operation, with an easily understood "road map" of where the cartilage is healthy or diseased, potentially improving the efficiency and accuracy of the surgical procedure.

Future Work: The MR-derived stiffness maps, validated by the indentation testing, can be used in the creation of models for a surgical simulator which incorporate both the geometry and stiffness of the scanned tissue. The total haptic input-output fidelity of the simulator can then be tested by connecting the tip of the strain-gage instrumented probe to the simulator force-feedback device. We can then compare the force trajectories measured during probing of a *virtual* cartilage surface with the *actual* force trajectories measured during probing of the real sample from which the simulator's model was derived.

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Figure 1: *left* Surgical probe (seen held in right hand) instrumented with strain gages and 6 DOF position tracking is used to examine the cartilage surface of a tibial plateau. The arthroscope (held in left hand) view is shown on the monitor in the background—the probe tip is visible as it touches the cartilage surface. *right* The sample is immersed in saline solution and placed on the stationary platform of the compression apparatus. A rigid indenter, affixed beneath a load cell, can be seen just touching the cartilage surface as computer-controlled displacements are applied and the resulting load signal is recorded.

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