Laboratory for Human and Machine Haptics: The Touch Lab

Academic and Research Staff
Dr. Mandayam A. Srinivasan, Dr. Orly Lahav, Dr. Gang Liu, Dr. David W. Schloerb

Visiting Scientists and Research Affiliates
Dr. Jianjuen Hu

Graduate and Undergraduate Students
Siddarth Kumar, Manohar Srikanth

Sponsors
National Institutes of Health (NINDS) – Grant RO1-NS33778
National Institutes of health (NEI) – Grant 5R21EY16601-2
Honda Initiation Grant 2006

Abstract

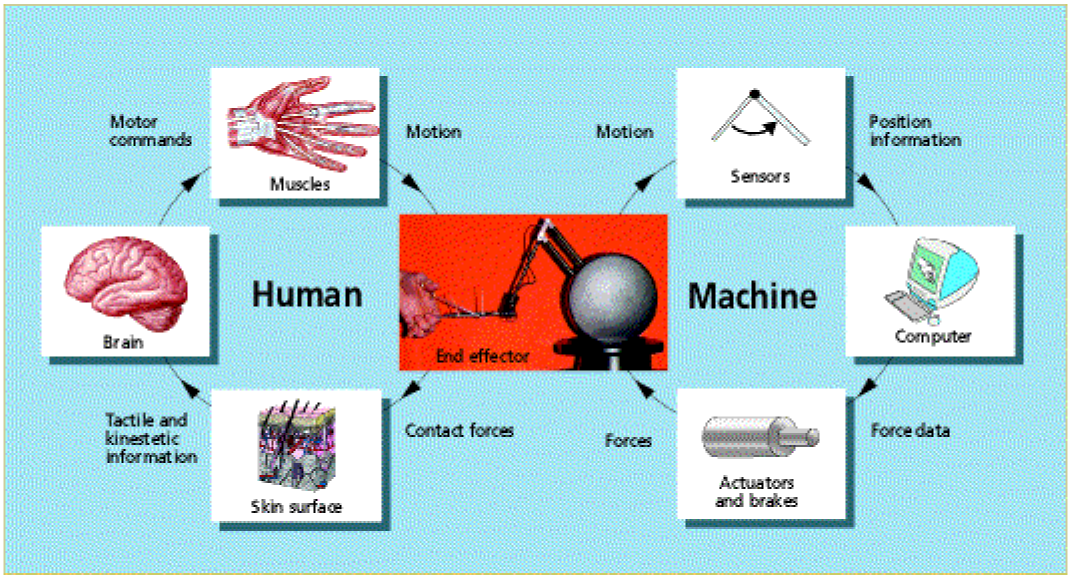
The work in the Touch Lab (formal name: Laboratory for Human and Machine Haptics) is guided by a broad vision of haptics which includes all aspects of information acquisition and object manipulation through touch by humans, machines, or a combination of the two; and the environments can be real or virtual. 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.

Key Words

Haptics, touch, skin biomechanics, tactile neuroscience, haptic psychophysics, human-computer interactions, virtual reality, medical training, brain-machine interfaces

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. Verifications 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 Characterization of Primate Skin Viscoelasticity by Single Point Indentation

The biomechanics of skin and underlying tissues plays a major role in the sense of touch in humans and primates. To develop a quantitative understanding of how spatio-temporal loads imposed on the surface of the skin are transmitted to mechanoreceptor locations within the skin, it is imperative to fully understand and characterize the mechanical properties of skin and its underlying tissues. Estimating mechanical properties of tissues presents significant challenges. Due to the difficulties in isolation of biological tissue specimens along with the challenges in preserving mechanical integrity of tissues in vitro, it becomes necessary characterize material properties using non- destructive in vivo methods.

In the recent past, the MIT Touch lab has developed two and three dimensional finite element models of the human and primate fingertip with realistic external geometry and internal layered structure of the skin and subcutaneous tissues (Srinivasan and Dandekar, 1996; Dandekar, Raju and Srinivasan, 2003). These models, developed to gauge the role of skin biomechanics in tactile response, were developed using a linear elastic model for the skin tissue where a Poisson's ratio of 0.48 was used (considering the tissue to be almost incompressible). The Young's moduli of the different layers were obtained by matching numerical experiments with available empirical data.

