Laboratory for Human and Machine Haptics

Academic and Research Staff
Dr. Mandayam A. Srinivasan, Dr. S. James Biggs, Dr. Suvranu De, Dr. Manivannan Muniyandi, Dr. Balasundar I. Raju, Dr. David W. Schloerb, Dr. Lihua Zhou

Visiting Scientists and Research Affiliates
Dr. Martin Grunwald, Dr. Suiren Wan, Dr. Xiaohan Sun

Graduate Students
Louis H. Buell, Hyun Kim, Jung Kim, Ning Lin, Boon Tay, Wan-Chen Wu, Manuel Herkt

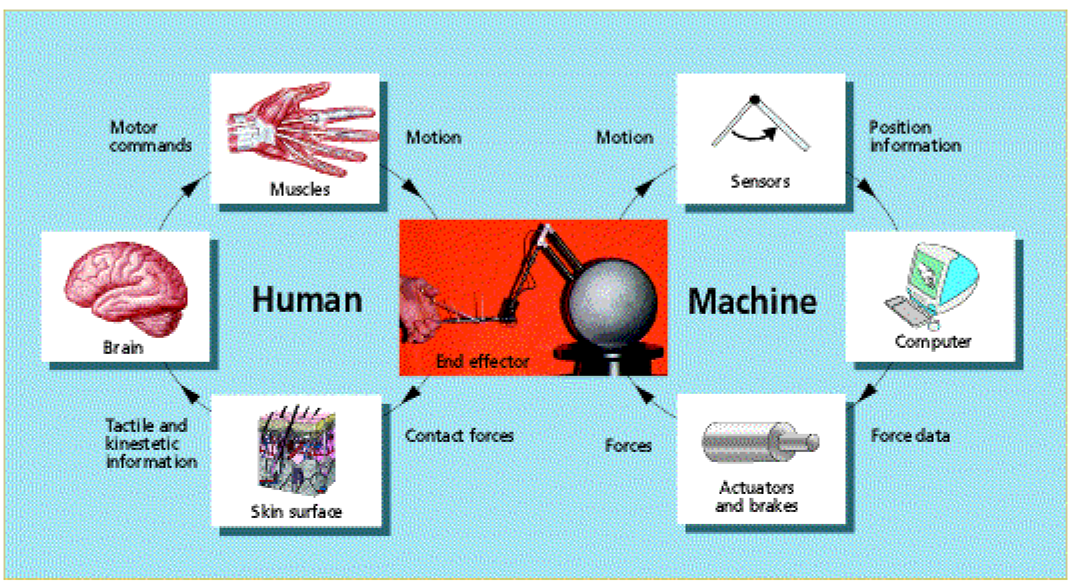
Undergraduate Students
Rumi Chunara, Kirk Phelps

Technical & Support Staff
Seth M. Hall, Eleanora Luongo, Monica Pegis

Sponsors
National Institutes of Health – Grant RO1-NS33778
Massachusetts General Hospital
Defense Advanced Research Projects Agency

Introduction

Haptics refers to sensing and manipulation through touch. Although the term was initially used by psychologists for studies on active touch by humans, we have broadened its meaning to include humans and/or Machines in real, virtual or teleoperated environments. The goals of research conducted in the Touch Lab are to understand human haptics, develop machine haptics, and enhance human-machine interactions in virtual environments and teleoperation. Human Haptics is the study of how people sense and manipulate the world through touch. Machine Haptics is the complimentary study of machines, including the development of technology to mediate haptic communication between humans and computers as illustrated in the figure.



In the figure, a human (left) senses and controls the position of the hand, while a robot (right) exerts forces on the hand to simulate contact with a virtual object. Both systems have sensors (nerve receptors, encoders), processors (brain, computer), and actuators (muscles, motors). The type of application depends on how the computer, in turn, interacts with the rest of the world (not shown).

Our research into human haptics has involved work on biomechanics of skin, tactile neuroscience, haptic and multimodal psychophysics, and computational theory of haptics. Our research into machine haptics includes work on computer haptics -- which, like computer graphics, involves the development of the algorithms and software needed to implement haptic virtual environments -- as well as the development of haptic devices. Applications of haptics that we have investigated include methods for improving human-computer interaction as well as medical diagnosis and training. An exciting new area of research we have initiated is the development of direct brain-machine interfaces, using which we recently succeeded in controlling a robot in our lab using brain neural signals transmitted over the internet in real-time from a monkey at Duke. Another of our research results that made world news headlines last year was the first demonstration of transatlantic touch where a user in our lab and a user in London collaboratively manipulated a virtual cube while feeling each other's forces on the cube. Our current projects are described in the following sections.

1. Biomechanics of Touch

Mechanics of the skin and subcutaneous tissues is as central to the sense of touch as optics of the eye is to vision and acoustics of the ear is to hearing. When we touch an object, the source of all tactile information is the spatio-temporal distribution of mechanical loads on the skin at the contact interface. The relationship between these loads and the resulting stresses and strains at the mechanoreceptive nerve terminals within the skin, plays a fundamental role in the neural coding of tactile information. Unfortunately, very little is known about these mechanisms.

In the Touch Lab, we develop apparatus and perform experiments to measure the mechanical properties of the skin and subcutaneous tissues. In addition, we develop sophisticated mechanistic models of the skin to gain a deeper understanding of the role of its biomechanics in tactile neural response. A variety of techniques have been used in our experiments, including videomicroscopy, Optical Coherence Tomography (OCT), Magnetic Resonance Imaging (MRI), high frequency ultrasound imaging, and computer-controlled mechanical stimulators. We use the empirical data to develop finite element models that take into account inhomogeneity in the skin structure and nonlinearities in its mechanical behavior. Analysis of these models in contact with a variety of objects generates testable hypotheses about deformations of skin and subcutaneous tissues, and about the associated peripheral neural responses. Verification of the hypotheses are then accomplished by comparing the calculated results from the models with biomechanical data on the deformation of skin and subcutaneous tissues, and with neurophysiological data from recordings of the responses of single neural fibers. We are currently engaged in a wide range of projects in this area.

