Laboratory for Human and Machine Haptics

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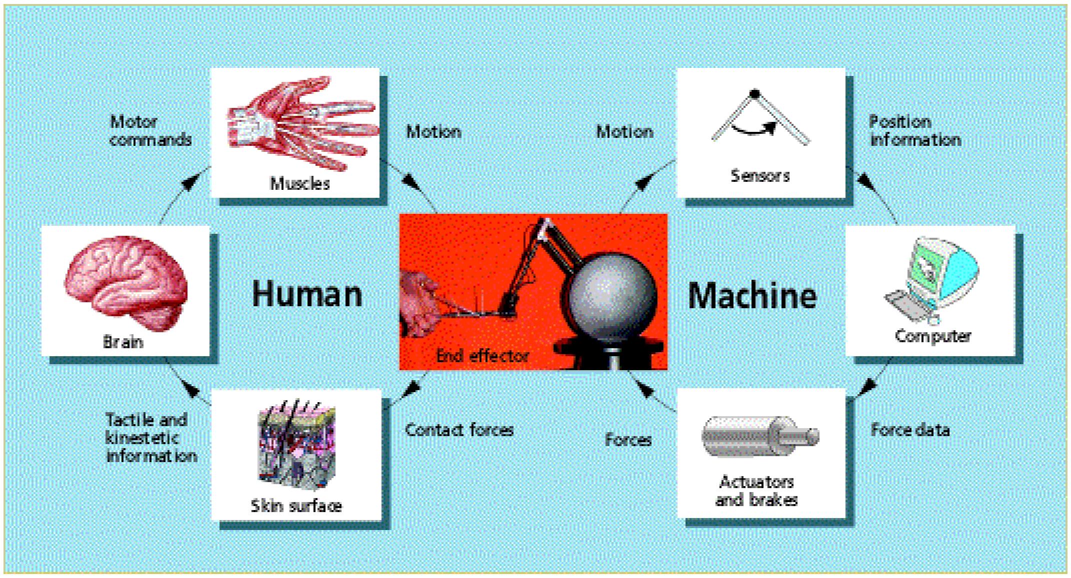
Introduction

The goals of research conducted in the Laboratory for Human and Machine Haptics (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 touch, 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 haptic interfaces. Our current projects are described in the following sections.

1. Role of Skin Biomechanics in Mechanoreceptor Response

Sponsor

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Overview

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. In spite of the fundamental importance of the sense of touch in our lives, very little is known about the mechanics and the mechanisms of touch. Analysis of mechanistic models generates testable hypotheses about deformations of skin and subcutaneous tissues, and about the associated peripheral neural responses. Verification of the hypotheses can then be accomplished by comparing the calculated results with biomechanical data on the deformation of skin and subcutaneous tissues, and with neurophysiological data from recordings of the responses of single neural fibers.

The research under this grant is directed towards applying analytical and computational mechanics to understand the biomechanical aspects of touch: the mechanics of contact, the transmission of the mechanical signals through the skin, and their transduction into neural impulses by the mechanoreceptors.

The research work consisted of four parts: (1) to develop 2 and 3 Dimensional (3D) mechanistic models of the primate fingertip, and gradually refine them so that their geometrical and material properties are increasingly realistic; (2) to expand the variety of stimuli that are pressed or stroked on the models in simulations of neurophysiological experiments; (3) to perform a series of biomechanical experiments under *in vivo* conditions using a variety of techniques including videomicroscopy, Optical Coherence Tomography (OCT), Magnetic Resonance Imaging (MRI), high frequency ultrasound, and computer controlled stimulators; (4) to obtain and analyze peripheral neural response data from monkey fingerpads for a variety of tactile stimuli (collaboration with Prof. LaMotte). During the past year, we have continued development of a novel device, the Ultrasound Backscatter Microscope (UBM), which is capable of imaging the papillary ridges as well as skin layers underneath at much higher resolution than MRI.

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The following sections describe progress over the past few years and are organized according to the research area: (1) biomechanics, (2) neurophysiology and psychophysics, (3) computational Models, (4) theory, and (5) device design and construction.

Biomechanics

Determination of Compressibility and Mechanical Impedance of the Human Fingerpad In Vivo

For mechanistic modeling of the human fingerpad, the Poisson's ratio, a measure of compressibility, is required. Accordingly, the Poisson's ratio for the human fingerpad in vivo was investigated. In previous noninvasive experiments on human subjects, we have measured the change in volume of the fingerpad under static indentations with different indenters. Our results show that the compressibility of the fingertip increases with increases in both the depth of indentation and the contact area with the indentor. The highest change in fingertip volume was about 5%. For dynamic indentations, reductions in fingertip volume are in phase with stimuli, as the mean volume reduction slowly creeps upward over time. The volume changes during the ramp phase increase linearly with indentor displacement and are independent of velocity; during saw tooth stimulations, however, the nature of the hysteresis loops depend on velocity of indentation.

We have also measured the force response of the human fingerpad, *in vivo,* to indentation by stimuli of varying geometry. A computer-controlled tactile stimulator delivered a combination of static, ramp and sinusoidal indentations normal to the skin surface, with the fingerpads of subjects held stationary and passive. Both input indentation depth and fingerpad force response were recorded as functions of time to capture transients and steady state features. Three rigid metal indenters, a point, a 6.35 mm diameter circular probe and a flat plate, were used for indentation to represent three general classes of loading profiles encountered in manual exploration and manipulation. With each stimulus, repeatability of the response was tested and the effects of varying amplitude, velocity, and frequency of indentation were investigated. The experiments revealed that the force response of the fingerpad is both nonlinear and viscoelastic with respect to indentation depth and velocity. A nonlinear Kelvin model was proposed and approximated as a piecewise linear set of springs in parallel with series spring-dashpots. Parameters were estimated for each subject and indenter. These “individual” models predicted data for that particular subject and indentor very well ($R^2 > 0.96$) but not as well for others. The means of the parameters across subjects were then used to construct more general, indentor specific versions of the model, which were able to predict better the force response of any subject’s fingerpad to a given indentation. These results were used in validating 2-dimensional and 3Dimensional (3D) mechanistic models of the primate fingertip.

Experimental Investigation of Frictional Properties of the Human Fingerpad

In manual exploration as well as manipulation, the frictional properties of the fingerpad play a dominant role in governing the forces applied, the amount of skin stretch, and the occurrence of slip. We used a tactile stimulator to indent and stroke the fingerpads of human subjects with different indentation depths, stroke velocities, and stroke directions. Three flat plates made of glass, polycarbonate, and acrylic were used as stimulus surfaces. During stroking, the normal and shear forces were recorded by a 2-axis force sensor. A videomicroscopy system captured images of the contact region between the fingerpad and the stimulus surface while stroking. The stimulator and the videomicroscopy system were synchronized so as to match the images with the corresponding force data.

The data show distinct frictional behaviors for different stimulus surfaces. For glass, the curves of normal as well as shear forces increased smoothly to steady state values. When the indentation depth was larger, the normal and shear forces were larger, but the friction coefficient was smaller. When the stroke velocity increased, the normal force was about the same for a given indentation depth, while the shear force and the friction coefficient increased. The stroke direction did not significantly influence the results. The images showed that relative motion between the fingerpad and the glass plate began at the periphery and propagated towards the center. Displacements of different finger ridges in the contact area also varied.