These structurally precise finite element models can be further improved by incorporating more precise material models of skin tissues, particularly that of skin ridges and grooves. For this purpose, we studied and characterized the viscoelastic properties of primate fingerpads by accurately characterizing the force-time behavior of different fingerpads in response to static micro-indentation in vivo. We also compared the variation of material properties across different fingers of an anaesthetized primate using a calibrated single point indentation apparatus.

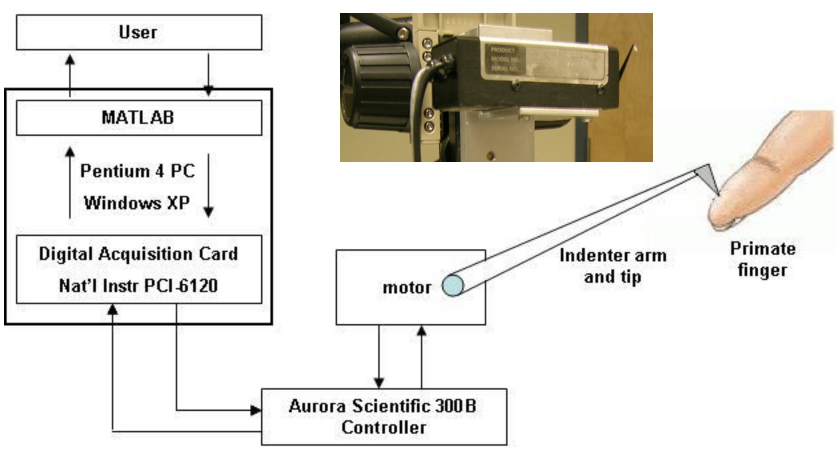


Figure 1.1-1*: (a) A Schematic of the setup used for characterizing the viscoelastic properties of the primate fingerpad. The inset figure shows the custom designed cantilevered indenter used for the experiments.*

The indentation apparatus consisted of an Aurora Scientific Series 300B Dual-Mode Lever Arm System (Aurora Scientific Inc.), a custom designed indenter setup consisting of 3 cm cantilevered indenter lever arm with a 0.5 mm diameter circular indenter tip, a computer equipped with a digital acquisition card (National Instruments PCI-6120) with MATLAB as the programming language. A custom program (MATLAB) was written to control the position characteristics of the motor (lever) while measuring and recording the force response at the indenter tip.

Indentation experiments were performed on each of the five fingers of the primate. The indentation stimuli consisted of a displacement step. The step stimuli consisted of a hold (2 seconds) followed by a steep ramp (500µm/s) indentation to a desired depth (20, 40, 60 or 80 µm) followed by a hold (7 seconds) and then another withdrawal ramp until the indenter leaves contact with the finger. For each finger, five independent static indentation experiments were performed at each of the four indentation depths (20µm, 40µm, 60µm and 80µm). During each experiment, the force response of the finger was measured and tabulated. Five independent experiments were conducted at each indenter depth for each finger.

