

Human and Machine Haptics

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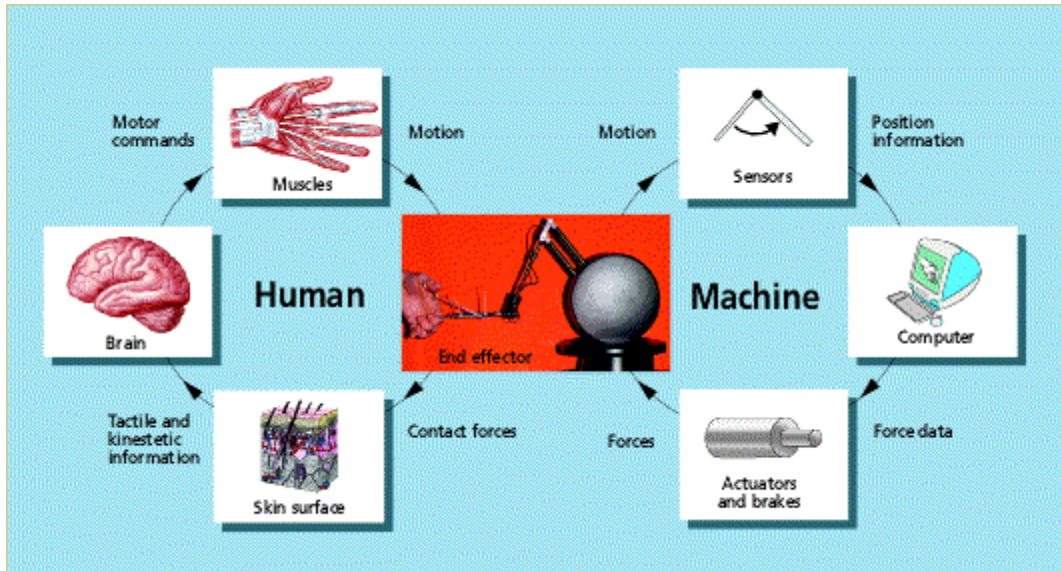
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Abstract

The work in the Touch Lab (formal name: Laboratory for Human and Machine Haptics) is guided by a broad vision of haptics which includes all aspects of information acquisition and object manipulation through touch by humans, machines, or a combination of the two; and the environments can be real or virtual. We conduct research in multiple disciplines such as skin biomechanics, tactile neuroscience, human haptic perception, robot design and control, mathematical modeling and simulation, and software engineering for real-time human-computer interactions. These scientific and technological research areas converge in the context of specific application areas such as the development of virtual reality based simulators for training surgeons, haptic aids for people who are blind, real-time haptic interactions between people across the Internet, and direct control of machines from neural signals in the brain.

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 following 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). Applications of this science and technology span a wide variety of human activities such as education, training, art, commerce, and communication.

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 novel tools for medical diagnosis and virtual reality based medical training. An exciting new area of research we have initiated is the development of direct brain-machine interfaces, using which we 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 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. The following sections present summaries of our work in the various research areas including descriptions of progress over the past year in our current projects.

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 Backscatter Microscope (UBM) 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.

1.1 Identification of relevant stimuli that trigger mechanoreceptor response

Relevant stimuli play a key role in the process of tactile neural encoding by mechanoreceptors embedded in the skin. The identification of the relevant stimulus in terms of the stresses, strains or a combination that triggers the receptor response is a vital step towards the successful understanding of neural mechanisms that underlie touch perception. Over the last year we did a study in order to identify the most appropriate one among 18 candidate mechanical stimuli. The study was carried out by using finite element simulation involving nonlinear contact mechanics together with analysis of data from previously completed neurophysiological experiments. The outcome demonstrates, as shown in figure 1.1-1, that there is a hierarchy in the appropriateness of the candidates that are suitable for representing the spatial neural response of primate SA-1 mechanoreceptors. Panel a of figure 1.1-1 shows that candidates E13, E12, E23, and S11 may be easily excluded since their patterns are far from the empirical neural response as displayed in panel c. EP2, SP3, SED, and E33, on the other hand, are much closer. E33 and SED (strain energy density) are especially close to the SA-1 spatial response, as shown in panel b. E33 even matches the sloping down feature of the initial stage of the curves of SA-1 recordings shown in panel c. If further analysis is consistent with this result, the indication is that transverse deformation around the neighborhood of mechanoreceptors might be the direct cause which triggers the generation of the neural signals of touch.