Measurement of Spatial Pressure Distribution on the Human Skin during Tactile Sensing of Objects

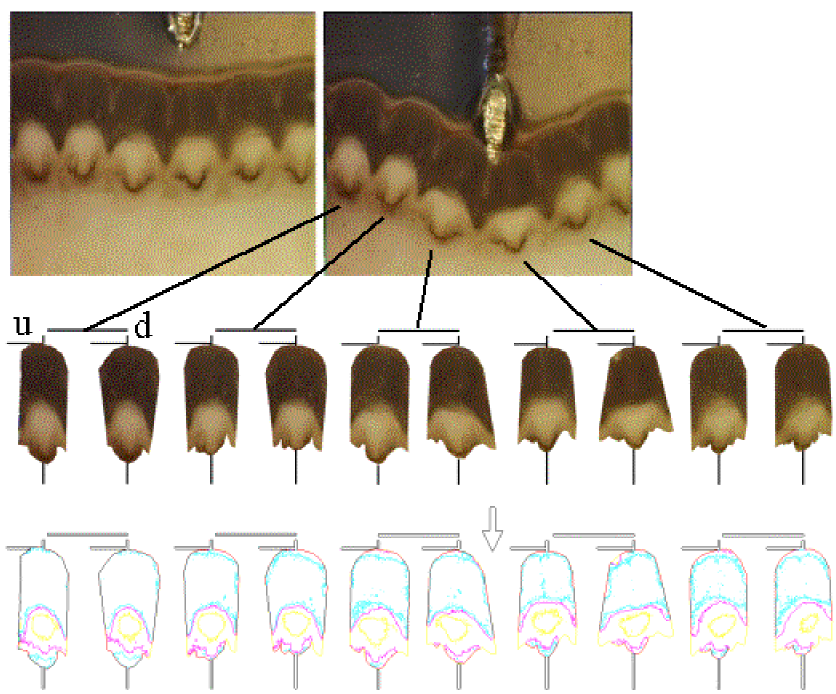
The sense of touch aids humans in determining the physical properties of objects such as surface texture, shape, and softness. The force distribution on the skin in contact with an object is the primary stimulus to the human tactile system. In this study, the spatial distribution of normal pressure on the surface of the finger pad in contact with cylindrical objects was measured using a sensitive pressure sensor array that was purchased from a vendor (Pressure Profile Systems, Inc.). Effects of object curvature and contact force on the pressure distribution were studied. Deconvolution, a signal processing technique, was used in an attempt to increase the spatial resolution of the empirical data.

The characteristics of the pressure sensor array were determined first by using a 3-axis motion platform and a high precision single axis motor to apply controlled stimuli. The behavior of individual elements of the pressure sensor array was examined for drift, repeatability, linearity and anisotropy in converting contact pressures to voltages. In addition, sensitivity to spatial positioning of the stimulus and inter-element variability were also studied. The sensor response was shown to be approximately linear and anisotropic, and the gain for each element of the sensor was variable.

The pressure distribution on the skin surface of 5 subjects was measured when cylindrical objects of two different diameters were indented onto the finger pad. A single sensor element was moved in small increments relative to the contact region to see if smaller step size between measurements produced better results. The correlation between the pressure distribution and the fingerprint was also studied. Dips in surface pressure roughly corresponded to grooves in the fingerprint, though these features were at the limit of the spatial resolution of the sensor. The pressure records were compared with the pressure distribution predicted by Hertz theory of contact mechanics. Hertz theory was found to model the observed pressure distribution reasonably well, though it failed to account for observed anisotropy and pressure concentration due to finger ridges.

To improve the limited spatial resolution of the pressure sensor, application of deconvolution was investigated. Deconvolution was not able to increase the spatial resolution of pressure measurements enough to fully resolve pressure concentrations due to individual finger ridges. This was most likely due to sensor noise and the complexity of the spatial response profile of the pressure sensor.

Video-microscopic Investigation of Primate Fingertip Mechanics



Video microscope images of cadaver primate finger pads cut in cross section have been gathered in order to observe tissue biomechanics with spatial resolution (~2 μm/pixel) higher than *in vivo* methods (MRI and UBM) allow. Using MATLAB, we developed algorithms to track material particles and calculate strain fields as the skin is indented by points, lines, bars and cylinders.

These measurements provide data to improve current models of touch biomechanics. The results are compared with finite element simulations and with previously obtained neurophysiological data from the corresponding experiments.

The figure (top row) shows six finger ridges in cross section, before (left) and after (right) the skin is loaded with a line indentor 50 micron wide. In the middle row, the epidermal and dermal tissue associated with individual finger ridges is shown in the undeformed (u) and deformed (d) states, with rigid body motion subtracted. Changes in shape of the intensity isocontours (bottom) provide a means of estimating strains in the tissue.

Initial efforts assessed the usefulness of cadaver tissue for understanding biomechanics of living tissue. Measurements of mechanical impedance to sine and step inputs with a point indentor showed that fresh, unpreserved cadaver tissue exhibits stiffness and viscoelastic recovery that falls within the spread of values seen in living tissue, indicating that it is suitable for these experiments. To date, data have been collected from five human cadaver fingers and six primate fingers. Cylinders spanning a range of diameters, bars, and line indentors have been applied at controlled forces ranging from 2 to 320 mN. Two of the primate fingerpads have yielded images suitable for strain estimation. Strains in the tissue have been estimated by hand-digitizing material points, and by solving numerically for strain fields that optimally warp portions of the undeformed image to match the deformed image. Results of this work are now in preparation for publication.