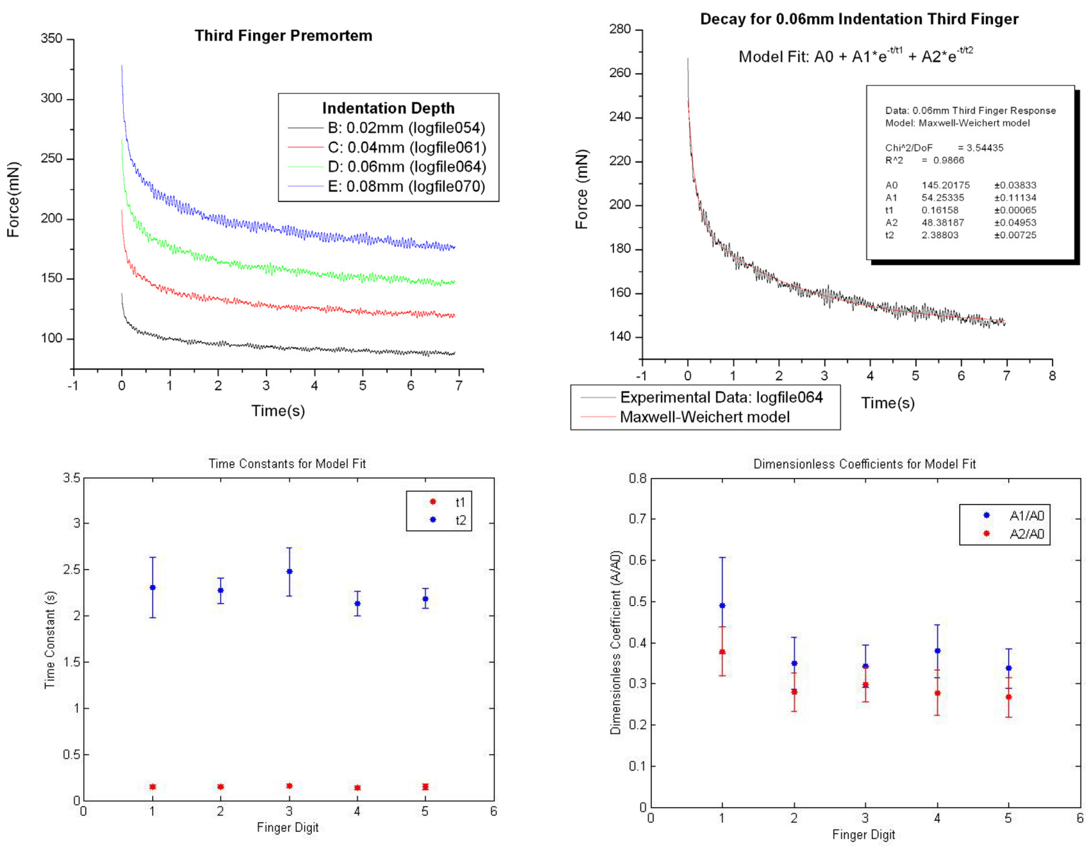


Figure 1.1-2: *Model fits (a) shows the variation of the two exponential decay parameters across all 5 fingers (b) shows the variation of the dimensionless coefficients across all 5 fingers, it is to be noted that each point represents n=19 readings while the index finger (1) observations has n=10. The finger digit represents 1.Index Finger 2. Middle Finger 3.Third Finger 4.Smallest Finger 5.Thumb*

A variation of the Maxwell-Weichert model comprising of a linear stiffness function and a bi-exponential stress relaxation function is proposed to describe the behavior of the different fingers. This single model successfully described the force displacement behavior of all the fingers of the primate to different indentations. In order to compare the response of different fingers for each of the observations, we determine the model fit parameters; the exponential decay parameters $t_1$and t_2, the quasi static force parameter A_0 and dimensional coefficients A_1/A_0 and A_2/A_0 for each of the different fingers at different indentation depths. Each experimental data set was fitted with the above mentioned model and fit parameters were extracted and tabulated. A summary of the results is shown in figure 1.1-2.

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.

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.

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.[1] In the experiment, subjects held the handle of the computer-controlled device in a pinch grasp and overcame a preprogrammed resistive torque to rotate the handle. Other devices, like the Epidural Injection Simulator (see photo), have been developed in the lab to augment medical training.[2] Using this device, the trainee manipulates a syringe and feels realistic forces as he or she attempts to position the needle and inject a fluid. Another example of augmenting performance is on the development of machines that can be directly controlled by neural signals in the brain.[3] [4].

---

[1] Jandura L and Srinivasan MA, Experiments on human performance in torque discrimination and control, in Dynamic Systems and Control, Vol. 1, Ed: C. J. Radcliffe, DSC-Vol.55-1, pp. 369-375, ASME, 1994.