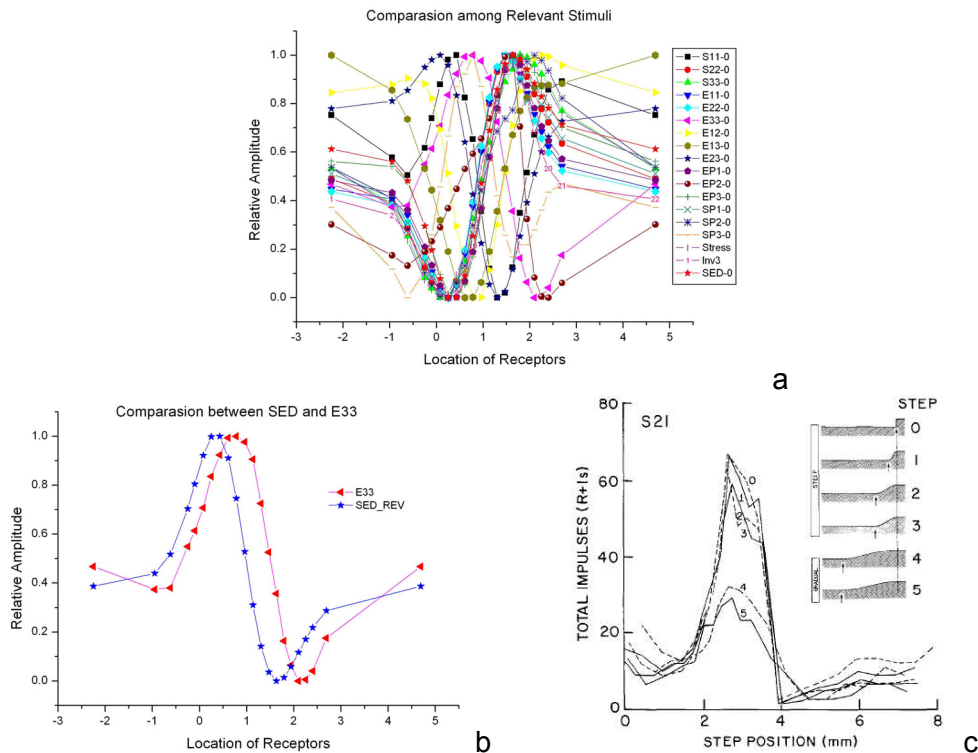


Figure 1.1-1 Spatial response profiles of SA-1 mechanoreceptors: (a,b) comparison among candidate relevant stimuli from finite element analysis, (c) empirical data for SA-1 response to step shapes.

2. Tactile Neuroscience

Tactile neuroscience is concerned with understanding the neural processes that underlie the sense of touch originating from contact between the skin and an object. Traditional studies have focused on characterizing the response of mechanoreceptors in the skin to various stimuli such as vibrating probes or indenting sharp edges. In contrast, we have tried to determine how object properties such as shape, microtexture, and softness, and contact conditions such as slip, are represented in the peripheral neural response.

Most of our work in this area has been done in collaboration with Dr. Robert H. LaMotte of the Yale University School of Medicine. In the experiments, microelectrodes monitor the discharge rate of tactile receptors in the skin of anesthetized monkeys while the surface of the skin is mechanically stimulated. Computer-controlled stimulators press and stroke carefully designed objects on the fingerpads. Frequently in conjunction with these neurophysiological measurements, we have also performed psychophysical experiments with human subjects using the same apparatus.