Frequency Response of Human Skin In Vivo to Mechanical Stimulation

In prior years, we made *in vivo* measurements of the force response of skin at several body sites (fingertip, wrist, forearm, and forehead) to stimulation at various frequencies, amplitudes, and mean depths, in directions both normal and tangential to the surface of the skin. In addition to scientific interest and the relevance to Touch Lab research in general, the initial motivation for this project was to help determine specifications for tactile displays fabricated using MicroElectroMechanical Systems (MEMS) technology. We have continued to refine the analysis of the experimental data during the past year (2002) in preparation for publication.

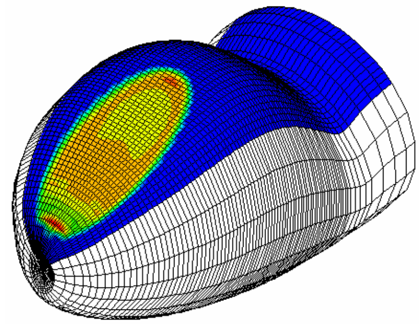
The measurements were made using the Skin Dynamics Test Apparatus (SDTA), which is comprised of an Aurora Scientific Inc. Dual-Mode Lever Arm System that is controlled by a PC via an A/D card. The apparatus continuously samples both the position and the resulting force on a 0.5 mm diameter probe as it is first pressed against the skin and then displaced sinusoidally about the mean pre-indentation depth.

The measured force-displacement response of the skin was used to calculate the mechanical impedance, power absorption, and duty factor (an estimate of the fraction of time that the stimulator is in contact with the skin). Initial results showed the mechanical impedance generally increasing in magnitude with frequency and higher in magnitude for tangential stimulation than for normal stimulation. Power absorption linearly increased with frequency, and duty factor decreased with increasing frequency and amplitude. The measured properties varied widely between body sites and subjects. We hope to publish further results in the near future.

Finite Element Models of the Primate Fingertip

Finite element models for both monkey and human fingertips have been developed by taking into account contact mechanics of the fingerprint ridges, geometry of the inner skin layers, and viscoelastic material properties. The models are capable of predicting biomechanical variables such as skin displacement, reaction force, spatial pressure distribution, subsurface strain and stress fields that are generated when the fingerpad is loaded by various shapes of indentors. The models are improved with the aid of Optical Coherence Tomography (OCT), videomicroscopic imaging and contact pressure measurement. Predictions from the models provide hypotheses for further experiments, ultimately helping us to understand the biomechanics of tactile perception.

We have made progress in the computational study of the primate fingertip by simulating the videomicroscopic investigations described above. By comparing the displacements, strains and reaction forces, it is concluded that the half fingertip model is accurate enough for further prediction.



3D Finite Element Model of Monkey Fingertip

Based on the high-resolution images of fingertip skin obtained using OCT, we have improved our previous 2D finite element model for the human fingertip by taking into account the ridge substructure. Comparison of model predictions with experimental data shows that it can predict the reaction force better than the model without ridges. For sphere indentors with the radius ranging from 7.752 mm to 77.52 mm, the prediction error was less than 8 gwt (11% of the maximum force applied).

By use of the 3D primate fingertip model, pressure distribution was computed when the fingertip was loaded by various shapes of indentors. The load cases are exactly the same as those used in the pressure distribution experiments described above. The figure above shows the pressure contours when the fingertip is indented 1.5 mm by a cylinder with radius 6.35 mm. The indentor is tilted to 30^{o} with reference to the horizontal surface, which is the typical finger orientation when people try to feel an object using their fingertip.

2. Sensorimotor Psychophysics

Psychophysics is the quantitative study of the relationship between physical stimuli and perception. It is an essential part of the field of haptics, from the basic science of understanding human haptics to setting the specifications for the performance of haptic machines. It is also quite natural to extend psychophysical methods to the study of motor control in this case, investigating the relationship between intention and physical effect, because the haptic channel is inherently bi-directional.

We have conducted pioneering psychophysical studies on compliance identification and discrimination of real and virtual objects, and determined the human resolution (i.e., Just Noticeable Difference, JND) in discriminating thickness, torque, stiffness, viscosity, and mass under a variety of conditions. Furthermore, using the virtual environment systems that we have developed, we have conducted psychophysical experiments under multimodal conditions, such as the effect of visual or auditory stimuli on haptic perception of compliance. We have also conducted a number of studies on the human ability to apply controlled forces on active and passive objects. Psychophysical experiments related to the detection of extremely fine--75-nanometer high--textures and the detection of slip have also been performed in conjunction with neurophysiological measurements. Currently we are engaged in the various tactile threshold measurements.

Tactile Perception Threshold Measurements

The goal of this project is to determine the limits of perceptual resolution for various kinds of vibratory tactile stimulation at various body sites. The nominal spatial resolution paradigm will involve observing the minimum distance between two probes that allows a person to distinguish between two probes and one probe when they are pressed against the skin. Two novel features of the experiments are, (1) precise control of the stimuli via computer and (2) simultaneous measurement of both position and force applied to the skin. In addition to scientific interest and the relevance to Touch Lab research in general, the initial motivation for this project was to help determine specifications for MicroElectroMechanical Systems (MEMS) tactile displays.

One-point threshold measurements were made in our lab in prior years with the help of Charlotte M. Reed, Lorraine A. Delhorne, and others using the Skin Dynamics Test Apparatus (SDTA) that we initially developed to study biomechanical properties of the skin. It uses an Aurora Scientific Inc. Dual-Mode Lever Arm System that is controlled by a PC via an A/D card. The apparatus continuously samples both the position and the resulting force on a 0.5 mm diameter probe as it is first pressed against the skin and then displaced sinusoidally about the mean pre-indentation depth. Analysis of the data from those tests for publication continued during the last year (2002). We also continued development of an improved apparatus intended primarily for perceptual measurements.