[2] Dang T, Annaswamy TM and Srinivasan MA, Development and Evaluation of an Epidural Injection Simulator with Force Feedback for Medical Training, Medicine Meets Virtual Reality Conference 9, Newport Beach, CA, January, 2001.

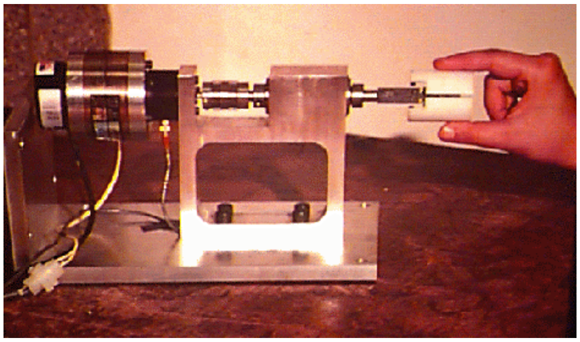


***Figure 4 -1** Instrumented Screw Driver*

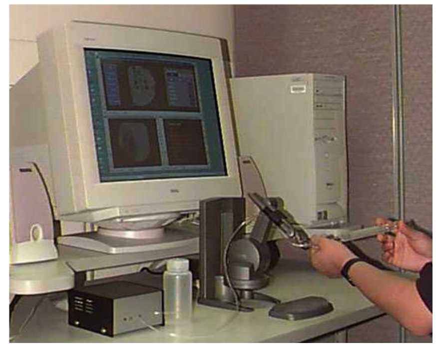


***Figure 4 -2** Epidural Injection Simulator*

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.

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 BlindAid: A Virtual Reality System that Supports Acquisition of Orientation and Mobility Skills by People who are Blind

Over the few past years, the MIT Touch Lab has developed and tested the BlindAid system that combines 3D audio and a haptic feedback. The users interact with virtual environments (VEs) through a haptic interface that enables users to touch and feel a VE through a hand-held stylus. The goal of the project was to develop a user friendly system which allows people who are blind to explore and build cognitive maps of unknown virtual spaces through haptic exploration supported with audio feedback.

The system consists of a software package that we developed to provide a VE for people who are blind and a hardware station, which consists of a haptic interface and audio feedback devices, in addition to a visual display for the experimenter. The haptic interface allows the user to interact with the VE and provides two functions: it moves the avatar through the VE and it provides force feedback to the user that gives clues about the space, similar to those generated by the white cane (Figure 1). In the study we used the Phantom (SensAble Technologies) as the haptic interface that presents high fidelity in force generation and position tracking for the user.

---

[3] Wessberg J, Stambaugh CR, Kralik JD, Beck P, Laubach M, Chapin JK, Kim J, Biggs SJ, Srinivasan MA and Nicolelis MAL, Adaptive, real-time control of robot arm movements by simultaneously recorded populations of premotor, motor and parietal cortical neurons in behaving primates, Nature, Vol. 408, No. 6810, pp. 361-365, 2000.

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

Over the last year, we performed experiments to determine the robustness of the developed system in order to gauge its usability and effectiveness in helping blind users build cognitive maps and traverse unknown real spaces after training on the system. These usability experiments were focused on the effectiveness of haptic and the auditory feedback as well as user navigation tools. In addition to this, the user's ability to explore the VE, to construct a cognitive map, and to apply this new spatial knowledge in his orientation tasks in the real space were also tested.

The results showed that the participants preferred to keep the haptic interactions with solid objects simple so as to cause minimal confusion as it involved assimilating less information. Adding stereo audio feedback to haptic feedback helped users remain in an absolute frame of reference while exploring the virtual environment. On the other hand, gathering information through haptic and mono-audio feedback added an additional variable that the participants needed to track: the users had to keep track of their orientation at the time he/she interacted with any objects in the VE.