2.1 PDMS chip based cell culture of C.Elegans mechanoreceptors

Methods have already been developed by Christensen et al¹ (*) to culture C.Elegans embryonic cells that differentiate into mechanoreceptors. Current procedures mass produce these eggs by lysing a large number of gravid nematodes together and then separate out the eggs for differentiation. These procedures require the use of additional equipment (for centrifugation etc.) to help separate out the eggs from the resulting debris. Moreover, there is also not much control over the process. In our lab, experiments are underway to develop a quick and economical method to isolate eggs (embryos) from a single gravid C.Elegans nematode and differentiate them into mechanoreceptors using reusable PDMS micro fluidic chips.



Figure 2.1-1 The basic lysing process where C.Elegans is exposed to hypochlorite dissolving it and releasing eggs from the gravid nematode. We are developing ways to gain better control over this process through the development of PDMS chips.

3. 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.

¹ "A Primary Culture System for Functional Analysis of C. elegans Neurons and Muscle Cells." Christensen et al. Neuron, Volume 33, Issue 4, Pages 503-514

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.

4. 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.² 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 medical training.³ 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 neural signals in the brain.^{4 5}

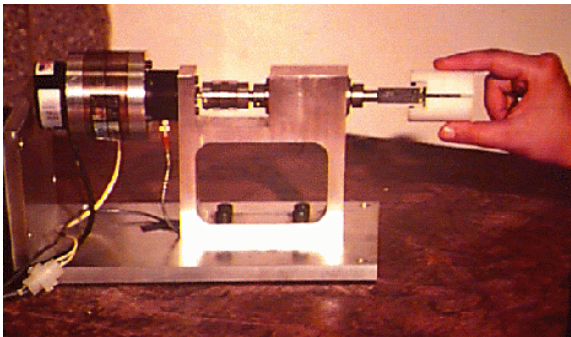


Figure 4 -1 Instrumented Screw Driver



Figure 4 -2 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 existing 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.

² 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.

³ 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.

⁴ 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.

⁵ Nicolelis MAL and Chapin JK, Controlling Robots with the Mind, *Scientific American*, 287 (4), pp 46-53, 2002.

5. 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.

5.1 Virtual environment technology to improve spatial perception of people who are blind

We have started to develop a virtual environment system that includes 3D haptic and audio feedback. Unfamiliar spaces can pose great difficulties for blind individuals and our hope is that the new system will allow blind users to interact with virtual models of real spaces in order to learn about them before actually going there in person. We also plan to use this system to explore how people who are blind explore virtual spaces, how they construct cognitive maps of unfamiliar spaces, and how they activate the cognitive maps in negotiating through the real space. This research is being done in collaboration with the Carroll Center for the Blind.

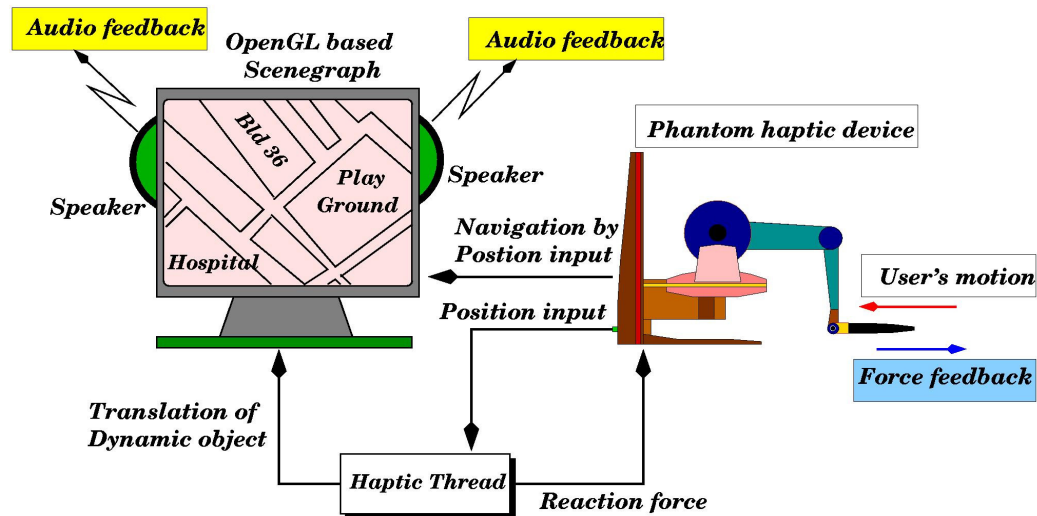


Figure 5.1-1 Hardware schematic of the virtual environment system.