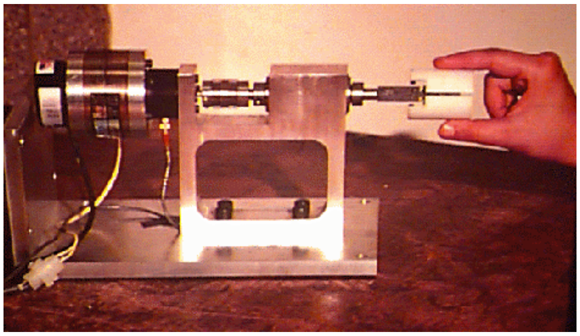
Detection threshold measurements have been made at three body sites (finger, wrist, and forearm) on three adult subjects (a fourth subject took part in the finger tests) for sinusoidal stimulation at eight frequencies in the range of 2 to 256 Hz. Thresholds were estimated using a two-interval forced-choice adaptive-level procedure with trial-by-trial correct-answer feedback. Each run began with the stimulus level set well above threshold. Presentation level was changed following two correct responses (resulting in a decrease in stimulus level) or one incorrect response (resulting in an increase in stimulus level). The step size was set initially to 4 dB (re 1 micron) but was changed to 2 dB after the first reversal. A run was terminated after 8 reversals in level and the threshold for that run was calculated by averaging across the levels of the final 6 reversals. The two observation intervals were 500 msec in duration and were separated by 200 msec. Visual cueing of the observation intervals was provided on a computer terminal. The tactual stimulus was presented in one of the two observation intervals, selected at random on each trial. Data were collected in 8-run blocks with random ordering of the 8 frequencies within each block. Five blocks of data were collected on each of the subjects, leading to five threshold estimates at each of the 8 frequencies (2, 4, 8, 16, 32, 64, 128, and 256 Hz). Reliable threshold estimates were obtained in the one-point test that appear to be consistent with other measurements reported in the literature. Unfortunately, some measurements at the higher frequencies were limited by the resolution of the apparatus. Specifically, the position resolution of the Aurora stimulator is about 1 micron, which made it impossible to measure the smaller thresholds at 128 and 256 Hz. Fortunately, we do not expect this to be a major problem for our spatial resolution experiments because the relatively sensitive receptors that are responsible for the low tactile thresholds (Pacinian Corpuscles) tend to be more widely spaced in the skin than other receptors.

The principal innovation of our one-point experiments is that we were able to measure the reaction force of the skin and calculate the mechanical power transmitted into the tissue at threshold. We plan to perform additional tests and to publish this data in the near future.

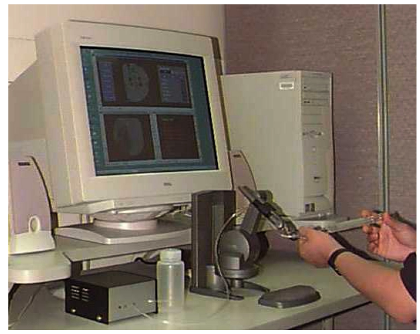
3. Haptic Device Development

Haptic devices are used to investigate, augment, or replace human haptic interactions with the world. For example, haptic devices like the Instrumented Screw Driver (see photo) have been developed and used in the Touch Lab to investigate human performance. The Instrumented

Screw Driver was used in an experiment to study a person's ability to sense and control torque.[1] In the experiment, subjects held the handle of the computer-controlled device in a pinch grasp and overcame a preprogrammed resistive torque to rotate the handle. Other devices, like the Epidural Injection Simulator (see photo), have been developed in the lab to augment surgical training.[2] Using this device, the trainee manipulates a syringe and feels realistic forces as he or she attempts to position the needle and inject a fluid. Another example of augmenting performance is on the development of machines that can be directly controlled by brain neural signals.[3] [4] Work to "replace" humans (e.g., through the development of robotic hands) is part of our plans for the coming year.



Instrumented Screw Driver



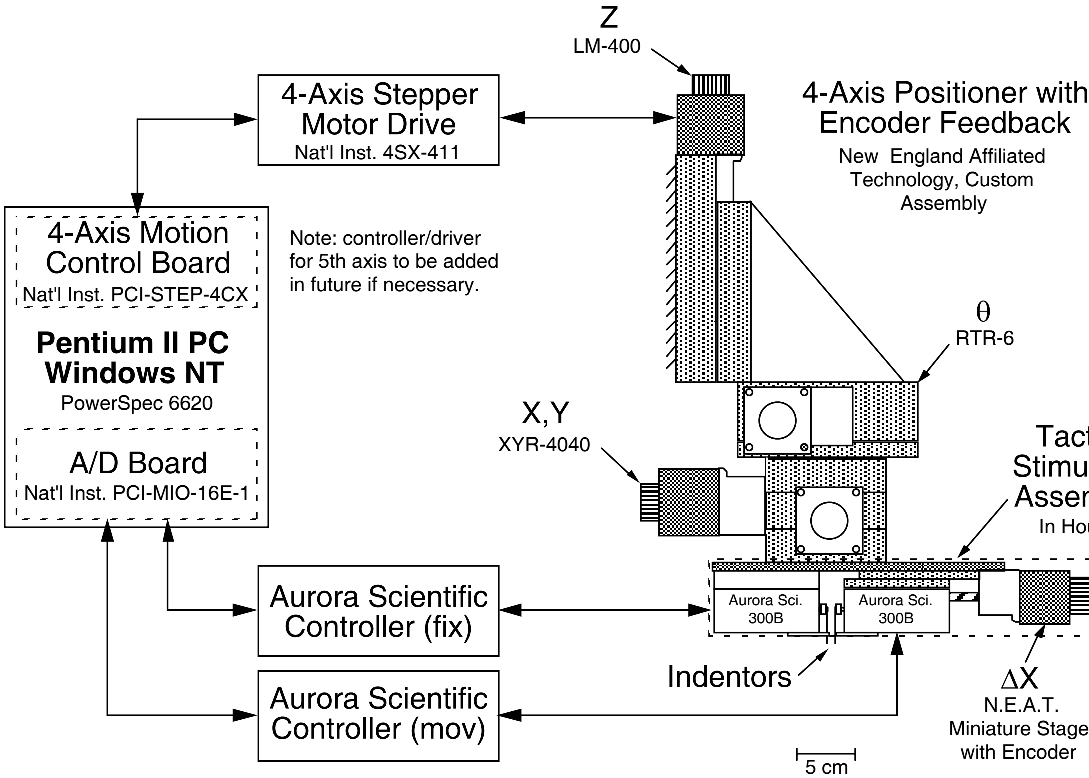
Epidural Injection Simulator

Primarily, the development of haptic devices in the Touch Lab is driven by our need for new types of experimental apparatus to study haptics and its applications. Our work in this area includes the design and construction of new devices as well as the modification/enhancement of exiting apparatus to meet specific needs. Our current work on haptic devices focuses on the development of tactile sensors, displays, and stimulators in connection with our projects related to Biomechanics of Touch, Sensorimotor Psychophysics, and Brain Machine Interfaces.