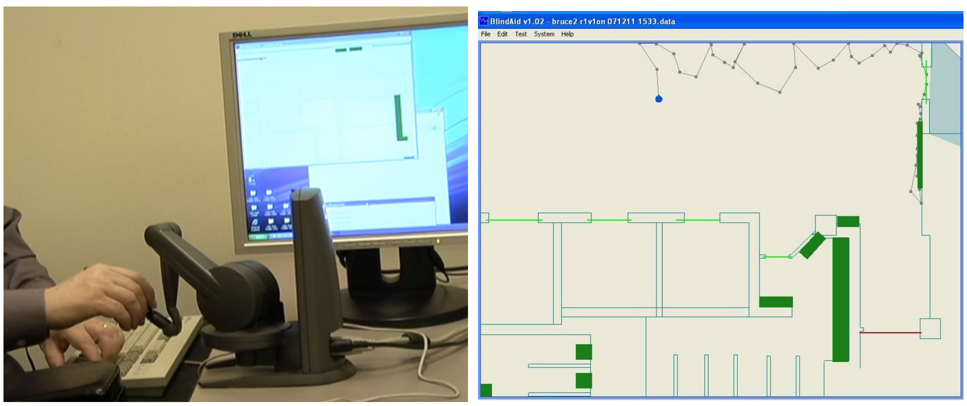


Figure 5.1-1*(a) BlindAid user's interface (b) shows the UI of a virtual environment used in the usability tests. The visual interface helps the experimenter conduct the experiments.*

It was also seen that complex user interfaces as well as complex haptic and audio feedback leads to confusion in the participants due to an overload of information. Gathering information effectively while exploring new spaces in a comprehensive manner is a prerequisite for the construction of useful and effective cognitive maps of these spaces. It also improves the ability of people to navigate these spaces. While walking in a real space, a strategy used by blind subjects who are confident of their environment is the object-to-object strategy, reported in previous research as a strategy frequently used by successful navigators (Golledge, Klatzky & Loomis, 1996; Hill, et al., 1993; Lahav & Mioduser, 2008).[5] [6] [7]

[5] Golledge, R.G., Klatzky, R.L., Loomis, J.M., 1996. Cognitive mapping and wayfinding by adults without vision. In: Portugali, J. (Ed.), The Construction of Cognitive Maps. Kluwer Academic Publishers, Netherlands, pp. 215–246.

[6] Hill, E.W., Rieser, J.J., Hill, M.M., Hill, M., Halpin, J., Halpin, R., (1993).How persons with visual impairments explore noval spaces: strategies of good and poor performers. Journal of Visual Impairment and Blindness 87 (8), 295–301.

[7] Lahav, O. & Mioduser, D. (2008). Haptic-Feedback Support for The Cognitive Mapping of Unknown Spaces by People who are Blind. International Journal of Human-Computer Studies, 66(1), 23-35.

Figure 5.1-2 *(a) Blueprint of the Carroll Center for the Blind campus (b) map of the campus from maps.live.com (c) a preliminary VE of the campus constructed from the above two maps*

The object-to-object strategy represents higher spatial skills of the participants. It was seen that when participants explored the VE primarily by perimeter strategy and by systematic exploration, the researchers could predict what their navigation will be in the real space, the resulting cognitive maps built by them were also better. This was also reflected in the participants' performance when they were taken to the actual space and assigned tasks). The participants relied less on spatial aids such as walls, walked in the middle of the corridor, using only audio landmarks (e.g., a recess area) while completing their tasks indicating a more complete awareness of their surroundings as a result of a better built cognitive map during exploration on the VR system.

The second stage of the project, which was done in collaboration with the Carroll Center for the Blind, a private, non-profit rehabilitation center based in Newton MA, was focused on integrating the BlindAid system with the traditional Orientation and Mobility (O&M) rehabilitation program taught at the Center. During this phase, we designed an experiment protocol, built ten VEs which represented three main buildings at the Carroll center campus along with the outdoor and surrounding area of the center. The ten virtual environments were built based on the blue prints of the buildings and the surrounding area along with available online maps (maps.live.com) (figure 5.1-2). Fifteen participants took part on this study.