Polycarbonate and acrylic surfaces, although similar in smoothness and appearance to glass, caused a radically different frictional behavior: stick-slip phenomenon occurred consistently all through the stroke in every trial. An analysis of the stick-slip frequency and the stick-slip shear force was conducted with respect to various indentation depths and various stroke velocities. Based on adhesion theory a hypothesis about junction forming rate and junction breaking rate was proposed to explain the different results for glass and polycarbonate. The frictional data have been incorporated into our models of the primate fingertip to make the simulations of stroking of stimulus objects more realistic.

Measurement of the Pressure at the Skin to Surface Interface with Fine Spatial Resolution

Over the last year, we have begun measuring the pressure distribution at the skin/object interface with sub-millimeter spatial resolution. Pressure distributions developed by cylinders ranging from 1/8 to 1-inch radius are being measured, using a 16 x 16 array of capacitive pressure sensors. A motion platform indents the cylinder with good (~12 micron) precision, while a load cell measures net reaction force. To achieve spatial resolution finer than the spacing of the sensor elements (2mm on center), we are using deconvolution. By taking 500 measurements, each shifted slightly via the motion platform, we are obtaining fine spatial resolution (1 sample/0.1mm). The system is now being calibrated on data from a series of micro-machined ridges separated by 2.0 to 0.020 mm.

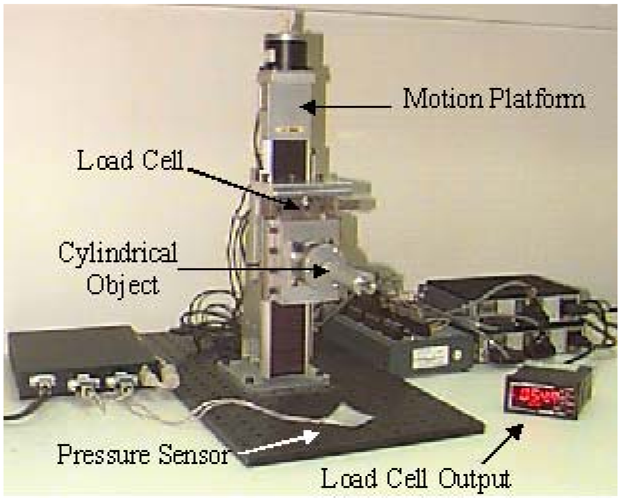

Figure 1-1. An apparatus for measuring pressure at the skin-to-surface interface with fine spatial resolution.

Investigation of the Internal Geometry and Mechanics of the Human Fingertip In Vivo *using Magnetic Resonance Imaging*

To gain insight into the mechanistic bases of the human tactile sensory system, we have developed a series of increasingly detailed biomechanical models of monkey and human fingertips. These models are necessary to generate testable hypotheses on tactile neural coding. Although 3D models of human and monkey fingertips with realistic external geometry and multi-layered interior have been completed, the geometry and material properties of the internal layers have been idealized. Empirical data on deformation of the internal layers is essential for validating these models.

We employed advanced techniques in Magnetic Resonance Imaging (MRI) to obtain realistic internal geometry and deformation of the tissue layers of the *in vivo* human fingerpad. The fingerpads of four subjects were statically loaded with various indenters to examine the effects of indentation depth and indentor shape on tissue deformation. Geometric surfaces, such as edges, rectangular bars, and cylinders were used to load the fingertip. Using a 4.7 Tesla magnet and a RARE sequence, we obtained images with in-plane resolutions much higher (125μm x 125μm) than typical clinical MRI data. Digital image processing was used to filter the images and to detect the boundaries of the tissues located in the fingertip. Edge detection algorithms based on conformable contours ("snakes") allowed separation of tissue layers. Published data on histology and anatomy were used to identify each tissue layer in the fingertip.

The geometric information extracted from each tissue layer was used to examine tissue deformation during loading, and is being used to improve the realism of the computational models. These data confirmed our earlier simulations that predicted that soft tissues of the fingerpad act as low pass filters, attenuating the high spatial frequencies of edges and corners imposed on the skin surface before they reach the mechanoreceptors below. Additionally, MRI confirmed that the fingerpad is compressible under load.

Videomicroscopy of Ridged Skin Biomechanics
We have begun using dynamic video microscopy (Figure 1-2) of cadaver finger pad cut in cross section 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.

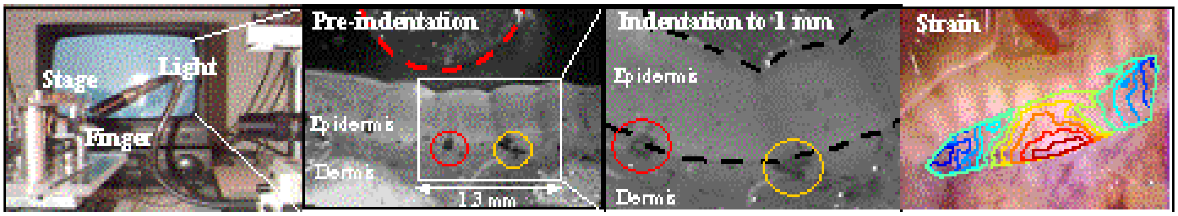

Figure 1-2. A video microscopy system (left image) provides high resolution images of skin. A cylindrical indentor loads a cadaver finger pad, while the tissue is viewed in cross section (middle 2 images). Strains around mechanoreceptors are estimated from displacements of markers on the tissue (right image).

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. Further work has improved the method. A color CCD is now used to differentiate epidermis from dermis. Material points in the tissue are now tracked with high contrast markers. A jig has been developed to ensure cross-sections are planar. To date, data have been collected from five human cadaver fingers and six primate fingers.

This technique facilitates study of some basic issues in touch transduction. Specifically, we hope to observe whether the papillary ridges concentrate strain in the tissue around mechanoreceptors. If so, we will have empirical evidence for a sensory function of fingerprints.

Optical Coherence Tomography of Ridged Skin Biomechanics
We have begun a first-of-a-kind effort to use Optical Coherence Tomography (OCT) to study touch biomechanics. In collaboration with Dr. Johannes deBoer at the Massachusetts General Hospital, a high speed single-mode fiber-based polarization-sensitive optical coherence tomography (PS OCT) system has been fabricated and used to get *in vivo* images of finger pad skin (Figure 1-3). The low-coherence light source (AFC technologies) has a FWHM bandwidth of 80 nm centered at 1310 nm and its polarization state was selected optically such that the power

can be as high as 8 mW. The finger pad was scanned over a 1.68mm*1.68mm area, with 1.5mm in depth. 112 images were taken over the 1.68mm length in axial direction of the finger. Spherical (15F, 25F, 35F, 50F, 100F, and 150F) and cylindrical (22.2F) lens with a variety of focal lengths were used to apply indentation with different curvature and varied loading conditions (0, 5g, 10g, 20g, 30g, 50g, 100g).