The Tactile Perception Test Apparatus

The Tactile Perception Test Apparatus (TPTA) will ultimately include two Aurora-Scientific-based tactile stimulators and it will incorporate a 5-axis micro-positioning assembly (x, y, z, theta, and stimulator separation). Under computer control, the motorized micro-positioning assembly will be able to continuously adjust the position of the two stimulators over the course of hundreds of successive experimental trials. The figure presents a schematic diagram of the TPTA.

[1] Jandura L and Srinivasan MA, Experiments on human performance in torque discrimination and control, in Dynamic Systems and Control, Vol. 1, Ed: C. J. Radcliffe, DSC-Vol.55-1, pp. 369-375, ASME, 1994.
[2] Dang T, Annaswamy TM and Srinivasan MA, Development and Evaluation of an Epidural Injection Simulator with Force Feedback for Medical Training, Medicine Meets Virtual Reality Conference 9, Newport Beach, CA, January, 2001.
[3] Wessberg J, Stambaugh CR, Kralik JD, Beck P, Laubach M, Chapin JK, Kim J, Biggs SJ, Srinivasan MA and Nicolelis MAL, Adaptive, real-time control of robot arm movements by simultaneously recorded populations of premotor, motor and parietal cortical neurons in behaving primates, Nature, Vol. 408, No. 6810, pp. 361-365, 2000.
[4] Nicolelis MAL and Chapin JK, Controlling Robots with the Mind, Scientific American, 287 (4), pp 46-53, 2002.



During 2002, Rumi Chunara (an undergraduate student at Caltech who obtained her own funding through a program at Caltech to come work in the Touch Lab over the summer) made significant progress in mechanical assembly, wiring, and programming of the TPTA. She demonstrated operation of the major components under computer control and began implementation of a software design where experiments are run under Matlab. The proposed software design will make it easier for students to develop experiments with the apparatus in the future. Additional hardware and software development is required. We hope to complete this during the next year.

4. Human Computer Interactions

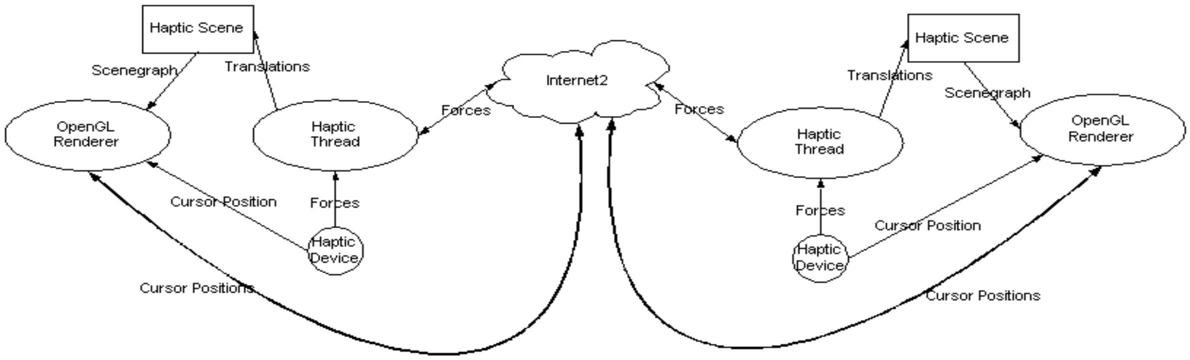
An important general application of our research is the use of haptics to improve communication with, or mediated by, computers. Just as the graphical user interface (GUI) revolutionized human computer interactions (HCI) compared to earlier text-based interfaces in the early 1980's, adding haptics has the potential of significantly expanding the communications channel between humans and computers in a natural and intuitive way. Specific goals range from the development of a standard haptic user interface (HUI) for a single user to improved virtual environment and teleoperation systems with users who collaborate over large distances.

Some of our work in this research area has focused on fundamental issues related to the development of haptic interfaces, such as quantifying human users' abilities and limitations in performing haptic tasks with or without the accompaniment of visual and/or auditory displays.

An interesting application we have studied is the interaction of multiple users in a shared virtual environment, described below.

Collaborative Haptics

In this project, the use of haptics to improve human-computer interaction as well as human-human interactions mediated by computers is being explored. A multimodal shared virtual



Software architecture used in the transatlantic touch experiment

environment system has been developed and experiments have been performed with human subjects to study the role of haptic feedback in collaborative tasks and whether haptic communication through force feedback can facilitate a sense of being and collaborating with a remote partner. The results of the study in which the partners were in close proximity within the Touch Lab were reported in Basdogan et. al., 2000.[5] Last year, in collaboration with Prof. Mel Slater's group in University College, London, we extended the previously developed techniques and demonstrated, for the first time, 2-way communication of touch signals across the Atlantic.

The transatlantic touch experiment examined ways in which pairs of people interact directly via a haptic interface over a network path that has significant physical distance and number of network hops (Jordan et. al., 2002). The aim of the experiment was to evaluate the use of haptics in a collaborative situation mediated by a networked virtual environment. The task of the experimental subjects was to cooperate in lifting a box together under one of four conditions in a between-groups design. Questionnaires were used to report about the ease with which they could perform the task, and the subjective levels of presence and co-presence experienced.