During this second study, the participants at the Carroll Center explored the VEs using various tools provided by the BlindAid system which included haptic and 3D audio aids; multi-scale environments (that enables haptic zooming to help the user feel the size of the objects at different scales); and by using different exploration techniques. After each exploration of a virtual environment, the subjects were asked to describe the environment and to perform five orientation tasks in the real space. Results of these experiments are being analyzed. Additional research and development efforts will enable transformation this promising technology into a useful diagnostic tool that will allow a researcher or an O&M teacher to be able to track and observe participants during their exploration while gaining insight into improving training procedures. In addition to this, the BlindAid system can be used to train O&M teachers.

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)[8], 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 techinques. Our long-term goal is to develop prostheses and other assistive robotic systems to aid individuals who are paralyzed or otherwise mobility-impaired.

Over the last year, we did two preliminary experiments in collaboration with Dr. Seppo P Ahlfors, Dr. Matti S Hamalainen, and Dr. Thomas Zeffiro at the MGH/MIT/HMS Martinos Center for Biomedical Imaging. The experiments were carried out with the approval of both MIT and MGH human subject internal review boards. In both tests, we used the 306 channel magnetoencephalography (MEG) system at the center to observe the evoked responses of a single human subject while he performed hand-eye tasks (see Figure 5.2-1). 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.

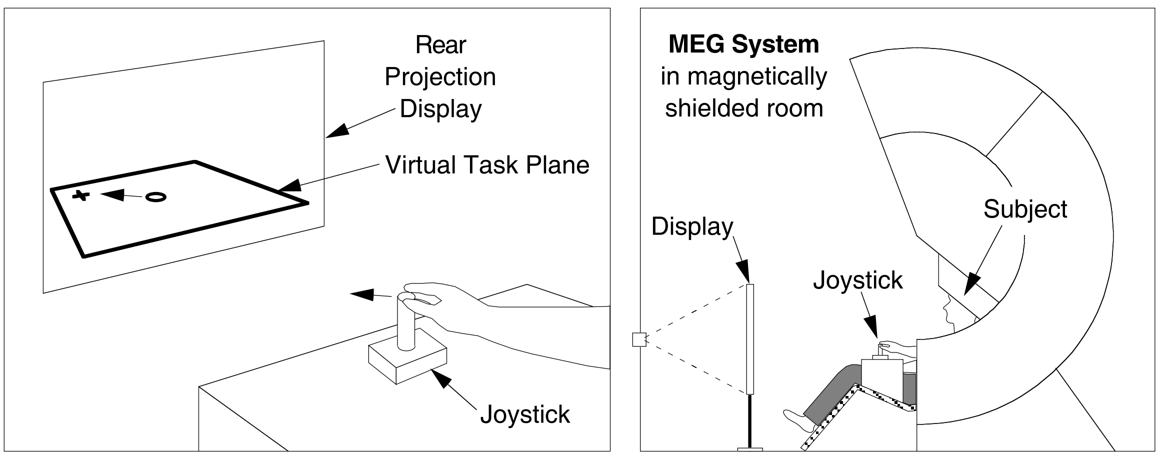


Figure 5.2-1 *Experimental arrangement for initial evoked response tests. The subject's brain is scanned by MEG (right) while he performs a two-dimensional position tracking task (left). In the illustration, the joystick controls the movement of the circle, a computer-generated graphic image on the display, and the task is to move the circle to the location of the target cross. Note that the actual tests used the same setup, but with slightly different tasks (see text).*

Our first test was based on the work of Georgopoulos et al. (2005)[9]. Specifically, the subject's task was to trace a pentagon on the computer display and we attempted to predict the time-sampled joystick coordinates from the MEG data. Our test involved 2 runs of ten 45-sec segments. In both runs, the segments alternated with the subject actively tracing the pentagon in the first 45-sec segment of the run, then sitting still during the second segment, then actively tracing again in the third, and so forth.