Over the last year we completed development of an initial version of the application software and began our pilot experiments for determining optimal VE system parameters. The Windows XP application, which runs the system, is written in C++ using OpenGL, OpenHaptics (SensAble Technologies), and a custom audio library. Four participants took part in the pilot experiments, which involved a total of 18-24 hours per subject. These experiments included 18 virtual environments and four real spaces. During the tests the participants explored various components of the VE: haptic and 3D audio components; multi-scale environments (haptic zooming); and different exploration techniques. The last four tasks included exploration of virtual models of real indoor spaces unfamiliar to the participant. After the virtual environment exploration, each participant was asked to perform orientation tasks in the real space. We are currently analyzing the results.

5.2 Non-invasive brain-machine interfaces for robot-augmented human manipulation

The MIT Touch Lab, in collaboration with Dr. Miguel Nicolelis and others (Wessberg, Stambaugh, Kralik, Beck, Laubach, Chapin, Kim, Biggs, Srinivasan, and Nicolelis, 2000), demonstrated, for the first time, direct control of a robotic arm by a monkey through an *invasive brain-machine interface* (BMI). Because it may be many years before the Food and Drug Administration approves chronic implantation of invasive electrodes in human cortex, it seems appropriate to investigate *non-invasive* alternatives concurrently. To that end, the Touch Lab is investigating the practicality of non-invasive BMI using conventional brain imaging techniques. The work is being done in collaboration with Dr. Seppo P Ahlfors, Dr. Matti S Hamalainen, and Dr. Thomas Zeffiro at the Martinos Center for Biomedical Imaging.

In the current study we are using the 306 channel magnetoencephalography (MEG) system at the Martinos Center to read the neural signals of human subjects, with the goal of demonstrating real-time thought control of a robot. 64 channels of Electroencephalography (EEG) may also be observed simultaneously. Our long-term goal is to develop prostheses and other assistive robotic systems to aid individuals who are paralyzed or otherwise mobility-impaired.

Figure 5.2-1 presents the setup for our preliminary evoked response tests. The primary purpose of these tests is to identify the neural signals that may then be used to control a robot in a similar task in future experiments. We also plan to perform these tests using Magnetic Resonance Imaging (MRI). MRI will also be used to image the MEG subjects in order to improve analysis of the MEG data.