5. Medical Applications

Touch Lab research has a wide range of medical applications. On a fundamental level, our investigations of human haptics offer insights into the functioning of the human body that should ultimately lead to improved medical care. Many of the experimental techniques and apparatus developed in these studies also have specific clinical uses that are explored in collaboration with various medical researchers. For example, the ultrasound backscatter microscope developed to study the biomechanics of touch is being investigated for possible use in screening for skin cancer in collaboration with the Wellman Laboratories of Photomedicine at the Massachusetts General Hospital. The lab's primary medical focus, however, has been to develop machine haptics and other virtual environment technologies for specific medical needs. The major thrust to date has been the development of virtual reality based medical simulators to train medical personnel, similar to the use of flight simulators to train pilots.

We have developed an epidural injection simulator and a laparoscopic surgical simulator with novel real-time techniques for graphical and haptic rendering. The epidural injection simulator, developed in collaboration with Dr. Thiru Annaswamy of UT Southwestern Medical Center, Dallas, TX, has been tested by residents and experts at two hospitals. It is currently exhibited at the Boston Museum of Science where the general public can experience the feel of performing a

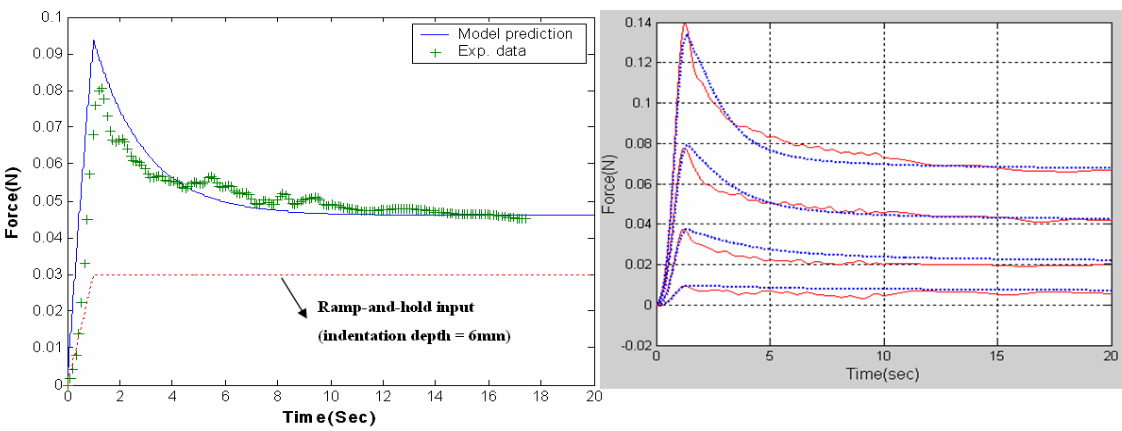
[5] Basdogan C, Ho C, Srinivasan MA and Slater M, An Experimental Study on the Role of Touch in Shared Virtual Environments. ACM Transactions on Computer Human Interaction 7(4), 443-460, 2000.

needle procedure without any risk to a patient. Another project we have pursued has been on developing haptic and graphical rendering techniques in the context of laparoscopic esophageal myotomy (Heller myotomy). The organ models used by the laparoscopic simulator are currently being improved by measuring the *in vivo* mechanical properties of real organs in collaboration with laparoscopic surgeons at the Massachusetts General Hospital and the Harvard Center for Minimally Invasive Surgery. Work on improved graphics, meshless simulation methods for tool-tissue interactions such as cutting and ablation, multimodal rendering, and training effectiveness are also ongoing in our lab. Following is a summary of some of the work done in connection with this project.

In Vivo *Characterization of the Mechanical Behavior of Soft Tissues for Surgical Simulation*

The lack of data in current literature on *in-vivo* material properties of soft tissues has been a significant impediment in the development of virtual reality based surgical simulators that can provide the user with realistic visual and haptic feedback. We have performed *in-vivo* force-displacement measurements of the liver and lower esophagus of pigs in collaboration with a group of surgeons at the Massachusetts General Hospital (MGH). In these measurements, the tissue is subjected to ramp and hold as well as sinusoidal indentations delivered using a robotic device (a Phantom from SensAble Technologies, Inc.) employed as a mechanical stimulator.

In the experiments conducted at the Harvard Medical School, the pig was first put under general anesthesia and placed on the surgical table. A midline incision was made at its abdominal region and dissection carried out on the anatomical structures to expose the organs. The tip of the Phantom, with a special purpose indenter attached, was then lowered into the abdominal region and the measurements were made.



Stress relaxation predicted by the Kelvin model. Various force responses predicted by the nonlinear springs and experimental data for the liver (right).

The results show that (1) pulse and breathing affect the tissue reaction forces significantly, (2) organs exhibit nonlinear viscoelastic characteristics (evidenced by force relaxation corresponding to a fixed displacement stimulus and hysteresis during sinusoidal excitation), and (3) the lower esophagus is significantly stiffer than the liver.

Tool – Tissue Collision prediction

In rendering a heterogeneous scene in real time, various tasks occur simultaneously and modalities with different update rates are integrated with the scene. Moreover, the computationally expensive rendering of a scene forces us to arrange each task very carefully so as to maximize the realism of the scene with/without a real time constraint. Collision prediction is one example. In rendering a deformable object haptically and visually in real time, collision detection and collision response from the model are the dominating tasks in the computation.

Because these two tasks are both computationally expensive and need high update rates, the two tasks have a trade-off relationship that limits the performance of whole system. Collision prediction removes this trade-off relationship by separating the two tasks. The idea of collision prediction starts from two observations. The collision response does not take time before collision and the collision detection time can be reduced significantly after first contact by applying local search of successive contact points.