[8] Wessberg, J., Stambaugh, C.R., Kralik, J.D., Beck, P.D., Laubach, M., Chapin, J.K., Kim, J., Biggs, S.J., Srinivasan, M.A., Nicolelis, M.A.L. (2000). Real-time prediction of hand trajectory by ensembles of cortical neurons in primates. *Nature*. 408(6810):361-5.

[9] Georgopoulos, A.P., Langheim, F.J.P., Leuthold, A.C., Merkle, A.N. (2005). Magnetoencephalographic signals predict movement trajectory in space, Exp Brain Res, 25: 132–135

Our analysis to date includes only the data for the first 45-sec segment of each run. The X and Y coordinates were predicted separately using multiple linear regression. Figure 5.2-2 shows our results for run 1 based on the same run 1 training data. Our results for run 2 based on the run 1 training data are not as good although one can see some correlation between the actual and predicted values in that case. We expect the predictions may be improved with further analysis based on the results reported by Georgopoulos et al. (2005) and because we used a simplified version of their regression equations.

Our second test involved a radial tracking task as follows. At the start of each trial, the subject moved the cursor to a "home" box at the center of the display and then waited for a "go" signal. Two seconds prior to the go signal, a target appeared at one of 24 positions (8 directions x 3 distances) selected at random. At the go signal, the subject moved the cursor from the home to the target in a single quick move. The cursor disappeared during the move so that the subject would not be influenced by visual feedback while moving. The cursor reappeared as soon as the move ended and the endpoint was marked on the display briefly to give the subject feedback about his performance. The endpoint of the move was determined by the computer.

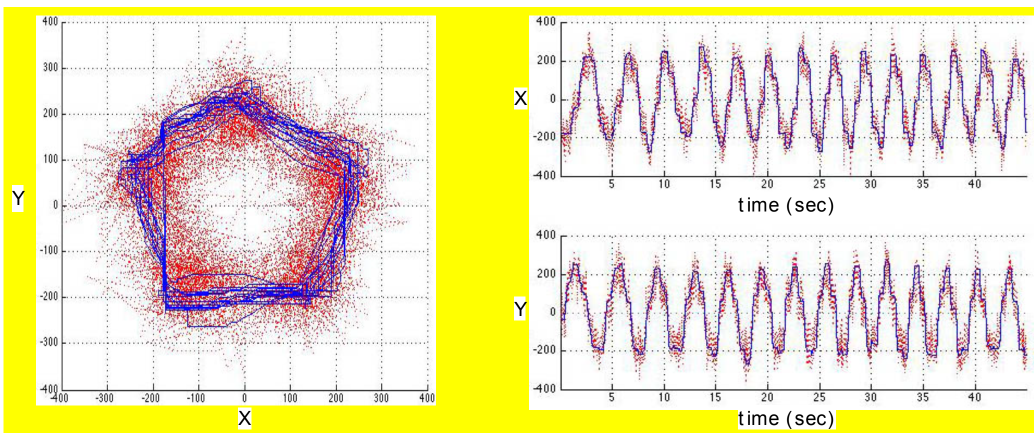


Figure 5.2-2. *Pentagon tracing test results with the actual (solid blue line) and predicted (red dots) X and Y values plotted against each other (Left) and as a function of time (Right). The X and Y values are in joystick units based on encoder counts.*

Figure 5.2-3 presents the arrangement of the display, showing the home, all the targets, and all the actual move endpoints for one run. The test consisted of 2 runs that differed only in the trial order. Each target was presented 10 times in pseudo-random order for a total of 240 trials per run. Predictions were made for individual “test” trials from the MEG data by partitioning “training” trials into bins over the range of the given quantity (Q) to be predicted. In each bin, the MEG data for all of the “training” trials in the bin were averaged together and the mean value of Q for the trials was used as the value of Q for the bin. The predicted value for a “test” trial was then equal to the Q value of the bin whose MEG data was most similar to the “test” MEG data.