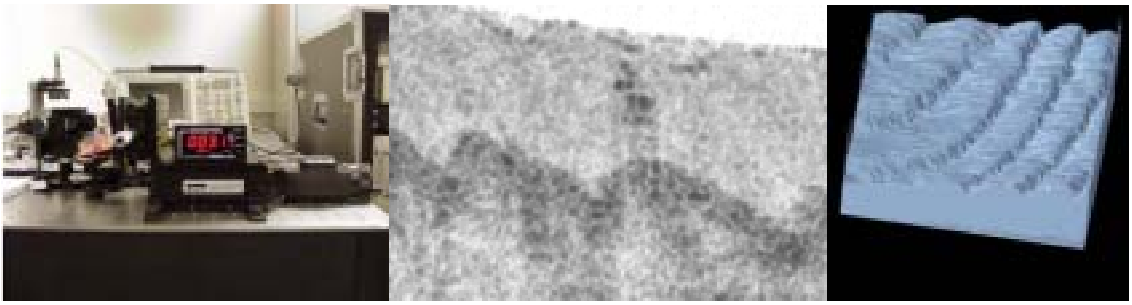

Figure 1-3. OCT setup (left) visualizes the skin in cross-section (left) showing epidermis and dermis deforming under a curved indentor. In OpenDX, the dermal/epidermal boundary of multiple slices are extracted, assembled, and rendered as a 3D surface (right).

Neurophysiology and Psychophysics

Tactile Coding of Shape

A salient feature of tactile sensing is its ability to encode and decode the shape of objects. In collaboration with Prof. LaMotte of Yale University School of Medicine, we have recorded the responses of SAIs and RAs to a variety of 2-D and 3D shapes stroked across the monkey fingerpad. One set of experiments involved 2-D "wavy surfaces", i.e., surfaces composed of smooth, alternating convexities and concavities of differing radii of curvature. The second set of experiments employed 3D toroidal objects mounted on a flat plate. With wavy surfaces, it was shown that only convexities were encoded in the neural responses; concavities evoked no responses. The primary findings from both sets of experiments were as follows: (a) discharge rates encode the magnitude and rate of change in the curvature of the skin produced by an object, (b) the orientation and shape of the two-dimensional outline of the object parallel to the skin are represented by the orientation and shape of the region of neural activity in both SA and RA populations, (c) object shape perpendicular to the skin is encoded in the shape of the object SA SPR (Spatial Population Response), (d) When object curvature is constant (e.g., circular cylinders), the slopes of the rising and falling phases of the SA response profile are constant, and (e) spatial measures of shape (width and average slope from base to peak) were generally found to be invariant with changes in the orientation of the object as well as the velocity and direction of stroking.

Using a novel paradigm we have also investigated how populations of RAs and SAIs encode shapes. Toroidal 3D objects were indented at a fixed location on the monkey finger pad, and an estimate of the responses from a spatially distributed population of mechanoreceptors was obtained by successively recording single fiber responses and plotting the collection of responses on a "virtual" monkey fingerpad. This was a shift from the usual experimental paradigm where "population response" is estimated by applying the stimulus to various locations in the receptive field of a single afferent fiber. A major conclusion from these studies was that the Spatial Population Response Profiles (SPR) of SAs coded stimulus shape and orientation unambiguously, while the RA SPR coded neither. This shape code is expected to be essentially invariant with changes in force or velocity of indentation, as demonstrated for raised toroidal objects on a planar surface described above.

Tactile Coding of Softness

Encoding of softness is perhaps even more important in tactile sensing than that of shape, because softness can only be sensed accurately by direct touch, whereas shape can be inferred through vision as well. We have described, for the first time, how primates discriminate between objects of different compliances and described the biomechanical and neural basis of the perception of softness. We have shown that compliant springs with rigid surfaces ("spring-cells") required both kinesthetic and tactile information for softness discrimination, whereas for soft rubber objects of different compliances, tactile information alone was sufficient. The reason is that for a given force applied by a compliant object to the skin, the spatial pressure distribution and skin deformation within the contact region depend on the specimen compliance if the object has a deformable surface (e.g., fruits), but is independent of the specimen compliance if its surface is rigid (e.g., piano key). Thus, tactile information alone is necessary and sufficient to encode the compliance of rubber-like objects.

We then focussed on finding a more quantitative neurophysiological and biomechanical basis for softness encoding. Using a computer-controlled tactile stimulator, we applied rubber specimens to the finger pads of anesthetized monkeys in a controlled manner and recorded the neural response from SAI and RA fibers. The discharge rates were observed to be lower in the SAI fiber's response to softer specimens compared to stiffer ones. In contrast, RA response was found to be practically indifferent to the relative variations in stiffness. Thus, it was concluded that tactile discrimination of softness was based more on the discharge rates from the SAIs than from the RAs. It was also found that when specimens were applied to the fingerpad at the same velocity, the softer the specimen, the lower the rate of change of net force and the higher the rate of change of overall contact area. Thus, at a given instant during indentation, the difference in the average pressure between the two specimens was higher than the corresponding differences in either the forces or the contact areas. Just as the pressure increased more slowly for the softer specimen, the SA discharge rate also increased more slowly, resulting in a slower increase in cumulative impulses. However, the velocity of indentation affected the force, contact area, and discharge rate. For the same specimen, the lower indentation velocity resulted in lower force and area rates, giving rise to a lower discharge rate at a given instant during the ramp. Since the discharge rate of a single fiber is affected by both the compliance of the specimen and the indentation velocity, specimens of differing compliances could be made to give rise to the same single fiber response by appropriate adjustment of indentation velocity. Thus, discharge rate in a single SAI fiber cannot unequivocally encode the compliance of an object, but a population of spatially distributed SAIs can.

Psychophysics of Tangential Skin Displacements

Tangential displacement of the skin (as opposed to normal indentation) is an interesting tactile stimulus. To detect small (< 1 mm) features, humans must scan the fingertip over a surface, presumably to induce tangential displacements. We have measured subjects' sensitivity to tangential displacements of skin on the finger pad and forearm. Subjects showed greater sensitivity to tangential displacements than normal displacements by a factor of about 3:2 at the finger pad and 3:1 at the forearm. These ratios were in rough agreement with a biomechanical analysis of how these tractions distribute energy to the mechanoreceptors embedded in the tissue. Subjects' high sensitivity to tangential tractions suggests that they are an efficient means of stimulating skin with tactile displays that are capable of providing only limited displacements (e.g. piezoelectric ceramics). Based on measurements of skin impedance, these results were also expressed in terms of forces. It was found that when a given actuator technology is limited primarily in terms of force (e.g. DC micromotors), tangential stimulation is still more favorable than normal stimulation of the forearm. However, at the finger pad, where the tangential stiffness of the tissue is 5-fold higher than at the forearm, applying a given force in the normal direction was found to elicit a perception of intensity more effectively than applying it in the tangential direction.

Computational Models

In order to better understand the mechanics of touch, it is necessary to establish a quantitative relationship between the stress/strain state at a mechanoreceptor location and the neural response of the receptor to a given mechanical stimulus. Due to the subsurface locations of the receptors and the opacity of the skin, the stress state and deformations in the close vicinity of a receptor cannot be observed experimentally in vivo. Moreover, no experimental techniques exist to record the responses from a population of mechanoreceptors. A mechanistic model of the skin and subcutaneous tissues that is validated through biomechanical and neurophysiological experiments is able to establish the stress/strain stimulus to a mechanoreceptor as well as predict the population response to a given stimulus. Therefore, we developed a series of increasingly realistic 2-D and 3D finite element models of the primate fingertip. We summarize below the development of the 3D model and the biomechanical and neurophysiological results obtained from it.