Since the user's hands holding the force-feedback devices have low frequency motion (of the order of 10Hz or less) compared to the sampling frequency of the system (100 to 1000Hz), the approach direction of the tools can be computed from the trajectories. In other words, the tool path can be predicted from a set of previous positions. We refer to the vector connecting the current position of tool with its previous position as the "tool path vector". Since the physiological tremor in the hands transferred into the tool trajectory appears like noise, low-pass filtering is required to determine the "mean tool path" (mean of several sequential tool path vectors) along the tool approach direction.

At the beginning of each cycle time, the intersection points between the mean tool path and the organs can be computed. These points are located on the surface of the objects and move along the mean tool path. After the tools are located within a certain distance (5mm-10mm), the motion of the tool is assumed to be along a straight line to the organs. The distance from the predicted points on the organ to the tool tip is then the only information needed in real time. The computation time reduces to one distance computation and one comparison (Boolean computation) from the time of collision detection algorithms, which normally increase with the complexity of organ geometry.

Another advantage of collision prediction is that we can reduce real time computational burden by running the collision detection part with a slower update rate than the update rate of the force feedback device.

Meshless Simulation Techniques

In advanced medical simulators, the Finite Element Method (FEM) is the top candidate for the underlying mechanistic computations. Although FEM models can simulate static and dynamic deformations, the high computational cost and the requirement of maintaining a high haptic update rate forces the use of *linear* and *isotropic* elements. However, soft-tissue behavior is nonlinear, anisotropic, and non-homogeneous. A solution to the problems that are faced by the finite element techniques is to use the method of finite spheres (MFS) that we have developed, which is a "meshless" computational technique.[6] [7] [8] The elimination of a computational mesh is greatly advantageous in terms of the saving in time required for mesh generation as well as the added capability to perform certain analyses (e.g., dynamic crack growth or cutting of soft tissues) which are not handled efficiently by finite element techniques. MFS has been accepted by the computational mechanics community as a robust and efficient numerical tool for the solution of solid mechanics problems.

MFS is a truly meshless computational procedure for the solution of boundary value problems posed on complex domains. In this method, the computational domain is discretized using a scattered set of points (which we will refer to as "nodes"). The displacement field is approximated using functions that are nonzero over small spherical neighborhoods of the nodes. Just as in the

[6] De S, On the Development of an Efficient Truly Meshless Discretization Procedure in Computation Mechanics. Ph.D. diss. Dept. of Mechanical Engineering. MIT. Cambridge. 2001.
[7] De S and Bathe JK, "The method of finite spheres." Computational Mechanics 25(4): 329-345. 2000.
[8] De S and Bathe JK, The method of finite spheres: a summary of recent developments. First MIT Conference on Computational Fluid and Solid Mechanics, pp. 1546-1549. Elsevier Science. 2001.

finite element scheme, a Galerkin formulation is used to generate the discretized versions of the partial differential equations that govern the behavior of the deformable medium. In this respect, the method of finite spheres can be viewed as a generalization of the finite element scheme (De et. al., 2002).

While the theory behind meshless techniques is rather straightforward, the generation of a computationally efficient scheme is quite difficult. Computational efficiency may be achieved by proper choice of the interpolation functions, effective ways of incorporating the essential boundary conditions and efficient and specialized numerical integration rules. The pure displacement formulation is observed to exhibit volumetric “locking" during incompressible (or nearly incompressible) analysis. A displacement/pressure mixed formulation is developed to overcome this problem. The stability and optimality of the mixed formulation are tested using numerical inf-sup tests for a variety of discretization schemes. Most recently a powerful discretization technique has been developed for the method of finite spheres that uses hierarchical subdivision of space using quadtrees/octrees. This results in the development of a powerful, fully automated simulation engine that can directly operate on a solid model developed using a commercial geometric modeler such as ACIS. Another recent development has been the coupling of the technique to the commercial finite element software program ADINA.

A very specialized application of the technique (point collocation-based method of finite spheres or PCMFS) to physically based real time medical simulations in multimodal virtual environments has also been developed. In the past year, the PCMFS technique has been coupled with a fast boundary element representation of organs to result in rapid physically based models for simulation of surgical events.

Graphical Rendering with Point-based Models

The use of points as geometric primitives is quite a deviation from the traditional use of triangular primitives that have connectivity information. To reconstruct connectivity information on the fly for point-based rendering, we use a "splatting" technique (De et. al., 2002). A reconstruction kernel associated with each point, called the footprint, determines the contribution of that point in the image buffer. The significance of this work is that point based models in surgical simulations can be rendered in realtime yet with lifelike visual effects such as glistening.

Sphere mapped esophagus.

Rendering of glistening anatomical organs, as shown in the figure, is very difficult to simulate using standard texture mapping techniques. We have used environment mapping techniques such as cube mapping and sphere mapping for glistening effects (Prakash et al, 2002). The significance of this work is that deformation with glistening can be displayed in real time together with force feedback. Such an effect has a significant impact on the realism that can be achieved in interacting with virtual environments for surgical simulation.

Multi-Rate Rendering

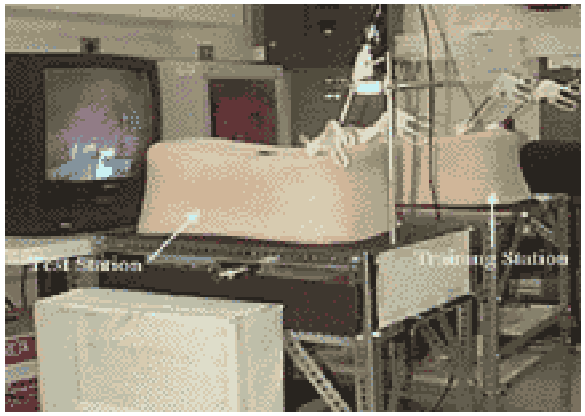
The required force update rate for stable real-time interaction is very high. Specifically, force feedback devices require an update rate of at least a few hundred Hz, which is an order of magnitude larger than the visual frame update rate. There is also a large difference between the update rate of the devices and the update rate that is needed to ensuring physically realistic behavior of the scene, particularly in the case tissues and organs that have relatively slow dynamics. Consequently, we use a multi-rate rendering scheme when various modalities are involved.