Figure 5.2-3*. Arrangement of the radial test display on a X,Y coordinate graph (not seen by the subject). The home box at the center and all 24 targets are shown as black squares (not to scale). Only one target and/or the home were visible at any one time. Also shown are all the actual move endpoints in run 1 (blue diamonds). Only one endpoint marker was visible at a time, for 1 sec after the move ended.*

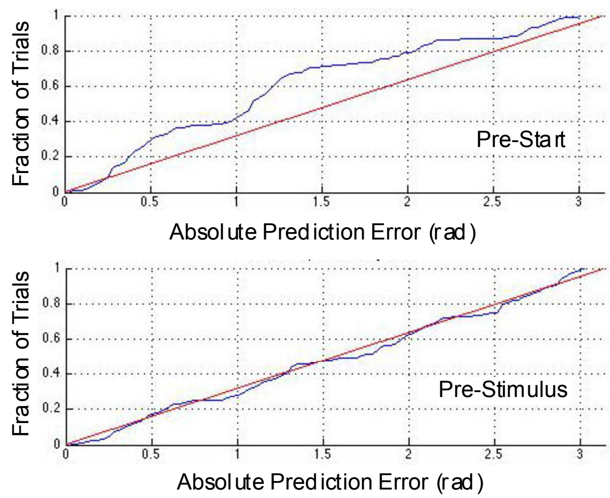


Figure 5.2-4*. Plot of absolute direction prediction error against the fraction of trials in which the error was less than the given value, similar to an ROC curve. The predictions are for run 2 based on training data from run 1. The top graph is based on MEG data immediately prior to the start of movement and the bottom graph shows a case when the subject had no knowledge about the target direction.*

Figure 5.2-4 shows the results of an 8-bin direction prediction for run 2 based on run 1 training data. The predictions are based on a 200 msec-long MEG data sample. Two sample periods were used. The "Pre-Start" sample was the 200 msec immediately prior to the start of movement when we expect there to be information in the MEG data about the subsequent movement. The "Pre-Stimulus" sample was prior to the appearance of the target on the display when there was no information available to the subject about the next move.

Due to the periodicity of direction and the large errors we observed, it was meaningless to simply plot actual vs. predicted direction. Instead, Figure 5.2-4 is a graph of the absolute prediction error vs. the fraction of trials within the given error. In this plot, like an ROC curve, the closer the actual (blue) curve gets to the upper left corner the better; a curve from (0,0) to (0,1) to (pi,1) would be the best possible prediction. The straight (red) line from (0,0) to (pi,1), on the other hand, corresponds to a random prediction.

As can be seen in the figure, the Pre-Start result is better than chance and the Pre-Stimulus result falls on the random prediction line. We think that this is clear evidence that direction information is available in the Pre-Start data. We are analyzing the data further at this time.

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

Lahav, O. & Mioduser, D. (2008). Haptic-Feedback Support for The Cognitive Mapping of Unknown Spaces by People who are Blind. International Journal of Human-Computer Studies, 66(1), 23-35.

Lahav, O. & Mioduser, D. (2008). Construction of Cognitive Maps of Unknown Spaces using a Multi-sensory Virtual Environment for People who are Blind. Computers in Human Behavior, 24, 1139-1155.

Book Chapters, In Press

Zimmer R, Jefferies J, and Srinivasan M.A., “Touch technologies and museum access,” In *Touch in Museums*, ed: Helen J. Chatterjee, (Berg Publishers, 2008)

Srinivasan M.A. and Zimmer R, “Machine Haptics,” in *New Encyclopedia of Neuroscience*, Ed: Larry R. Squire, (Elsevier Ltd., 2008)

Meeting Papers, Published

Lahav O., Schloerb D., Kumar S. & Srinivasan M. A. (2008), "BlindAid: A virtual exploration tool for people who are blind", 13th Annual CyberTherapy Conference June 23rd-25th 2008 in San Diego, CA

Lahav O., Schloerb D., Kumar S. & Srinivasan M. A. (2008). BlindAid: a Learning Environment for Enabling People who are Blind to Explore and Navigate through Unknown Real Spaces. Presented at Virtual Rehabilitation 2008, Vancouver, Canada.