Development of 3D Layered Model of Human and Monkey Fingertips

The external geometry of human and monkey fingertips was obtained from precise epoxy casts made using dental cement molds. These casts were extremely accurate in reproducing the finger print ridges, details of the nail and wrinkles on the skin. A videomicroscopy setup consisting of a monochrome CCD camera with zoom lenses, a frame grabber, and a PC was used to acquire images of the casts in different orientations. A stepper motor was used to rotate the fingertip about an axis parallel to the bone axis in 1-degree steps, and an image was grabbed at each step. The boundary of the fingertip in an image frame essentially represented the orthographic projection of the fingertip for that particular orientation. These 2D sections were imported into a solid modeler (PATRAN) and a 3D model of the fingertip with realistic external geometry was generated. The relative thickness of the bone in the distal phalanx was determined from X-ray images and a concentric bone was generated inside the fingertip. To account for the several layers of skin and the adipose tissue underneath, the mesh was generated in layers such that each layer could be assigned a distinct material property and mechanistic constitutive behavior. The material of each layer was treated as linear isotropic and the innermost layer was made several orders of magnitude stiffer than all the other layers to simulate the rigid behavior of the bone**.** Two models with 8-noded isoparametric elements were generated and the number of nodes in the two models were 8500 and 30,000 respectively. The typical diameter of the monkey fingertips was approximately 9 mm and element size in the region of contact with indenters was approximately 500 microns and 160 microns for the two models respectively.

In subsequent work, we have improved the model. Geometry of our prior model was taken directly from a cast of primate fingerpad that had been digitized with a laser range finder. Although this model was empirically correct, the sampling frequency of the range finder was not as fine as the individual ridges on the finger pad. Undersampling of these details led to discontinuities in the local curvature of the model, which sometimes led to non-physiologic predictions of the distribution of interfacial pressure. To overcome this problem, our new model has been fit with splines and ellipsoids (Figure 1-4, right panel) that have continuous higher derivatives. The model has also been re-meshed at three different spatial resolutions, so that a coarse simulation can be run rapidly on a desktop computer before a high-resolution (~48,000 nodes) simulation is sent to a remote supercomputer. Finally, the absolute stiffness of the tissues in the model has been calibrated in order to match reaction forces observed in primate fingerpads (Figure below, left 2 panels). This is an improvement over our prior model, in which only the relative stiffness of the layers was known.

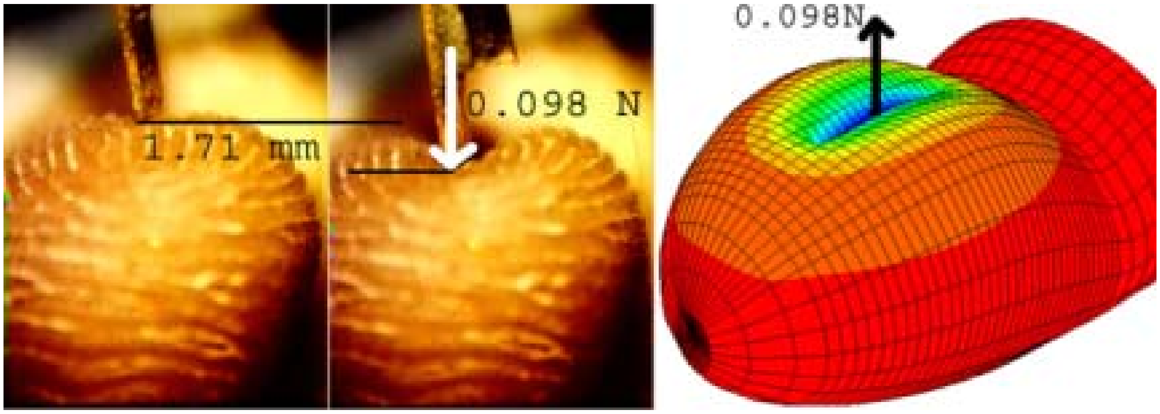

Figure 1-4: Video microscope images of primate finger pad (left 2 panels) show a robot indentor applying 0.098 N of force to a line load 4 mm long, indenting the tissue by 1.71 mm. Using this displacement as a boundary condition, the absolute stiffness of the tissues in a smoothed finite element model of the finger pad (right) were calibrated in order to match the observed reaction force

Encoding and Decoding of Shape during Static Tactile Sensing

The model described above was used to simulate static indentation of the fingertip by rigid objects of different shapes such as cylinders, rectangular bars, and sinusoidal step shapes. The large number of computations necessary to achieve a high spatial resolution and realism in the simulations required the use of a supercomputer (Cray C90). The results show that contact mechanics is important in governing the pressure distribution on the skin surface, which, in fact, is the stimulus unique to each shape. This surface pressure distribution within contact regions was found to be highly dependent on the curvature of the object that indented the finger. Further, we have shown that a simple equation is able to predict the surface pressure as a function of the indenting object's curvature and the local depth of indentation. To study the mechanism of transduction by the mechanoreceptors (transformation of the mechanical stress state into neural signals), 21 mechanical measures were obtained from the calculated stress and strain tensor at mechanoreceptor locations, and were matched with experimentally recorded neural response data. Three quantities - maximum compressive strain, maximum tensile strain and strain energy density - were found to be related to the neural responses of SA-I nerve fibers through a simple scaling-threshold model and are thus possible *relevant stimuli* for SA-I afferents. Among these, strain energy density is more likely to be the relevant stimulus since it is a scalar that is invariant with respect to receptor orientations and is a direct measure of the distortions of the receptor caused by the loads imposed on the skin.

To identify the object contacting the skin, the CNS should be able to compute surface loads imposed on the skin from the peripheral neural response. To simulate this inverse problem of decoding, a nonlinear shift-invariant system, which treats the surface pressure as input and neural responses as output, was developed. Because of the nonlinearity (the relevant stimulus measures, such as the strain energy density, are nonlinear functions of the Cartesian stress-strain components), a simple inverse transformation cannot be applied. A signal estimation technique using the university method used in non-linear optimization techniques was employed to decode the surface pressure function from the neural response function. The decoding was demonstrated to be valid for both the ideal case where no sensor noise is present as well as the case where the sensor noise (assumed to be additive Gaussian) is present, as long as the signal-to-noise ratio is greater than 20 dB. This result shows a method by which the central nervous system could infer the shape of the object contacting the skin from SAI population response under static conditions.

Modeling the Dynamics of the Primate Fingerpad

The previous section describes our fingertip models that are able to explain and predict both biomechanical and neurophysiological phenomenon observed in experiments with static stimuli. Encouraged by this success, we have now begun to model the dynamic behavior of the fingerpad in order to realistically simulate the neurophysiological experiments involving dynamic stimuli, such as under stroking of shapes. We have now incorporated viscoelasticity into our computational models of the primate fingertip. To this end, the biomechanical data obtained from the indentation of the fingerpads of several human subjects using different indentor geometries was used. A consistent normalization scheme was developed which showed that most of the variation in the data obtained across subjects was scalable by a single parameter. This led to the development of a second order Kelvin model that satisfactorily explains much of the observed force-displacement data for a truncated conical indentor. The Correspondence Principle was invoked to extend these results to obtain the material parameters of a generalized 3D linear viscoelastic continuum. These parameters were then incorporated into a 2D plane strain and a 3D layered finite element model. The results obtained from these computational models predicted the observed force-displacement data very well for all the indenters (truncated conical, cylindrical and flat-plate indenters) used in the earlier biomechanical experiments. These models are now being used to simulate dynamic stimuli imposed on the fingerpad, such as stroking of shapes in order to understand the role of mechanoreceptors during haptic exploration. Neurophysiological recordings from slowly adapting (SA) and rapidly adapting (RA) mechanoreceptors have been made for a variety of shapes, both statically indented and dynamically stroked across the fingerpad. Previous biomechanics research has been to determine the mechanics underlying the role of SAs during static indentation. Mechanical cues have been determined which relate curvature to impulse response of the receptor. The purpose of the current investigation is to determine the mechanical response of both SAs and RAs during dynamic stroking, and to develop a unifying model of the role of each mechanoreceptor in touch sensation.