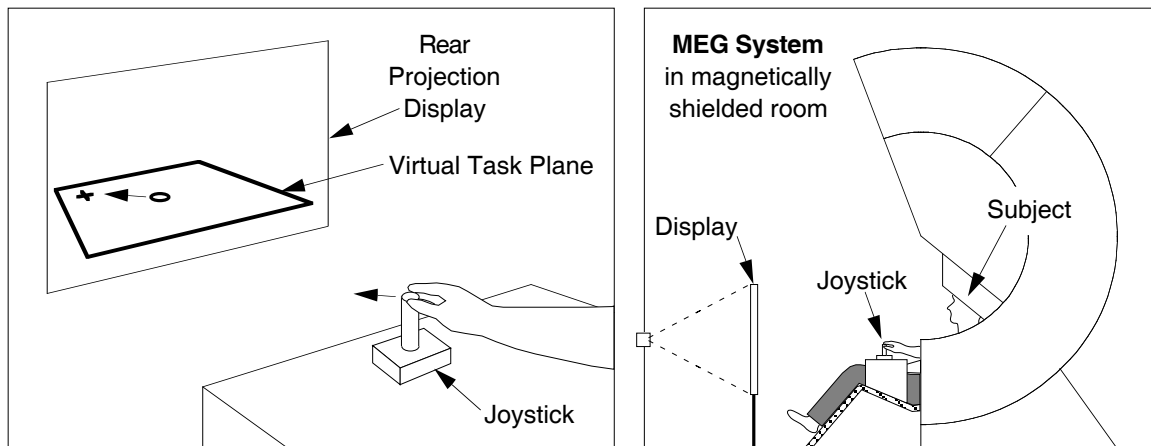


Figure 5.2-1 Experimental arrangement for initial evoked response tests. The subject's brain is scanned by MEG and EEG (right, EEG not shown) while he/she performs a two-dimensional position tracking task (left). The joystick controls the movement of the circle, a computer-generated graphic image on the display. The task is to move the circle to the location of the target cross.

5.3 Fitts' Law and human control of an electromyographic signal from the biceps brachii

Electromyography (EMG) has become a popular solution to the problem of controlling multi-axis prosthetic devices, however, many users are limited by the number of muscles which can be utilized for control. The limitation might be mitigated by partitioning a single EMG signal into multiple amplitude regions, each with its own function. For example, different EMG amplitudes might correspond to different grip forces. We speculated that Fitts' Law would provide a useful model for relating the widths, range and response times associated with the partitioning of a single, uni-dimensional signal. The applicability of Fitts' Law to user control of an EMG signal was tested by measuring the time needed for users to move their EMG signal between two targets on a computer screen. This was done under a range of conditions consisting of different amplitudes

(magnitudes of the EMG signal) and tolerances (widths of the target region). The response times were plotted as a function of task difficulty as defined by Fitts' Law (see Figure 5.3-1) and a linear model was fit to the data points.

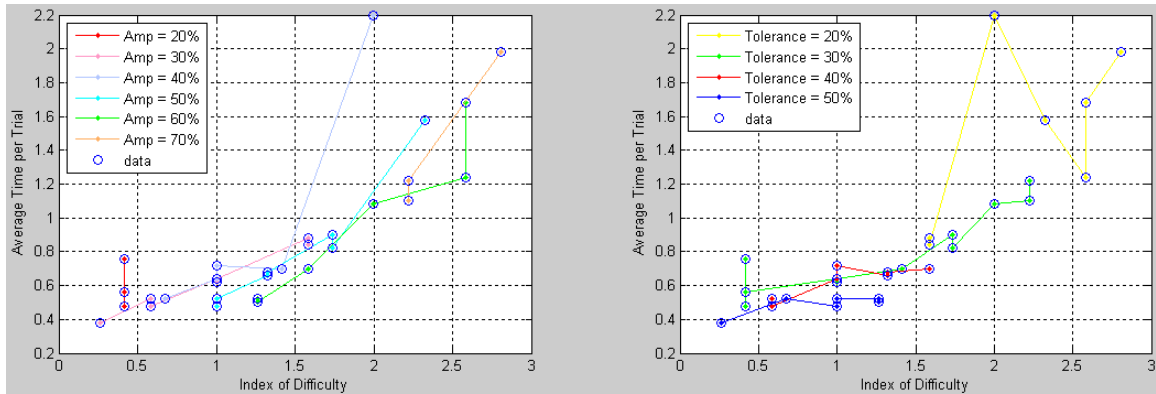


Figure 5.3-1 Sample data for one test of one subject showing the average movement times vs. index of difficulty. The same data is shown in both graphs differentiated by amplitude (left) and tolerance (right). Each data point corresponds to a different combination of amplitude and tolerance in units of % where 100% was the subject's maximum voluntary contraction measured at the start of the test.

The results of the experiment were consistent with Fitts' Law for five out of the six human subjects who participated in the tests. Specifically, the data for the five subjects agreed with Fitts' linear model with correlation coefficients ranging between 29% and 72%. In the case of the sixth subject, however, there was essentially no relationship between the average movement time and Fitts' index of difficulty. One explanation for why the results of the sixth subject did not obey Fitts' Law might be that she adopted a special "strategy" in how she performed the experimental task. Future testing should include more extensive training in order to avoid the use of such strategies and, in general, variability in the results might be reduced through better experimental controls.