Multi-rate rendering requires the generation of additional data points for the slower processes to match the higher update rates of the fastest process. The simplest way to generate this additional data is to repeat the most recent value from the set as the current value. Although this approach is simple and can prevent the application of large forces exceeding the limit of the haptic device, it may cause the users to feel discontinuity in the forces from the scene.

Another approach is to use an interpolation or extrapolation scheme. From the viewpoint of equation formulation, interpolation and extrapolation are identical except for the relative positions of computed and given data. We have used an N-th order polynomial function computing data explicitly. We note here that careful consideration of the order of the polynomial is needed because too high an order may generate very high value (extrapolation) or oscillation (interpolation).

Role of Fidelity of Multimodal Simulation in Virtual Reality based Surgical Training

One of the main issues in simulator based surgical training is how realistic does the simulation need to be for effective training? On the one hand, it is possible to learn the surgical practices with an unrealistic model, thereby leading to negative training transfer. However, because of the learning abilities and perceptual limitations of the sensory, motor, and cognitive system of the human user, perfect simulation is unnecessary. Furthermore, given the large variations in human anatomy and physiology, there is no single perfect model, but wide variations in geometry and material properties of the organs. The main question is how simple a simulation can we get away with, while at the same time preserving a level of fidelity between the virtual and real organ behavior that leads to positive training transfer. Thus, one goal of this continuing study is to find out what is actually needed for effective laparoscopic VR training prior to investing time and effort into developing complicated models of human organs and tool-tissue interactions.



Our study aims at unraveling the relationship between the fidelity of simulation and training effectiveness.

A two-station experiment platform (see photo) was setup in the real and virtual environment with analogous objects and surgical tasks in both. The real environment station has instrumented inanimate objects with which the subject performs tasks under laparoscopic surgical conditions. The same objects and tasks are simulated in the virtual station and displayed to the user through haptic and graphic interfaces. For the experiments, a subject would be trained for several sessions on the virtual station and then evaluated while performing the same tasks in the real station. Through such procedures the test-bed can measure the improvement in real environment skills as a result of virtual environment training. Therefore, the fidelity of the virtual environment simulation can be adjusted to determine relationship between the fidelity and training effectiveness.

Initial experiments were done involving bimanual pushing and cutting tasks on a nonlinear elastic object. The results showed that force feedback results in a significantly improved training transfer compared to training without force feedback. The training effectiveness of a linear approximation model was comparable to the effectiveness of a more accurate nonlinear model.

Various experiments similar in design to the above can now be done on this setup. Haptic fidelity experiments can be done by modeling material properties such as viscoelasticity and nonlinearity to varying degrees of accuracy. The effect of graphic fidelity can also be examined by having different levels of graphic accuracy. The results of these experiments would serve as the basis of future surgical simulation development by establishing the minimum requirements for environmental fidelity that can induce significant positive training transfer.

Publications

Journal Articles, Published
Raju B and Srinivasan MA, Statistics of Envelope of High-Frequency Ultrasonic Backscatter from Human Skin In Vivo, IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, vol. 49, no. 7, pp.871-882. 2002.

Book/Chapters in Books
Basdogan C and Srinivasan MA. Haptic Rendering in Virtual Environments. Handbook of Virtual Environments. K. Stanney. London, Lawrence Earlbaum, Inc.: Chapter 6. 2002.

Biggs SJ and Srinivasan MA, Haptic Interfaces. Handbook of Virtual Environments. K. Stanney. London, Lawrence Earlbaum, Inc.: Chapter 5. 2002

Meeting Papers, Published
Biggs SJ and Srinivasan MA, Tangential Versus Normal Displacements of Skin: Relative Effectiveness for Producing Tactile Sensations. 10th International Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, Orlando, FL, IEEE Computer Society. 2002.

Kim J, De S and Srinivasan MA, Physically Based Hybrid Approach in Real Time Surgical Simulation With Force Feedback, Medicine Meets Virtual Reality, 2002 (in press).

Reports
De S, Kim J, Muniyandi M, Srinivasan MA and Rattner D. Multimodal Simulation of Laparoscopic Heller Myotomy Using a Meshless Technique. Medicine Meets Virtual Reality: 10, pp. 127-132. Newport Beach, IOS Press. 2002.

Jordan J, Mortensen J, Oliveira M, Slater M, Tay BK, Kim J, and Srinivasan MA. Collaboration in a Mediated Haptic Environment. Presence 2002: The 5th Annual International Workshop on Presence, University Fernando Pessoa. 2002.

Kim J, De S and Srinivasan MA. Computationally Efficient Techniques for Real Time Surgical Simulation with Force Feedback. 10th International Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, Orlando, FL, IEEE Computer Society. 2002.

Prakash CE, Kim J, Muniyandi M and Srinivasan MA. A New Approach for the Synthesis of Glistening Effect in Deformable Anatomical Objects Displayed with Haptic Feedback. Medicine Meets Virtual Reality: 10, pp. 369-375. Newport Beach, IOS Press. 2002.

Tay B, Stylopoulos N, De S, Rattner DW and Srinivasan MA. Measurement of In-vivo Force Response of Intra-abdominal Soft Tissues for Surgical Simulation. Medicine Meets Virtual Reality: 10, Newport Beach, IOS Press. 2002.

Theses
Raju BI, High Frequency Ultrasonic Characterization of Human Skin In Vivo. Ph.D. diss. Dept. of Electrical Engineering and Computer Science. MIT. Cambridge. 2002.

Kim H, Role of Fidelity of Multimodal Simulation in Virtual Reality based Surgical Training, S.M. Thesis, Dept. of Mechanical Engineering, MIT. 2002.

Tay BK, In Vivo Characterization of the Mechanical Behavior of Soft Tissues for Surgical Simulation, S.M. Thesis, Dept. of Mechanical Engineering, MIT. 2002.