Skin Dynamics in the Tactile Encoding of Shape using a Realistic 2D Finite Element Model

Using previously obtained MRI images of the human finger, we created a multilayered finite element model that accurately represented the internal and external geometry of the human fingerpad. By matching model predictions with biomechanical experimental data, the viscoelastic parameters for each skin layer were estimated and the biomechanical behavior of the model was validated. Figure 1-5 compares the finite element analysis results of a 1/16 inch rectangular bar indenting the finger to the actual finger deformation obtained from MRI imaging. To simulate the mechanics of touch, surfaces of different curvatures were indented into the finger model, and the contact force was held constant until steady state conditions were reached. In addition, a surface of alternating convex and concave segments, each with a different curvature, was stroked across the finger at various velocities. The results from the simulation studies were compared with previously obtained neurophysiological data from the corresponding experiments.

The principal findings are as follows. (1) Under both indentation and stroking of shaped objects, the contact pressure across the fingerpad is the primary mechanical stimulus, and it is found to be directly proportional to the object curvature. (2) The use of a layered model, as opposed to a homogeneous model, has a profound effect on the shape of the contact pressure distribution across the skin surface. (3) The strain energy at depths below the skin surface can be predicted from a convolution sum of the contact pressure distribution. (4) A linear combination of the strain energy and the strain energy rate at typical mechanoreceptor locations can reasonably predict the SA-I neural response during both indentation and stroking experiments.

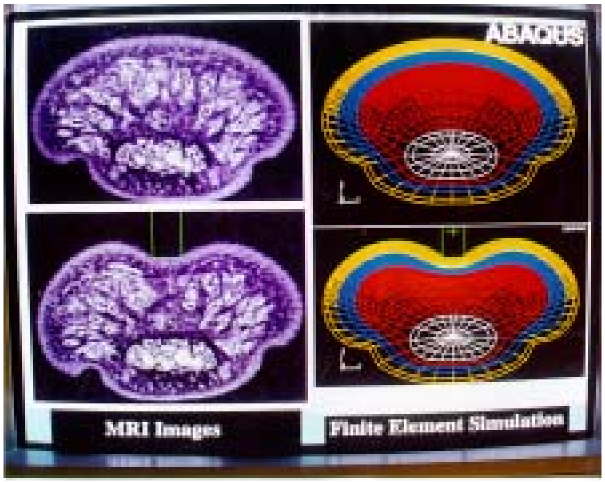

Figure 1-5. MRI data compared with finite element simulations. The images show the results for the undeformed human fingertip cross-section and its deformation under a 1/16 inch rectangular bar indenting the fingertip to a depth of 2 mm.

The method of finite spheres: a meshless computational technique for biomechanical simulations
We have used the finite element method extensively to model the fingerpad and analyze the stress/strain fields at the mechanoreceptor level. Both two-dimensional and three-dimensional models have been developed and analyzed using the finite element software package ABAQUS. Even though the finite element method is a robust numerical technique to solve elastostatic (e.g. indentation) and elastodynamic (e.g. stroking) problems, a considerable amount of time and energy is devoted to the development of the finite element mesh. Moreover, once a particular model has been developed, it is extremely time consuming to modify it. To overcome these problems we have developed a novel computational technique, the method of finite spheres, which does not require a background mesh for discretization. This technique is very similar to the finite element method and is equally robust, but uses a set of nodes sprinkled on the computational domain to develop the discrete set of linear algebraic equations. We have successfully tested the method on several example problems.

Theory

Nonlinear Dynamics of Mechanoreceptor Response
One of the most interesting aspects of dynamic tactile sensing in humans is the nature of mechanoreceptor response to dynamic stimuli. In contrast to the response of the fingerpad tissue, the receptors seem to exhibit nonlinear behavior even for very small indentations of the fingerpad skin.

The most classic example of such nonlinear response is the so called "tuning curves" which are nothing but the variations of dead-zone and saturation thresholds as functions of frequency of input sinusoids. In order to model these nonlinearities, a generalized class of cascaded LNL-type filter banks were developed. Such models, in general, incorporate a linear describing function block followed by a static nonlinearity and another linear describing function block. It was observed that different receptor classes could be described by specializing this general model. For instance, the behavior of the SAI mechanoreceptors could be explained very well using a Hammerstein type of structure (a static nonlinearity followed by a linear dynamic block). These models provided good fits to the empirically recorded mechanoreceptor responses. The next step appears to be a successful link between the finite element model describing the geometric and material properties of the fingerpad and the neuro-dynamic transduction blocks, describing receptor behavior for each class of receptors. We are now in a position to predict the spatial response profiles observed during the stroking of complex shapes (toroids, wavy surfaces and sinusoidal step shapes) on primate fingerpads.

Identification and Control of Haptic Systems: A Computational Theory
This research provides a theoretical framework for haptics, the study of exploration and manipulation using hands. In both human and robotic research, an understanding of the nature of contact, grasp, exploration, and manipulation is of singular importance. In human haptics the objective is to understand the mechanics of hand actions, sensory information processing, and motor control. While robots have lagged behind their human counterparts in dexterity, recent technological developments have made it possible to build tactile sensor arrays that mimic human performance. We believe that a computational theory of haptics that investigates what kind of sensory information is necessary and how it has to be processed is beneficial to both human and robotic research.

Human and robot tactile sensing can be accomplished by arrays of mechanosensors embedded in a deformable medium. When an object comes in contact with the surface of the medium, information about the shape of the surface of the medium and the force distribution on the surface is encoded in the sensor signals. The problem for the central processor is to reliably and efficiently infer the object properties and the contact state from these signals. We first investigated the surface signal identification problem: the processing of sensor signals resulting in algorithms and guidelines for sensor design that give optimal estimates of the loading and displacement distributions on the surface of the fingerpad. We have shown that three quantities, mean normal stress and the two shear strains at mechanosensor locations, are not only necessary and sufficient to infer the surface signals, but also maximize the spatial bandwidth of signal reconstruction. We then focused on how the information obtained from such optimal sensing can be used for exploration of objects. We have shown that an accurate reconstruction of object properties can occur using two basic building blocks of Exploration Strategy and Finger Control. Exploration Strategy pertains to the problem of inferring object properties such as shape, texture and compliance, and interference properties such as state of contact, from the estimated surface signals. This involves determining, in each case, what kind of sensor information and what kind of action is needed. Finger Control refers to the transformation of the action needed into a command trajectory for the fingerpad, which defines the desired direction of movement for manipulation. We have defined and analyzed the components of both these blocks, provided explicit mathematical formulation, and have solved numerical examples where appropriate. Our formulation of this computational theory of haptics is independent of implementation so that it is applicable to both robots and humans.