6. 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. 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 has been exhibited at the Boston Museum of Science where the general public were able to experience the feel of performing a 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).

Publications

Journal Articles, Published

Choeng J, Niculescu S-I, Annaswamy AM, and Srinivasan MA, Synchronization Control for Physics-based Collaborative Virtual Environments with Shared Haptics, *Advanced Robotics*, Vol. 21, No. 9, pp. 1001-1029, 2007.

De, S., Lim, Y.-J., Manivannan, M. and Srinivasan, M.A., Physically realistic virtual surgery using the point-associated finite field (PAFF) approach, *Presence*, Vol. 15:3, 2006.

Kim HK., Biggs J., Schloerb DW., Carmena JM., Lebedev MA., Nicoletis MAL. and Srinivasan MA, Continuous Shared Control for Stabilizing Reaching and Grasping with Brain Machine Interfaces, *IEEE Transactions on Biomedical Engineering*, Vol. 53, No. 6, pp. 1164-1173, 2006.

Kim H.K., Carmena J.M., Biggs S.J., Hanson T.L., Nicoletis M.A.L., and Srinivasan M.A.. The muscle activation method: An approach to impedance control of brain-machine interfaces through a musculoskeletal model of the arm. *IEEE Transactions on Biomedical Engineering*, 54(8), pp. 1520-1529, 2007.

Kim J, Choi C, De S, and Srinivasan MA, Virtual Surgery Simulation for Medical Training Using Multi-resolution Organ Models, *The Intl. Journal of Medical Robotics and Computer Assisted Surgery*, Vol. 3, pp. 149-158, 2007.

Kyung K, Ahn M, Kwon D-S, and Srinivasan MA, A Compact Planar Distributed Tactile Display and Effects of Frequency on Texture Judgment, *Advanced Robotics*, Vol. 20, No.5, pp. 563-580, 2006.

Lahav, O. and Mioduser, D. "Construction of Cognitive Maps of Unknown Spaces using a Multi-sensory Virtual Environment for People who are Blind." *Computers in Human Behavior*, in press.

Lahav, O. and Mioduser, D. "Haptic-Feedback Support for The Cognitive Mapping of Unknown Spaces by People who are Blind." *International Journal of Human-Computer Studies*, in press.

Liu Q, Prakash, EC, and Srinivasan MA, Interactive Deformable Geometry Maps: Efficient modeling for interactive deformation of non-rigid 3D objects, *The Visual Computer*, in press.

Tan HZ, Srinivasan MA, Reed CM and Durlach NI, Discrimination and Identification of Finger Joint-Angle Position Using Active Motion, *ACM Transactions on Applied Perception*, in press.

Tay BK, Kim J and Srinivasan MA, In Vivo Mechanical Behavior of Intra-Abdominal Organs, *IEEE Transactions on Biomedical Engineering*, Vol. 53, No. 11, 2006.

Meeting Papers, Published

Bolzmaacher C, Biggs J and Srinivasan MA, Flexible Dielectric Elastomer Actuators for Wearable Human Machine Interfaces, Proceedings of the SPIE, Vol. 4699, 2006.

Yang G-H, Kyung K-U, Srinivasan MA, and Kwon DS, Development of Quantitative Tactile Display Device to Provide Both Pin- Array-Type Tactile Feedback and Thermal Feedback. Proceedings of the Second World Haptics Conference, Tsukuba, Japan, pp. 578-579, 2007.

Theses

Kumar, S. *Design and Fabrication of an Optical Pressure Sensor for Skin Mechanics Studies*, S.M. Thesis, Dept. of Mechanical Engineering MIT, December 2006.

Chapter 20. Human and Machine Haptics

Kimberly L. Harrison, *Fitts' Law and Human Control of an Electromyographic Signal from the Biceps Brachii*, S.B. Thesis, Dept. of Mechanical Engineering, MIT, May 2007.