Device Design and Construction

Ultrasound Backscatter Microscope for In Vivo Imaging of Human Fingertip
One of the conclusions of our earlier MRI studies was that if a noninvasive imaging system with higher resolutions than MRI could be designed, it would be a powerful tool to observe deformations of the skin tissue around mechanoreceptors and would help validate our computational models. We have now developed an Ultrasound Backscatter Microscope (UBM), which is able to display the geometry and deformation of skin layers *in vivo*. UBM is similar to B-mode diagnostic ultrasound imaging, but uses higher frequency acoustic waves (about 50 MHz) to achieve resolutions of the order of tens of microns. In UBM, contrast depends on the mechanical properties of tissues, a feature that complements techniques such as optical microscopy, CT and MRI that rely on other tissue properties. This feature also makes UBM ideal for studying the mechanistic basis of tactile sensing. In addition, UBM is less expensive than most imaging techniques, and is also noninvasive. However, because of increased attenuation of the acoustic waves at higher frequencies, the tissues being imaged must be located within a few millimeters of the surface. A UBM system was designed and built using a high frequency PVDF transducer (nominal frequency of 75 MHz), a pulser, a digitizing oscilloscope, a scanning system and the IEEE488 interface.

The device was used to image the internal structure of the human fingertip skin *in vivo* (Figure 1-6). At each skin location, the transducer was energized and echoes from tissues at different depths were recorded. By mechanically scanning the transducer across the fingerpad surface and keeping track of signals from successive lateral locations, data on mechanical contrast in skin cross sections were assembled. Signal processing was done on the echoes to obtain 2-D images. Images of fingerpad skin of six human subjects showed three distinct layers up to a depth of about 1.2mm. Comparison images of fingertip skin on the dorsal side also showed a layered structure, with lesser thickness for the first two layers. The data obtained is consistent with known anatomical information that the three layers imaged are the stratum corneum, the rest of the epidermis, and the top region of the dermis.

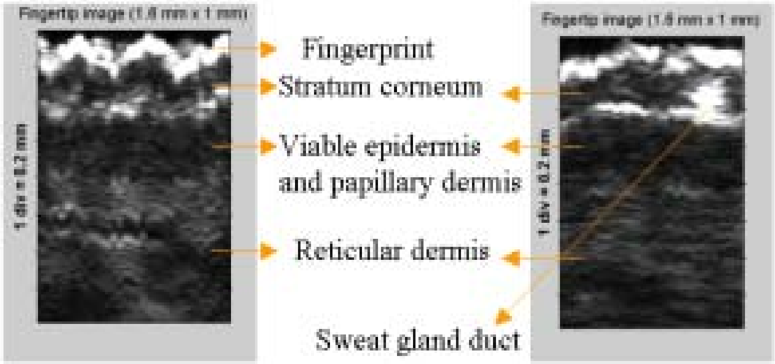

Figure 1-6. Two images from the ultrasound backscatter microscope. In the left image the scan direction was across the finger ridges and it is possible to identify the ridges on the surface and layers within the skin. In the right image, the scan is along the ridges and it is possible to identify even features such as a sweat gland duct within the stratum corneum.

We had previously developed an ultrasound backscatter microscope system that employed high frequency ultrasonic waves (50 MHz) for obtaining high-resolution images of the human fingertip. We are currently extending the research to clinical applications such as imaging and characterization of skin lesions. Potential applications include skin cancer detection and staging. The work focuses on the development of hardware for clinical imaging, collection of data from patients, and development of algorithms for characterizing skin lesions. Progress over the last year was achieved in four areas described below.

1. *Upgrading the existing system to a fast-scan system suited for a clinical environment*: The previous device used a digitizing oscilloscope and GPIB interface for transferring the ultrasound echo signal to the PC. Because of the inherent limitations in the transfer speed, the scanning of the transducer was done in steps: the transducer would be positioned over a particular region, the data collected and transferred to the PC, and then the transducer moved to another location, and the process repeated again. With this system, the maximum scan rate was about 0.1 mm/sec, implying that a typical scan of 5 mm would take close to a minute. The serious limitation of this was that subject motion artifacts would make the images very fuzzy. To overcome this limitation, we replaced the digitizing oscilloscope with a high-speed A/D board from Gage Applied Sciences Inc., which uses the fast PCI bus to transfer the digitized echoes to the PC's memory at a rate of 100 Mbytes/sec. Concurrently the software was also upgraded to seamlessly integrate the new A/D board with the existing system and also to perform high-speed calculations in software. With this system, scan rates are now 2 mm/sec, which is twenty times faster than what it used to be. A scan of 5 mm now takes only 2.5 seconds.

2. *Analysis of statistics of ultrasound echo envelope from normal skin tissues*: The statistics of envelope of high frequency ultrasonic backscatter signals from in vivo normal human dermis and subcutaneous fat were studied. The capability of seven probability distributions (Rayleigh, Rician, K, Nakagami, Lognormal, Weibull, and Generalized Gamma) to model empirical envelope data

was studied using the Kolmogorov-Smirnov goodness-of-fit statistic. The parameters of all the distributions were obtained using the maximum likelihood method. It was found that the Generalized Gamma distribution with two shape parameters provided the best fit among all the distributions. The Rayleigh and Rician distributions did not model the statistics well. Other non-Rayleigh distributions, especially the K and Weibull distributions also modeled the data well. The inter-subject variability in the estimated parameters was found to be comparable to the intra-subject variability. The capability of the estimated parameters to differentiate different tissues (dermis. vs. fat, forearm dermis vs. fingertip dermis) was also studied. These results are expected to be useful in differentiating normal from abnormal skin tissues.

3. *Data collection from patients with skin with skin lesions*: In the past year, we also moved the device to the Wellman Laboratory of Photomedicine at the Massachusetts General Hospital. We are collaborating with Dr. Salvador Gonzalez to explore clinical applications of the device. As a first example, we have collected data from patients having contact dermatitis (both allergic and irritant). Efforts are now underway to characterize these skin lesions using ultrasonic parameters.

4. *Development of algorithms for improving image (Figure below) quality using wavelet-wiener deconvolution techniques.*

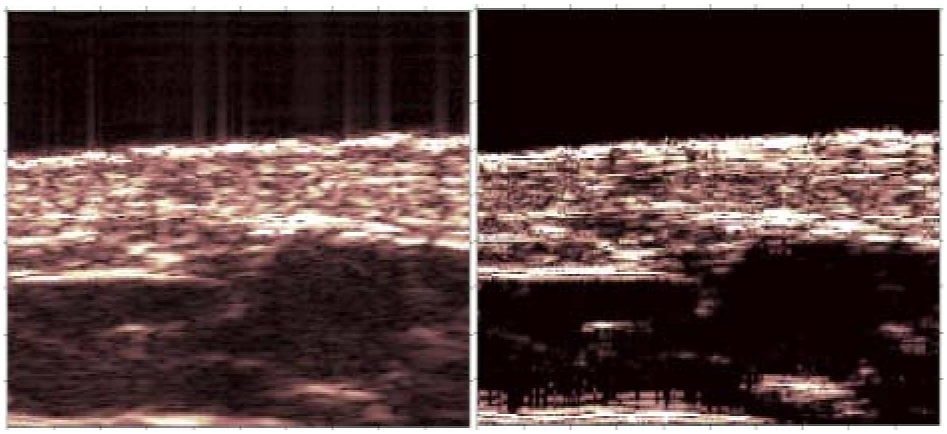

Figure 1-7. Improvements to contrast and resolution of ultrasound images of human skin (left) are being investigated, using axial and lateral deconvolution by wavelets (right).

Current work in this area is in four directions: (1) Further improvement in the device to make it portable (2) Collecting data from skin lesions such as skin cancer (3) Analysis of backscattered signals from skin lesions (4) Exploring the use of elastographic techniques to compute in vivo mechanical strains and properties such as elasticity. (Work also partly supported by a Grant-in-Aid of research from the national Academy of Sciences through Sigma Xi).

2. Tactile Displays Realized Using MEMS Actuator Arrays

Sponsor

Defense Advanced Research Projects Agency - Grant N00019-98-K-0187

Project Staff

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The purpose of this project was to develop new tactile interfaces that capitalize on advances in MicroElectroMechanical Systems (MEMS) technology to create high-bandwidth displays for stimulating the user's tactile sense. Such devices may also receive manual or other types of pressure/contact input. We envision two major classes of applications: (1) Tactile interfaces mounted on machines could indicate the state of the machine--such as the remaining charge in a battery--or it might respond to the operator's touch in subtle ways not possible with conventional controls, (2) Tactile interfaces attached to the human body--for example, through a glove or wrist band--could be used with wearable computers or communication devices for both input and output.

The project was a collaboration between the MIT Touch Lab at RLE and Prof. Kaigham J. Gabriel at the MEMS Laboratory at Carnegie Mellon University (CMU). The group at CMU constructed a 1 cm x 1 cm "test taxel chip" which contains 25 taxels on its surface and began characterization of the chip's electrical and mechanical properties. See the discussion of "Tactile Displays Using MEMS Actuator Arrays" on the web site of the CMU Microelectromechanical Systems Laboratory for further details (http://www.ece.cmu.edu/~mems/projects/index.shtml).

The work at MIT consisted of experimental studies of biomechanics and tactile perception that are intended to guide the design of tactile interfaces and to advance the science of human haptics. Experimental apparatus was specially developed for this research using conventional (non-MEMS) technology that could simultaneously control the displacement of a probe pressed against the skin while measuring the resultant force. During 2001, the final year of the project, one Master's thesis was completed at MIT (Diller, 2001) in which the mechanical impedance of human skin was measured in vivo at four body sites. Work also continued on data analysis of our prior experiments and preparation of the results for publication. Our preliminary analysis of the perception data suggests that the tactile threshold is relatively constant in terms of the power transmitted to the skin over a range of frequencies. Development of the experimental apparatus begun under this project was continued for use in future experiments.

3. Cortical Control of Robot Manipulators

Project Staff

Mandayam A. Srinivasan, S. James Biggs, Jung Kim, Miguel A. L. Nicolelis[3]

The MIT Touch Lab is now collaborating with the Laboratory for Neural Ensemble Physiology at Duke University. The Nicolelis lab has developed a system that continuously estimates hand position based on signals recorded from neurons in motor areas of the cortex of behaving primates. The Touch Lab has developed software that uses these signals to control a robot manipulator (Phantom, Sensable Technologies) in real time. Accurate, real-time predictions of one and three dimensional arm movement trajectories have been demonstrated in two monkeys at Duke. In addition, cortically derived signals were successfully used for real-time control a robot manipulator locally at Duke and remotely at MIT via the Internet.

Over the last year, hardware has been added to this system to close the sensory-motor loop. A PC-controlled, 16-dof vibrotactile display has been developed in the Touch Lab. The Nicolelis group is now using the display to provide primates with tactile feedback correlated with position of the robot manipulator.

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[3] Duke University Department of Neurobiology

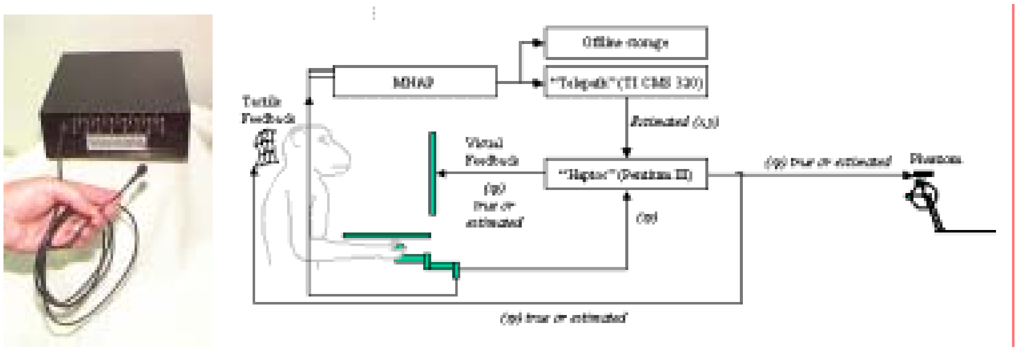


Figure 3-1: Vibrotactors developed at the MIT Touch Lab (left) are placed on the skin of primates at Duke University. The tactile feedback will be used to signal position of a remote manipulator controlled by the primate's cortical output during a planar positioning task (right).

4. Laparoscopic surgical simulation using visual and haptic feedback

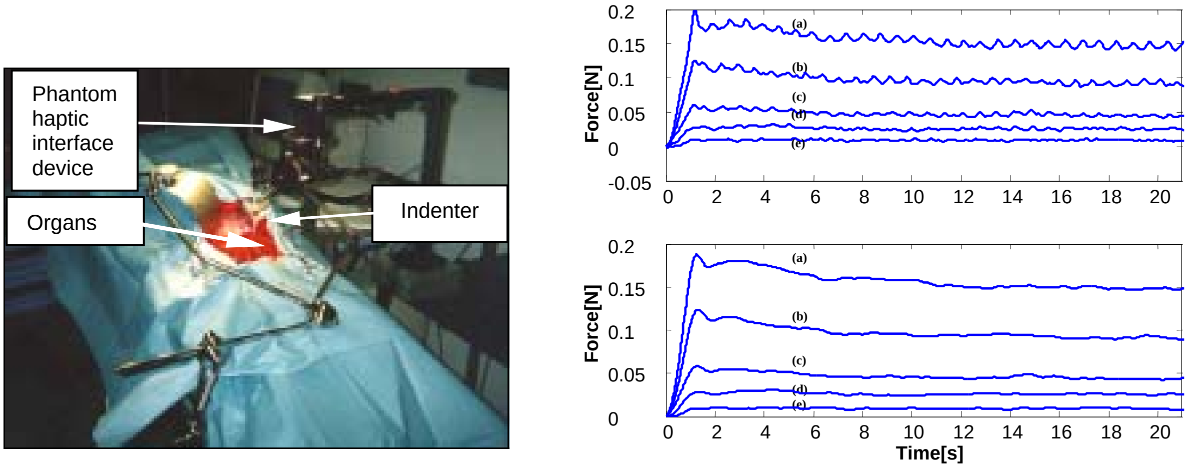
Sponsor
Harvard Center for Minimally Invasive Surgery and Massachusetts General Hospital

Project Staff
Mandayam A. Srinivasan (PI), Suvranu De, Hyun Kim, Jung Kim, Manivannan Muniyandi, Edmand C Prakash, and Boon Tay

Introduction

Although it has been recognized that virtual reality based surgical simulation can serve as a powerful aid in medical training, serious research on several fronts is needed to make this cutting edge technology useful in practice. For the past few years, we have investigated many of the major research problems such as biomechanical characterization of organs and tissues, methods of simulating tool-tissue interactions in real-time, haptic and graphical rendering of medical procedures, and optimal methods for effective training. We are currently using Heller myotomy procedure as the context to address these issues. For example, realistic simulation of tissue cutting, bleeding, and ablation are important components of a surgical simulator that will be addressed in this project. In the sections below, we provide a summary of our work done over the past few years.

Biomechanical characterization of intra-abdominal organs
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. As a first step towards characterizing the mechanical behavior of organs, we have performed preliminary *in-vivo* force-displacement characterization of the liver and lower esophagus of pigs when subjected to ramp and hold, and sinusoidal indentations delivered using a haptic feedback device, Phantom, employed as a mechanical stimulator. Our experimental setup is shown in Figure 4-1.



(a) (b)

*Figure 4-1***:** *Experimental setup for tissue property measurement of liver and lower esophagus of pigs is shown in (a). 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 the indenter attached, was then lowered into the abdominal region and experiments performed. In-vivo force response from the lower esophagus to ramp and hold stimuli under displacement control is presented in (b) where the different legends are as follows: (a) velocity of indentation=8mm/s, depth of indentation=8mm; (b) velocity of indentation=6mm/s, depth of indentation=6mm; (c) velocity of indentation=4mm/s, depth of indentation=4mm; (d) velocity of indentation=2mm/s, depth of indentation=2mm; (e) velocity of indentation=1mm/s, depth of indentation=1mm. Raw data is shown in the top panel and data with the effect of pulse on force response removed is shown in the bottom panel.*

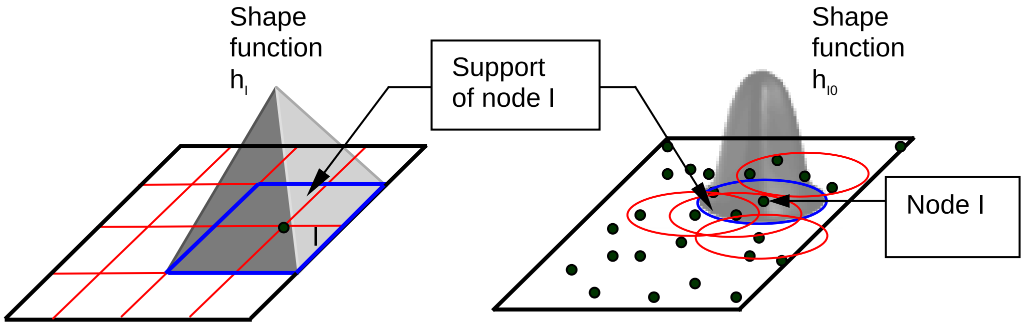
The results show that (1) pulse and breathing affect the tissue reaction forces significantly, (2) organs exhibit nonlinear viscoelastic characteristics (evidenced by force relaxation corresponding to a fixed displacement stimulus and hysteresis during sinusoidal excitation), and (3) the lower esophagus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

Meshless Simulation Techniques for Surgery

Only polygonal models have been used previously for modeling anatomical objects in surgical simulations. When the polygon size becomes the size of a pixel, connectivity information stored for each polygon becomes redundant and verbose. We now use a “point based” method, which is a meshless method of modeling objects.

Traditionally, Finite Element Method (FEM) is used for the underlying mechanistic computations in surgical simulations. Although FEM model can simulate static and dynamic deformations, the high computational cost and the requirement of maintaining high haptic update rate forced 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 a numerical technique that does not use a mesh. The method of finite spheres (MFS) that we have developed is one such “meshless” computational technique. The method of finite spheres has been accepted by the Computational mechanics community as a robust and efficient numerical tool for the solution of solid mechanics problems without using a computational mesh.

In the method of finite spheres, 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 (see figure 4-2). Just as in the 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). A comparison of the two techniques can be seen pictorially in figure 4-2.



(a) Finite element method (b) Method of finite spheres

Figure 4-2: Discretization of a domain in R^2 by the finite element method (a) and the method of finite spheres (b). In (a) the domain is discretized by quadrilateral elements with a node at each vertex point. The finite element shape function h_I is shown at node I. In (b) the domain is discretized using a set of nodes only. Corresponding to each node I, there is a sphere (i.e. a disk in R^2), centered at the node, which is the support of a set of shape functions corresponding to that node. One such shape function, h_{I0}, is shown in the figure.

Tasks for laparoscopic surgical simulation

Cutting based on Point based models: Traditionally, cutting task is defined and simulated as splitting polygonal surfaces along a collection of marked edges and vertices. The first stage in the haptic rendering of cutting operation involves finding the point of contact or collision detection. Collision detection algorithms available in the literature are only for polygonal meshes. Haptic rendering or collision detection algorithms for point-based models are not known. We have developed a Z-buffer based collision detection technique for point-based models.

Once collision is detected the tissue is deformed using the method of finite spheres. When the reaction force at the tool tip exceeds a critical value, the tissue is cut. Since point-based models do not have this connectivity information, we have developed special algorithms to find the neighboring points and move those points accordingly. After the tissue is cut, the layer beneath the surface is visible and the points are splat-rendered.

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.

After that the distance from the predicted points on the organ to the tool tip is 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 force feedback device.

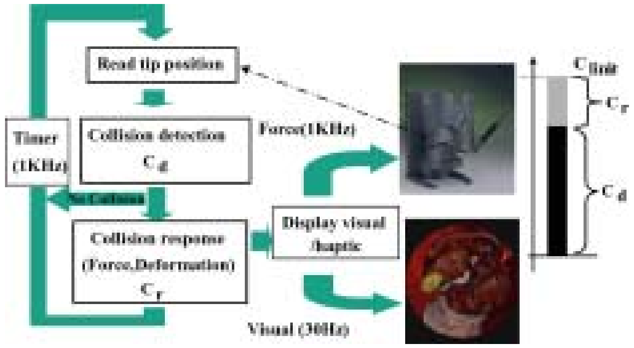


Figure 4-3: Collision detection for polygonal mesh

Multi-rate rendering
The rendered force from a scene is displayed through a force feedback device to the user. The requirement of the force update rate for stable real time interaction is pretty high. The majority of force feedback devices are capable of at least a few hundred Hz update rates, which is comparably larger than the visual frame update rate. Also there is large difference between the update rate the devices are capable of and the update rate of computations that ensure physically realistic behavior. Consequently, we should consider a multi-rate rendering scheme, especially when multiple sensory modalities are involved. The simplest way to generate data with a higher update rate from the set of given data is to use the latest value of given data for the current one. Although this approach is simple and can prevent the application of large forces exceeding the limit of the device, it may provide stepwise forces, which make the users feel discontinuity of 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 polynomial is

needed because too high order of polynomial may generate peak value (extrapolation) or oscillation (interpolation). In rendering of deformable anatomy, this multi-rate approach is essential because the physically based model computation of a deformable object is much slower than the update rate of the force feedback device. In a limit of slow tool motion, this approach generates continuous forces for the force feedback device.

Graphical Rendering for Surgical Simulations
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 rendering, we use splatting technique, a point-based rendering technique. A reconstruction kernel associated with each point, called footprint, determines contribution of that point in the image buffer. The significance of this work is that point based models in surgical simulations could be rendered realtime yet with lifelike visual effects, as described below.

Figure 4-4: Sphere mapped Esophagus

Glistening for Surgical Simulations: We believe that the visual realism is very important for surgical simulations. Current approaches for this effect use various texture mapping techniques. However, use of these techniques for deformable anatomical objects in surgical simulation has undesirable effects. Moreover, effects such as glistening which is characteristic in surgical simulations is very difficult to simulate using these techniques. We have used environment mapping techniques such as cube mapping and sphere mapping for glistening effects. The significance of the results is that deformation with glistening effect 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.

Training Effectiveness
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.

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